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2002

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Multiple Material Selective Laser Sintering

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Multiple Material Selective Laser Sintering

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Dissertation

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Doctor of Philosophy

The University of Texas at Austin

December 2002

FORTITUDINE VINCIMUS – BY ENDURANCE WE CONQUER

– *Ernest Shackleton*

Family Motto

Acknowledgments

I would like to thank my advisor, Dr. Joseph J. Beaman for the continuous challenges and dynamic work environment he provided during my pursuit of this work. He fostered a creative freedom in the pursuit of this investigation, but also provided insight when necessary. Additionally, his financial support of this work was invaluable during the fabrication phases of the project. My sincere appreciation also goes to Dr. Kris Wood, my co-advisor. His enthusiasm and excitement for engineering was a constant source of motivation. I would like to extend thanks to the other members of the committee. Dr. Crawford provided assistance in the computational aspects of this work while Dr. Bourell offered helpful and insight observations regarding the various material issues which developed during this project. I would also like to show my appreciation of Dr. Barlow and Dr. Longoria for their professional support of my work.

I also sincerely appreciate Cindy Pflughoft for her hard work and assistance with the many issues that developed during the development of the hardware for this project. I would also like to thank the personnel in the machine shop; Don Artieschoufsky, John Pedracine, Curtis Johnson, and Danny Jares; for their invaluable work and technical assistance during the development and fabrication of the workstation. When time was tight, I always knew I could count on these dedicated individuals.

This work would not have been possible without the assistance of other students in our research group. Most importantly, I would like to offer my deep appreciation to Julie Perez for her hard work in the off-line development of the powder delivery sub-system. Her contribution was critical during the development of this project and

her efforts and friendship were a constant source of support. I would also like to thank Brad Jackson for his assistance with the mechanical drawings of the components. I owe a debt of gratitude to Dan McAdams for his design and development of the powder roller subsystem. I was also lucky to have Seok-min Park as my friend and officemate. His insights regarding the computational aspects of the project were extremely helpful. Cheerful in all weather, he was a constant source of support and assistance. Suman Das provided needed technical assistance and a deep understanding of the SLS process. Finally, I would also like to thank the undergraduate research assistants who provide needed help at critical times during the project: John Wing, Andy Deck, and Melissa Pro.

I also appreciate the conversations and companionship of my other officemates: Neal Lipman, Doug Watson, Cary King, and Seok-young Ahn. Also, thanks to my tailgating friends for the good times at the games and watching when Ricky went all the way: Joe, Doug, Lio, Pedro, Daniel, Alfredo, and Julie.

I also need to mention my many colleagues at Ford during my summer internships. They provided much needed financial support and an enriching experience that enhanced my abilities as an engineer and scientist. I would like to thank my colleagues in the Rapid Tooling group at SRL: Dawn White, Dan Wilkosz, Richard Allor, John Nicholson, and Bob McCune. I would also like to thank my colleagues in the Engine Processes group at SRL: Jagadish Sorab, James Kovach, Mike Schroder, and John Glidewell.

I gratefully acknowledge the financial assistance for this research from the National Science Foundation.

Finally, I would like to express my sincere thanks to my parents and my brother for their support and encouragement during my work.

LARRY RAY JEPSON

The University of Texas at Austin

December 2002

Multiple Material Selective Laser Sintering

Publication No. _____

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The University of Texas at Austin, 2002

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The components making up modern devices must in general fulfill functional requirements which vary spatially throughout the component and are satisfied by the properties of the materials making up the component. Thus, it is necessary to vary the material properties in a spatial sense to properly match the spatial variation in functional requirements. Since material properties are an intrinsic characteristic of the material composition, this desire translates to a need to vary the material composition based on the variation of the functional requirements.

This problem may be described in abstract terms as: *How to control the spatial variation of material properties in a component to match the corresponding spatial variation in functional requirements?* Recent developments in the field of Rapid Prototyping (RP) offer new opportunities to control material composition during fabrication. Selective Laser Sintering was chosen as the RP technology for further investigation. Specifically, a redesign of the current powder delivery subsystem will lead to the development of a new process, Multi-Material Selective Laser Sintering (M²SLS). A tungsten carbide / cobalt drill bit insert was selected from the petroleum industry as a specific component to narrow the scope of our problem. Thus, a specific hypothesis may be

given as: *The desired matching of material properties to functional requirements may be achieved via the fabrication of drill bit inserts containing functional gradients with the Multi-Material Selective Laser Sintering (M^2SLS) process.*

A set of feasibility experiments were conducted to gain insights into the behavior of material gradients during laser sintering. The creation of these samples represents the first fabrication of FGM samples using the traditional SLS process. Following this work, the M^2SLS workstation was designed and fabricated. This work represents a significant functional enhancement beyond the basic processing abilities of the traditional SLS process. Finally, a series of verification tests were conducted to ensure correct operation. Results predict the ability to deposit and laser sinter multiple materials to create a gradient of material composition. However, poor atmospheric processing control results in generally poor part quality similar to that experienced in the initial development efforts of traditional SLS.

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Chapter 1

Introduction and Hypothesis

Engineering can be fundamentally described as the controlled application of the basic physical laws of nature by mechanisms, or machines, for the enhancement of the functional capabilities of man. Therefore, the design and development of these mechanisms are driven by the functional requirements of the task which society desires to accomplish. For example, individuals wish to travel quickly to a desired location in comfort; thus, planes, cars, trains, etc. are developed. In general, all mechanisms can be broken down in successively simpler mechanisms until one reaches what is known as a component. In general, a component is simple static structure which does not move relative to itself. Just as a mechanism has functional requirements that it must fulfill, a component also has functional requirements. These functional requirements can be broken down into two broad categories.

The first of these categories consists of the functional requirement that the component must supply based on the functional needs of an interacting component. These type of functional requirements can be thought of as dealing primarily with the interface between two components. For example, the threads of a screw must supply a frictional force that holds the screw stationary with respect to the material in which the screw is placed. The second of these categories consists of functional requirements associated with the transfer of various physical phenomena through the inner volumes of the com-

ponent. Traditionally, this would consist of load paths through a mechanical component and associated stress fields. However, the requirement for the transmission of thermal energy through a component represents another example of this type of functional requirement. Thus, we see that a given component must fulfill a number of functional requirements and that these functional requirements are dependent upon the specific relative location on or within the component.

In general, a given functional requirement at a specific point in a component is satisfied by one or more properties of the material making up the component at the location of interest. For example, the load bearing function of points along a given load path are satisfied by the stress-strain properties of the material along the path. Thus, it is desired to have the material properties in a given component spatially vary in a manner so as to match the variation in the functional requirements. Since material properties are an intrinsic characteristic of the material, this desire translates to a need to vary the material composition in a component based on the spatial variation of functional requirements in a component.

1.1 Abstract Problem Statement

Thus, we arrive a problem encountered in the design and fabrication of generalized components: *How to control the spatial variation of material properties in a component to match the corresponding spatial variation in functional requirements?* Due to constraints in component fabrication technologies, most components are monolithic in material composition and have a uniform variation in material properties. The stated problem is then usually solved in one of two primary ways dependent upon the nature of the variation in functional requirements. The set of functional requirements can be such that they act in harmony so that one or material properties can satisfy all of the functional requirements without conflict. A simple structural component will possess a stress field that varies over the component with a maximum value of stress occurring at a given location. A material can usually be chosen so that maximum stress is absorbed

by the material without failure. In this case, the functional requirements at other locations in the component (*i.e.* the lower stress states) are also satisfied by the selected material. Thus, all the functional requirements are met with a sufficiently high value of a given material property. While all the functional requirements are satisfied, this part is not optimal in nature. Most locations in the component have material of excessive strength for the given local stress state.

The second, more complex, set of functional requirements do not act in harmony with respect to their satisfaction based on a set of corresponding material properties. These functional requirements are such that the set of corresponding material properties that act to satisfy them act in conflict. An example of this situation would be components that must withstand both abrasive wear and high dynamic, or shock, loads. These functional requirements are satisfied by the material properties of hardness and toughness, respectively. Thus, following the strategy used above, it is natural to select a very hard material to meet the functional requirements of abrasive wear. However, very hard materials are very low in ductility and, in general, do not resist shock loading. Thus, our material properties act in conflict; increases in hardness decrease toughness, and vice versa. It becomes very difficult to design and fabricate a monolithic material component that can meet functional requirements of high dynamic loads and resistance to wear. The traditional solution to this problem has been to separate the component into two monolithic components which each separately possess the desired material property and then bond the components together. Another solution to this situation is to attempt to vary the material composition to produce a non-monolithic component, for example, by coating the outer, or working, surface.

The traditional solution of creating separate components to meet different functional requirements generates a set of subsequent problems. In general, the creation of additional components increases the complexity of a given system which increases cost and decreases robustness. This increase in cost is primarily associated with the need to design and fabricate additional components. Also, extra components require the de-

velopment and use of a bonding process. In addition to the cost and complexity of the use of this bonding process, the presence of an interface generates additional functional requirements on the newly generated components. The new components must be able to interact and bond along the interface. The satisfaction of this bonding requirement is often difficult to fulfill due to unexpected and poorly understood physical phenomena present at interfaces.

Let us examine a simple clamping arm (Ref. Figure 1.1) as an example component. The traditional design must fulfill a number of functional requirements. The primary function of this component is to exert a force at the end of the arm. This basically translates to transferring a mechanical load from the end of the arm down the length of the arm into the base structure. As one moves down the arm toward the base, the bending moment exerted across the constant cross-sectional area of the arm increases and reaches a maximum at the base of the arm. Thus we have a functional load-carrying requirement that increases as one approaches the base of the arm. Additionally, at the base of the arm, a sharp corner is present. This corner acts to concentrate the stress field. The location of this stress-concentrating corner at the point of maximum load generates the point of maximum stress in the component. Thus, the functional requirement of “resist stress” is a maximum at one location in the component and possesses lower values at other locations.

The traditional approach is then used in which a maximum load to be supported by the arm is assumed followed by a calculation based on a given geometry to arrive at the maximum expected stress in the component. This maximum expected stress is then used to determine the material required for use throughout the monolithic component. As explained above, this results in the use of an excessively strong material for most locations in the component.

However, we have an additional functional requirement along the clamping surface. During clamping with a monolithic arm made of a strong material, the clamping surface is normally rather hard. This hard surface, when combined with the force ex-

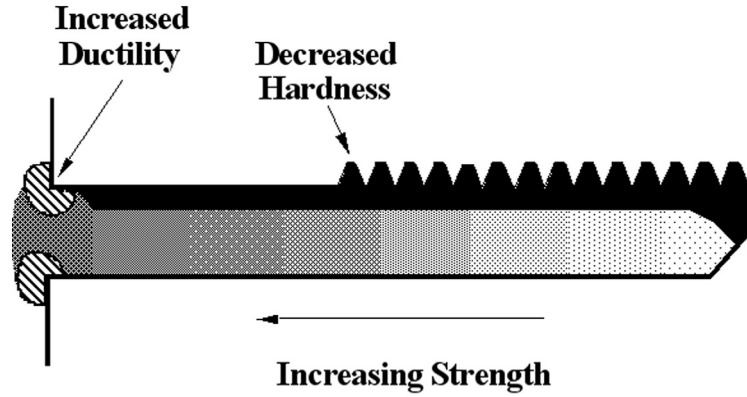


Figure 1.1: Fully Optimized Clamping Arm Component

erted by the arm, can easily damage a softer material being clamped. Thus, we would prefer to have a relatively soft clamping surface to prevent this damage from occurring. As stated above, this represents two functional requirements that generate conflicting material properties. We desire a soft clamping surface and a strong, and usually hard, supporting material. The traditional solution to this problem is to develop a soft secondary component and attach it to the upper surface of the clamping arm. Thus, we frequently see clamping surfaces which possess rubber pads to prevent damage to objects being clamped. This solution requires the development of additional components and a technique to attach the pad to the clamping arm.

A fully optimized component would consist of an integral unit in which material properties would match the functional requirements throughout the component. For our example component, the material composition would be controlled so that the strength decreases as one moves out along the distance of the clamping arm. Thus, the strength of the material making up the arm is matched to the expected stress field. Additionally, ductility would be increased at the stress concentrating corners near the base of the arm. The increased level of ductility would tend to prevent crack propagation and increase the overall resistance of the clamping arm to failure. Finally, the hardness of

the material would be decreased locally near the upper surface to provide a soft non-damaging clamping surface. Thus, we would have a clamping arm with strong material only in regions of high stress, ductility in stress concentrating locations, and reduced hardness along the clamping surface. Component integrity is maintained and discrete interfaces are removed from the component.

Thus, the primary constraint which requires the use of the two techniques described above consists of the current level of development regarding fabrication technology. Current fabrication technologies are limited in their ability to produce multiple material components; rather, they are primarily focused on the development of monolithic components. Traditional fabrication techniques have focused their efforts on the enhancement of the ability to control the geometric shape of the component being manufactured. Only recently have new techniques been developed to fabricate components of arbitrary geometry, aside from the traditional technique of one-off, or custom, machining.

In order to create fully optimized components, in which the variation of material properties are matched to the variation in functional requirements, we need a fabrication process with the following characteristics. The first and most critical requirement is the ability to control the variation of material properties in a component by precisely controlling the variation in material composition. Note that this variation in material composition must take into consideration the relationship between a given material composition and the desired material properties. Second, the resulting component should be a single integral unit that does not possess any discrete interfaces. The presence of discrete interfaces generates a number of associated problems described above and does not clearly separate this ideal process from that of simply separating a given component into two simpler sub-components and then connecting the sub-components. Third, we desire that the process is capable of producing arbitrary geometric complexity. This is the primary limitation of current multiple material fabrication techniques in use today, they tend to be severely limited in the types of geometries they can produce. For

example, coatings allow the fabrication of multiple material components, however, the geometry is strictly one-dimensional and limited to shallow surface effects.

However, the recent development of Rapid Prototyping (RP) techniques have allowed the fabrication of components of arbitrary geometry. Additionally, the additive nature of these techniques offer the potential to control the composition of the material which is used to build up the component. Note that this level of control is simply not possible in traditional machining processes, where geometry is achieved via the controlled removal of unwanted material. Therefore, the use of multiple material RP technologies offer the potential fabrication of fully optimized components, in which the variation of material properties are matched to the variation in functional requirements.

1.2 Background

Of the various RP technologies currently in use, Selective Laser Sintering (SLS) was chosen as the specific process to examine for the potential development of multiple material processing capabilities and the fabrication of the fully optimized components discussed above. The current SLS process is only capable of manufacturing monolithic component materials, due to the nature of its powder delivery subsystem.

In this subsystem, the powder to be used is stored in powder cylinder. During processing, this powder is raised by the powder piston to expose a small amount of powder used to form a new layer. This powder is then transferred by a counter-rotating roller to the part cylinder to form a new layer of powder above the partially fabricated component. The counter-rotating roller also smoothes the new layer during powder transferral. Following the deposition of the new layer of powder, a laser is used to selectively sinter the powder and additively build up the partially fabricated component in a layerwise fashion.

In order to fulfill our general problem statement, we need a process that will allow us to vary the material composition throughout a component in a controlled fashion. Thus, we must extend the current SLS process to allow the fabrication of multiple ma-

terial components by a new process, Multi-Material Selective Laser Sintering (M²SLS). The primary modification of the current SLS process consists of the design and development of a new powder delivery subsystem. Most of the rest of the process remains relatively unmodified and is carried over to the new process. The new powder delivery subsystem would have to be able to store and deliver more than one type of powder. Additionally, the composition of the powder bed would have to be varied in a controlled manner during fabrication to yield a component with a controlled variation in material composition and material properties.

As stated previously in Section 1.1, we desire a component that does not possess discrete interfaces between regions of differing material composition. This type of material is known as a Functionally Gradient Material (FGM). The primary distinguishing characteristic of FGMs is the continuous distribution of material composition and corresponding material properties. For example, a ceramic/metal component with a vertically oriented FGM could be 100% metal at the bottom of the component and gradually change to 100% ceramic at the top of the component.

The two primary types of FGMs which could potentially be fabricated with the M²SLS process are distinguished by their degrees of dimension. The most obvious type of FGM is a one-dimensional FGM which naturally arises from the layerwise fabrication technique inherent in the SLS process. For this type of FGM, each layer has a distinct material composition that does not change within the layer. However, the material composition varies in controlled manner from one layer to the next. Thus, the material composition can be made to vary slightly between layers so that a discrete approximation to a continuous FGM is developed in a vertical orientation.

The second type of FGM is a two dimensional FGM in which the material composition is varied across a given layer of powder. Note that this variation can occur simultaneously along both the x- and y-coordinates, where the xy-plane lies parallel to the layer. In general, the variation across the layer can be continuous or discrete in nature dependent upon the design solution used for powder deposition. While more

flexible, this type of FGM would also be more difficult to implement. Development of a two dimensional FGM in combination with the previously described one dimensional FGM would allow the fabrication of a FGM component in which material composition varies simultaneously in three dimensions.

Thus, the fabrication of FGMs with the M²SLS process offers the potential to fulfill the previously developed requirements of our ideal fabrication process. The FGM component would be manufactured in a single step in which the FGM is developed in an additive fashion as the component is built up. By definition, the FGM component will not possess any discrete interfaces. In the one dimensional FGM concept, discrete interfaces are present. However, the large number of interfaces and the relatively small change in material composition across each interface results in a series of discrete interfaces that closely approximates a continuous FGM. The basic nature of the SLS process ensures that the M²SLS process will possess the ability to produce components of arbitrary geometry. Finally, the proper design and development of the new powder delivery subsystem will allow the deposition of the desired variation in material composition through the component. This desired variation in material composition then naturally leads to a corresponding variation in material properties that, hopefully, fulfill the spatially varying functional requirements.

1.3 Specific Problem Statement

Thus, we have a somewhat general problem statement and corresponding proposed solution. However, before we can begin work on the development of the solution, we require a more specific problem statement to narrow the design space of the M²SLS process. The current problem statement is too general in nature to allow the proper design and development of the M²SLS process. This narrowing of the problem statement will serve to focus the scope of the research investigation. Additionally, it is deemed prudent to conduct a series of feasibility trials to examine the fabrication of FGMs with the SLS technique. These feasibility trials must be completed before the initiation of

the design and development process. A more focused, narrow problem statement is required to allow the initiation of these feasibility experiments.

This focusing of the research investigation should be driven by a relevant industrial process. This will ensure that the investigation addresses a problem of relevance to current industrial concerns. Additionally, the resulting process is more likely to be useful to industry. Thus, the first step in our focusing effort is the identification of an industrial problem which parallels our research efforts. A research investigation into potential applications of FGMs reveals an relevance in the general field of cutting tools. Specifically, an application was identified in the petroleum industry regarding the down-hole components used to drill oil wells.

During drilling operations, a tri-cone drill bit head is lowered into the drill hole and used to break up the subsurface rock formations encountered during drilling. The broken fragments of rock are then pumped out the hole with the use of fluid known as drilling mud, which also serves to lubricate the bit to prevent overheating. The drill bit head contains a number of small bullet-shaped inserts which act as cutting teeth against the rock formations (Ref. Figure 1.2). These inserts eventually wear down and must be replaced to maintain effective drilling rates.

An examination of the worn drill bit head indicates two primary failure modes in the inserts. First, the tip of the insert is observed to erode due to abrasive wear. Second, some inserts are observed to break off at the base due to brittle fracture. These observations naturally lead to our two functional requirements. The tip of the insert must resist abrasive wear and maintain the proper cutting geometry. The body of the insert must also possess sufficient ductility and toughness to mitigate the brittle fracture failure mode.

The drill bit insert is composed of a tungsten carbide / cobalt (WC/Co) composite material. This material consists of angular tungsten carbide particles in a cobalt matrix. The tungsten carbide particles act to provide the needed hardness while the more ductile cobalt matrix provides toughness by hindering crack propagation. The ra-

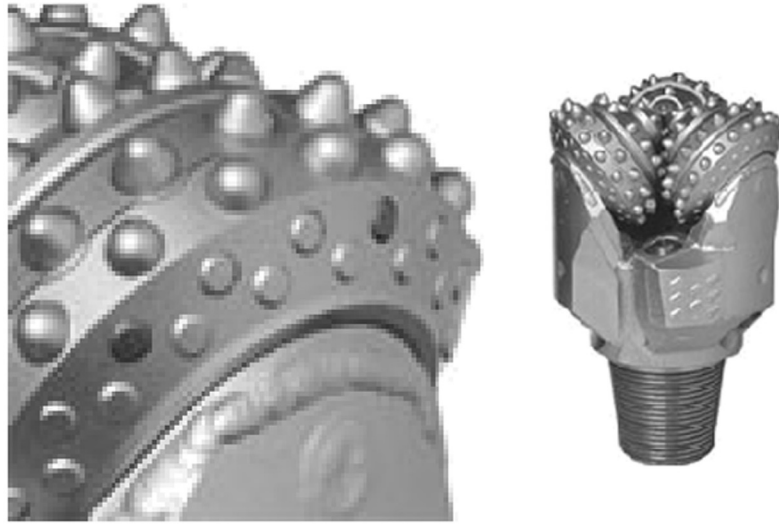


Figure 1.2: Drill Bit Head with Inserts

tio of hardness to toughness is directly related to the ratio of tungsten carbide to cobalt in a given alloy. Therefore, hardness can be increased by increasing the relative amount of tungsten carbide, however, this will cause a corresponding decrease in the ductility of the alloy. Thus, we have the conflicting functional requirements and material properties described above. Given a monolithic component, a compromised alloy must be selected that only partially meets each of the functional requirements.

In an ideal case, we desire relatively larger amounts of tungsten carbide at the tip of the insert to provide enhanced wear resistance. The body of the insert would then possess relatively larger amounts of cobalt to provide more ductility and enhance resistance to brittle failure. Thus, we arrive at a more specific, industrially relevant problem statement.

1.4 Hypothesis of Problem Statement

Given our newly focused problem statement and the proposed development of a M²SLS process, we can formally state our proposed solution as a formal hypothesis.

The desired matching of material properties to functional requirements may be achieved via the fabrication of drill bit inserts containing functional gradients with the Multi-Material Selective Laser Sintering (M²SLS) process.

1.5 Summary of Work Performed

Following our definition of the hypothesis, a research investigation was undertaken to attempt to prove or disprove the hypothesis, in following with the traditional scientific method. First, additional information was collected regarding the use of FGMs in tungsten carbide / cobalt cutting tools in order to gain further understanding of our specific problem. Additionally, research was conducted regarding the development of other multiple material rapid prototyping processes to properly ascertain the state of the art in this field.

Next, a series of feasibility experiments were conducted in which FGMs were fabricated via the traditional SLS process. These trials usually involved the manual development of an FGM and then laser sintering of the FGM. These experiments were performed prior to the actual initiation of the development process in order to gain insights to the behavior of FGMs during laser sintering and to determine overall feasibility. Next, a design and development effort for the construction of an M²SLS workstation was initiated. This fabrication process took up a significant amount of the time and resources expended on the investigation.

This process was basically broken into two areas of effort based on the amount of similarity to the existing SLS process. The powder delivery and deposition subsystem represents the distinguishing characteristic of M²SLS versus traditional SLS and thus was the focus of a separate, off-line development effort. The remaining subsystems,

which are very similar to SLS, were then developed to form the basis of the M²SLS workstation. Finally, the powder delivery subsystem was integrated into the overall workstation to complete the fabrication process. During and following the fabrication of the workstation, a series of tests were conducted to measure the performance of the workstation. These tests were used to quantify the ability of the workstation to form an FGM in the powder bed during processing. Finally, some very preliminary tests were conducted to attempt to build a tungsten carbide / cobalt drill bit insert which contained a gradient of the two constituent materials. These tests were limited in nature and did not attempt to address the numerous issues involved with the optimal laser sintering of a metal / ceramic material system.

Chapter 2

FGM Drill Bit Inserts: An Application of Multiple Material Solid Freeform Fabrication

Following the development and identification of the hypothesis of our investigation, it was necessary to collect information regarding the state of the art in the field of the fabrication of FGM components. Thus, we become aware of the significant developments in the field and are also more able to properly determine the correct path of scientific inquiry. Secondly, it is also necessary to investigate our specific research problem at a more detailed level to gain additional information and insight. This investigation reveals the primary problems in this field and various states of resolution of these problems due to earlier research endeavors.

First, we will include a brief description of the history of the development of the SLS process for those readers not familiar with this technology. Then we will investigate the current state of the art in the fabrication of FGMs by various methods, and then more specifically, by the different Rapid Prototyping technologies currently in use. Finally, we will examine the fabrication of FGMs in our material system of

interest, namely, the tungsten carbide / cobalt material system. Specifically, the use of functional gradients in tungsten carbide / cobalt drill bit inserts will conclude this section.

2.1 Early Development of SLS

The first documented record of the basic SLS process was described by Householder [35]. This patent describes the SLS process in which a laser is used to selectively fuse particles in a layerwise fashion to gradually build up the part. This patent also includes a simple description of the laser scanning system in which mirrors are used to direct the laser beam and also describes the concept of using powder and part cylinders to store the powder and the part during fabrication. Another early description of this process is given in Hull which defines the term “stereolithography” which is one of the primary Rapid Prototyping technologies currently in use [37]. However, this process differs from SLS at a fundamental level in that an ultraviolet–curable liquid is selectively cured to a solid layer with a ultraviolet light source. After the solid layer is formed, the layer is lowered and the ultraviolet–curable liquid is allowed to flow over the solid layer in preparation for further selective curing.

Another similar process was developed by Crump [15]. This process consists of a dispensing nozzle which is supplied with a solid material. This material is then melted and held at a controlled temperature just above solidification so that the liquid will solidify almost instantaneously upon extrusion through the nozzle. The nozzle is contained in a movable head that is translated in the XY plane in a controlled manner so as to build up an article in a layerwise fashion due to the controlled deposition of the material onto the partially fabricated component.

The initial development of the traditional Selective Laser Sintering process (SLS) was performed by Deckard and Beaman [19, 18]. The basic process is very similar to that described by Householder above, however, this work represented the first working device to form components of arbitrary geometry from the selective, layerwise sintering

of a fusible powder. Initial work focused the control of dimensional accuracy in polymer material systems. The thermal environment of the working volume was found to strongly impact deleterious effects such as curl and thermal growth that lead to dimensional inaccuracies. This initial work lead to the development of a business venture, known as DTM, to design, develop, and market a commercial version of the SLS process.

Following the initial development of the SLS process, initial modeling was accomplished by Nelson [48]. A part of the modeling effort was the development of the Andrew number, A_N , as given by

$$A_N = \frac{P (SP)}{k (SS) \delta} \quad (2.1)$$

where A_N is the energy density, P is the laser power, k is a system constant which depends on the machine geometry, SS is the scan speed, SP is the scan period, and δ is the scan spacing between vectors.

An indirect SLS process was developed in which metal powders were coated with a polymer. This polymer is then laser sintered to form a green shape which is then post-processed at an elevated temperature to remove the polymer binder and fuse the metal particles together [56]. Additional investigations into the pressureless infiltration of a liquid metal matrix into a ceramic green part were also conducted [59]. Lastly, considerable research has been conducted into a direct metal SLS process in which metal powder is directly melted by a powerful laser to form the resulting component in one step. This process eliminates many of the complicating factors inherent in post-processing steps, however, stringent control of the thermal and atmospheric processing environment must be maintained to produce proper sintering behavior [25, 16].

2.2 Fabrication of FGMs: Recent Developments

Next, we turn to recent developments in the fabrication of functionally gradient materials, or FGMs. Much of the work in this field has occurred in Japan, primarily from a large government research initiative, with a smaller body of work performed in Europe.

Relatively little research into this field has occurred in the United States.

The Japanese initiative has led to the need for thermal barrier materials to be used to protect aerospace vehicles from the extreme thermal environment developed during reentry. In general, metal / ceramic composites are the material of choice for this application due to their ability to remain structurally sound at elevated temperatures. The primary failure mode for these applications is due to the large thermal stresses developed by extreme temperature gradients developed across the components. The use of FGMs to gradually vary the ceramic phase allows the relaxation of thermal stresses and a tailoring of the surface to provide enhanced thermal resistance.

Hirai and Sasaki have examined the fabrication of thin film FGMs in which the material composition changes in a direction perpendicular to the deposition surface. Specifically, they have fabricated Ti-TiC and Ti-TiN FGMs using physical vapor deposition (PVD) and SiC/C FGMs using chemical vapor deposition (CVD) [34]. A general reduction in cracking due to thermal shock loading is observed for the SiC/C FGM samples [54].

Fukumoto investigated the development of thick nitride coatings via a reactive plasma spray process [26]. The reactive plasma spray process allows the rapid deposition of a thick coating which is simultaneously nitrided to increase hardness. It was observed the degree of nitriding of the coating could be controlled by changing the coating deposition rate. Based on this principle, the coating deposition rate was altered during processing to develop an FGM in which the degree of nitriding, and thus hardness, changed from the substrate to the coating surface. Kitaguchi developed a $\text{ZrO}_2\text{-8wt\%Y}_2\text{O}_3$ (YSZ)/Ni-20wt%Cr (NiCr) FGM using a low-pressure plasma spraying (LPPS) process to cause a relaxation in the thermal stresses developed during the use of this component as an airframe thermal barrier material [41]. Variation in the powder feed ratio of the two materials proved effective in mixing and melting the two constituent materials. A large temperature gradient was developed across the FGM as a functional test and a noticeable decrease in thermal stress development was observed

in the FGM components.

Sampath examined the development of cermet FGMs using thermal spray processes in an attempt to spread out and reduce the thermal stresses present due to the large coefficient of thermal expansion mismatch [52]. Specifically, a NiCrAlY-(ZrO₂/Y₂O₃) FGM was developed as a thermal-barrier coating. Hardness was observed to increase with volume fraction of the ZrO₂/Y₂O₃ while the modulus of elasticity decreased. This gradual change in material properties is expected to significantly reduce the thermal stresses at the interface. Similar work was also conducted on a Ni-Al₂O₃ material system. Watanabe also examined a partially stabilized (PSZ)/Mo material system for thermal barrier applications [57]. FGM fabrication was achieved via traditional powder metallurgy (PM) methods including stacking of powder premixes according to a predesigned composition profile followed by compaction of the stacked powder heap and sintering. Specifically, deposited compacts were cold isostatically pressed (CIP) and then consolidated via hot isostatic pressing (HIP).

A review to the presented literature indicates a general application of FGMs in an attempt to reduce the thermal stresses developed in metal / ceramic composites. Additionally, the majority of the processes develop an FGM as a coating or a very simple shape in some of the PM processes. However, our process desires the flexibility to produce components of arbitrary geometry inherent in Rapid Prototyping processes. Therefore, next we will examine the intersection of the fields of Rapid Prototyping and FGMs.

2.3 Rapid Prototyping and FGMs

The first process to be examined consists of a research investigation by Jasim in which powder particles are injected into a laser cladding process [39]. This work represents an initial research investigation that offers the potential for the arbitrary geometry seen in more mature RP technologies. Specifically, a continuous wave 2 kW CO₂ laser was used to produce clad tracks on a nickel alloy substrate with powder mixtures of Al-

10wt%SiC, Al-30wt%SiC, and Al-50wt%SiC. Successive deposition of the clad tracks was observed, however, the microstructure of the resulting deposit was found to be very sensitive to the processing conditions due to the complex interactions among the large number of alloying additions in the substrate.

Recent developments of the LENSTM process have focused on improved powder feeding capabilities to allow the fabrication of graded or layered material parts [31]. This process directs powder streams into a melt pool generated by a focused Nd:YAG laser beam and is used to directly fabricate metal parts in the typical layerwise fashion. This work examines the fabrication of a two component vertically oriented FGM consisting of stainless steel 316 (SS316) blended into Inconel 690 (In690). The expected increase in nickel content was observed as one moves into the In690 regions. Hardness was observed to increase linearly with increasing percentages of In690 due to increasing amounts of nickel and chromium.

Shape Deposition Manufacturing (SDM) is a process in which metal powders are injected into the focal spot of a laser beam to create a melt pool [23]. Powder injection is performed by three computer controlled powder feeders. The deposition head is translated across the workplane to build up a layer, followed by milling to improve edge definition. In this investigation, metallic samples containing Invar and SS316L were fabricated to form an FGM. Oxidation of the Invar/SS316L samples reveal a gradient of oxidation resistance from the low resistance of the Invar to the high resistance of the SS316L. A gradual change in hardness values (R_c) was also observed in the FGM sample.

Laminated Object Manufacturing (LOM) is a process in which ceramics are tape cast and then deposited to build up a part in the typical layerwise fashion [50]. The geometry of the part is developed by selectively cutting away each deposited layer to form the correct cross-section. A functionally graded $\text{Si}_3\text{N}_4/\text{SiC}$ material system was examined in an attempt to induce surface compressive stresses due to differing coefficients of thermal expansion in the two constituent materials. A functionally graded

sample was created in which a 1:1 ratio of the two materials was graded from the center of the sample to a 100% Si_3N_4 composition at the surfaces of the sample. The resulting FGM samples exhibited an estimated surface compressive stress of 100 MPa (10^4 torr).

Robocasting is a developing process in which highly loaded ceramic slurries are extruded through an orifice to build up parts in a layerwise fashion [38]. An advanced dispensing head with an integrated mixing chamber and the ability to dispense up to four different materials has been developed. This system has demonstrated the ability to generate a continuous bead which gradually changes composition from one material to another as it is deposited.

Tetracast is a build style used to produce lattice-filled patterns using SLA photopolymers which possess an internal three-dimensional tetrahedron morphology. A Gradient Tetracast form is a variant in which the branch thickness of the lattice is increased in a controlled manner to effect a proportional change in volume of the material constituents [29]. A secondary composite material is then introduced into the lattice and due to the variation in lattice branch thickness, a gradient of the composite is produced. In this study, a tensile bar pattern was produced so that the volume percentage varied from $\sim 10\%$ to greater than 70% . An SLA photopolymer was used for the lattice structure, while a glass-filled epoxy was utilized as the filler composite material. As hypothesized, increasing volume percentages of the filler material correlated to increased stiffness and values of Young's Modulus.

2.4 Use of FGMs in WC/Co Drill Bit Inserts

Next, we turn to an examination of the previous work regarding our specific problem, namely, the fabrication of drill bit inserts containing a functional gradient. First, a general paper regarding the grading of the tungsten carbide / cobalt material system will be presented. A number of patents are then presented which discuss our specific component of interest. The large number of patents discovered regarding our problem indicates that the need for a proper matching of material composition to functional

requirements has been recognized for some time. Additionally, given the narrow focus of this problem, a relatively large number of ideas have been presented as potential solutions.

Sampath has investigated the use of a ceramic (WC/Co) / metal (steel) FGM as a liner for gun barrels [36]. The repeated firing of the barrel leads to thermal shock and fatigue issues which will rapidly fail a normal steel barrel. Thus, ceramic liners are often used to shield the steel barrel. However, failure often occurs at the bore–liner interface, due to the abrupt CTE mismatch present at the discrete interface between the liner and the barrel. The use of an FGM to grade out the CTE mismatch has the potential to enhance the performance of the liner. Thus, the ceramic–rich FGM would be exposed to the highest temperature with the composition gradually changing to a metal–rich FGM at the surface of the gun barrel. The compositional gradient would then parallel the temperature gradient that is developed in the liner / barrel system. FGMs were deposited via the High Velocity Oxy–Fuel (HVOF) process which involves the high–pressure combustion of oxygen and fuel gas. A metal or cermet powder is then injected axially into the resulting flame, where they melt or soften as they are accelerated to the substrate. A specific SS316L/WC–12%Co material system was developed and tested for thermal shock using a water quench technique. A linear transition between the steel substrate to the 100% WC/Co region was observed on micrographs of the resulting samples.

One of the first specific investigations of the use of FGMs in WC/Co drill bit inserts was described by Skoda Works in 1951 [60]. This work basically describes the need to match high hardness values at the cutting edge of the insert while maintaining a tough interior to prevent brittle failure. Additionally, it is proposed that this matching of functional requirements to spatial locations in the component can be achieved via a control of the percentage of binding metal at the locations of interest. An 11 to 13% cobalt content at the core of the insert is suggested with a gradual transition to a cobalt content of 5% at the surface.

Haglund also describes a proposed insert consisting of two or more layers in which the layers near the surface possess higher hardness and reduced toughness [33, 32]. The increased hardness is proposed to be achieved via a reduction in the local cobalt content. Lees describes a process for developing a coarse cutting tool which maintains its proper cutting profile during abrasion [45]. This characteristic is achieved via a lamination process in which the individual sheets are graded according to abrasion resistance. A highly abrasion resistant sheet is used for the uppermost layer which is then sequentially bonded to sheets of gradually reducing abrasion resistance. The sheets are bonded using an adhesive substance and the additional use of heat and/or pressure as necessary.

Bomford proposes a method of fabricating a material with locally different properties via traditional powder metallurgy methods [12]. This process consists of filling a form with two different component powders such that the ratio of the two powders varies in a continuous fashion over the spatial extent of the part. The resulting powder filled form is then compacted and sintered to consolidate the powder. It is proposed that the two powders are delivered by means of a conveyer and proportioning screws. This system then delivers the correct ratio of the component powders to a mixing device which then combines the powders before final deposition in the form.

Drake proposes a similar method in which a gradient is established from a region of high hardness to a region of high toughness [21, 20]. Powder mixtures with different ratios of the component powders are introduced to a mold for subsequent consolidation. The use of drill bit inserts creates a so-called “metallurgical notch” that is created across the interface between the insert material and the alloy steel of the drill bit body. The use of graded insert would act to smooth away the notch and to create a compositional structure at the bottom of the insert that parallels the composition of the drill bit body. Another embodiment of this work consists of the fabrication of a drill bit body with integral drill bit inserts. Higher concentrations of the cemented carbides are placed in regions of high wear which correlate to the locations of the drill bit inserts. These higher concentrations are reduced as one moves geometrically out into the regions of drill bit

body to enhance toughness. The resulting powder form is then consolidated into an integral structure using conventional powder metallurgy techniques.

Abrahamson proposes a pressing process to develop a drill bit insert with two regions of differing properties [7]. A mixture of tungsten carbide and 4 to 11 % cobalt is placed in a die shaped in the form of the crown, or working surface, of the drill bit insert. This mixture is then compacted under high pressure, followed by the addition of a mixture of tungsten carbide and 12 to 17 % cobalt to form the bulk of the body of the insert. The two mixtures are then exposed to high pressure and sintered to form the resulting component which possesses a crown of higher hardness relative to the body of the insert.

Another drill bit with just two regions of differing properties is proposed by Langford, Jr. [44]. However, in this case, the two regions are joined by a parting plane which extends to the earth-engaging surface of the insert. The region possessing reduced wear resistance is oriented at the leading edge of the insert. This arrangement allows the insert to maintain a crest-like configuration on its working surface during normal wear.

Stroud proposes an insert in which a harder inner body is surrounded by a more ductile outer body in such a manner so that the inner body protrudes from the top of the insert to engage the rock surface [55]. The more ductile outer body protects the hard inner body from brittle failure while the protruding inner body wears more slowly. The reduced rate of wear of the protruding inner body as compared to the surrounding outer body also acts to maintain a proper cutting profile during operation. The two bodies are sintered separately and then brazed together with a relatively low temperature braze.

Another insert configuration is proposed by Begg in which a surface layer is present with a high percentage of tungsten carbide [10]. This surface layer gradually transitions via decreasing percentages of tungsten carbide into the body of the insert and then transitions into a steel substrate at the bottom of the insert. These transitions

are developed by placing the appropriate mixtures in a container under pressure and then consolidating the container and its contents via the HIP process. This process must be carefully controlled to prevent migration of the cobalt binder and a loss of the gradient structure.

Colin has investigated the effects of solid state and liquid-phase sintering on graded WC/Co cermet structures [13]. All of the samples were prepared by premixing two to three blends of the cermet and then pouring layers of the powder in a container followed by cold-pressing of each layer. Solid-state sintering was performed with good adhesion between layers and a lack of mixing between the layers. Liquid-phase sintering was also performed with full density reached in 15 minutes at 1353° C. For this case, the interfaces between layers remained visible. However, processing at longer time scales (60 minutes) leads to a complete homogenization of the structure. Therefore, precise control of the sintering time is required to prevent a loss of the gradient structure.

A powder metallurgy process is proposed by Mirchandani in which a die is first filled with a given premixed blend of powder [47]. A second portion of the die is then filled with a powder of a different composition. Additionally, a metal sleeve may be used to temporarily separate the two powders during pouring to enhance the flexibility of the process. The powders are then pressed to the desired shape and then sintered at the appropriate temperature to produce the desired component.

Krall proposes a method to manufacture a WC/Co product with a tough inner core containing relatively more cobalt and outer layers of a harder consistency containing relatively more tungsten carbide [42]. The first step in the process is the fabrication of a number of premixed slurries containing the correct blend of metal powders and a liquid vehicle. The appropriate slurry is then applied via spraying or painting to an unsintered green compact shape, which will become the core of the resulting article. The applied slurry is allowed to dry in air after which the article with the applied slurry may be sintered. Alternatively, after the slurry has dried, additional layers of slurry of the same or alternate types may be applied before the final sintering step.

Finally, Fisher has proposed a unique means of fabricating a cemented carbide drill bit insert to create a gradient of an eta-phase (intermediate phases such as M_6 -carbides or W_3Co_3C) and the binder metal [24, 8]. First, a green compact is formed with a substoichiometric content of carbon. This green compact is sintered to form a component containing the desired eta-phase. Next, the desired gradient of eta-phase is produced via a carburizing process that reduces the binder content and eliminates the eta-phase at the outer surface of the component. Thus, a shallow FGM of eta-phase is produced.

2.5 Summary

From this quick review of the current literature, some simple observations can be drawn. Most of the initial interest in FGMs has developed within the last 10 to 15 years, primarily in Europe and Japan. The primary driving force behind these investigations in Japan was a large investigation of these materials by government agencies. Recent developments in Rapid Prototyping has also resulted in some developments in gradient materials, primarily after the base RP process was sufficiently developed. Several of these processes offer much promise in our field, however, FGM materials are not seen as a primary driver of the various RP technologies. Lastly, the use of graded structures in WC/Co drill bit inserts has been a subject of interest for a considerable amount of time. The primary focus has been the development of different traditional powder metallurgy techniques to develop graded structures. Only recently as the opportunity emerged to investigate the development of graded drill bit inserts with newly developed rapid prototyping technologies.

Chapter 3

Feasibility Experiments

The design and development of the M²SLS process requires knowledge of the physical behaviors associated with the laser sintering of powder mixtures of varying material composition. This knowledge provides insights to the design of the workstation and also allows one to determine the feasibility of the overall process. Therefore, a series of experiments were performed prior to the actual initiation of the design process to gain insights into the physical behavior of material gradients during the laser sintering process. The performance of these experiments with the traditional SLS process in general require the manual fabrication of FGMs in the powder bed followed by laser sintering. A number of methods of manual FGM fabrication were developed before the final selection of two methods.

The first of these methods is a straightforward manual banding technique. Blends of the different ratios of the two materials are premixed with a roller mixer. These different blends are then manually deposited on a dish in such a manner that the ratio of the two materials varies in a gradual manner across the surface of dish. However, the discrete nature of the different blends results in a discontinuous FGM. This effect can be mitigated somewhat with the deposition of a large number of very thin bands. Additionally, the nature of this process limits it to the development of single layer samples only.

A second similar process for the fabrication of single layer samples utilizes the powder roller to deposit and smooth the layer. In this process, the different blends are poured in small mounds in a row in front of the powder roller. The blends are arranged in such a manner so that the powder ratio gradually changes along the row of mounds. Next, the powder roller transfers and spreads the powder out. Ideally, this process would not alter the FGM since it is oriented perpendicularly to the direction of the roller movement. However, the uneven nature of the mounds could potentially cause the layer to be spotty in nature and unless care was taken with the spacing and sizing of the mounds, the FGM gradient would not change in a consistent manner.

A third process consists of building a vertical FGM in the powder side cylinder. Premixed blends would be deposited in the powder side cylinder in such a manner as to cause a gradual change in the powder mixture composition as one moves up through the powder cylinder. During processing, the powder roller would transfer the powder over to the part cylinder for laser processing. As the process was repeated, the powder composition would gradually change, resulting in a part with a material gradient in the vertical direction. Note that the resulting part material gradient will be oriented oppositely to the gradient in the powder cylinder.

The final process is similar to the third process in that the powder cylinder is used to contain the powder FGM prior to sintering. However, in this case, the orientation of the FGM is horizontal and perpendicular to the direction of roller movement. Basically, this technique takes the mounds created in the second method and stores them in the powder cylinder. As the powder cylinder is raised, the FGM is presented to the roller for transferal to the part cylinder for processing. This technique possesses the disadvantages of the second method. Additionally, the fabrication of the horizontally oriented FGM in the powder side cylinder would be highly difficult.

Of these processes, the first and third were chosen for experimental studies. The first process was used to fabricate single layer samples while the third technique was utilized to examine multi-layer processing.

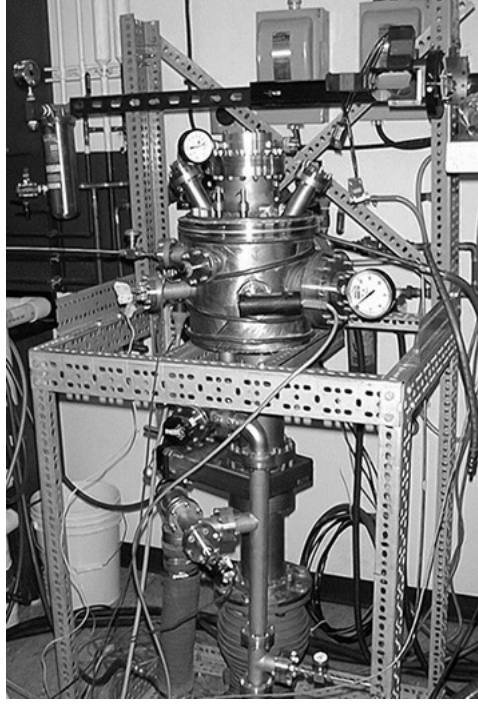


Figure 3.1: Single Layer Workstation

3.1 Single Layer Experiments

Prior to the development of single layer samples containing an FGM, a number of samples were fabricated in which each sample contained only one mixture or ratio of WC/Co. These experiments are described followed by those samples containing a number of different ratios of WC/Co, or FGMs. All of the single layer samples fabricated in this work were developed using a single layer workstation. This workstation was originally developed for fabrication of abrasive cermet components and possesses advanced atmospheric and thermal management capabilities (Ref. Figure 3.1)

% Co	Mass of WC (kg)	Mass of Co (kg)
10	1.125	0.125
20	1.00	0.25
30	0.875	0.375
40	0.75	0.5

Table 3.1: Blend Compositions for Non-FGM Bearing Single Layer Samples

3.1.1 Fabrication of Single Blend Samples

The first step in the fabrication of these samples consists of mixing the different blends. Four blends or ratios were selected for fabrication, with one dish of each blend placed in the single layer workstation for laser sintering. A total powder blend mass of 1.25 kg (2.76 lbs) was selected with ratios of 10, 20, 30, and 40 volume percent of cobalt. Table 3.1 indicates the resulting masses of the constituent materials. These masses were measured out and then mixed in a roller mixer for 8 hours for each blend.

Following mixing of the powder blends, it becomes necessary to determine the number of samples to produce and their orientation on the processing dish. The energy density, or Andrew number, A_N , was chosen as the parameter of variation (Ref. Equation 2.1). Four values of A_N were selected for each of the four blends. For each value of A_N , three samples were fabricated for a total of 12 samples per blend. Samples were chosen to be 12.7 mm (0.5 in) square with a 6.35 mm (0.25 in) separation between samples on the powder bed.

Next, the powders were baked out in the single layer workstation to reduce oxides and moisture content in the powder bed. The heater subsystem was turned on with minimum current and allowed to come to a steady state temperature of approximately 625°C. Each blend was then placed in the workstation and allowed to bake out for 7 hours followed immediately by laser processing. The bake-out process and all laser sintering were performed under a hard vacuum of approximately 10^{-3} Pa (10^{-7} torr). Additionally, laser processing was performed under a preheat of approximately 800°C.

Parameter	Value
P	70 watts
k	17.2
SP	27
δ	0.00396 mm (0.000156 in)

Table 3.2: Processing Parameters for Non-FGM Bearing Single Layer Samples

During laser sintering, a number of operational parameters must be set. These parameters for laser processing were chosen as shown in Table 3.2 with scan speed altered to provide the variation in energy density. Table 3.3 provides the selected scan speeds and corresponding energy densities for each blend. The power (P) and machine constant (k) are determined by the available hardware. Scan period (SP) was fixed at the nominal value of 27.

The default scan spacing is 0.508 mm (0.02 in) between vectors. In general, decreasing the scan spacing between vectors improves the part quality. Scan spacing is controlled by determining the scaling of the part in the x direction. In order to reduce the scan spacing, it is necessary to take a long part (in the x direction) and scale it down so that the vectors are compressed together. The practical limit for scan spacing is 0.00254 mm (0.0001 in).

A number of part files have been developed for use on the single layer workstation, including the fabrication of square samples. Given the practical limit for scan spacing and a desired coupon length of 12.7 mm (0.5 in), our task becomes the selection of a part file of sufficient length. The scaling factor, given the length of a part file and the length of a desired coupon, is given by

$$\text{Scaling Factor} = 0.02 \frac{\text{Length of Coupon}}{\text{Length of File}} \quad (3.1)$$

Use of this equation and an examination of the available part files results in the selection of the *64X05* part file. This part file is 1.63 m (64 in) long and when used in the previous equation, yields a δ of 0.00396 mm (0.000156 in) which is sufficiently

Scan Speed	Energy Density [kJ/mm ²]
25	0.0437
16	0.0682
12	0.0909
10	0.1092

Table 3.3: Energy Densities for Non-FGM Bearing Single Layer Samples

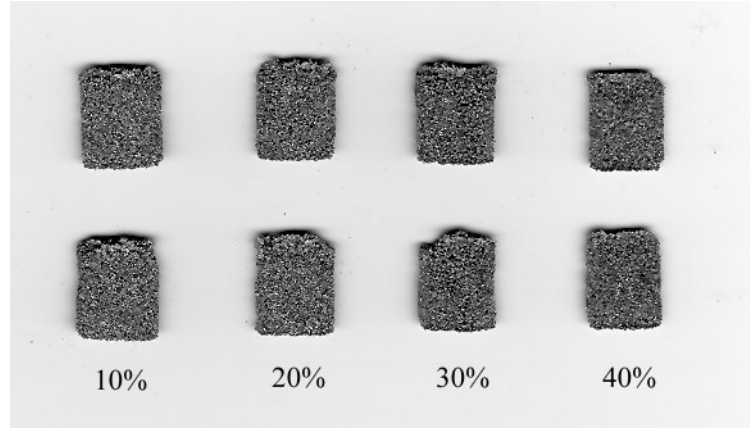


Figure 3.2: Single Layer Samples (No FGM Present, $A_N \approx 70$, Wt. % Co as Indicated)

small. Use of this part file and δ will result in a one half inch long sample with 3200 vectors.

Results of this work indicate similar processing behavior for all blends, with a mild increase in starting edge balling with increasing cobalt content (Ref. Figure 3.2).

3.1.2 Fabrication of Single Layer FGM Samples

Following the fabrication of coupons containing only one blend of material, experiments were conducted to examine the laser sintering of single layer samples containing an FGM. Of the four techniques for FGM fabrication for use with traditional SLS, the manual banding technique was selected.

First, the operating parameters of variation are chosen. As before, the energy density will be varied via changes in scanning speed. The additional presence of the FGM must also be considered. A potential interaction between the orientation of the FGM and the vectors used to scan the part may exist. Therefore, it was decided to scan both parallel and perpendicular to the FGM orientation (direction of material gradient) to access the impact of this interaction on the behavior of the laser sintering process.

For this series of experiments, a prealloyed 12% cobalt blend was mixed with increasing amounts of pure cobalt powder. The prealloyed powder consists of powder particles made up of a cobalt matrix (12%) surrounding smaller tungsten carbide particles (88%). This powder was selected due to powder availability and also with the expectation that the prealloyed powder should produce better sintering behavior.

Next, the percentages of cobalt used to make up the FGM were selected. The percentages of cobalt used in industrial environments generally range from approximately 3% to 12%. While the most industrially relevant choice would have been a series of roughly 10 blends ranging from 3% to 12% cobalt, the resulting material composition gradient would have been somewhat mild. A steeper gradient in which the percentage of cobalt ranges from roughly 10% to 100% will tend to reveal the effects of changes in the laser sintering parameters more strongly than a mild material composition gradient. Therefore, the composition of the different blends started from the 12% cobalt prealloy and increased in increments of roughly 10% up to a fully 100% cobalt metal blend as shown in Table 3.4. The mixing of the pure cobalt powder with the 12% cobalt prealloy was performed using an industrial roller mixer for approximately 8 hours per blend.

The FGM sample size was chosen to be 12.7 mm (0.5 in) square with a resulting band width of each blend of roughly 1.59 mm (0.0625 in) as shown in Figure 3.3. This small size allowed several samples to be fabricated in one experimental run and yielded a more continuous FGM by forcing the bands widths to be narrow. In order to optimize the number of samples which could be fabricated, the FGM bands were oriented as shown in Figure 3.4. Note that the band labeled “FGM” only contained the 24% Co to

Blend Number	% Cobalt	% Tungsten Carbide
1	12	88
2	24	76
3	36	64
4	48	52
5	60	40
6	72	28
7	84	16
8	100	—

Table 3.4: Blend Compositions for FGM Single Layer Samples

84% Co blends since the 12% Co and 100% Co blends also acted as boundaries between the FGM bands. This arrangement allowed the processing of 12 samples per run and the raster scanning of samples both parallel and perpendicular to the FGM gradient.

Before scanning was initiated, the SLS chamber was brought to a high vacuum state and the powder bed was preheated to approximately 700°C. Proper alignment of the scanning location and the FGM bands was of critical importance to the fabrication of relevant FGM samples. An iterative process was used with a solid state positioning laser to confirm the scanning location prior to actual laser sintering. All of the samples were scanned using constant laser power with control of laser energy input achieved via changes in scanning speed.

Using the Andrew number equation (Ref. Equation 2.1) generates the following three unique values of energy density: (1) 31.4 kJ/in², (2) 15.7 kJ/in², and (3) 10.5 kJ/in². Four samples were fabricated for each of the three unique energy densities. Two samples for each density were scanned parallel to the FGM and the remaining two samples were scanned perpendicular to the FGM. This arrangement allowed three unique energy densities and two scanning orientations to be examined. Two samples were created for each of the six possible combinations of experimental parameters for a total of 12 samples. Scanning was initiated in the 12% cobalt region for all samples

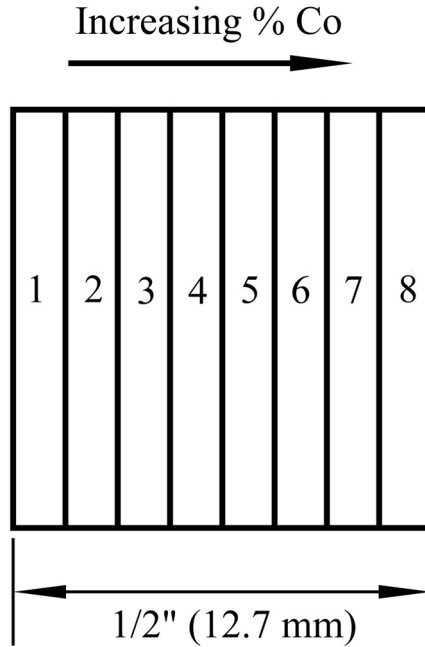


Figure 3.3: FGM Sample Coupon

scanned parallel to the FGM.

3.1.3 Fabrication of Multilayer FGM Samples

Following the fabrication of the single layer samples, experiments were conducted to fabricate a multiple layer component. Of the four fabrication techniques discussed, the vertical technique consisting of building up an FGM in the powder side cylinder was utilized. Thus, the resulting component possessed a vertical FGM in which the material composition changed as one moves vertically through the part.

This work took place on a small simple workstation which does not possess the thermal and atmospheric management capabilities of the single layer workstation discussed previously. However, this system does possess the ability to process multiple layer components. Basically, this system consists of a manually activated two cylinder

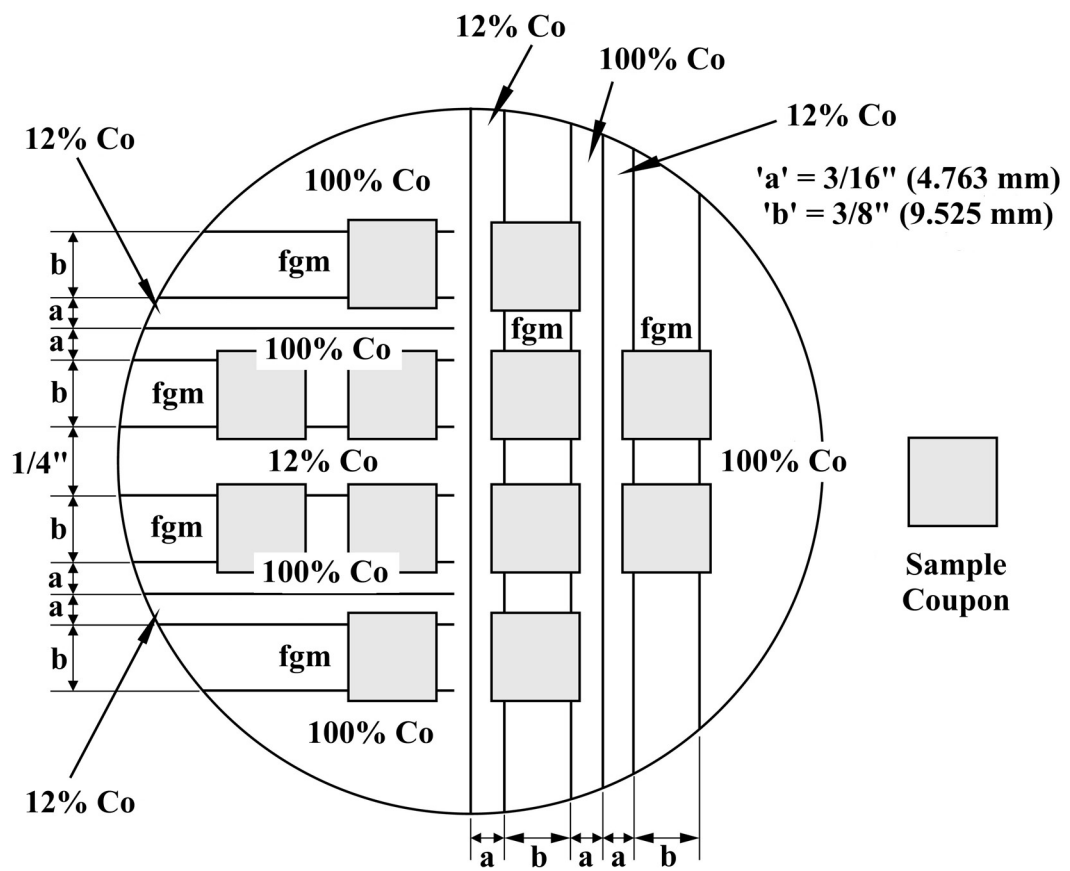


Figure 3.4: FGM Sample Locations

and roller assembly. This assembly was filled with powder and then placed in a vacuum chamber with rough vacuum sealing capabilities. Rotational ports through the chamber walls allows manual control of the vertical displacement of the powder and part cylinders as well as the powder roller. This chamber sits atop an XY-table which translates to move the laser beam across the surface of the powder bed.

The scanning system for this workstation consists of a 50 watt CO₂ laser and a computer controlled XY-table, unlike the galvanometer heads used with the traditional system. The smaller laser power, in addition to the inability to bake-out or preheat the powder bed, was anticipated to produce a lack of sufficient sintering energy. Additionally, the XY-table is limited due to hardware constraints to a maximum scanning speed of 10.16 mm/sec (0.4 in/sec).

First, we must determine the thickness of the FGM layers which will be built up in the powder cylinder. The eight blends used for the single layer work were also utilized for this work (Ref. Table 3.4). The powder cylinder possesses a depth of 9.525 mm (0.375 in). Conversion of this measure and allowing for loose powder above and below the FGM yields a working depth of $\sim 8,000 \mu\text{m}$. Thus, we have a FGM layer thickness of $1,000 \mu\text{m}$ for each of the eight blends (Ref. Figure 3.5)

The ratio of turns of the manual input for cylinder movement to cylinder displacement is 1 turn : $45 \mu\text{m}$. Given the FGM depth above, the manual input to displace one FGM layer is approximately 22 turns of the powder cylinder input. In order to account for spillage of powder during the roller transferal process, the part cylinder was lower at 0.75 times the rate of advancement of the powder cylinder.

The layer thickness for scanning was set at 3 to 4 times the average particle diameter. Normally, some freedom can be applied to this parameter, however, the low laser power and lack of bake-out drives one to minimize this value. The average cobalt particle size was found to be $\sim 45 \mu\text{m}$ in diameter, while the prealloyed WC/Co particles were found to be $\sim 10 \mu\text{m}$ in diameter. Thus, we arrive at an average layer thickness of $200 \mu\text{m}$.

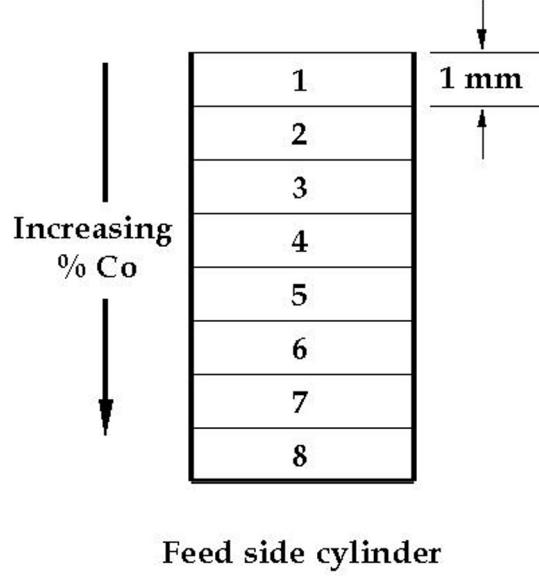


Figure 3.5: Powder Side FGM

Due to the previously stated limitations on scanning speed, the primary method of controlling the energy density is via the scan spacing. For this system, scanning is controlled by two parameters. *Amplitude* controls the length of the vectors drawn by the laser, while *Number of Lines* controls the number of vectors drawn per inch.

In order to determine the desired scan spacing, we chose a relatively high value of energy density of 0.0775 kJ/mm^2 (50 kJ/in^2). Using this value and the Andrew Number equation (Ref. Equation 2.1) we can find the scan spacing to be

$$\delta = \frac{P}{vA_N} = \frac{50\text{W}}{\left(0.4 \frac{\text{in}}{\text{sec}}\right) \left(50,000 \frac{\text{J}}{\text{in}^2}\right)} = 0.0025 \text{ in} = 63.5 \mu\text{m} \quad (3.2)$$

Note that P is laser power and v is scan speed.

Given this scan spacing, an *Amplitude* of 6,000 and *Number of Lines* of 96 yields a sample of approximately 154.8 mm^2 (0.24 in^2). This is a relatively small sample, however, it is appropriately sized given the dimensions of the powder and part cylinders.

Following development of the FGM, the assembly was placed in the chamber.

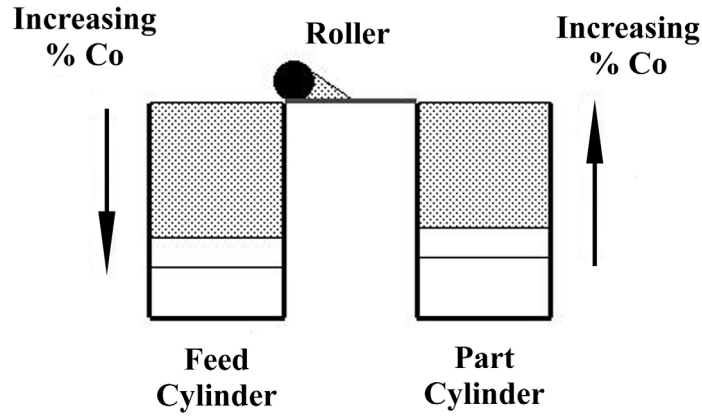


Figure 3.6: FGM Inversion during Processing

The chamber was sealed and pumped down to a rough vacuum followed by an argon gas backfill. This process was repeated three times to lower the oxygen content in the chamber. Following this preparation, laser processing was begun. A solid state positioning laser was used to confirm the scanning location prior to actual sintering. Scanning speed and laser power were held constant throughout the build and the powder cylinder was translated upwards until all of the powder was used. As the powder cylinder was translated upwards, the roller incrementally transferred the FGM to the part cylinder for laser processing, resulting in a multilayer sample component with an inverted FGM (Ref. Figure 3.6).

During processing, some balling behavior was observed. This behavior causes interference between the powder roller and previously sintered layer which can lead to part shifting and an abortion of the run. In order to prevent this behavior, the layer thickness was increased from 200 μm to 300 μm . This increased layer thickness also further indicates the need for the previously chosen high value of energy density.

Additionally, sparking and particle ejection from the powder bed was observed at the beginning of each run. Two potential causes of this behavior have been considered. The first potential causal factor is a thermal shock effect when the laser first impacts

the powder bed. The other factor is the rapid vaporization of moisture and other contaminants in the powder bed when laser sintering is initiated. As scanning proceeds and a melt pool is established, a much less severe thermal gradient is developed within the bed, reducing thermal shock and allowing a more gradual driving off of moisture trapped in the powder. This gradual driving off of moisture does not cause the particle ejection behavior observed at the beginning of layer processing. This behavior was not observed in the single layer work since the more advanced thermal management control hardware allowed a preprocessing bake-out which eliminated the trapped moisture prior to processing.

3.1.4 Examination of Microstructure

Following the processing of the samples, the microstructure was examined to determine the presence of an FGM. Scanning electron micrographs (SEM) of the surface of the single layer samples was conducted. The samples were then sectioned and polished for examination with an optical microscope. Both low and high power optical micrographs were acquired for single and multiple layer samples.

First, the single layer samples were examined at a low SEM power of x400 (Ref. Figure 3.7). An examination of the micrographs reveal porosity in regions of low cobalt content. It appears that the cobalt wets the nearby tungsten carbide particles but does not form a sufficient melt pool to consolidate the particles and eliminate the porosity. Next, high power SEM micrographs (x2500) were collected (Ref. Figure 3.8). These reveal few additional details, however, the presence of cobalt grain boundaries can be observed in the left of the figure. The white structures present are believed to be a contamination of the sample.

Next, both the single layer and multiple layer samples were sectioned and polished for optical examination. First, a low power (x40) optical micrograph was collected of the overall sample (Ref. Figure 3.9). This micrograph was annotated as shown to indicate the locations of a series of higher power micrographs which were also collected.

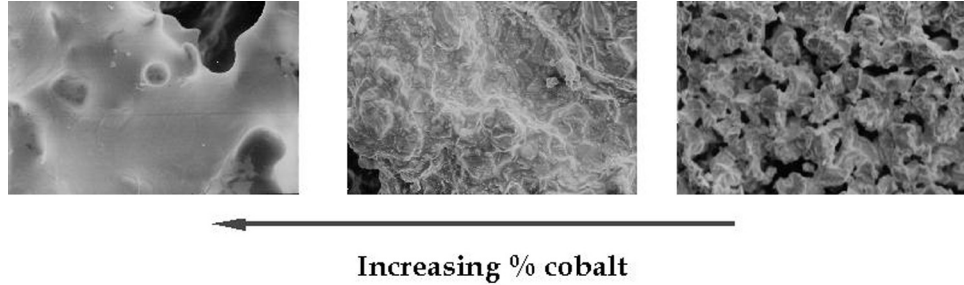


Figure 3.7: Low Power SEM Micrographs of Single Layer Samples

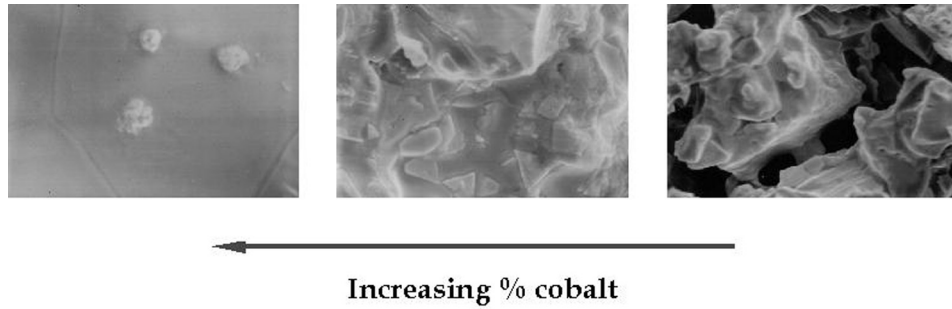


Figure 3.8: High Power SEM Micrographs of Single Layer Samples

The number on the left is the actual distance along the sample in millimeters, while the number on the right is a normalized distance along the sample. The percentage of cobalt decreases as one moves up the samples. A lack of through-thickness melting can be observed between the 0.25 and 0.5 locations.

A similar process was repeated for the multiple layer sample (Ref. Figure 3.10). A large amount of porosity is visible in this sample due to poor atmospheric and thermal control in the multilayer workstation.

Next, a series of high power (x200) optical micrographs were collected at five locations along the FGM (Ref. Figures 3.11 & 3.12). The numbers under each micrograph indicates the normalized distance or location along the sample where the micrograph was collected. The large black regions represent porosity in the sample, while the smaller

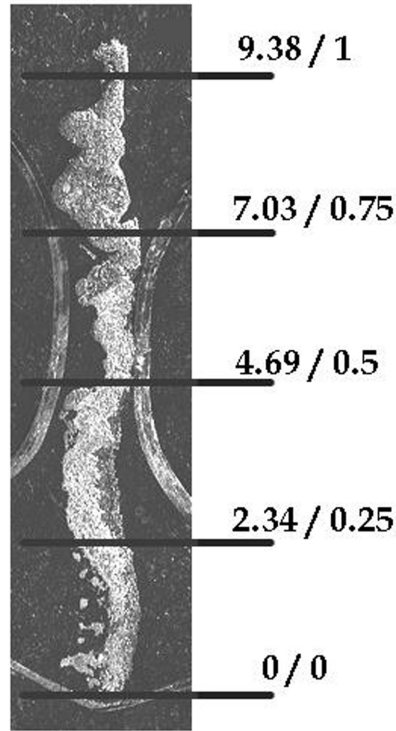


Figure 3.9: Low Power Optical Micrograph of Single Layer Sample

angular forms are the tungsten carbide particles. A lack of focus in some regions is attributed to a lack of complete flatness in the sectioned plane due to incomplete or inaccurate polishing. Interlayer boundaries may be observed in the multiple layer sample at the 0.5 and 0.75 locations. As before, this is due to poor atmospheric control.

A cursory examination of the high power micrographs visually demonstrates an increase in the angular tungsten carbide particles with decreasing cobalt content. Next, one must quantitatively measure this change to determine the nature of the material gradient. Additionally, material property characterization in the form of microhardness testing was performed in order to correlate material composition and material property gradients.

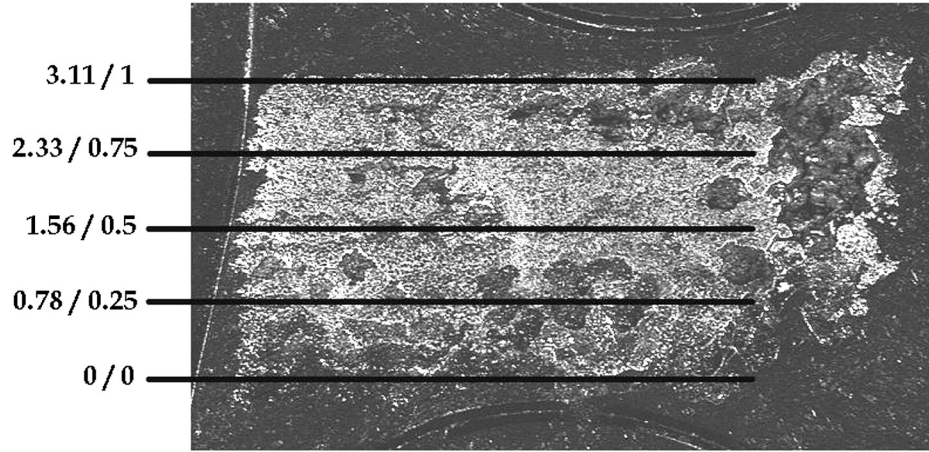


Figure 3.10: Low Power Optical Micrograph of Multiple Layer Sample

3.1.5 Testing for Presence of FGM

The micrographs developed in the previous chapter were examined to measure the change in material composition along the sample. The relative areas of the cobalt and tungsten carbide were measured in the five optical high power micrographs for both the single and multiple layer samples. The relative areas were measured with an image analysis software that calculates area based on grayscale values. However, manual image enhancement was necessary for the software to properly calculate the areas. This enhancement represents a source of error in the final values determined for the ratios of the two materials. Contamination of the sample represents the other significant error source.

The resulting areas were used to calculate the cobalt content relative to the tungsten carbide. The resulting values are plotted versus the normalized distance along the sample (Ref. Figure 3.13). Additionally, the theoretical values of cobalt content based on the mixed blends was also plotted.

Next, it was desired to collect a material property at various points along the FGM to confirm a gradient of material properties which correlate with the gradient

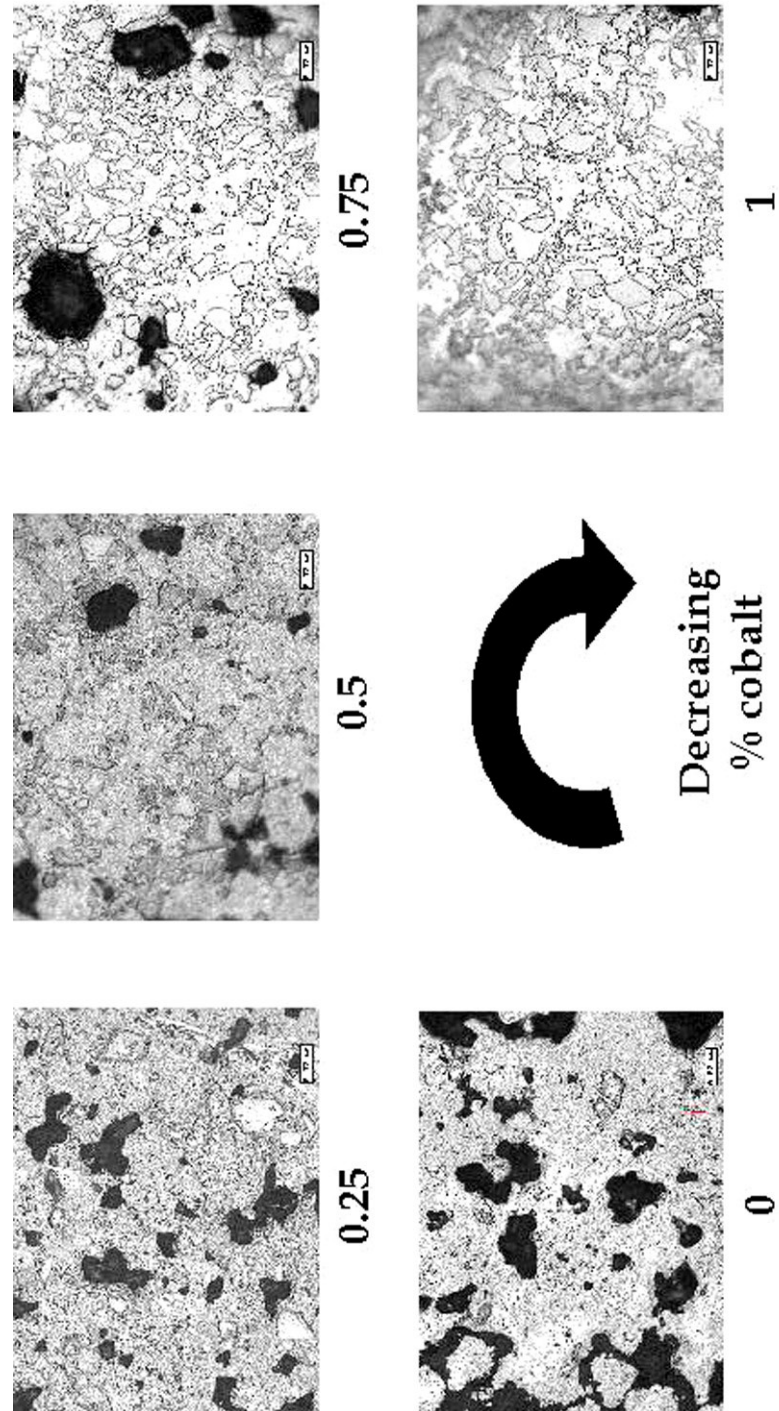


Figure 3.11: High Power Optical Micrographs of Single Layer Sample

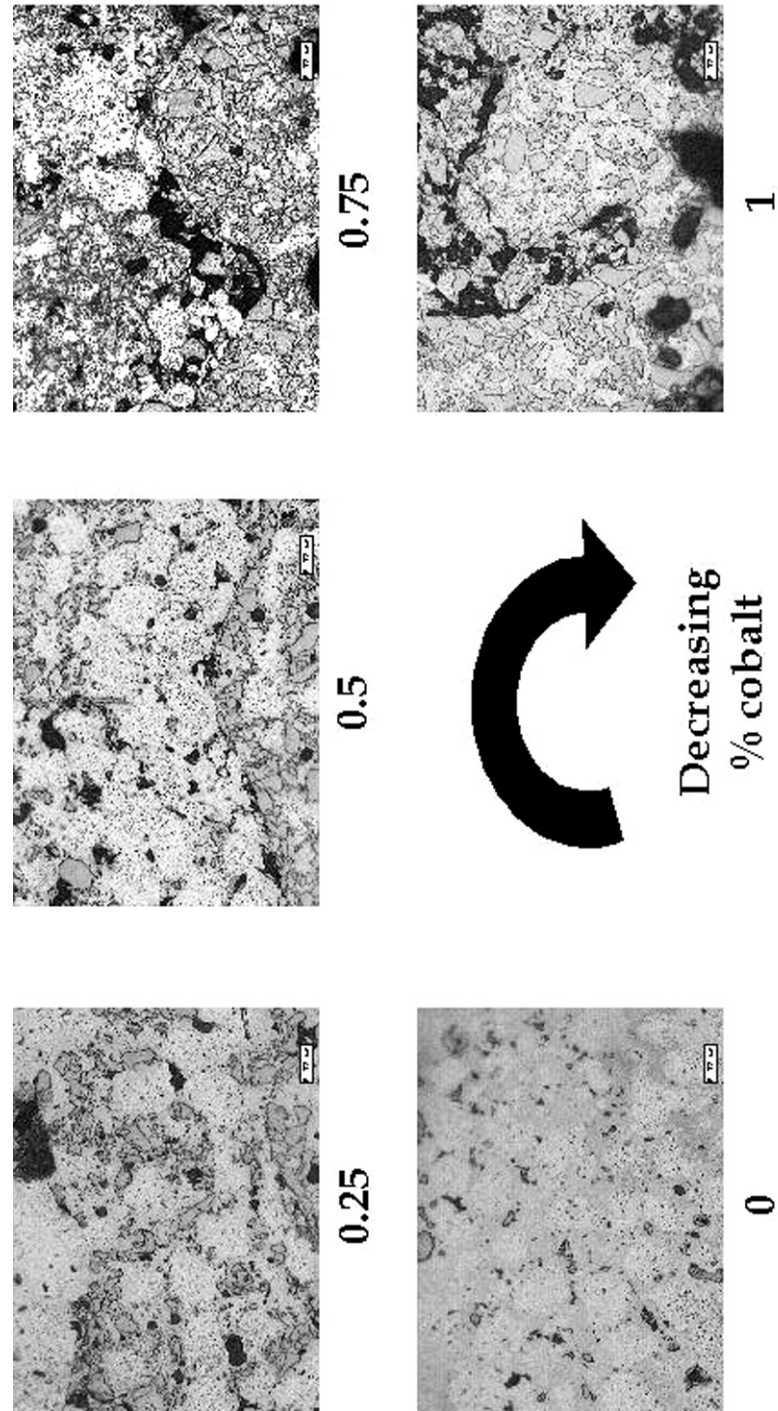


Figure 3.12: High Power Optical Micrographs of Multiple Layer Sample

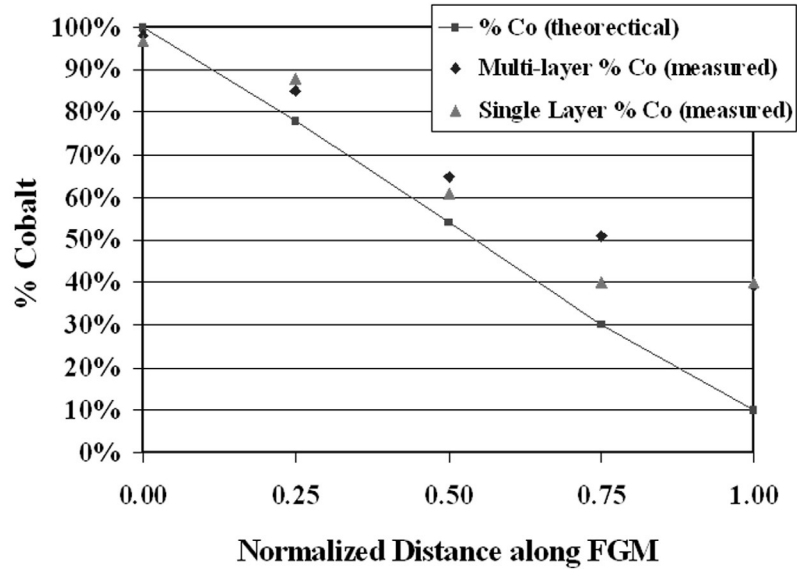


Figure 3.13: Percent Cobalt versus Normalized Distance along FGM

in material composition. The material property collected was microhardness. This property is directly relevant to the functional needs of the drill bit insert and additionally is well suited to the small size of the samples. The microhardness was collected at the five locations which correlate to the high power optical micrographs.

Measurements were collected using the standard Vickers microhardness test. In this test, a load is set on the equipment and then a diamond shaped indenter is driven into the sample of interest. Measurement of the diagonals of the resulting indentation is used with the load value to generate the Vickers microhardness number. One point of concern with the performance of this test with composite materials is that the indentation is sufficient large to span both materials making up the overall material. A selection of a very light load will lead to a small indentation, which if centered on a tungsten carbide particle, will yield the hardness of the tungsten carbide particle and not the overall material. Therefore, relatively high loads were used to form large indentations.

A load of 1.6 kg (3.53 lbs) was chosen as a sufficiently high value. This load

Location on FGM	DPH	HRA
0.00	216	40
0.25	326	60
0.50	402	75
0.75	550	77
1.00	973	86

Table 3.5: Vickers (DPH) and Rockwell (HRA) Hardness Values for Single Layer Sample

Location on FGM	DPH	HRA
0.00	216	40
0.25	250	47
0.50	376	70
0.75	569	77
1.00	727	83

Table 3.6: Vickers (DPH) and Rockwell (HRA) Hardness Values for Multiple Layer Sample

and the measured diagonal of the resulting diamond shaped indentation was used in the following equation to generate the Vicker's microhardness number (DPH).

$$\text{DPH} = \frac{2L \sin \frac{a}{2}}{d^2} \quad (3.3)$$

where L is the load, $a = 136^\circ$ which is the angle of the indenter, and d is the diagonal length.

The Vickers microhardness numbers were then converted into Rockwell Hardness A (HRA) numbers for comparison to tabulated data for this material system [9] (Ref. Tables 3.5 & 3.6). First, the measured and theoretical values of cobalt content are plotted versus the measured Rockwell Hardness A values at the five locations along the samples (Ref. Figure 3.14). Additionally, tabulated values from the ASM Handbook of cobalt content versus HRA were plotted on the same graph to determine the degree of agreement between the measured and tabulated values [53]. The tabulated values were

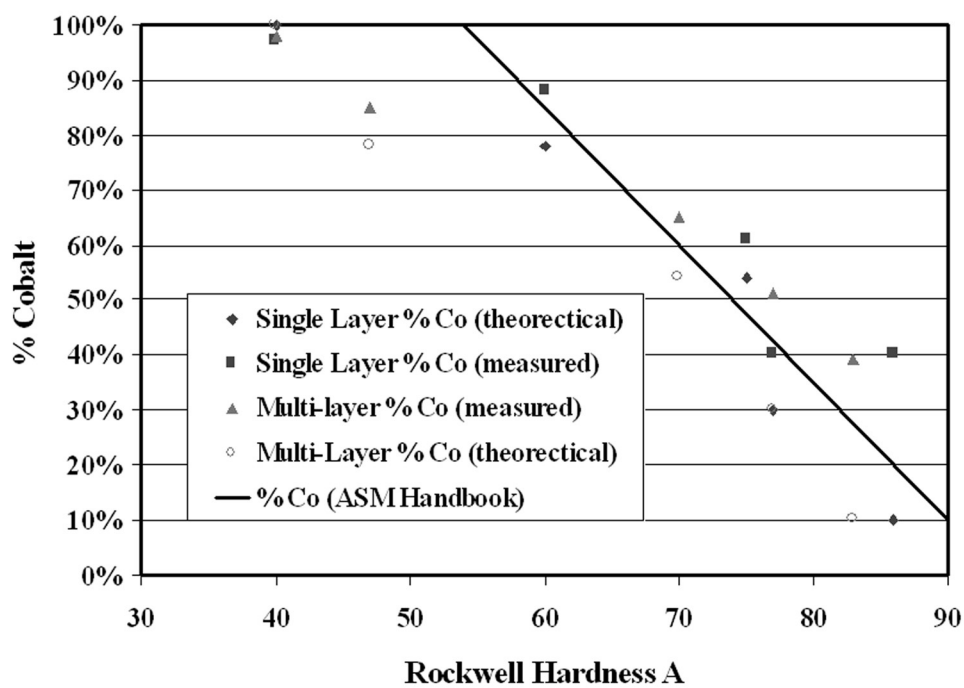


Figure 3.14: Percent Cobalt versus Rockwell Hardness A

limited to relatively low values of cobalt content, due to the prevalent use of these values in industry. Linear interpolation of the existing data was used to provide the additional tabulated values at high percentages of cobalt. A linear interpolation was selected for use as material properties generally scale linearly with material composition in metal / ceramic composites.

An examination of this plot reveals that the lowest measured values of hardness fall below the minimum predicted by the tabulated values. This discrepancy could potentially be due to errors associated with the experimental measurement of the percentage of cobalt. However, the presence of this discrepancy for the theoretical as well as the experimental values indicates another potential root cause. The inappropriate use of a linear interpolation could also contribute to this difference. The rest of the data

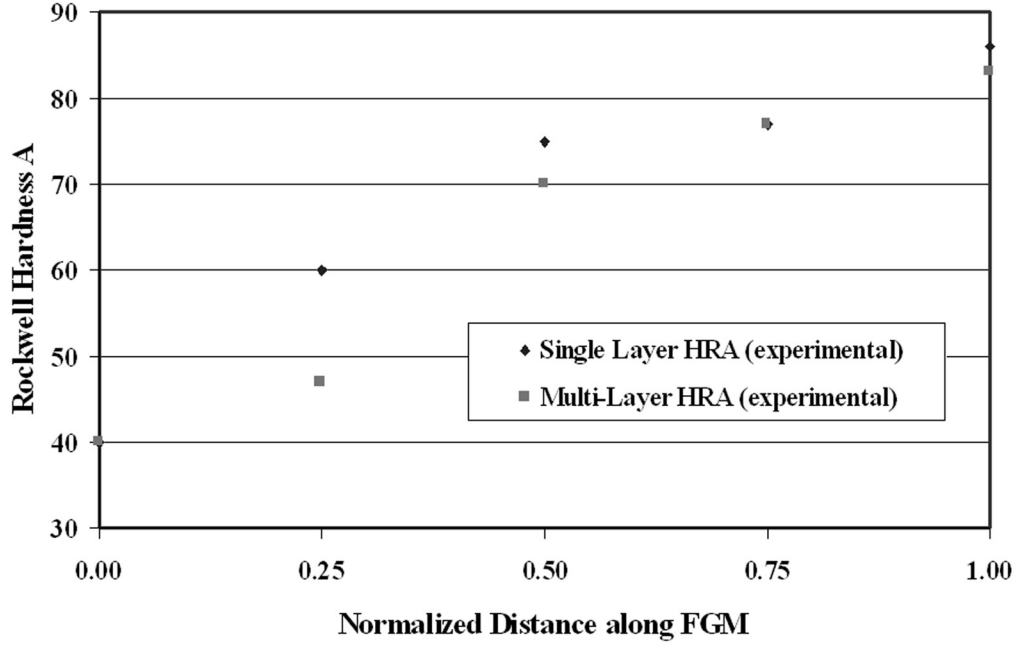


Figure 3.15: Rockwell Hardness A versus Normalized Distance along FGM

matches the general trend of the tabulated values, however, the experimental values tend to be rather noisy due to experimental error in the measurement of the percentages of cobalt.

Next, the Rockwell Hardness A values were plotted versus the normalized distance along the FGM (Ref. Figure 3.15). This plot reveals the correlation between the desired material property of hardness and the spatial location along the FGM which is the desired characteristic of FGMs. As expected, the decrease in cobalt content along the FGM correlates with an increase in hardness along the FGM.

3.1.6 Conclusions

This work represents one of the first attempts to generate an FGM with traditional SLS processing. Powder-based FGMs were developed using a manual banding technique for

single layer samples and a vertical building method in the powder cylinder for multiple layer samples. Eight premixed blends were used in which the cobalt content varies from 12% to 100%. SLS processing of the single layer samples was conducted with parallel and perpendicular scanning orientations relative to the FGM and three unique values of energy density.

Some initial conclusions can be drawn from a simple visual inspection of the single layer samples. A lack of through thickness melting is observed for regions with high cobalt content. Since this behavior is not present in regions of lower cobalt content, it is theorized that this effect is simply due to a lack of sufficient energy density to completely melt all the cobalt in regions of high cobalt content. This observation leads to possible need to control energy density input for different regions of the FGM due to the differing relative amounts of metal constituent which must be melted.

Starting edge balling was also observed in many of the samples. While this is normally due to the dynamics of melt pool initiation, the presence of low cobalt content could also impact this behavior. However, all of the scanning for these samples was initiated in the low cobalt content region, thus making it difficult to determine the causal impact of this parameter.

From an examination of the samples, it appears that scanning parallel to the FGM produces less cracking and balling then scanning perpendicular to the FGM (Ref. Figure 3.16). During scanning parallel to the FGM, the laser alternates rapidly between regions of differing cobalt content and attempts to build a melt pool across these regions. However, the high cobalt content regions absorbs much of this energy and prevents excessive melting which normally leads to a large melt pool and contributes toward starting edge balling. However, for scanning perpendicular to the FGM, the laser alternates rapidly across the region of low cobalt content. The low cobalt content is rapidly melted and forms a large melt pool which leads to greater starting edge balling.

The other parameter of variation during the single layer scanning was the scan-

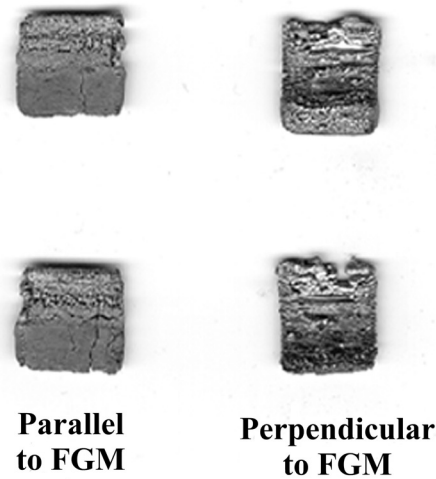


Figure 3.16: Effect of Scanning Orientation on Single Layer FGM Samples

ning speed which directly impacts input energy density (Ref. Figure 3.17). For a scanning orientation parallel to the FGM, increases in scanning speed was observed to decrease the amount of starting edge balling and also the amount of through thickness melting. The increase in scanning speed leads to a decreased energy density which melts less of the cobalt.

For a scanning orientation perpendicular to the FGM, no correlation between starting edge balling and scanning speed could be observed. While the energy density is reduced due to increased scanning speed, the time the laser remains in the low cobalt region is dependent on the scan vector spacing and thus is much less sensitive to the scanning speed. The effect of the perpendicular scanning orientation overwhelms the effects of changes in scanning speed and prevents the observation of a correlation in this case. Thus, through thickness melting and starting edge balling appear to be more sensitive to changes in scanning orientation than changes in scanning speed.

Low power optical micrographs of the samples were collected followed by high power optical imaging of the FGMs at five locations. Image enhancement and processing

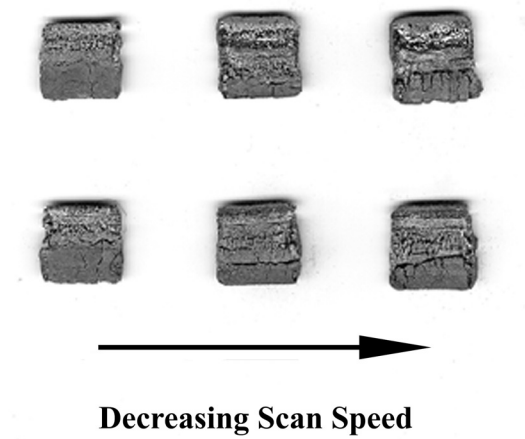


Figure 3.17: Effect of Scanning Speed on Single Layer FGM Samples

software were utilized to measure the relative areas of the cobalt and tungsten carbide materials. Vickers Microhardness testing was performed at the five selected locations to determine a correlation between the material property of hardness and distance along the FGM. Resulting hardness values were compared to tabulated data and reveal a general agreement. Potential error sources consist of the use of image enhancement software to determine the cobalt content via measurement of the relative areas and use of a linear interpolation of tabulated hardness data to include high cobalt contents. Hardness along the FGM was observed to correlate with increased tungsten carbide content.

In general, the feasibility studies indicate the ability to control the material properties at a given spatial location via a control of the local material component. The selective laser sintering process was found to be compatible with the laser sintering of powder with a varying material composition. While some unique behaviors were observed with this type of material system, no significant problems arising from the physics of the process was observed.

In general, part quality was not optimal with relatively large amounts of porosity observed in the samples. Additionally, poor processing behaviors consisting of starting edge balling and sparking behaviors was observed. However, these effects are traditionally observed in normal selective laser sintering processes in which the thermal and atmospheric control of the process is not optimized. No strong evidence was revealed in these initial tests that these behaviors were significantly increased by the varying material composition.

Thus, these initial tests indicated no significant physical barriers to the development of a multiple material selective laser sintering process. The primary barriers become the technical and engineering implementation of this process in hardware, specifically, a multiple material selective laser sintering workstation.

Chapter 4

Design and Development of a Multiple Material SLS Workstation

Following the completion of the feasibility experiments, the design and development of the multiple material workstation was initiated. One of the first tasks during the development of the workstation was the determination of the general functional requirements of the system. In general, many of the functional requirements of the workstation duplicate those of traditional selective laser sintering. However, the functional requirements of powder delivery are fundamentally different for the multiple material system.

One of the most significant design decisions during the development process was to determine what type of FGM the workstation would be capable of fabricating. The results of this decision impact significant functional aspects of the overall system, especially the interaction of the powder delivery subsystem with the rest of the workstation. However, other subsystems are not effected by this decision and remain similar to traditional SLS.

The primary characteristic that distinguishes this workstation from other selec-

tive laser sintering processes is the powder delivery subsystem which allows the laser processing of multiple material components containing an FGM. The bulk of the development and testing work for this subsystem was performed by Julie Perez in the pursuit of her Master's degree in Engineering. A brief summary of her work and the powder delivery subsystem will be presented while the reader should refer to her thesis for a more detailed description and examination [49]. The majority of this work was performed off-line from the overall workstation followed by an integrating process in which the powder delivery subsystem was installed in the primary workstation.

Laser scanning hardware represents one of the first primary subsystems developed for the workstation. This subsystem consists of a large CO₂ laser, associated optics, and a computer-controlled laser scanning system. The installation of the laser and the specification and installation of the optical hardware and scanning system will be presented. In general, this part of the workstation was functionally similar to traditional selective laser sintering. Additionally, a part piston/cylinder assembly with a powder plate to support the powder bed was developed. A powder roller assembly was also designed and fabricated to spread the powder over the part cylinder. The presence of this assembly and the nature of the part piston/cylinder assembly are highly dependent on the specified FGM processing requirements described below in Section 4.1. Controlling hardware, including a PC for user control, was stored in a dedicated electronics cabinet. Finally, following external development and testing of the powder delivery hardware, this system was installed in the overall workstation. This process occurred simultaneously with the installation of a simple enclosing box around the sintering location. The enclosing box was designed to both provide structural support for elements of the powder delivery subsystem and to assist in the pooling of shield gas. The relatively simple fabrication of the shield gas flow system represents the final development of the multiple material workstation.

4.1 System Level Design: FGM Processing Capability

A system level design of the multiple material workstation first must identify which subsystems of the workstation are functionally similar to traditional SLS workstations and which require additional functionality. The laser scanning subsystem consisting of the laser, required optics along the beam path, supporting laser table, scan heads, and accompanying controllers is basically the same as the traditional SLS system. The part cylinder / piston assembly with accompanying actuator and the surface to contain the powder during sintering are also very similar to traditional systems.

The powder storage function must now be modified to include the storage of two or more different powders. Additional functionality consisting of powder mixing is also required of the system. The powder delivery function, performed by the counter-rotating roller on the traditional system, must now be enhanced to include the flow of powder from the storage containers through the mixing assembly and onto the sintering location. The nature of this function, and the resulting form of the required hardware, is dependent on the FGM processing requirements of the workstation.

As described previously in Section 1.2, three types of FGMs are possible. The simplest form is a FGM that is oriented vertically in which the material composition changes discretely from layer to layer. The obvious solution to this functional requirement is the continued use of the current powder roller subsystem for powder transport and smoothing. The powder, instead of being raised up in front of the roller as in the traditional system, is deposited in front of the powder roller after mixing is completed. The roller then moves and smoothes that given blend of mixed powder over the part cylinder for laser processing.

The next more complex FGM is a two dimensional FGM in which the material composition changes within one layer. The functional solution of this requirement in hardware is much more complex. In general, one must be able to precisely deposit a mixed blend of the correct composition in the correct XY location on the bed. This requires translation hardware to properly position a depositing assembly relative to

the powder bed. Additionally, flow of powder onto the powder bed must be highly controlled.

The third and most complex FGM consists of a fully three dimensional FGM in which the material composition can change with respect to three axes simultaneously. In general, the additional functional complexity of this type of FGM compared to a two dimensional FGM is not significant so that the step from two to three dimensions is relatively easy compared to the step from one dimension to two dimensions.

Initial development of functional requirements assumed the ability to fabricate a two dimensional FGM with material variation within a given layer. However, an investigation into the hardware required to meet these functional requirements indicated a lengthy and expensive design and fabrication process. Given the time and financial constraints of the project, a more gradual development strategy was undertaken. This strategy would initially concentrate on just the development of a one dimensional FGM with a gradual addition of processing capability to include multiple dimensions. This strategy was found to more proper align with the available resources for the project. A similar strategy was also utilized in the development of the atmospheric control subsystem, as described in Section 4.8.

Therefore, as described above, a powder roller assembly was fabricated and assembled with an accompanying actuator. This assembly was positioned relative to the scanning surface with appropriate support structures. The separately developed and tested powder delivery subsystem was integrated into the overall workstation so as to deposit the mixed powder in front of the roller (Ref. Figure 4.1).

4.2 Powder Delivery and Mixing Subsystem

The traditional selective laser sintering process utilizes a piston/cylinder arrangement to store the powder to be sintered. The powder to be used in a given layer is then supplied to the process by a vertical displacement of the powder piston followed by a horizontal transfer of the powder via a counter-rotating roller. The powder roller is also

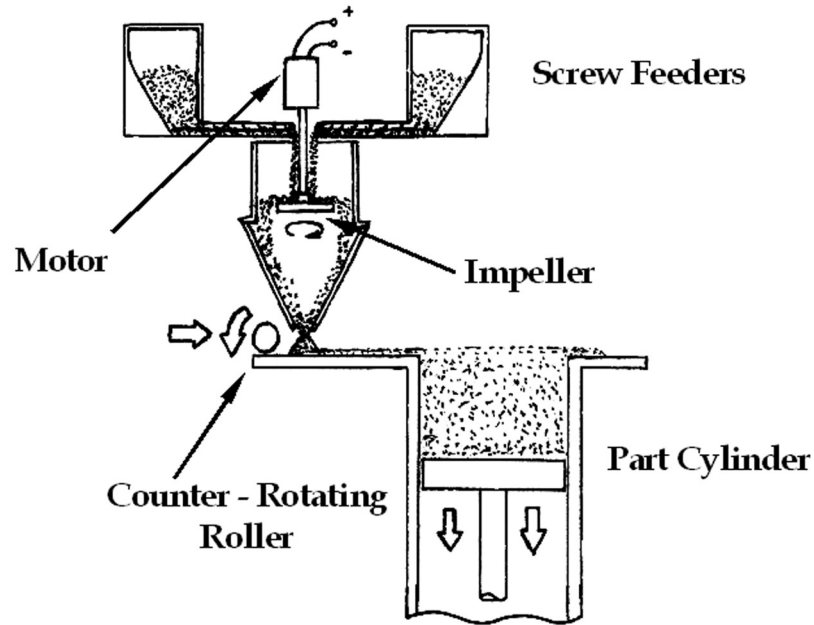


Figure 4.1: Schematic of Powder Flow Through Workstation

used to smooth the powder bed prior to laser sintering.

However, in addition to powder storage and delivery, our multiple material workstation must also mix the powders in the correct ratio to generate a unique blend of powder. Additionally, this mixing process must be controllable so the ratio of the two mixed materials can be varied during the build. These additional functional requirements are the focus of the development effort with respect to this subsystem.

4.2.1 Conceptual Development of the Powder Delivery Subsystem

The design of the powder delivery subsystem followed a formalized design methodology. First, a function structure was developed for the multiple material workstation in order to determine the functional relationships between the powder delivery subsystem and the rest of the workstation as well as the basic functional requirements of the powder delivery

subsystem. These requirements were then matched to potential hardware solutions via a morphological matrix technique.

Next, the potential hardware solutions were combined to form a number of conceptual designs, or variants. A “natural mixing” concept was developed in which powder mixing occurs via a downward migration of the two powders in a narrowing funnel. A “mixing on bed” concept was also developed in which two part cylinders are used to store the powders. The powder bed for a given layer is then developed by deposition of one powder via a counter-rotating roller immediately followed by deposition of the second powder. Mixing of the two powders to form a uniform blend is assumed to occur during formation of a fully fluid melt pool.

A third concept, “rotating impeller”, uses a mechanical auger device to deliver the two powders in controlled rates into a mixing chamber containing a rotating disk, or impeller, that is used to mix the powders together. The mixed powders are then delivered to the powder bed. A “pre-blends with nozzle” forms the final concept developed in which a number of blends are mixed externally to the machine and then stored in a number of containers on the machine. Feed lines run from the powder storage containers to a switching box which determines which of the pre-mixed blends will be deposited. Transferral of the selected blend from the switching box to the powder bed is accomplished via a single line and a nozzle.

These conceptual designs were evaluated using Pugh’s method and the functional requirements of the system to choose the best of the designs. The final concept selected is a combination of the “natural mixing” and “rotating impeller” designs. The two powders are placed in a mixing chamber and allowed to mix as they descend through a gradually narrowing cross-section of the chamber. An rotating impeller is added to the center of the funnel to enhance the mixing of the powders.

A very simple alpha prototype of this system was developed. An impeller was connected to a motor via a rotating drive shaft. Impeller speed was controlled by a variable voltage source which powers the impeller motor. A plastic container with two

ports at the top for the introduction of powder was used to enclose the impeller. Tubes were used to transfer the powder from receiving funnels into the ports on the plastic container with simple clamps used to control the relative rates of powder flow. This prototype was tested for mixing capabilities.

Results of this testing indicate the need for powder storage via a hopper system with a mechanically controlled auger to precisely meter out the powder flow as the valve, or clamping, approach did not yield sufficient control over the powder flow rate. Additionally, testing was performed to determine the optimal nature of the deposited mound of powder. A simple circular mound was found to be inadequate due to the large amount of powder that must be deposited to fully cover the part cylinder and the large amount of waste powder generated as a result of this approach. The most efficient shape was found to be slit along the bottom of the powder mixing chamber that is perpendicular to the direction of roller motion. This slit will deposit a line of powder in front of the powder roller which will then be transferred to the part cylinder in an efficient manner.

4.2.2 Fabrication and Description of Hardware

Following the initial prototype development and testing, hardware was specified for fabrication and assembly to form a fully functional powder delivery system. A computer controlled powder feeder system was purchased to store the powder and then meter the powder into the mixing chamber at the correct rate. Additionally, a mixing chamber with the necessary slit along the bottom was fabricated. Finally, a impeller assembly consisting of impeller, connecting shaft, DC motor, and controlling variable voltage power supply complete the hardware developed for powder delivery.

The powder feeder system consists of a storage hopper and a control module for each powder type and associated Labview software to allow control of the powder feed rates. The hardware consists of an AccuRate Model 100 dry material feeder. The storage hopper contains an agitation paddle to assist material flow down to the feed auger that

delivers powder from the hopper. Powder flow rate is controlled by a AccuRate Analog Input Module which accepts a 0 – 10 analog controlling voltage to determine feed rate and a 0 – 5 digital on/off voltage. Sample tungsten carbide and cobalt powders were sent to AccuRate for generation of calibration curves. These resulting curves related mass delivered to voltage applied for each of the material systems of interest.

The controlling voltages are supplied by Labview programs written for powder feed rate control. The Labview programming language allows one to develop customized virtual instruments which the user can control from a typical PC. User inputs to the virtual instrument are then translated into controlling voltages which are supplied to the powder feeder control module through a PC-mounted input/output card. Following calibration of the controllers, a simple controlling virtual instrument was developed in which the user is able to control the amount of time each feeder is driven and the driving voltage.

A round mixing chamber was fabricated from sheet metal in which the lower portion of the chamber converged to a thin slit at the bottom. As described above, the slit allows the powder to be deposited in a line shape along the roller to minimize the size of the required powder deposit. A Pittman 12 VDC motor is selected to drive the impeller. Power is supplied via a variable voltage DC power supply. Control knobs at the front of the power supply allow control of the supplied voltage, which in turn controls motor and impeller rotational speed. Calibration of the impeller speed reveals that at less than 2 volts, impeller speed was insufficient to eject the powder. At voltage inputs of greater than 7 volts, impeller speed was so high that the powder was immediately ejected from the impeller so that no mixing could occur. A range of 3 to 4 volts of power supply input was found to be optimal.

The hardware was initially set up in a temporary arrangement for testing purposes before later integration with the multiple material workstation. The output nozzles of the two powder feeders were positioned over the impeller. The mixing chamber and impeller were mounted on a temporary stand with the impeller positioned inside

the mixing chamber (Ref. Figures 4.2 & 4.3).

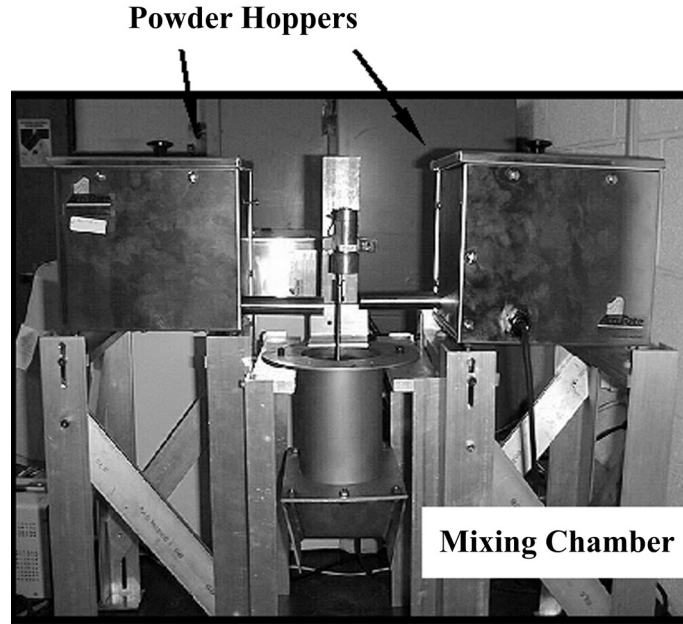


Figure 4.2: Side View of Mixing Chamber and Powder Feeders

4.2.3 Functional Testing of Hardware

In order to fully test out the powder delivery subsystem before integration with the rest of the system, a relationship between supplied voltage ratio and resulting mixture ratio must be developed. The first step is to determine the given voltages that must be applied to the powder feeders for a given desired ratio of materials. Assuming that the desired ratio is in terms of percent volume, the first step is to convert this measure into terms of percent mass. This is necessary since the calibration curves for the powder feeders were generated by AccuRate in terms of mass.

Assuming a given layer volume, a relationship can be developed using the density of the materials to relate a given mass ratio to a volume ratio. It was found to be necessary to determine the density experimentally with a standardized procedure.

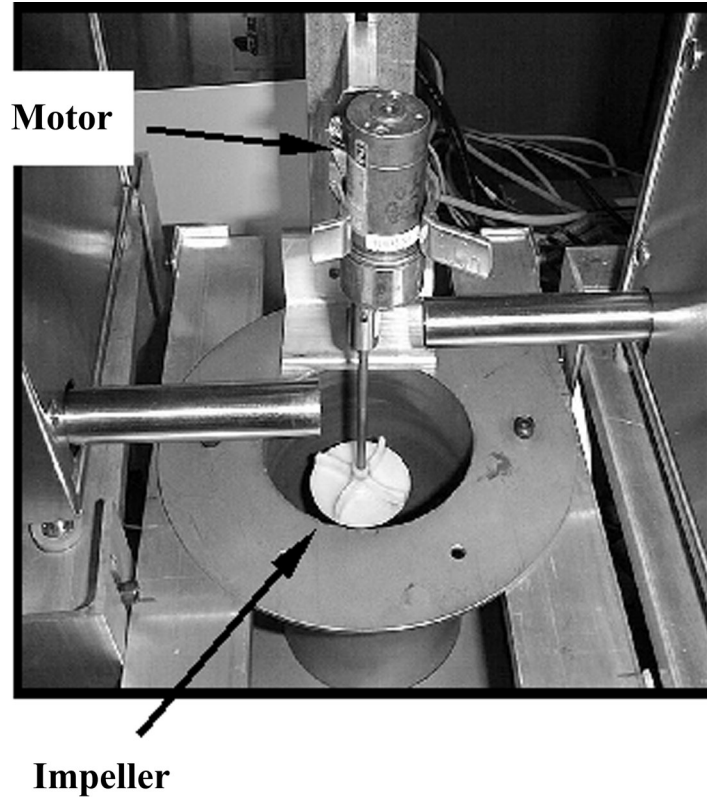


Figure 4.3: Impeller Subassembly

Standard tabulated values of density are not relevant to the density of powders in which packing density plays a critical role in the bulk density measure. In general, powder morphology plays a strong role in packing density so that the packing density of a given powder is unique. Thus, it is necessary to experimentally determine the density of a given powder. This was achieved by packing the powder in a consistent manner and then measuring its volume and mass.

Following the development of the relationship of mass and volume ratios, the calibration curves developed by AccuRate are used to determine the ratio of the voltages supplied to the two powder feeders. Next, the actual ratio of the resulting blend must

be experimentally measured.

The resulting sample was packed in the similar manner used to experimentally determine the powder density described above. The resulting mass and volume was then measured. Since the density of the cobalt and tungsten carbide materials have been determined using the same experimental procedure, a simple linear proportionality can be used to relate the density of the mixture to the ratio of materials in the mixture.

A number of trials were completed in which the powder feeders were ran at different voltages. Data analysis examined the factors of repeatability, uniformity, and accuracy. Repeatability was examined by determining the degree of variability in samples collected from the same location in the deposited line with the same voltages applied to the powder feeders. This measure describes how consistently the powder delivery subsystem will perform at a given point of operation. Results of this analysis indicate a variability of 7%.

Uniformity was examined by collecting samples at three locations along the line of powder deposited from the mixing chamber. This measure determines the degree of variation of the given material blend along the deposited line. A variability of approximately 10% was determined from an analysis of the data. Finally, the accuracy of the system was examined by relating the actual deposited ratio to that used to determine the powder feeder voltages. Accuracy was acceptable when a mass ratio was assumed as an input to the system. Use of a volume ratio resulted in a discrepancy between the requested and delivered material ratio. It is assumed that the source of this discrepancy is an incorrect correlation between mass and volume ratios of the material system.

4.3 Laser Scanning Subsystem

The first primary subsystem which was developed for the multiple material workstation was the laser and associated optical hardware required to properly control and deliver the laser beam to the sintering location. The hardware making up this subsystem form a major part of the overall system and its installation and fabrication consumed a sig-

nificant portion of the project resources. Functionally, the hardware is similar to that used in traditional selective laser sintering so that little original design work was required for this hardware. The bulk of the work focused on the specification, acquisition, installation, and fabrication of the various components making up this subsystem. Additionally, a significant amount of debugging and trial-and-error work was required to fully understand the workings of the hardware.

In general, the system consists of a large, 0.5 kilowatt EverLase CO₂ laser which is used to generate the laser beam. A closed loop water chiller located in another room provides a heat sink to dispose of the waste heat generated by the laser during operation. The beam is then directed upwards and turned ninety degrees with directional mirrors. The beam is then directed down the length of a laser table upon which various optical components are mounted. The first primary optical component is 2X beam expander used to enlarge the beam. The enlarged beam is then passed through a focusing lens used to narrow the beam to a point. As the beam is narrowed, it passes through a set of XY-galvo scan heads that control beam position on the powder bed for scanning purposes. The scan heads are controlled with a dedicated scanning controller. This controller in turn accepts information to build its scan vector table from the general controlling PC which acts as a user interface for the multiple material workstation.

4.3.1 Laser Installation and Hardware Description

One of the first pieces of equipment acquired for the project was the CO₂ laser used to generate the energy required for processing. The laser was donated to the project by the Gillette Company at the completion of a industrial application. Upon donation of the laser, a laboratory was selected for installation and the future development of the multiple material workstation.

At the time of laboratory selection, an considerable amount of pre-existing equipment was present. These materials were removed from the laboratory and it was prepared for laser installation. Some modifications, including the addition of a double door

Gas Type	Percentage (%)
CO ₂	4.5
N ₂	12
He	82

Table 4.1: Laser Gas Blend Composition

at the back of the laboratory, was required to accommodate the laser. Following the completion of these renovations, the laser was physically brought into the laboratory and placed in the correct location. Additionally, a separate closed loop chiller was installed in a small separate room at the back of the laboratory.

Necessary electrical connections were made to provide power to the laser. Cooling lines were connected between the chiller and the laser. These lines are used to carry cooling water between the laser and the chiller where the waste heat from the laser is dumped into the air via a water-to-air heat exchanger. A gas cylinder of the correct composition was purchased and connected to the laser (Ref. Table 4.1). After all the necessary connections were completed, a start-up procedure was undertaken to initially fire the laser.

Initial attempts to fire the laser were unsuccessful until it was realized that the laser safety interlocks had been modified from their original state. The necessary adjustments were made to the interlocks and the laser was fired. During the initial period of figuring out the correct operation of the laser, a good deal of uncertainty was present regarding the correct and efficient operation of the laser. It was decided to have a company representative examine the laser. A Convergent representative visited for a day during which laser operator training was conducted and the laser was tuned for optimal operation. Additionally, a number of simple components were tested and replaced to bring the laser to a fully operational condition as shown in Figure 4.4.

As stated above, water is used to carry the waste heat from the laser to a separate chiller unit (NesLab Model HX-500 air cooled chiller). This chiller unit then uses a heat

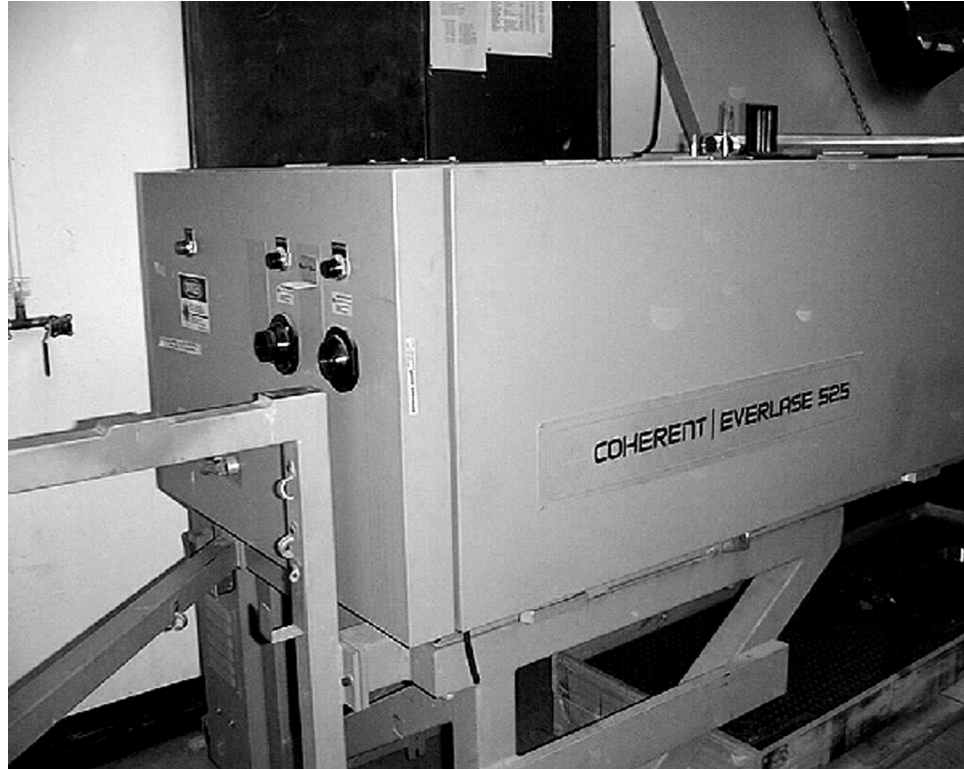


Figure 4.4: Processing Laser

exchanger to dump the waste heat from the water out into the ambient air. Power is supplied to the separate chiller via a circuit box on the wall behind the laser. A minimum water flow is required to maintain an open safety interlock and allow normal operation of the laser. Inside the laser, a separate self-contained oil is used to directly transfer heat from the laser to the external coolant plumbing system.

The electrical system is separated into two distinct systems. First, a relatively low voltage system is used to power the electronic controls in the laser, as well as the coolant and gas pumps used in the support functions. When the laser is initially powered from the control panel, power is only supplied to these systems. A separate high power system is used to apply extremely high voltages across the length of the tubes containing the gas blend. With the correct blend composition at the correct pressure, an arc is

struck along the tubes and they fill with a plasma. This plasma then lases to form the laser beam. The high voltage system is not energized until the laser beam is turned on at which time the plasma is generated and the gas is lasing. However, for the beam to exit the system, the shutter at the end of the laser must also be supplied with power and then opened. The high voltage system is also dependent upon the correct positioning of the high voltage circuit breaker (CB501) which is located at the back right side of the laser. This breaker is used in the normal start-up procedure to prevent an accident activation of the high voltage system.

The laser beam is directly generated from a series of tubes which contain a special blend of CO₂ gas. In order to initiate lasing of the gas filled tubes, the tubes are first evacuated with a mechanical pump contained in the laser. This pump is automatically activated when the system is turned on before the laser is fired. The mechanical pump will evacuate the air from the tubes until a rough vacuum is achieved. The pressure in the tubes may be observed via a simple dial gauge on the back right side of the laser.

The pressure in the tubes is controlled via the tube pressure control knob, which basically controls how much pressure the mechanical pump is allowed to exert on the tubes. Normally, the pressure in the tubes is controlled via this input to maintain a pressure of 2.4 – 2.67 kPa (18 – 20 torr) in the tubes. This pressure is required for the proper lasing of the carbon dioxide gas blend. An interlock is also present to monitor the pressure of the gas in the tubes and will shut down the high voltage system if the pressure is not in the normal operating range.

The gas blend is stored in a separate cylinder that is attached to the laser with a steel-reinforced gas line. Gas pressure at the cylinder must be set at approximately 0.0689 MPa (10 psi) for proper operation. A safety interlock is also present which will terminate laser operation if insufficient gas pressure is present.

The laser may be operated in one of two primary modes. These modes are “raw” and “recycle”. These two modes determine the nature of the gas that is being used in the laser and is controlled via the gas purge rate. This input basically controls the rate

at which gas is introduced into the laser. During lasing of the gas blend, the induced plasma alters the blend composition, making the gas increasing more difficult to lase. Therefore, it is necessary to purge the gas from the system and replace it with more fresh gas with the correct composition.

In the raw mode, the gas is pulled from the cylinder, fed into the tubes and then allowed to exit the laser. The tube pressure knob is closed so that the full pressure of the mechanical pump is allowed to pull against the tubes and the purge rate is set to control the flow rate of the gas through the system to maintain the proper pressure at $2.4 - 2.67$ kPa ($18 - 20$ torr). This condition provides the optimal blend of gas to the laser and allows a strong plasma arc to form. However, this arrangement tends to use the gas blend at a very fast rate.

In order to conserve the gas, a gas recycling system is present on the laser. This system routes the gas through a catalyst to restore the correct blend composition following lasing. After passing through the catalyst, the gas can be reused for additional lasing. In the “raw” operating mode, gas does flow through the catalyst, however the blend is correct so the gas is relatively unchanged.

In order to enter the “recycle” mode, in which gas flow is minimized, the purge rate is turned down. This tends to reduce the flow rate of gas through the laser so that the blend composition becomes non-optimal. As the blend composition changes, the catalyst begins to react with the altered blend to bring it back to the correct composition. Thus a correct composition is maintained while gas usage is reduced. However, a reduction in purge rate with the pump pulling fully against the tubes will quickly drive the pressure outside of the optimal range.

Thus, in the recycle mode, the pressure is maintained at the correct value via control of the pressure control input. In general, the purge rate is set as low as possible while still getting good lasing behavior. Sufficiently low values of the purge rate will cause the rate at which the blend is altered by lasing to exceed the processing rate capability of the catalyst and the plasma will become unsteady. A value of approximately

4 was found to be suitable for good operation in the “recycle” mode.

The catalyst in the laser is temperature sensitive and must be allowed to heat up before one can enter “recycle” mode. Catalyst heating is most quickly achieved by running the laser in the “raw” mode with a good plasma present in the tube, but no beam being generated. Then the waste heat generated is used to rapidly heat the catalyst into an operational state. The effect of blend composition can be observed in the warm-up state by attempting to enter recycle mode. As the purge rate is slowly reduced while the pressure control is slowly opened, the gas flow through the system is gradually reduced. If the catalyst is not warmed up, the blend composition will become sub-optimal and the plasma arc will become unsteady and some of the tubes will lose the plasma arc. Finally, it will not be possible to maintain a good arc. Note that an attempt to generate a plasma when the tubes are filled with air at the correct pressure will lead to excessive currents in the high voltage system and damage to electrical components.

The primary controls on the laser are broken into two groups. First, the back right side of the laser contains the gas flow controls (tube pressure and purge rate controls) discussed above. Also, this area contains the pressure gauge which displays the current pressure in the tubes. Additionally, the CB501 High Voltage breaker is present in this area as well as separate switches to control power to the gas and water flow systems.

The other primary area containing controls is located at the back left corner of the laser. These controls are the primary interface between the user and the laser. A key lock and push-button switch are used to power the laser system. As stated above, this powered state only consists of the low voltage system being activated. A rotary knob is used to turn the laser (*i.e.* the high voltage system) on and off. An additional rotary knob is used to control the operating mode of the laser.

The laser can be operated in one of three modes. First, continuous beam mode (CW) can be selected, in which the laser fires a continuous beam of laser energy. Pulsed mode makes up the second of the operational modes, in which the laser energy is allowed

to build up in the resonant chamber to a high level before being released through the shutter. This mode allows high peaks of laser energy useful for drilling or cutting operations. A number of other control inputs are present to control the frequency and timing of the pulse trains used in the pulsed mode of operation.

The two primary control inputs for pulsed operation are pulse period and pulse length. The pulse period is simply the time between the start of sequential pulses. The pulse length is the length of time that the laser is on during one pulse. The ratio of pulse width to pulse period is defined as the duty cycle of the laser. The duty cycle should be maintained below 50% for proper pulsed operation of the laser. Additionally, the pulsing frequency should not exceed 1 kHz.

The last operational mode, “ext”, allows the activation of the laser beam to be controlled from an external source, usually a controlling computer. The signal for this mode of operation is supplied via BNC connector on the beam end of the laser.

For initial testing purposes, the laser was typically fired in the CW mode. However, for sintering purposes, the mode is set to “ext” and firing signals are sent via the BNC line from the scanning controller which coordinates beam position on the powder bed with firing commands to the laser.

The operating power of the laser is controlled via a controlling current knob located next to a gauge which displays the level of the current. A switch is also present which allows the user to determine the voltage level being generated along the tubes to form the arc. During CW mode, the controlling current should not exceed 50 mA.

The final control system consists of the shutter which allows the laser beam to exit the system. A key lock and power button similar to that used for laser activation is present for this control. Activation of this control will energize the shutter for potential changes of state. The actual shutter can be opened or closed via toggles switches located on the beam end of the laser. These switches have three possible configurations consisting of open, closed, or external control. In the normal operating mode for sintering, the shutter was opened and the laser activated via computer control. External control of the

shutter via computer control was considered, but not implemented. Consultations with Convergent technical support personnel indicated significant technical difficulty with respect to electrical compatibility for computer control of the shutter versus computer control of the actual laser activation.

4.3.2 Beam Path Optical Hardware

After the laser beam is generated and exits the laser, the beam is directed and focused using a system of optical hardware. The first step in the development of this hardware was the design and fabrication of a supporting frame for a laser table. The laser table is positioned upon the supporting frame and then the various optical hardware components are positioned on the laser table. The supporting frame is also used to support steering mirrors which direct the beam upward and the down the length of the laser table into the appropriate optical hardware. Additionally, the frame must contain an open volume beneath it which will contain the power plate and part cylinder subassemblies. The laser table supports two primary pieces of optical hardware. First, the beam passes through a beam expander which enlarges the beam for better focusing behavior. Next, the enlarged beam passes through a focusing lens that causes the beam to converge to a point on the powder bed.

A large supporting frame was developed from Uni-Strut and accompanying hardware. The frame was then leveled along the top to ensure a flat surface for the laser table to rest on. This frame was also designed with a large open space in the front and the primary stiffening members located in the back and sides of the frame. The large open space was designed to accommodate the presence of the part cylinder and powder plate subassemblies to be developed later.

Next, a laser table specification was developed for the purchase of this hardware. A Kinetic Systems VIBRALITE SS laser breadboard was selected in which the bulk of the table is made up of a honeycomb structure of aluminum sandwiched between two thin layers of aluminum. This structural arrangement results in a relatively light, low

cost table with high stiffness. This specific breadboard measures 51 mm (2 in) thick, 0.607 m (2 feet) wide, and 1.83 m (6 feet) long (Model #: 5602-2472-21). The top of the laser table possesses a grid of tapped holes (1/4-20 sealed mounting holes on 1" centers) to aid in the installation of optical hardware. During the specification of the laser table, a 152.4 mm (6 in) diameter port was specified at one end of the laser table. This port will allow the laser beam to pass through the laser table and down to the sintering surface. It is over this port that the laser scan heads are installed.

Following the fabrication of the frame, it was placed at a 90° angle to the laser and used to support the steering mirrors to direct the laser beam after it exits the laser. In order to correctly direct the laser beam down the length of the laser table, it is necessary to turn the beam 90° upwards and then turn it another 90° to the left (looking down the length of the laser). These turns are accomplished via a set of two Convergent Energy directional steering mirrors (Model #: 0155-092-02). These mirrors are coated for high power densities and are delivered assembled with a mirror adjustment plate which allows a fine control of the angular deflection of the mirror. A supporting elbow bracket was also purchased into which the mirror assembly is mounted (Model #: 0714-032-03). Additional brackets were fabricated to allow the attachment of mirror mounts to the frame.

Following the mounting of the mirrors on the frame, lengths of beam shielding material were fabricated from standard size aluminum tubing. These tubes were cut to the correct length and then machined to form threads at each end. These threads were developed to allow the tubes to screw into the mirror mounts and the laser beam exit port on the laser. Then, the tubes were assembled with the mirror mounts to direct the laser beam to the correct alignment with the laser table (Ref. Figure 4.5). Additionally, the shield tubes were observed to substantially enhance the stiffness of the steering mirror mounts relative to the frame.

After the steering mirrors were assembled, a series of laser paper targets were developed. The laser was fired at extremely low power with accompanying adjustments

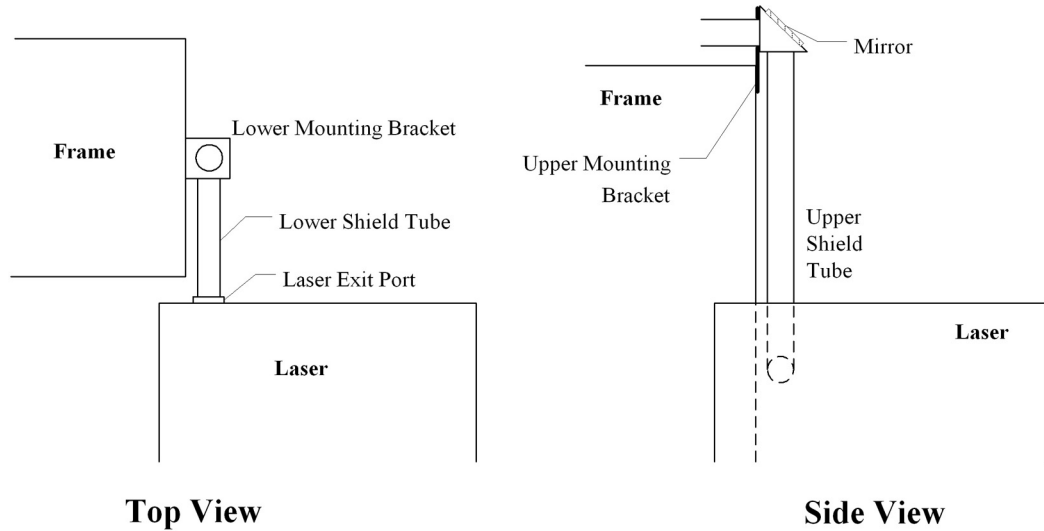


Figure 4.5: Arrangement of Steering Mirror Assembly

to the angular positioning of the mirrors. This process was repeated in an iterative fashion until the mirrors were properly aligned.

After the laser beam is directed down the length of the laser table, it is captured by a 2X beam expander. This beam expander doubles the diameter of the beam which is then fed into a focusing lens. The degree of beam expansion is an optimal value which depends upon various conflicting effects.

First, beam expansion is maximized due to an inverse relationship between the size of the laser beam hitting the focusing lens and the minimum possible size of the laser spot formed as a result of the focusing process. Thus, it is critical to enlarge the beam as much as possible before focusing occurs to form a very small spot. A reduction in spot size allows better side wall definition and the formation of small features on the formed component.

However, beam expansion is limited by the aperture size of the scanning heads. The XY-scan head subassembly has a limited aperture size. For the hardware selected for our system, the scan head possesses an aperture size of 30 mm (1.18 inches). If

the laser beam entering the scan head assembly is too large, the outer edges of the laser beam will fall outside of the edge of the scanning mirrors during certain mirror configurations. Thus, the size of the laser beam at the scan head is limited to a maximum size. Additionally, the beam should also be as large as possible to prevent damage to mirror coatings. Highly focused laser beams in which the focal spot is near the mirror surface can exceed the rated energy density of the coatings on the mirror and damage the mirrors. However, since we desire a fully expanded beam for other reasons, this is not a concern in our design process.

Thus, it becomes apparent to produce a minimum possible spot size, one must move the beam expander and focusing lens as far from the scan head as possible. This will allow beam expansion to be at a maximum value given a constraining scan head aperture. However, after the beam passes through the scan head, it must also travel down to the scanning surface. Due to space requirements of powder delivery equipment between the laser table and the powder layer, the laser beam must travel a relatively long distance from the focusing lens to the sintering location. This effect is amplified if the previous procedure is used to minimize spot size.

This long focal distance results in a beam that converges slowly after it has passed through the focusing lens. Thus, moving the focusing lens away from the scan head does not dramatically change the degree of beam expansion allowed. However, another factor also influences the positioning of the beam expander.

As the laser beam exits the laser, the beam diameter will very gradually converge to a minimum value known as the waist before diverging. The ideal placement of the beam expander should occur at the waist as the beam is in its most coherent state at this location. In order to determine the waist location, the manufacturer of the laser (Convergent Energy) was consulted and revealed the following specifications (Ref. Table 4.2).

In this specification, the beam diameter is defined as the diameter of an aperture that accepts 87% of the laser's power, assuming a continuous wave Gaussian beam. This

Specification	Value
Emergent Beam Diameter	18 mm
Distance to Waist	5.5 m
Waist Diameter	14 mm

Table 4.2: Laser Beam Specifications

is also known as the $1/e^2$ radius. In a similar fashion, we can define a $1/e$ beam radius as the diameter of an aperture that accepts 63% of the transmitted laser power.

The beam divergence, ϕ , can be calculated using these values. First, a power meter with a fixed aperture is used to measure the laser power at different locations along the length of the beam. Specifically, the locations along the beam corresponding to 63% and 87% of total power are recorded. Then the beam divergence is given by Equation 4.1.

$$\phi = \frac{\Delta D}{r} \quad (4.1)$$

where $\Delta D \equiv$ change in beam diameter between the two locations and $r \equiv$ distance between measured locations.

Given the desired spot size and the length of the laser table, a number of possible configurations were examined. A doubling of the beam diameter was found to be an optimal beam expansion ratio as a result of this process. Given this requirement a suitable expander was purchased from the vendor, Laser Power Optics.

Following the determination of the degree of beam expansion, a beam expander was specified and purchased. A suitable expander was chosen from the BX-1500 series (Model #: BXZ1.5-2X-21244). These expanders are a Galilean design in which a negative lens is used for expansion and then a positive lens collimates the beam.

Additionally, a lens to focus the collimated beam to a point on the powder bed was also fabricated. The selection of an appropriate focusing lens requires the selection of a focal length and lens diameter. With the previously given waist diameter and a 2X beam expander, the lens diameter becomes roughly 28 mm (1.10 in). This is then

multiplied by 1.25 to account for the Gaussian nature of the laser beam to yield a final lens diameter of 35 mm (1.38 in).

As stated previously, the focal length of the laser must be sufficiently long to allow the installation of powder delivery hardware between the laser table and the sintering surface. However, excessively long focal lengths lead to larger spot sizes on the sintering surface due to dispersive effects. This relationship is describe by Equation 4.2 and selected focal lengths must be checked against this equation to ensure reasonable spot sizes.

$$d = \frac{2.44\lambda f}{\phi} \quad (4.2)$$

where $d \equiv$ spot diameter, $\lambda = 10.6 \mu\text{m} \equiv$ wavelength of CO₂ laser beam, $f \equiv$ focal length, and $\phi \equiv$ lens diameter.

Based on these values, a optical component manufacturer was contacted for specification and purchase of the lens. Laser Power Optics was selected as a lens supplier in order to allow joint development of the lens and the beam expander. A 38.1 mm (1.5 in) diameter, 610 mm (24 in) focal length lens was selected for fabrication (Model #: LPZ1.5-24'-2139). Use of this focal length in Equation 4.2 yields a laser spot size of 450 μm . This lens was mounted onto the exit end of the beam expander to form a single component (Model #: BXZ1.5-2X-Modified).

This arrangement simplifies alignment of the optical components and allows one to mount only one component instead of two. Finally, a mount was fabricated locally to allow proper orientation and mounting of the beam expander on the laser table. Flexible positioning of the beam expander in three dimensions was a primary design criteria for the beam expander mount. Following fabrication of the mount, the beam expander was mounted in the correct location on the laser table. Proper final positioning of the beam expander was accomplished via firing of extremely low power laser beams onto a target made of laser paper followed by appropriate adjustments of the position of the beam expander.

4.3.3 Laser Scanning Control

After the beam has exited the focusing lens, the next optical component of interest is the scan head assembly. This assembly consists of two coated mirrors which act to direct the laser beam on the scanning surface. In general, each mirror directs the laser along a given axis of movement, which when combined allows the formation of general 2-D curves on the sintering surface. The mirrors are coated in order to prevent damage to the mirror surface by the laser beam. Mirror rotation is accomplished via a galvo motor which is controlled via a dedicated scan controller.

In order to reduce equipment costs, a previously used General Scanning DE2000 scan system consisting of scan head (Model E00-Z2300, Serial # 113323) and controller (Model # E10-1203816, Serial #'s 113321 & 113322) was acquired from surplus equipment and installed. The scan head mirrors possess a gold high-power coating capable of handling our power densities. Specifically, the gold coating reduces mirror absorptivity of the laser beam to allow usage at high power densities. Consultations with General Scanning indicated that our coating is sufficient to handle 500 W in continuous wave mode assuming the beam is fully expanded. The scan heads must be installed above the previously fabricated port in the laser table. While the existing mirror assembly was mounted in a bracket, this was not sufficient to allow proper mounting and positioning of the hardware above the port. In a manner similar to the beam expander mount, a custom mount was designed and fabricated locally. The scan head assembly was then fixtured to this mount and properly positioned above the port (Ref. Figure 4.6).

The scan heads are connected via data cables to the dedicated scan controller. This scan controller acts as an interface between the operating PC and the scan heads. The PC program will generate a table of values that defines a set of vectors or scan lines. This vector table is then sent to the controller which then converts this table into appropriate driving voltages for the scan head galvos. In addition to the control of the scanning mirror, the scan controller also generates a controlling signal which is sent to the laser. This signal is linked to the vectors so that the start and end of a given scan

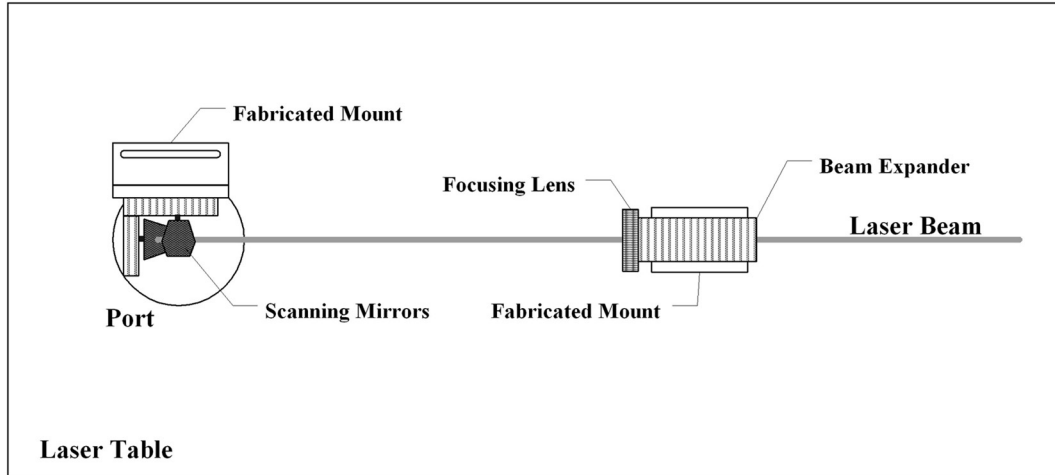


Figure 4.6: Location of Optical Components

vector is a signal to turn the laser on or off.

These signals are sent to the laser via a BNC cable which then plugs into the end of the laser and is used to turn the laser on and off at the appropriate times. As discussed previously, the current system modulates the state of laser activation and does not open and close the shutter. During the installation of the scanning system, it was discovered that conditioning was required of the signal from the scan controller to the laser. Suitable electrical components were purchased and soldered onto a small piece of breadboard. This was then mounted into a small package and connected between the scan controller and the laser.

4.3.4 File Conversion Software

After the scanning hardware and software was installed, the system was tested. In order to properly test the system, a sample drill bit file was acquired from Hughes. This solid model file was then converted into the appropriate `.stl` file format used in rapid prototyping technologies. Next, a commercial SLS machine was used to build a part file in the `.mtg` file format. This format basically consists of a list of data points which

define the beginning and end of the vectors making up the part file with appropriate markers to separate layers and indicate the end of the part.

Research into the DE2000 controller and the software installed in our system indicates a lack of compatibility between the `.mtg` file format and our system. Specifically, our system requires a `.dti` file format. On a general level, the `.mtg` and `.dti` file formats have the same form, however, the markers and order of the data are sufficiently different to generate a functional incompatibility.

Therefore, it was found to be necessary to write a small program to convert the `.mtg` file format to the `.dti` file format. Basically, the program must read in the `.mtg` file and convert the markers and reorder the data as necessary to generate a `.dti` file. The basic program was developed and tested. During this process, a rather laborious debugging issue developed regarding value typing which lead to trial and error process to determine the appropriate number type to be written into the `.dti` file. Following the completion of this work, another error was observed which prevented the scan controller from operating properly. Following further debugging efforts, it was discovered that a scaling error was present in the conversion program. This scaling error lead to the generation of a part that exceeded the spatial limits of the scan heads. In other words, vector endpoints were generated which did not fall in the range of valid values. This error would cause the scan controller to hang without generation of any appropriate error codes. Following the location and resolution of this error, the scan controller was tested and found to operate normally.

Initial part files tended to be rather small with a small number of scan vectors and large distances between adjacent scan vectors. These large values of scan spacing would lead to poor part quality, so it became necessary to generate a number of different part files with varying values of scan spacing in the `.mtg` file format and then convert these files to the `.dti` format.

Converter Source Code

The source code used to convert the .mtg file format to the .dti format is presented below.

```
/*  
converter/main  
by Larry R. Jepson
```

Dec. 20, 1999

main program

This project consists of a converter for changing a .mtg vector file format generated by S. Park into a .dti vector file format for use in an old scanning program originally developed by S. das.

This project calculates and generates true values for the X and Y values on the part bed.

These value are then shifted to make them all positive. Next, the data is scaled up by 5000 and converted to unsigned short int's for writing into the .dti file.

Scaling of the data by 5000 requires the use of a 0.0002 scale factor in the scanning program.

```
*/
```

```
#include<iostream.h>  
#include<fstream.h>
```

```

#include<stdio.h>
#include<stdlib.h>

main()
{
    // Open .mtg file as binary input stream 'in'
    ifstream in;
    in.open("insert_00015.mtg", ios::binary, 0);

    // Open .dti file as stream 'out'
    ofstream out;
    out.open("h_15.dti", ios::binary, 0);
    out.seekp(0, ios::beg);

    // Open text output file as stream 'test'
    ofstream test("cout");

    // Test to see if input file has opened properly
    if(!in)
    {
        cout << "Cannot open input file." << endl << endl;
        return 1;
    }

    // Test to see if .dti file as opened properly
    if(!out)
    {
        cout << "Cannot open output file." << endl << endl;
    }
}

```

```

        return 1;
    }

    // Test to see if text output file has opened properly
    if(!test)
    {
        cout << "Cannot open text output file." << endl << endl;
        return 1;
    }

    // Move the current get pointer up to the first factor location
    in.seekg(418, ios::beg);

    // Read in and store first factor
    double factor[2];
    in.read((unsigned char *) &factor[0], 8);

    // Read in and store second factor
    in.read((unsigned char *) &factor[1], 8);

    // Read in and store first center value
    double center[2];
    in.read((unsigned char *) &center[0], 8);

    // Read in and store second center value
    in.read((unsigned char *) &center[1], 8);

    // Move current 'get' pointer up to the end of the header

```

```

in.seekg(304, ios::cur);

// Check and see if we are at the end of the header
long int head_end;
in.read((unsigned char *) &head_end, 4);
if(head_end != 65521)
{
    cout << "Error:  Not at end of header." << endl << endl;
}

// Initialize data storage variable
long int inout = 0;

// Initialize state variable to switch between x and y values.  When
// state = 0, write out x value; when state = 1, write out y value.
short int state = 1;

// Enter  infinite while loop to process data
while(1)
{
    // Read in a data value
    in.read((unsigned char *) &inout, 4);

    // If statement for processing End of Layer marker
    if(inout == 65523)
    {
        // Read in next value to overrright .mtg End of Layer marker
        // which we do not want
    }
}

```

```

in.read((unsigned char *) &inout, 4);

// Initialize Hexadecimal End of Layer marker as unsigned short int
unsigned short int end_layer = (unsigned short int) 0xfffe;

// Write End of Layer marker into .dti file
out.write((unsigned char *) &end_layer, sizeof(end_layer));

// Write out the value as a test
test << "End of Layer:  " << end_layer << endl;

// If statement to check to see if we are at the end of part
// Note that this must occur after an End of Layer marker
// is encountered in the .mtg file
if(inout == 65524)
{
    // Initialize hexadecimal end of part marker as unsigned short int
    unsigned short int end_part = (unsigned short int) 0xffff;

    // write end of part marker into .dti file
    out.write((unsigned char *) &end_part, sizeof(end_part));

    // Write out the value as a test
    test << "End of Part:  " << end_part << endl;

    // Break statement to leave loop
    break;
}

```

```

}

// If statement to ignore beginning of grid markers
// During normal X and Y value processing
if(inout != 65522)
{
    // Switch state variable
    state = !state;

    // If statement for x case
    if(!state)
    {
        // Calculate true value of x based on center and factor values
        double x = ((double) inout - center[0]) / factor[0];

        // Shift data so it is positive
        x = x + 1.0;

        // Scale data and convert to unsigned short int
        x = x * 5000;
        unsigned short int x2 = (unsigned short int) x;

        // Generate message if value exceeds 7500
        if(x2 >= 7500)
        {
            cout << "Error:  value exceeds 7500" << endl << endl;
        }
    }
}

```

```

// Generate error message if values are negative
if(x2 <= 0)
{
    cout << "Error:  Calculated values are negative" << endl;
}

// Write x value into .dti file
out.write((unsigned char *) &x2, sizeof(x2));

// Write out the value as a test
test << "X Value:  " << x2 << endl;
}

// If statement for y case
if(state)
{
    // Calculate true value of y based on center and factor values
    double y = ((double) inout - center[1]) / factor[1];

    // Shift data so it is positive
    y = y + 1.0;

    // Scale data and convert to unsigned short int
    y = y * 5000;
    unsigned short int y2 = (unsigned short int) y;

    // Generate message if value exceeds 7500
    if(y >= 7500)

```

```

    {
        cout << "Error:  value exceeds 7500" << endl << endl;
    }

    // Generate error message if values are negative
    if(y2 <= 0.00)
    {
        cout << "Error:  Calculated values are negative" << endl;
    }

    // Write y value into .dti file
    out.write((unsigned char *) &y2 , sizeof(y2));

    // Write out the value as a test
    test << "Y Value:  " << y2 << endl;
}
}

// Close up all the streams
test.close();
out.close();
in.close();
return 0;
}

```

4.3.5 Operation Manual

In order to assist in the future operation of the laser and scanning subsystem, the following operational manual is presented.

Laser Start Up Procedure

1. Turn the gas and water on
2. Set gas flow to 10 psi
3. Ensure that coolant and vac switches are on
4. Ensure that High Voltage breaker (CB501) is off
5. Ensure that mode control knobs are set to off and CW mode
6. Ensure that current is turned to zero and then raised slightly
7. Turn power on
8. Close tube pressure control knob
9. Adjust purge rate to get a reading of 18 - 20 torr
10. Turn laser power off
11. Turn CB501 on
12. Turn laser power on
13. Ensure that you have 25 kV potential across the tube drives.
14. Wait for pressure to come to 18 - 20 torr
15. Turn beam on, CW mode
16. Set current level to 25 mA. Drive voltage should read about 15 kV

17. Wait 30 minutes for laser to warm up
18. Turn beam off
19. Turn CB501 off
20. Set purge rate to about 4.0
21. Adjust tube pressure control to get 18 - 20 torr
22. Turn laser power off
23. Turn on CB501. *Do not turn CB501 on with laser power turned on.*
24. Turn laser back on
25. Ensure that tube pressure has fallen to 18 - 20 torr
26. Turn beam on

Laser Shut Down Procedure

1. Turn beam off
2. Wait 5 minutes for laser to cool down
3. Shut laser down
4. Shut down water and close gas supply

Scan Control Start Up

1. Double click on the icon **Shortcut to newpproc**
2. Hit **S** to center the scanners. This is not necessary, however, observation of resulting mirror movement serves as a useful check of proper system communications.
3. Hit **U** to open a **.dti** file.

4. Type `list` to browse the files
5. Choose the desired file.

At this stage, the user can scan the entire part or just one layer. The user must pick the layer to scan, go into the program, scan it, and then return to pick the next layer. Normally, this process is automated so that more than one layer at time can be scanned automatically, but current roller actuator control is not integrated into the software.

Setting up the Layer

- Hit `P` to process part
- Hit `V` to process vectors only.
- Hit `B` (not shown) and then hit `yes`.
- Hit `X` for scaling
- Choose $\delta X = 0.0002$ and $\delta Y = 0.02$ (default)
- Hit `P` to choose part parameters
- Set `X offset` = 0.8
- Set `Y offset` = 0.8
- Leave `SP` at the default of 27, just hit `enter`
- Set `SS` to be 16

The offset control determines where the laser will start scanning on the powder bed. This value should be such that the part is centered on the cylinder. If the values are incorrect, an iterative process must be used in which values are entered and then a short burst of laser light is allowed to strike the powder bed. Adjustments are then made

based on the position of the resulting mark. The **SS** value determines how fast the laser is scanning. Reductions in this value reduce the speed of the laser. In general, below about 10, little differences will be observed and 64 is the upper limit of the scanners. The normal range of operation varies between 12 and 28.

In order to initiate scanning, hit **R** and then hit **enter**. The program will process through the vectors and then start sending them to the scan head. When this happens, the controller will also turn on the laser. A small red light will come on on the front of the controller and the laser will turn on if the system is functioning correctly.

4.4 Part Cylinder Subsystem

Following the development of the optical subsystem, the next primary fabrication activity focused on the design and development of the part cylinder subassembly. The primary structural component making up this assembly is a large flat powder plate which serves as the supporting surface for the powder bed. This plate is joined to the part cylinder which serves to contain used powder and the sintered part. The other mechanical component is the part piston which moves within the part cylinder to gradually lower the part as fabrication proceeds. This movement is accomplished by a stepper motor driven linear actuator that drives the part piston. Control is accomplished via a dedicated hardware that interfaces with the user via a custom developed Labview virtual control panel.

4.4.1 Powder Plate and Part Cylinder

During the development of this assembly, a number of components were fabricated in the local machine shop. These components were then welded together followed by mechanical assembly of the remaining components. Table 4.3 presents the various components making up this subassembly, while Figure 4.7 shows the various components in an assembly view and Figure 4.8 shows the assembled component. Stainless steel was used in the fabrication of all components making up this subsystem. This subassembly forms

the core of the system and will be used in all future versions of the multiple material workstation as additional capability is added to the workstation. Since these capabilities may include the use of pre-heat or high vacuum atmospheric control, stainless steel was chosen as the primary fabrication material due to its superior performance under these conditions.

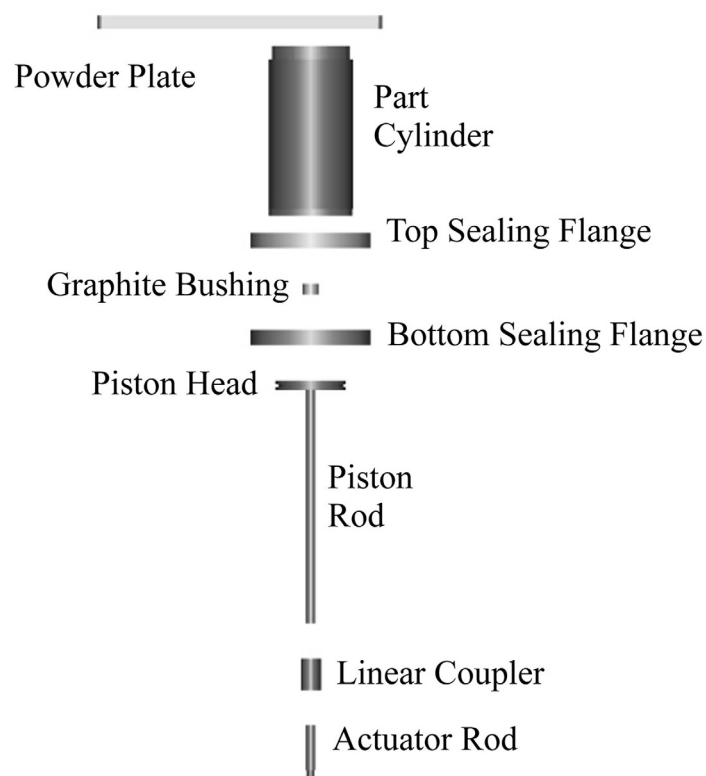


Figure 4.7: Part Cylinder / Power Plate Components

The first step in the development of the powder plate is the specification and acquisition of a large piece of flat stainless steel. A stainless steel 304L rectangular plate was selected with a thickness of 19.05 mm (0.75 in), length of 419.1 mm (16.5 in), and width of 215.9 mm (8.5 in). Following the acquisition of the raw materials, the plate was machined smooth and number of 1/4–20, 12.7 mm (0.5 in) deep holes were added on the

Part Name	Vendor	Model Number
Powder Plate	EMJ	512212
Part Cylinder	EMJ	121681
Top Sealing Flange	MDC, Inc.	110028
Bottom Sealing Flange	MDC, Inc.	110027
Copper Sealing Ring	MDC, Inc.	191015
Flange Clamping Bolts (12)	MDC, Inc.	190046
Piston Head	Local Stock	
Piston Ring	Greg-Co Piston Rings	4 Inch EndSeal
Piston Rod	Local Stock	
Graphite Bushing	Graphite Metallizing	117-8-411
Linear Coupler	Ruland	CLX-8-8-F
Actuator Rod	Local Stock	

Table 4.3: Powder Plate and Part Cylinder Component List

upper surface of the plate approximately 12.7 mm (0.5 in) from the outer edge. These holes are intended to allow the attachment of various shield gas and support structures to the plate.

Additionally, a 111.13 mm (4.375 in) diameter hole was formed in one end of the plate to accept the part cylinder. This hole was centered 101.6 mm (4 in) from the end of the plate and half-way across the width of the plate. A corresponding stainless steel cylinder was selected. The initial cylinder selected was SS316 stainless with an inner diameter of 95.25 mm (3.75 in), 12.7 mm (0.5 in) wall thickness, and 304.8 mm (12 in) length. This initial cylinder was machined to the proper dimensions and then welded to the powder plate to form the part cylinder. Following welding, honing of the inner surface of the part cylinder was found to be necessary to remove thermal distortions and bring the inner surface back into spec.

Next, a lower cap for the bottom of the part cylinder was selected and purchased from a high vacuum hardware supplier which consisted of two components making up a stainless steel flange. The upper component was a 171.45 mm (6.75 in) conflat flange with a 101.854 mm (4.010 in) inner hole. This hole was machined open to a diameter of

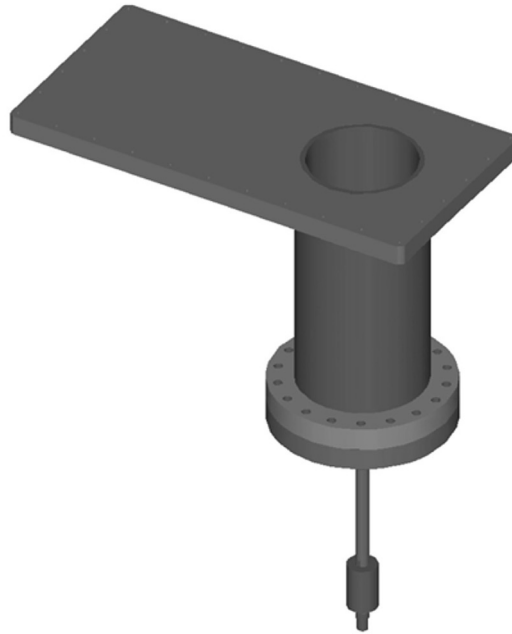


Figure 4.8: Part Cylinder / Power Plate Subassembly

120.65 mm (4.75 in) to match the part cylinder. Next, the modified flange was welded onto the bottom end of the part cylinder. The bottom component of the matched set was a 171.45 mm (6.75 in) blank conflat flange, which is basically a mating duplicate of the upper component without the inner through hole. These two mating components are formed to accept a copper sealing ring. When the two components are bolted together, the copper ring is deformed by sealing flanges on the mating surfaces of the two components. This process allows the formation of a robust, high vacuum seal. The use of this type of flange instead of a simple stainless steel cap greatly simplifies any future addition of high vacuum capabilities to the overall system.

The bottom component was then machined to form a support socket for a graphite impregnated bushing. This bushing is used to support and lubricate the piston rod as it is driven up through the bottom flange component. Specifically, a Grade

411 Graphalloy bushing was purchased from Graphite Metallizing, Inc. This bushing accepts a shaft with a maximum diameter of 12.598 mm (0.496 in) which was used to determine the diameter of the piston rod. Consultations with the vendor revealed the need for a support socket of 22.047 mm (0.868 in) inner diameter and a depth of 16.002 mm (0.630 in). The bottom flange was 21.336 mm (0.84 in) thick, thus a supporting lip was fabricated to assist in stabilizing the bushing following press fit installation.

The end of the piston rod is then connected to the linear actuator via a simple Ruland carbon steel linear coupler. Additionally, it was found to be necessary to manufacture a small threaded rod that screws into the end of the linear actuator and then attaches to the coupler. This component was primarily formed to ease assembly and maintenance procedures.

The next group of three components make up the part piston. First, a piston rod was fabricated which connects to the coupler, extends up through the graphite bushing and then attaches to the part piston. The outer diameter of the piston rod was sized to fit the previously discussed bushing. Additionally, the top end of the piston rod was threaded for attachment to the bottom of the part piston. Next, the part piston was fabricated to match the diameter of the part cylinder with a 50.292 mm (1.98 in) radius resulting in a 0.508 mm (0.02 in) gap between the edge of the piston and the cylinder wall. This gap must be sealed by the piston ring.

A 101.6 mm (4 in) diameter piston ring was selected from the vendor, Greg-Co Piston Rings. This piston ring is used to seal the interface between the outer edge of the piston head and the inner surface of the part cylinder and prevent leakage of powder. The selected piston ring possessed a height dimension of 4.674 mm (0.184 in) and a radial dimension of 4.064 mm (0.16 in).

This results in a mounting slot in the edge of the piston with a depth of 4.064 mm (0.16 in) and a height of 4.801 mm (0.189 in). Note that the depth of the slot exactly matches the radial dimension of the ring. Thus, when fully compressed, the ring will exactly fit in the slot. However, during normal operation, the ring has an outer

diameter greater than 101.6 mm (4 in) and is in a partially compressed state when it is mounted in the cylinder. In this partially compressed state, it will exert an outer force that will cause the outer edge of the seal to engage the cylinder inner wall. A 12.7 mm (0.5 in) deep hole was drilled and tapped in the bottom center of the piston to allow attachment of the piston rod.

Hardware assembly was accomplished with the following procedure to yield the component shown in Figure 4.9. First, the graphite bushing was press-fit into the bottom flange component. A copper sealing ring was placed between the flange components and then the flange components were clamped together. Next, the piston ring is installed on the piston head. Then the piston rod is pushed through the bushing and the piston head with accompanying piston ring is installed in the part cylinder. It is necessary to compress the piston ring with a ring clamp before installation in the cylinder. Then the piston head is gradually driven down into the part cylinder which gradually forces the ring clamp off of the piston head and allows the piston ring to engage the inner surface of the part cylinder.

4.4.2 Actuator Hardware and Controls

The movement of the part piston is driven by a linear actuator in which power is supplied by a stepper motor which drives linear motion via an enclosed gear train (Ref. Figure 4.10). A dedicated controller supplies the required voltages and currents to the stepper motor. The controller accepts as an input a pulse train which basically determines the number of steps the motor will take which then translates to a given distance of linear translation. The speed of translation is controlled via changes in the frequency of the pulse train.

The first step in the development of this hardware was the selection of an appropriate supplier and then the generation of the correct model number based on a part selection process and the functional requirements of the actuator. Texonics was selected as the appropriate vendor. Use of their model selection template and our functional re-

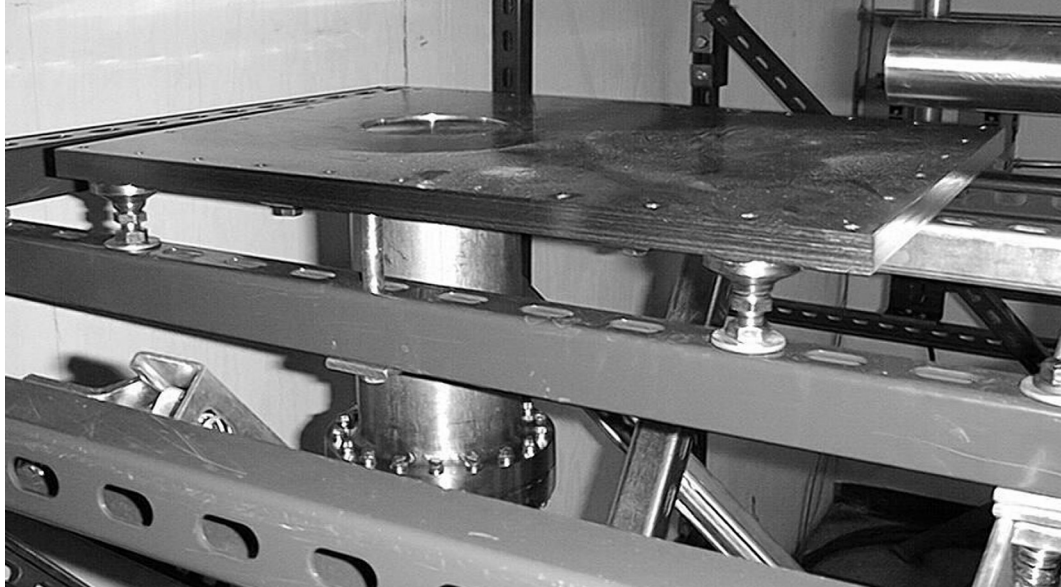


Figure 4.9: Fabricated Part Cylinder / Powder Plate

quirements resulted in a ETS32-A04-PA21-BF200 model being selected. The ETS32 series is one of the smaller models and was selected to reduce the cost. A04 designates an ACME lead screw with a 4x load amplification to produce approximately 1780 N (400 lbs) of driving force. This was deemed sufficient to overcome the frictional force exerted by the piston ring seal. PA21 designates a parallel mounted NEMA 23 motor with a cable grommet for easier electrical connections. BF200 designates a female ended actuator rod with a 200 mm (7.87 in) stroke length. This hardware was then purchased and securely mounted to the frame of the workstation.

Next, the controller was configured for our application. A ZETA4 series drive was selected as the dedicated controller to drive the linear actuator. This controller accepts a pulse train and converts that to a driving voltage for the linear actuator. Additionally, the ZETA4 controller also contains an integrated power supply to generate the correct currents and voltages. The controller was connected to the motor using a standardized cable. A LabView virtual control panel was developed which served as a

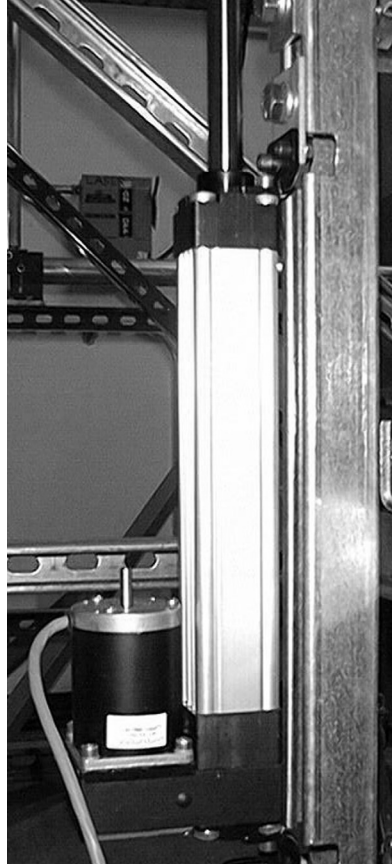


Figure 4.10: Powder Piston Actuator

user interface for control of the actuator as well as the necessary LabView software to supply the appropriate input signals to the actuator controller (Ref. Figure 4.11). The user interface allows the user to control the length of stroke, speed of translation, and direction of movement.

Following assembly and testing of the system, it was discovered that the piston head would become jammed in the cylinder after a number of cycles. This effect was primarily attributed to powder causing interference between the piston ring and the inner surface of the part cylinder. Additionally, the inner diameter of the part cylinder was near the minimum allowable diameter for the given piston ring.

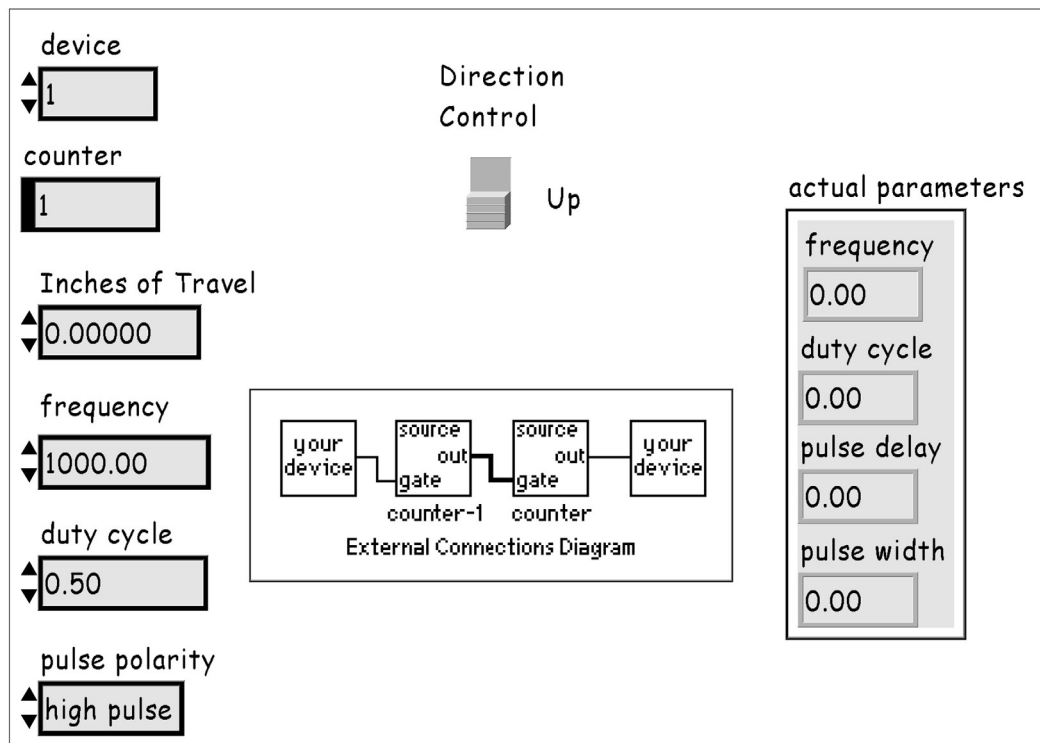


Figure 4.11: Piston Control Panel

Two actions were taken to reduce the occurrence of this behavior. First, the piston ring was removed and lightly sanded along the outer edge to slightly reduce the tightness of the fit. Second, a graphic spray was used to enhance lubrication between the piston ring and the inner surface of the part cylinder.

4.5 Powder Roller Subsystem

Following the development of the powder plate / part cylinder assembly, a powder roller subassembly was fabricated. The powder roller is used to transfer the powder from its deposition location to the sintering location on the part cylinder. This functional requirement is met by translating the powder roller head with a linear actuator.

To provide additional space in the sintering and powder deposition regions, the linear actuator is located outside this area. This arrangement also allows the actuator to be mounted outside a potential future enclosed sintering area.

In general, this leads to a design in which the linear actuator is connected to a thrust end of a shaft. This shaft then extends into the work area and terminates in a powder roller head that contains the powder roller. This powder roller is used to form a smooth layer during the powder transferral process.

The primary means of smoothing the powder is to rotate the roller in a direction counter to that normally induced by the translation described above. This tends to lift the powder as it is transferred and leaves a smooth bed during powder transferral. A number of hardware solutions were considered to generate this motion.

The first obvious solution is to mount a motor on the roller head and drive the roller rotation in a direct manner using the motor and a gear train. While this is a simple, direct solution, it introduces a new power source and complicates the design. A more novel solution was benchmarked from current commercial SLS workstations.

This solution uses a pulley and a drive cable to rotate the roller based on the translating movement of the roller head. Basically, a pulley is attached to the side of the roller. Next, a drive cable is looped around this pulley and then the ends are mounted to the frame of the machine. The drive cable is then pulled tight so that the loop around pulley links the position of the roller head to the angular position of the roller. After this arrangement is developed, a movement of roller head causes a corresponding rotation in the roller. The primary advantage of this approach comes from the elimination of the cost and complexity of a separate motor and associated gear train. This increases the robustness of the overall design. The only disadvantage to this approach is a loss of control of the roller rotation independent from the translation motion. This arrangement was deemed an acceptable trade-off.

In addition to the production of a smooth layer, it is necessary that the resulting layer is flat. The traditional arrangement of the powder roller head located in a free,

unsupported state at the end of a relatively long thrust shaft creates a long cantilever arm effect. Based on this arrangement and experience from previous development efforts, a problem can occur in which the powder head dips downward as it reaches the end of its stroke. This produces an uneven layer. To prevent this problem, a linear actuator with an incorporated rail system was specified and purchased. Specifically, a R3D-205B-24-P-ASE Track-Actuator Assembly from MSI Technologies was purchased. This actuator utilizes a ball screw drive and a driving 24 volt DC Servo motor mounted in a parallel configuration. A pitch of 5 was specified on the driving ball screw to generate a 2:1 drive ratio. Stroke length was specified at 609.6 mm (24 in) while an angle bracket mounting option was selected for attachment to the workstation.

Following specification of the linear actuator rail, a long thrust shaft was selected to connect the actuator to the roller head. The thrust shaft was purchased from EMJ, Inc. with an outer diameter of 50.8 mm (2 in), wall thickness of 6.35 mm (0.25 in), and length of 812.8 mm (32 in). A bracket was designed to mount the thrust shaft to the translating portion of the linear actuator. Stiffness was a primary design requirement of this bracket development. Next, the powder roller head was designed to mount to the end of the thrust shaft and support the powder roller. The powder roller mounts into the roller head using press fit bearings. Additionally, a pulley is mounted onto the side of the roller. Table 4.4 provides a detailed list of the components making up the roller subassembly.

Following the completion of the design phase, the various individual components were fabricated and then assembled to complete the development of the powder roller subsystem. Mounting and integration of the subsystem in the larger workstation made up the bulk of the assembly process. First, frame modification was found to be necessary for mounting of the linear actuator rail. The proper mounting of the rail is a critical operation in order to ensure a level movement of the roller over the powder bed and to ensure the correct distance between the roller and top surface of the powder plate (Ref. Figure 4.12). It was also found to be necessary to develop structural components upon

Part Name	Stock Description	Quantity
Roller	Stainless Cylinder 50.8 mm Diameter x 165.1 mm (2 in Diameter x 6.5 in)	1
Top Bracket	Stainless Block 12.7 mm x 53.98 mm x 155.58 mm (0.5 in x 2.125 in x 6.125 in)	1
Bearing Block	Stainless Block 12.7 mm x 44.45 mm x 53.98 mm (0.5 in x 1.75 in x 2.125 in)	2
Roller Bearing	ABEC 7 Bearing 6.35 mm (0.25 in) bore (Part #: S9912Y-G2550PS2M)	2
Pulley	Part #: S1086Y-PC-03	1
Thrust Block Bottom	Stainless Block 76.2 mm x 38.1 mm x 53.98 mm (3 in x 1.5 in x 2.125 in)	1
Thrust Block Top	Stainless Block 76.2 mm x 38.1 mm x 54 mm (3 in x 1.5 in x 2.126 in)	1
Thrust Shaft	Stainless Tube 812.8 mm long x 50.8 mm OD x 38.1 mm ID (32 in long x 2 in OD x 1.5 in ID)	1
Cantilever Bracket Bottom	Aluminum Block 76.2 mm x 76.2 mm x 25.4 mm (3 in x 3 in x 1 in)	2
Cantilever Bracket Top	Aluminum Block 76.2 mm x 38.1 mm x 25.4 mm (3 in x 1.5 in x 1 in)	2
Mount Plate	Aluminum Plate 177.8 mm x 177.8 mm x 19.05 mm (7 in x 7 in x 0.75 in)	1
Track – Actuator Assembly	Part # R3D-205B-24-P-ASE with D2301 Controller	1

Table 4.4: Roller Assembly Component List

which to attach the roller driving cable. These structural components were designed to form the front and back walls of the shield gas enclosure, described below in Section 4.7.1. Following the development of these components, the powder roller head was mounted onto the end of the thrust shaft and the roller drive cable looped around the pulley and connected to the mounting components (Ref. Figure 4.13).

Following the fabrication and installation of the necessary hardware, control of the linear actuator rail was developed. A dedicated controller (D2300) was selected as part of the specification process for the linear actuator rail. Following installation of



Figure 4.12: Linear Actuator Rail with Partially Assembled Roller Subassembly

the rail, the D2300 controller was connected to the appropriate leads and configured for use. Stroke length of the actuator is controlled via placement of magnetic stops (RPS1) along the side of the actuator. These stops interact with magnets mounted internally on the carriage to indicate carriage position and control stroke length. The use of these magnetic stops simplifies the user interface since the speed of translation and stroke distance are set in hardware and are not controlled by the user. Therefore, a simple switch circuit was developed which allows the user to actuate the roller.

Roller actuation is initiated by pushing a start button. The actuator will then execute its stroke, return to the beginning of the stroke, and then begin another cycle. A stop button is utilized by the operator to stop the movement of the roller actuator. Proper timing by the operator is required to cause a cessation of movement at the desired location.

This control arrangement requires some skill on the part of the operator to ter-

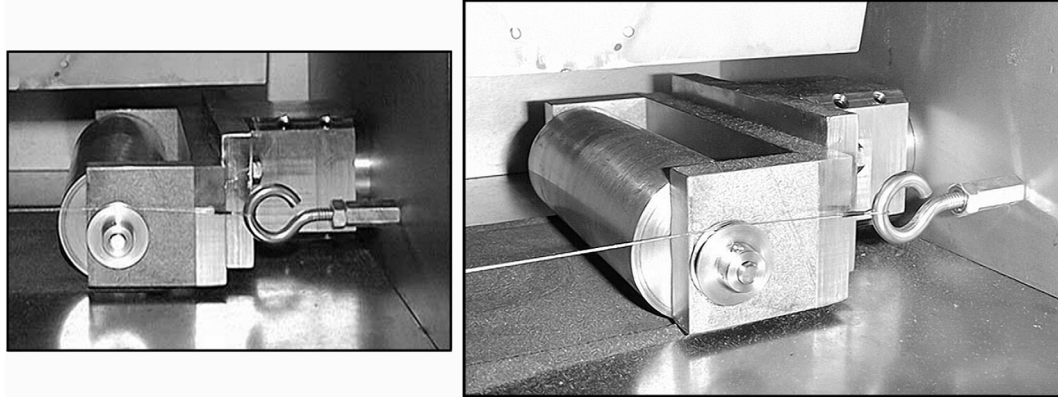


Figure 4.13: Powder Roller Head

minate actuation at the correct time. While a simpler control action is desired, this method was selected due to the relatively rapid development time compared to a more sophisticated control. Also, during testing of the powder roller subsystem, it was observed that the actuator would freeze if the stop button was pressed when the actuator was at a position that exactly correlated with the beginning of the stroke where the actuator switches directions. A loosening and slightly shifting of the magnetic stop on the side of the linear actuator rail was found to “unfreeze” the actuator and return the system to proper operation. Therefore, actuator motion should be terminated just before the beginning of the return stroke to prevent the previously discussed problem while still returning the roller head to the front of the powder plate. A more sophisticated and robust control strategy is desired so that the previous inconsistency is eliminated and less skill is required of the user.

4.6 Electronics Cabinet and PC

During the development of the multiple material workstation, a number of different controllers were purchased and installed to drive the various mechanisms of the workstation. A dedicated PC was also specified and purchased to allow the user to interact

and control the various subsystems from one location. This PC is used to drive two primary systems. First, data from the scanning program is fed through the parallel printer port to the scan controller. The second primary control method is the use of Labview programs to control the powder hoppers and the part piston. A dedicated Labview card was installed into the PC to allow proper communication between the programs and the equipment. This card is then linked via ribbon cable to a pin-out board (Model # CB-68) which allows wiring to be developed between the dedicated hardware controllers and the Labview card.

This hardware and associated wiring soon became unmanageable. In order to properly store the various controllers in one location and create a more manageable wiring layout, a dedicated electronics cabinet was purchased and installed between the protruding end of the roller actuator and the laser. Table 4.5 provides a list of the hardware stored in the electronics cabinet, while Figure 4.14 shows the cabinet and associated controllers.

Part Name
Powder Hopper Controllers (Accu-Rate Analog Input Module)
User-Interface PC
CB-68 Pin-out Board
Laser Scanning Controller (General Scanning DE2000: E10-1203816)
Laser On/Off Signal Conditioning Box
Part Piston Actuator Controller
Mixing Impeller Power Supply
Powder Roller Controller (D2300)

Table 4.5: Electronics Cabinet Component List

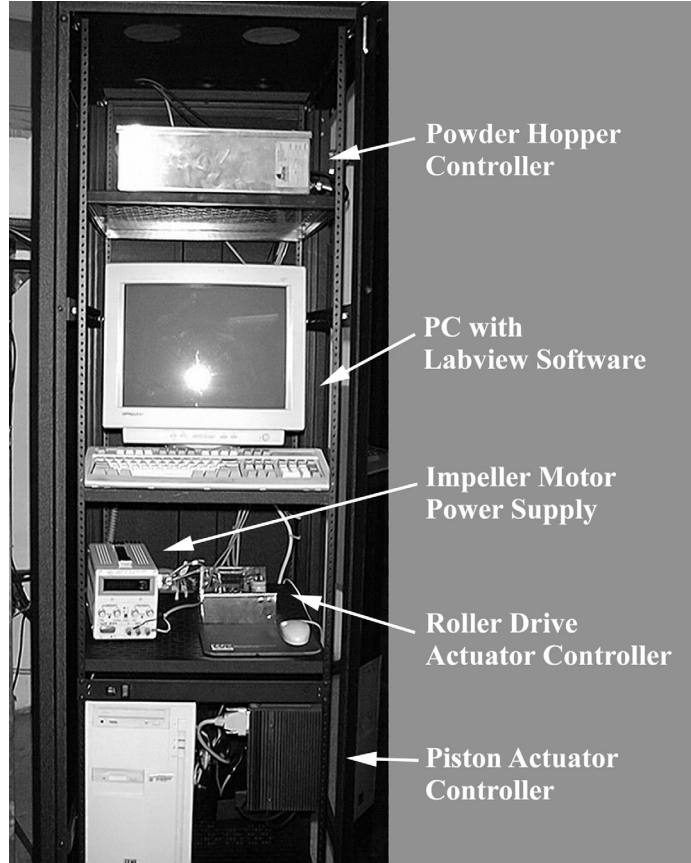


Figure 4.14: Electronics Cabinet and Components

4.7 Integration of Powder Delivery Subsystem

One of the final steps in the development of the multiple material workstation is the integration of the separately developed powder mixing and deposition subsystem. This integration process requires the development and fabrication of various support structures, primarily to hold the powder mixing chamber. During the integration process, consideration was also being given to the development of atmospheric control subsystems and the selection of the most suitable design variant for this subsystem (Ref. Section 5.1.1). This process yielded a simple shield gas arrangement as the initial design

iteration of this subsystem.

The development of this design variant simply requires the design and fabrication of an open-topped box that assists in pooling the shield gas as it is flowed over the sintering location. The form of the shield gas structure naturally lends itself to also support the powder mixing chamber.

4.7.1 Shield Box Development

Therefore, the first step in the integration of the powder mixing system is the development of a simple open-topped shield gas box. Four sides were fabricated with a series of 1/4-20 holes arranged along the bottom edge of the side plates. These holes were used to attach appropriately sized 90° angular pieces which were attached to the previously machined 1/4-20 holes along the perimeter of the powder plate.

The height of the gas enclosure walls was determined by the available space between the powder plate and the bottom of the laser table. This distance had already been properly spaced to accommodate the powder mixing chamber during the mounting of the powder plate to the support structure.

The plate at the front and back of the box also contained appropriately placed 1/4-20 holes to attach the fixed cable which loops around the roller pulley and is used to drive roller rotation during powder transferral. The height of these holes was determined based on the height of the roller head above the powder plate and the placement of the cable pulley at half the height of the roller head. The distance between the cable mounting holes and the center of the front and back walls was found by measuring half the width of the roller head plus the additional distance that the pulley protrudes.

A hole for the passage of the roller thrust shaft from the actuator into the processing area was also machined in the front plate. Additionally, it was found to be necessary to cut and remove a section from the front angle bracket to allow passage of the roller thrust shaft. An appropriate sealing element was selected and purchased for use in this location. Specifically, a spring-loaded Variseal shaft seal (Part #: W11-MS-

R-266-W-T01) was purchased from Busak–Shamban. A flange was added to the inner surface of the hole to support the spring-loaded seal. During the forward stroke, the seal is driven by friction back against the mounting plate and remains firmly in place. However, during the return stroke, the frictional force of the thrust shaft tends to pull the seal out of the flange. A retaining plate was developed and fabricated that bolts over the seal and holds it in its flange during the return stroke. The thrust shaft was also polished to reduce the frictional force exerted on the seal. Figure 4.15 shows the partially assembled enclosure with the roller thrust shaft.

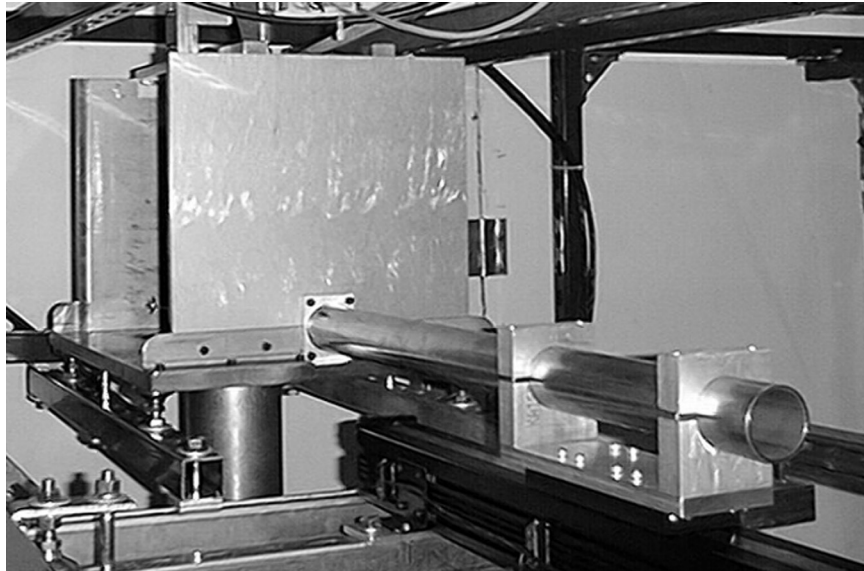


Figure 4.15: Partially Assembled Shield Gas Enclosure

During testing of the system, it became desirable to be able to observe the operation of the roller and the sintering of the powder during processing. Therefore, the designed left steel wall of the box was replaced by a shorter plexiglass side that allowed the observation of the system during operation. Also, during testing of the system, it was observed that the position and relative angle of the thrust shaft relative to the seal was critical for the smooth movement of the shaft. Therefore, it was necessary

to realign the linear actuator rail to minimize friction between the seal and the thrust shaft during operation.

4.7.2 Mounting of Powder Mixing Hardware

The next step in the integration of the powder mixing subsystem was the development of simple support brackets to hold and support the mixing chamber in the shield gas box assembly. These brackets were designed to simply fit over the front and back walls of the gas enclosure for easy removal and installation. Additionally, the attachment points between the bracket and powder mixer were slotted to allow flexible positioning of the powder mixing chamber. The proper positioning of the mixing chamber in the gas enclosure was severely limited due to two factors. First, it is desirable to move the powder mixer as close to the sintering location as possible to minimize the distance the powder must be transferred by the powder roller. This reduces the amount of powder that must be initially deposited to form the starting powder bed and also increases processing time by reducing the required powder roller stroke length.

However, the distance between the deposition point of the powder falling from the mixing chamber and the part cylinder is constrained by the laser beam. The laser beam must have a clear path to the sintering location. Improper placement of the powder mixing chamber near the part cylinder could result in potential blockage of the beam during certain portions of the build. Thus, the location of the powder mixing chamber was set as close to the part cylinder as possible while preventing potential blockage of the laser beam (Ref. Figure 4.16).

Another potential problem involves the powder roller. The powder roller head extends a certain set distance into the gas enclosure when it is at the return position of the processing stroke. If this distance is too great and extends under the set location of the powder mixing chamber, the powder will be deposited on top of or behind the powder roller head. Fortunately, the powder falls just to the front of the powder roller head, allowing proper operation of the system.

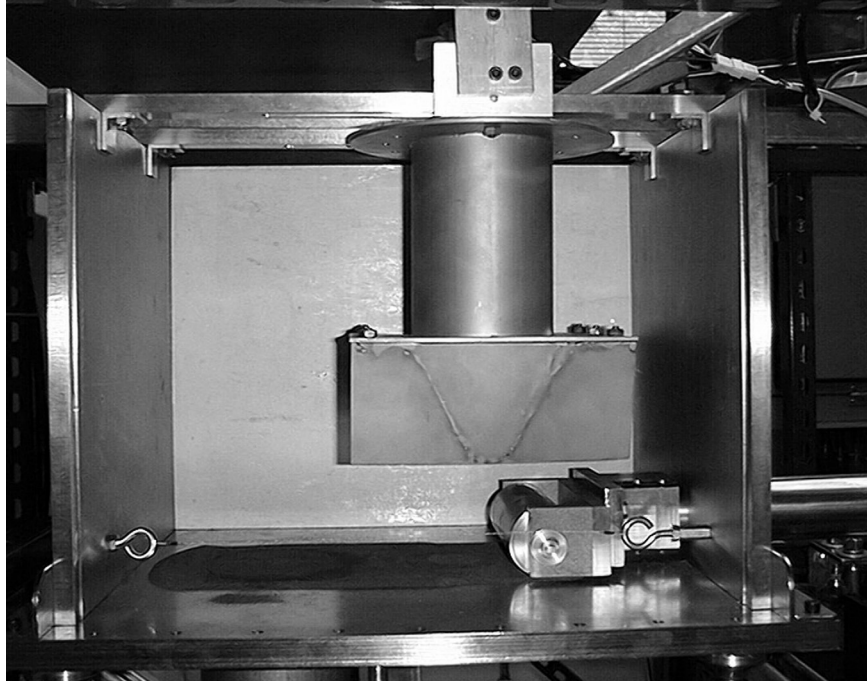


Figure 4.16: Powder Mixing Chamber shown Integrated into Workstation

However, during testing, it was observed that the powder would disperse somewhat to form a mound when it was deposited. It became critical to have the powder roller stop basically against the back wall of the gas enclosure to prevent some powder from spilling onto the back side of the powder roller. This requirement tends to generate waste powder and increases the difficulty in machine operation to properly time the cessation of the return stroke of the roller head.

During the installation of the powder mixing chamber, it was observed that the support bracket which holds the motor and impeller subassembly was too high to fit in the space between the top of the mixing chamber and the bottom of the laser table. The height of the mixing chamber is constrained by the set height of the powder plate plus a required gap to allow the passage of the roller head under the bottom of the mixing chamber. Therefore, this bracket was redesigned to minimize its height and

the length of the drive shaft connecting the DC impeller motor and the impeller was reduced. Following these modifications, the assembly height was sufficiently reduced to allow insertion between the top of the mixing chamber and the bottom of the laser table.

4.7.3 Chute Development and Powder Hopper Placement

Following the insertion of the powder mixing chamber, the powder hoppers were located to feed powder down onto the mixing impeller. During the off-line testing of the powder delivery subsystem, the powder hoppers were simply located above and to the sides of the powder mixing chamber so that the powder was simply fed from the metering tubes through an elbow directly onto the impeller. However, for our arrangement, the presence of the laser table prevents a duplication of this positioning arrangement.

It became necessary to position the powder hoppers along the front of the laser table (Ref. Figure 4.17). Powder is then delivered to the impellers via a chute delivery concept. This concept consists of a simple chute with a U-shaped cross-section and a ring clamp at the upper end to attach to the elbow which is fitted to the end of the metering tubes. The U-shaped cross-section is approximately 25.4 mm (1 in) square at the top and tapers down to approximately 9.525 mm (0.375 in) at the end. The simple ring clamp is fitted around the bottom end of the elbow and secured into position (Ref. Figure 4.18). The design of these chutes was developed to allow fabrication via sheet metal bending, thus reducing time and cost during the production of the chutes.

The length of the chutes was determined based on the distance from the impeller to the powder hopper, the spatial constraints between the powder hopper and the laser table, and available powder hopper mounting locations on the frame. The final factor controlling the length of the chutes is the assumption of a 30° angle between horizontal and the chute. It was assumed that this angle would be sufficient for proper flow of the powder from the hopper to the mixing impeller.

Following fabrication of the chutes, the powder hoppers were mounted onto the



Figure 4.17: Powder Hopper Placement following Integration

frame and the system was tested. For some cases, the powder flow down the chutes was smooth. However, in a number of cases, the powder would accumulate at the top of the chute resulting in a sporadic and uneven flow of powder onto the impeller. Obviously, this was not satisfactory for the proper operation of the workstation. The chutes were fabricated again with a 45° angle of descent and the powder hopper raised on their mounts accordingly. Additionally, the inner surface of the chutes were coated with dry graphite lubricant and then rubbed smooth to decrease frictional effects. Following these modifications, the powder flow down the chutes became smooth and uniform.

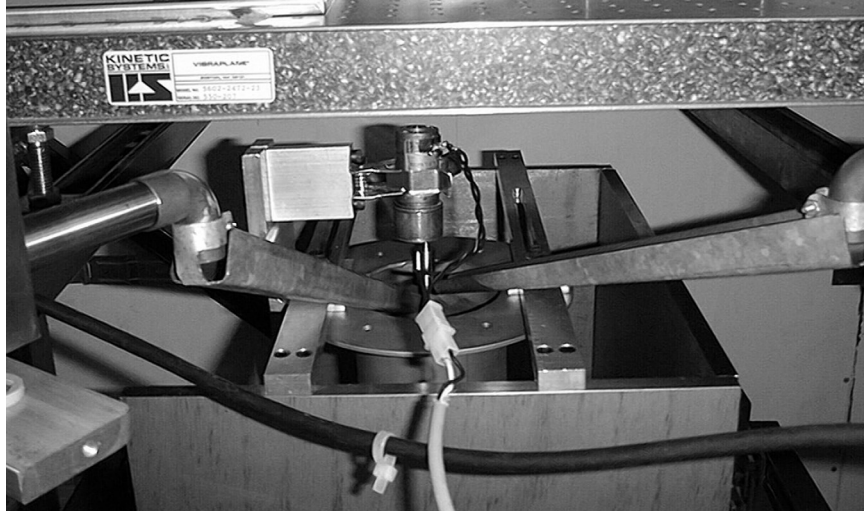


Figure 4.18: Chute Delivery Concept

4.8 Shield Gas Flow System

Following the installation of the shield gas box and the integration of the powder deposition subsystem, the final hardware development to occur consisted of the installation of a very simple gas flow system to deliver the shield gas into the gas enclosure. First, an Argon gas mixture was selected for use as a shield gas. The high density of Argon gas relative to air allows it to settle to the bottom of the enclosure and displace the air from the sintering location. Small amounts of hydrogen were also added to the gas mixture to promote a forming gas effect in which oxygen is reduced by hydrogen gas rather than the metal being sintered. This effect tends to reduce the development of undesired oxides in the final part.

A suitable cylinder of the selected gas mixture was purchased and installed next to the workstation. A Praxair 300 Series two stage regulator was also specified and purchased to control the flow of the shield gas. This regulator feeds the gas via a steel-jacketed gas line to a fixture mounted on the upper edge of the gas enclosure. This fixture clamps the end of the gas line to the enclosure wall and directs the flow

of gas toward the bottom of the enclosure. During processing a very low flow of gas is fed through the system to displace the air in the enclosure and improve the processing atmosphere.

Chapter 5

Experimental Verification of Workstation Design

During the design and development of the multiple material selective laser sintering workstation, a number of design decisions were necessary. One of the critical design decisions concerned the atmospheric control subsystem that determines the processing gas in which the laser sintering takes place. A number of options were developed and then considered for implementation within cost and timing constraints. These constraints, normally high for traditional SLS systems, were amplified by the additional powder delivery requirements of the multiple material SLS workstation.

Following the integration of the powder delivery subsystem with the rest of the workstation, tests were conducted to determine the effect of the powder roller on the resulting powder bed blend. Specifically, a possible segregating effect could occur as the powder was moved by the roller, resulting in a separation of the two constituent materials. Additionally, these tests also determine the presence of any change in the material composition across the powder bed.

Finally, some initial attempts at part fabrication were conducted. The primary part examined with these attempts was the drill bit insert of interest. Part fabrication was attempted in both air and shield gas environments with mixed results observed. In

general, additional thermal and atmospheric management subsystems were found to be required for proper part processing and good part quality.

5.1 Impact of Processing Atmosphere on Part Quality

In general, SLS requires a low oxygen processing atmosphere to prevent the formation of oxides during laser sintering. These oxides interfere with the wetting and flow characteristics of the melt pool which causes improper sintering. Additionally, these oxides remain in the fabricated component, reducing its overall strength [43]. Therefore, it was deemed necessary to develop hardware to control the processing atmosphere of the workstation.

5.1.1 Atmospheric Subsystem Design Variants

A number of options were developed during the design process. These options were considered versus the existing time and financial constraints and the most appropriate option was selected.

The first and most expensive option considered was a fully developed high vacuum system. This system would be able to pull down to approximately 10^{-3} Pa (10^{-7} torr). The achievement of this pressure level requires a thick-walled pressure vessel. Access to the interior would be accomplished via a sealable door. Ports for mechanical inputs into the interior of the chamber for this pressure requirement are mechanically complex and require expensive specialty made components. Chamber pump-down would be achieved via a mechanical roughing / diffusion pumping subsystem with accompanying hoses and valves assemblies.

Pressure vessel development can be achieved via two possible routes. A large custom-made vessel could be fabricated via in-house machining and welding. Considerable expense and debugging of leaks are required of this approach. The second option would be the purchase of an off-the-shelf cylindrical pressure vessel which would be fabricated off-site with the necessary ports and entry openings. While this option is less

expensive than the custom fabricated system, the spatial constraints of this approach are significant. A redesign of the powder delivery subsystem to minimize occupied volume would likely be required of this approach. Cost estimates of these options would be in the tens of thousands of dollars with an associated lead time of months to a year.

A second less expensive option would be the development of a similar pressure vessel designed to achieve a rough vacuum of 0.10 Pa (10^{-3} torr). This approach would still require a thick-walled pressure vessel. However, sealing elements for entry and mechanical input ports can be simplified for this lower pressure requirement. Additionally, the pumping sub-system can be simplified to include only a roughing pump. While these changes will reduce the cost of the system, the overall cost will still be the same order of magnitude as the previous option.

The third option considered consisted of a thin-walled container that is designed to be run in an overpressure condition with an inert or forming gas atmosphere. This system would not have to support a large pressure difference and thus would be simpler and less expensive to fabricate. Sealing requirements would also be simplified. This system is operated by filling the chamber with an inert gas such as argon or an oxygen reducing forming gas blend. System pressure is brought above atmospheric so that an overpressure condition is developed resulting in a small flow of gas out of the system in the event of a leak. An oxygen monitor is normally used to indicate the oxygen level present in the chamber. The simplification of sealing requirements and the lighter pressure vessel structure reduce the cost into the thousands of dollars. Associated lead times are reduced into weeks to months.

The final and simplest option considered is a flowable shield gas system similar to those used in welding applications. An inert shield gas, preferably heavier than air, is flowed over the worksite to reduce the local oxygen concentration. A simple containing structure is sometimes used to pool the shield gas and reduce the required gas flow rate. While the oxygen concentrations for this approach are significantly higher than those of the previous options, the associated cost is in the hundreds of dollars and lead times

are on the order of weeks.

In order to better understand the effect of atmosphere on part quality, a simple series of experiments were conducted on the single layer workstation discussed in Section 3.1. The advanced atmospheric hardware associated with this system allows one to test a variety of atmospheric conditions. The results of these tests were considered with the given tight financial constraints to select an atmospheric processing subsystem.

5.1.2 Effect of Processing Atmosphere on Part Quality

The first test was the fabrication of a simple single layer coupon in an argon gas atmosphere following a purge to a high vacuum of 10^{-3} Pa (10^{-7} torr). This test produced good part quality with good melting and flow behavior. The next test was performed in an argon atmosphere following a purge to a rough vacuum of 0.10 Pa (10^{-3} torr). As expected, a decrease in part quality was observed.

The third test consisted of laser sintering in an argon gas flow approach similar to those used in welding processes. This test was conducted by removing the top of the chamber in the single layer workstation. A small argon gas flow was allowed to fill the chamber and overflow the top. Following this procedure, laser processing was performed. The resulting part quality was further reduced from the rough vacuum purge test. The final test was to simply run the sample coupon in air to serve as a baseline test. This test showed a decrease in part quality and increase in porosity compared to the argon gas flow experiment (Ref. Figure 5.1).

In general, these tests agree with the expected results. Increasingly more severe vacuum levels reduces the partial pressure of oxygen in the chamber, resulting in less oxide formation and better part sintering behavior. Unfortunately, increasing levels of vacuum are also associated with increasing costs in hardware development.

A significant financial investment in an advanced atmospheric management subsystem was not possible due to the financial limitations of the project. Given the financial constraints associated with the project, it was decided to gradually develop

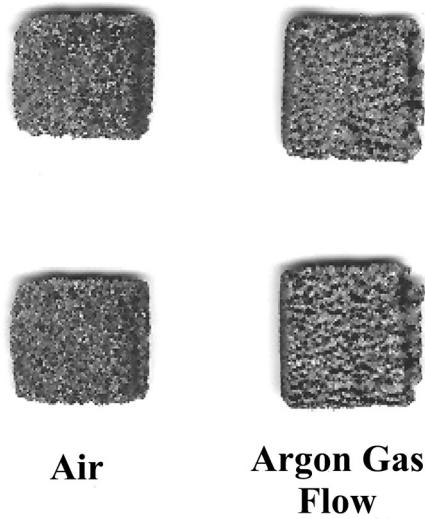


Figure 5.1: Effects of Processing Atmosphere on Part Quality

the atmospheric capabilities of the multiple material workstation. The initial development consisted of a simple shield gas flow arrangement similar to those used in welding processes. As discussed previously, this system was developed and deployed on the multiple material workstation.

Future developments regarding the atmospheric control subsystem would likely first consist of the development of a fully enclosed overpressure system as described above. The third generation of atmospheric control hardware would be initiated by a redesign of the current powder delivery subsystem to minimize occupied volume. This would be followed by the design and development of high vacuum pressure vessel with accompanying sealing elements. This vacuum system would be designed to allow the full functionality of the multiple material workstation within a high vacuum of approximately 10^{-3} Pa (10^{-7} torr).

5.2 Uniform Material Composition on the Powder Bed

In addition to atmospheric control, the powder delivery subsystem is a critical component in the multiple material workstation. As discussed previously, this system was developed and tested separately from the overall system (Ref. Section 4.2.1). Following fabrication of the powder delivery subsystem, testing was performed to correlate desired material ratios to actual ratios generated by the hardware [49].

A given ratio of the two constituent materials was used to generate appropriate powder hopper voltages which were supplied to the hardware. The hoppers then were driven at the appropriate rates and the two powder streams fed through the mixing impeller. The resulting deposit of mixed powder was then tested for the correct mixture ratio using the relative difference in density of the cobalt and tungsten carbide constituents. The hardware was found to operate satisfactorily, however, resulting blend ratios were observed to possess noise with a roughly 10% variability in the resulting blend ratio from the given powder hopper voltage ratio .

Following development and testing of the powder delivery hardware, this subsystem was installed and integrated with the rest of the multiple material workstation. As discussed previously, the resulting powder flow from the powder delivery subsystem is deposited in front of the powder roller (Ref. Section 4.7.2). The powder roller is then actuated to drive and smooth the powder into a bed over the part cylinder. A question of critical importance arises as a result of this process. Does the variability in the powder mixture ratio increase as a result of this roller transferal process?

5.2.1 Sample Collection Procedure

In order to access this question, a number of samples were collected from the powder bed at different locations and with different voltage ratios selected as inputs to the powder hoppers. These samples were then examined under an optical microscope to determine the ratio mixture at different locations on the powder bed. These tests will determine the variability in the powder mixture ratio at different locations on the powder bed.

Run Number	Cobalt Hopper Voltage	Tungsten Carbide Hopper Voltage
1	2	4
2	3	3
3	4	2

Table 5.1: Hopper Driving Voltages

The variability will then indicate the uniformity of the ratio.

The first step in the collection of the samples was the determination of the blends to examine. It was decided to examine three different blends in order to assess the impact of differing cobalt content on the potential degree of segregation. These different blends were generated by driving the powder hoppers at three different pairs of voltages (Ref. Table 5.1).

In general, the relationship between the ratios of the hopper voltages and the ratio of the two materials is not linear. The nonlinear nature of the relationship is due to a number of factors, including particle shape, powder packing ability, and material density. The path to find this relationship is to generate an empirical correlation by running the powder delivery subsystem with a number of different input voltages and then experimentally measuring the results. Given this set of data, a curve-fitting approach can be used to generate the relationship. However, this procedure will generate a valid relationship for only one given powder material system. A change in powder will require a recalibration of the powder delivery system to account for changes in the powder.

This approach was used in the initial calibration of the powder delivery system [49]. However, the powder system used for those experiments differed from our powder system, thus making the relationship invalid. However, the primary purpose of these experiments is to determine the degree of segregation induced in the powder mixture by the powder roller. Thus, this effect can be quantified by measuring the difference in

the cobalt content from a location near the roller and a location on the powder bed. The generation of a new empirical relationship between powder ratio and voltage ratio, while of some interest, is not directly needed for these experiments and thus was not performed.

During the initial attempts to collect this data, some adjustment of the powder delivery subsystem was found to be necessary. First, adjustment of the deposition chutes was required. Correct placement of the end of the chutes was found to be critical for good mixing (Ref. Figure 5.2). A final arrangement was selected in which the chutes were positioned so the two powder streams deposited powder at the same location on the impeller. This location was also selected so that the impeller blades were moving into the powder streams and not away from the streams. It was observed that when the impeller blades were moving away from the streams at the point of impact, the powder would tend to quickly fly off of the impeller and not mix as thoroughly.

Due to spatial constraints of the ends of the chutes and a minimum chute angle required for good flow of the powder down the chutes, it became necessary to adjust the position of the hoppers. Following this adjustment, the impeller speed was also examined. Results of previous work were examined to determine the optimal impeller speed [49]. The optimal impeller speed was found to occur between three and four volts. Higher voltages caused excessive impeller speed and ejected the powder off of the impeller without proper mixing. An operating voltage of 3.25 volts was selected for testing.

Next, the roller was actuated to spread out the powder. Then four samples were collected from the powder bed. The first sample was collected at a location just forward of the powder roller. The remaining three samples were collected near the edge of the part cylinder with a radial separation of 120° (Ref. Figure 5.3). Samples were collected using strips of adhesive tape. These adhesive tapes were cut to size and then gently placed on the powder bed to collect a very thin layer of powder from the top of the powder bed. These tapes allowed one to easily and rapidly collect powder samples

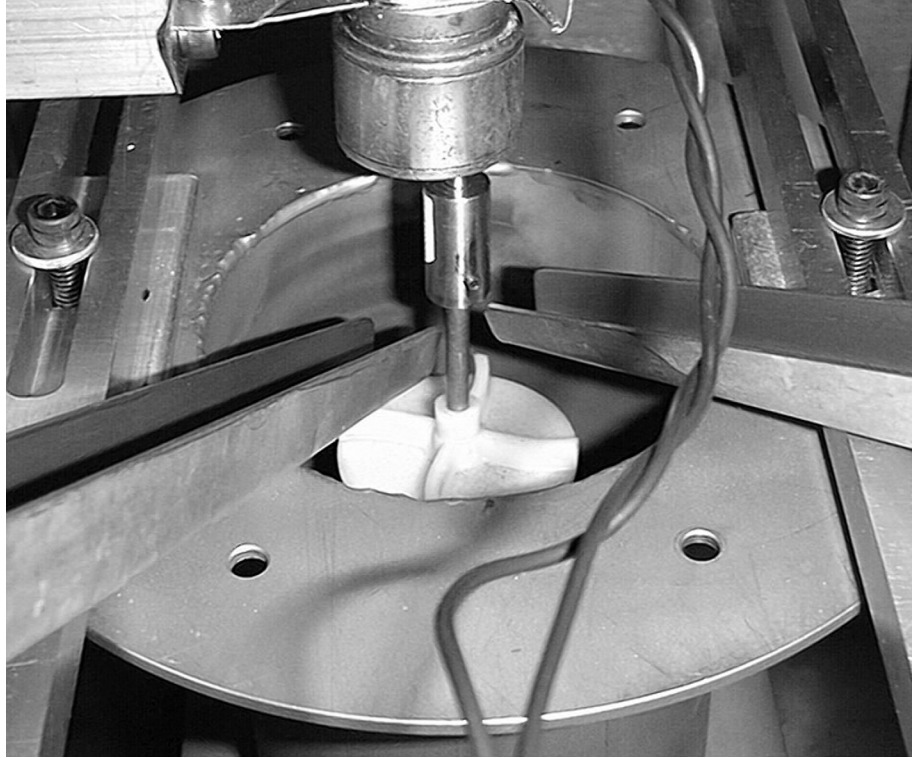


Figure 5.2: Chute End Placements

without disturbing the bed. Additionally, the resulting samples were easily viewed with an optical microscope.

However, some problems were present with this method. First, this method only collects powder from the top of a given layer and does not address powder at the bottom of a layer. However, segregation effects will in general impact the entire layer and will produce a decline in the relative amounts of one of the constituent materials at the surface of a given layer.

Additionally, the relatively small size of the strips prevents one from making a comprehensive examination of the entire powder bed. Finally, the collection of the sample from Location 1 after the roller has been used to smooth the layer may generate an error in the cobalt content for this location. The small amount of initial movement

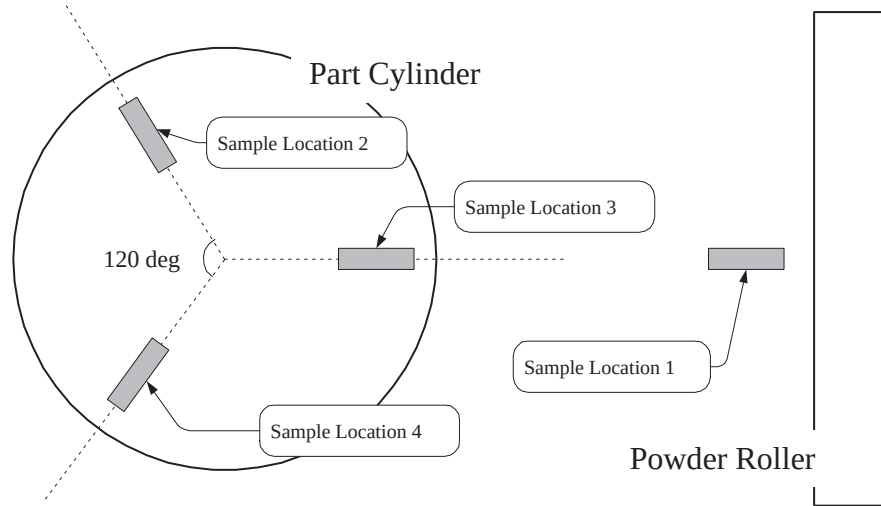


Figure 5.3: Sample Collection Locations

of the powder deposit at this location may cause some initial segregation of the powder before the roller passes over Location 1. It is assumed that the bulk of any segregation effects occur during the transport of the powder from the region just forward of the powder roller to the part cylinder.

Following collection of the samples, the adhesive strips containing the collected powder were examined under an optical microscope. Digital images were collected for each of the samples (Ref. Figure 5.4). These images were then examined to determine the relative number of particles of tungsten carbide and cobalt. The number of each type of particle was recorded for each image. Additionally, the diameters of each particle in the image was recorded. These diameters were then used to calculate the volume of the particles. These calculations were performed to account for the different sizes of the tungsten carbide particles and the smaller cobalt particles.

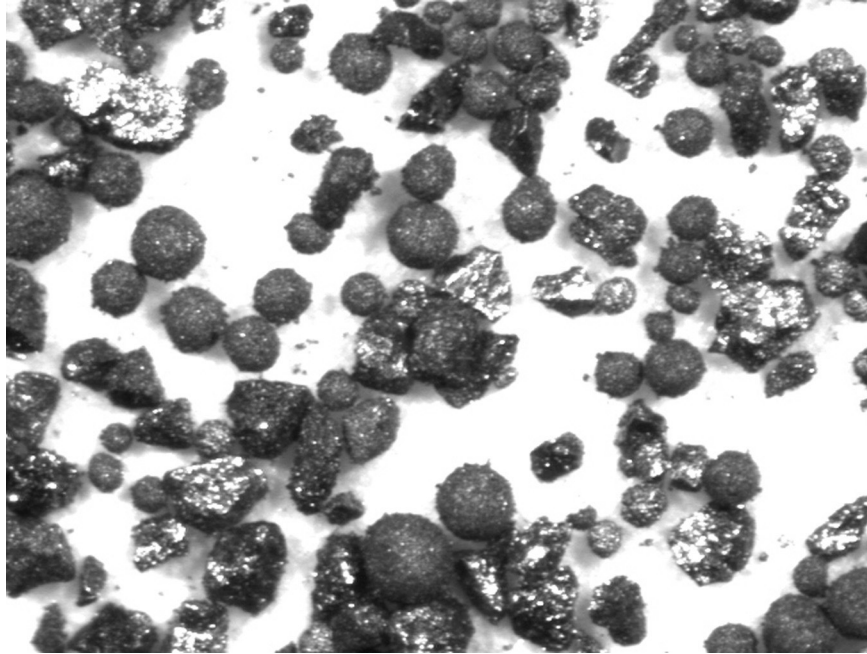


Figure 5.4: Example Image from Sample Adhesive Pad

5.2.2 Analysis of Results

Next, the numbers of cobalt and tungsten carbide particles were used to calculate a percentage ratio of the two materials. The diameters and number of particles were used to generate an average cobalt and average tungsten carbide particle diameter. These diameters were then used to calculate an average cobalt and tungsten carbide volume for each particle. Next, these average values were multiplied by the number of particles for each of the two materials. Finally, the resulting total volume of each material was used to generate a final ratio or percentage of each material. Thus, we have two separate measures of the ratio of the materials for each location, one based on number of particles and the other based on volume.

The volume based ratio is expected to provide more accurate results as the cobalt particles tend to be smaller than the tungsten carbide particles. As a result, the count

based ratio will tend to show excessively high values of cobalt content. However, this measure can still provide information relative to other locations. This error effect will tend to be consistent at the different locations and thus differences in the ratios at the locations still possess significance.

The use of the optical microscope to image a region of the adhesive strip for the collection of information regarding the number and size of particles tends to narrowly focus on only a small amount of the powder on the adhesive pad. In general, this tightly focused examination will not yield a good averaged measure of the material ratio on the adhesive strip. In order to alleviate this problem, three images were examined for each sample. While a more extensive collection of images from each sample would result in a more accurate representation of the overall material ratio for the sample, the collection of information from the images was a time-consuming process. The nature of the process limited the number of images that could be examined for a given sample while still allowing good coverage of all of the samples collected.

Following the collection of data for the samples, the cobalt content was plotted for the four sample locations for each of the three different runs collected (Ref. Figures 5.5, 5.6, and 5.7).

The plotted data results from an averaging of the values obtained from the three different images. The error bounds on the data are developed from the average deviations of the data points from their mean value. As expected, the values from the particle count method yield higher values of cobalt content than those from the volume method. Error bounds for the various data values range up to $\pm 10\%$. These errors are most likely generated from the close examination of a small region of the adhesive pad. A broader examination of a large portion of the adhesive pad would tend to produce less noisy experimental data.

In order to more closely examine the difference between the sample locations on the part cylinder and Location 1, the percentage differences in cobalt content between these samples were plotted. These differences reveal the extent of segregation that

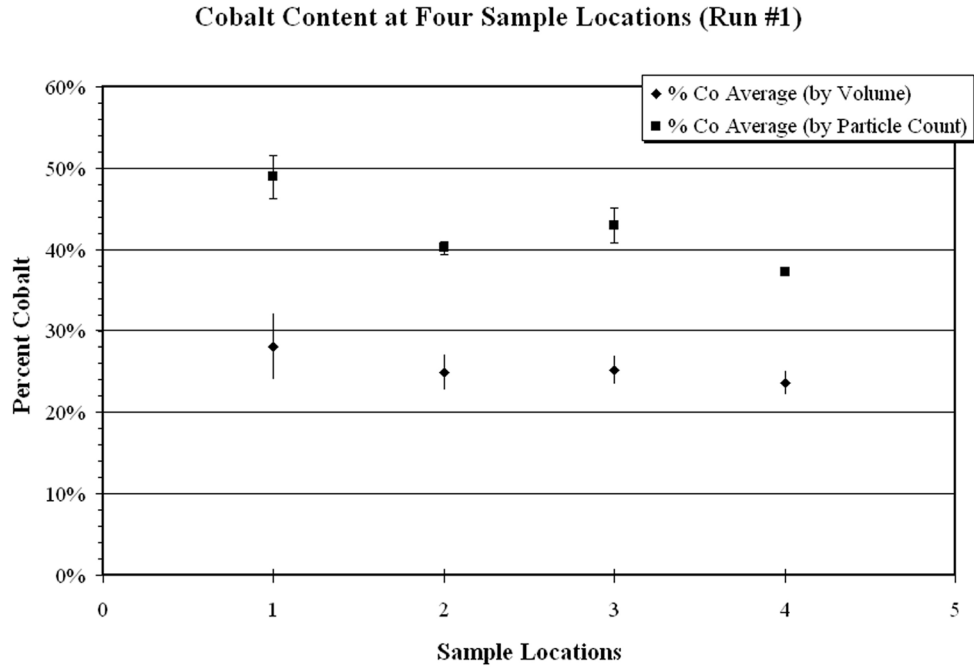


Figure 5.5: Cobalt Content versus Sample Location for Run 1

occurs in the powder as it is transported by the roller (Ref. Figures 5.8, 5.9, and 5.10).

5.2.3 Conclusions

It is assumed that segregation will tend to cause the cobalt to gradually shift to the bottom of a given layer. This is primarily due to two factors. First, the cobalt particles tend to be spherical and thus can flow more easily than the angular tungsten carbide. The spherical nature of the cobalt also allows it to pack more efficiently than the tungsten carbide. Secondly, the smaller size of the cobalt particles will enhance their ability to move downward through the powder bed. However, tungsten carbide possesses a higher density than cobalt, which may tend to offset the previous effects somewhat.

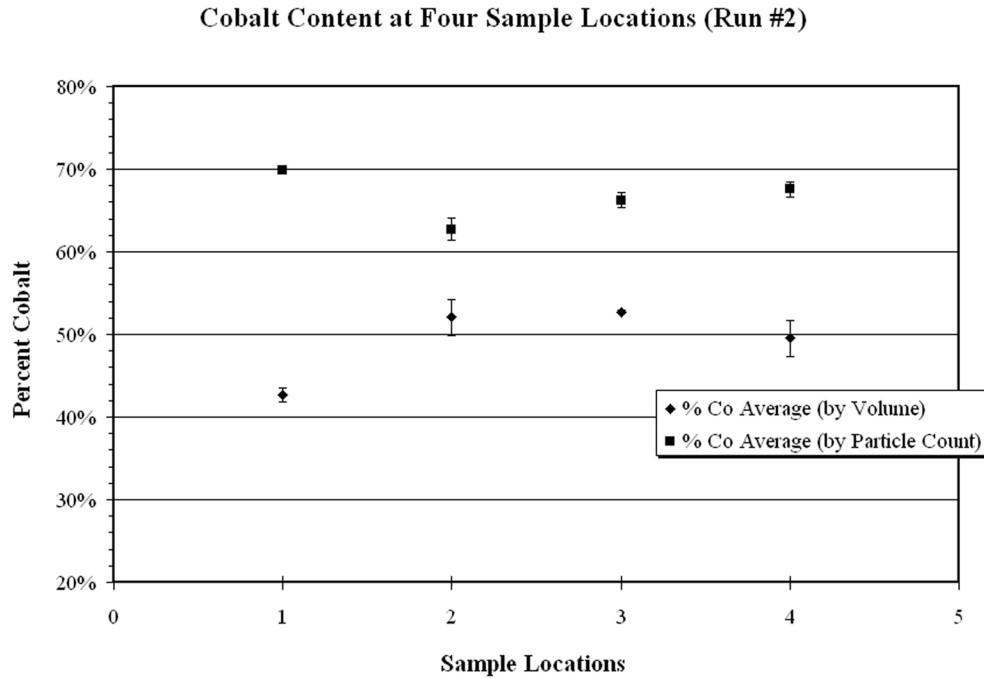


Figure 5.6: Cobalt Content versus Sample Location for Run 2

Given the relatively high amount of noise in the data, segregation would be revealed by a decrease in the cobalt content in the locations on the powder bed relative to Location 1. An examination of the previous graphs indicates that cobalt content increases for the first and third runs and decreases for the second run for the volume measure. Use of the count measure reveals a general increase in the cobalt content.

The general increase in cobalt content in most of the data seems to indicate a small segregation effect may be occurring due to the greater density of the tungsten carbide. However, a number of observations make this conclusion very tentative. First, data for the second run indicates a decrease in cobalt content with the volume measurement method and an increase in cobalt content with the count measurement method. The most likely explanation for this contradictory information is that an experimental error is generating noise in the data. If this is the case, then most of the other data fall

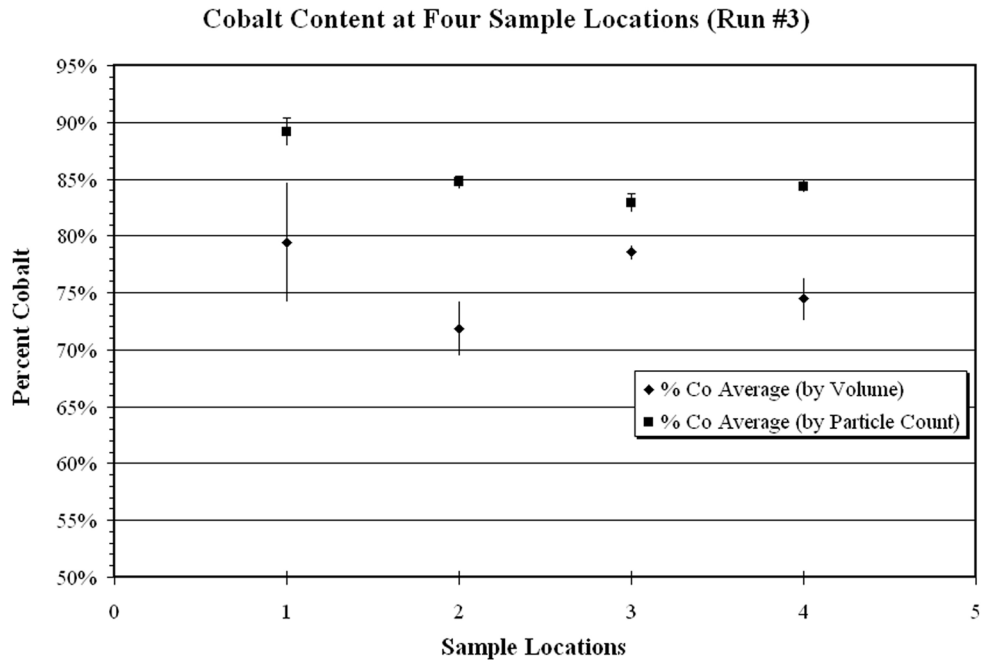


Figure 5.7: Cobalt Content versus Sample Location for Run 3

well into the range of experimental noise and thus any segregation effect could also be explained by experimental error.

Second, the primary causal factors for segregation, particle size and shape, indicate a likely downward migration of the cobalt particles and not the tungsten carbide particles. This movement is in opposition to the potential segregation effect observed in the data. Third, the variability in the material ratios from the powder delivery subsystem was also observed to be approximately 10%. This variability describes the noise present in the resulting blend based on a given voltage input. This variability when coupled with the experimental error generated from the measurement methods makes any claims to a segregating effect based on the presented data very tentative. In order to make a valid claim of an observed effect given the levels of experimental noise, a much more significant trend needs to be observed.

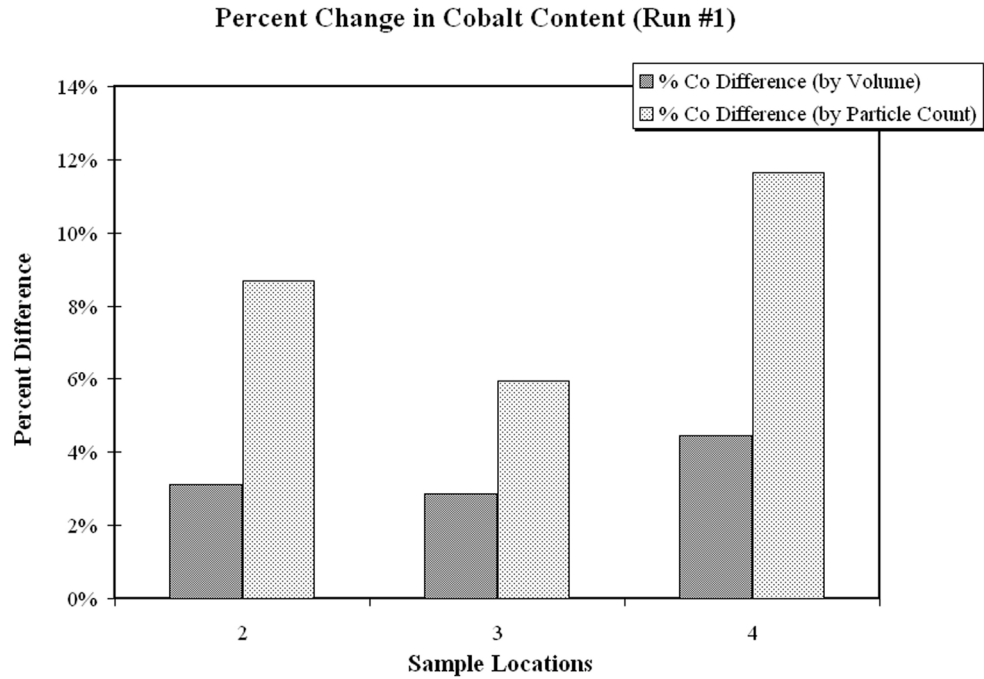


Figure 5.8: Change in Cobalt Content from Location 1 for Run 1

Additionally, if such a mild segregating effect was present due to the roller, the overall operation of the workstation would not be strongly impacted. The variability induced in the resulting blend from the powder delivery subsystem would overwhelm the effect and it would become lost in the preexisting experimental noise.

5.3 Sample Part Fabrication

Following the integration of the powder delivery subsystem and the previously described testing, some very preliminary work was performed to attempt to fabricate the drill bit insert of interest. This work was performed to test the abilities of the workstation in order to evaluate its state of current performance. However, due to the limited nature of the thermal and atmospheric subsystems developed for the workstation, poor part

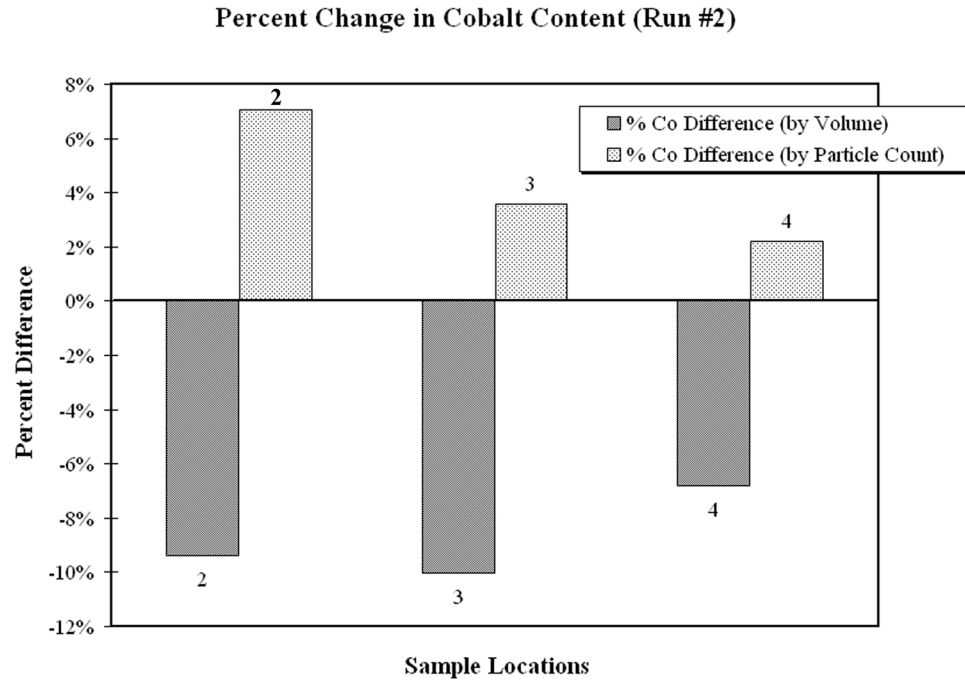


Figure 5.9: Change in Cobalt Content from Location 1 for Run 2

quality was expected. This expectation was based on the results of previous work in the direct fabrication of metals in which advanced thermal and atmospheric management was found to be necessary [17]. The absence of this type of capability was found to produce a number of detrimental effects.

The primary cause of these effects is due to oxidation of the melt pool. This leads to starting edge balling effects which reduce the accuracy of the part. Additionally, this behavior can also lead to shifting of the part due to adverse interactions between the powder roller and the partly fabricated component. Another effect of oxidation is inappropriate melt pool behavior leading to porosity and lack of through-thickness melting. Thus, given the primitive state of these subsystems in the multiple material workstation, these effects were expected in sample components fabricated.

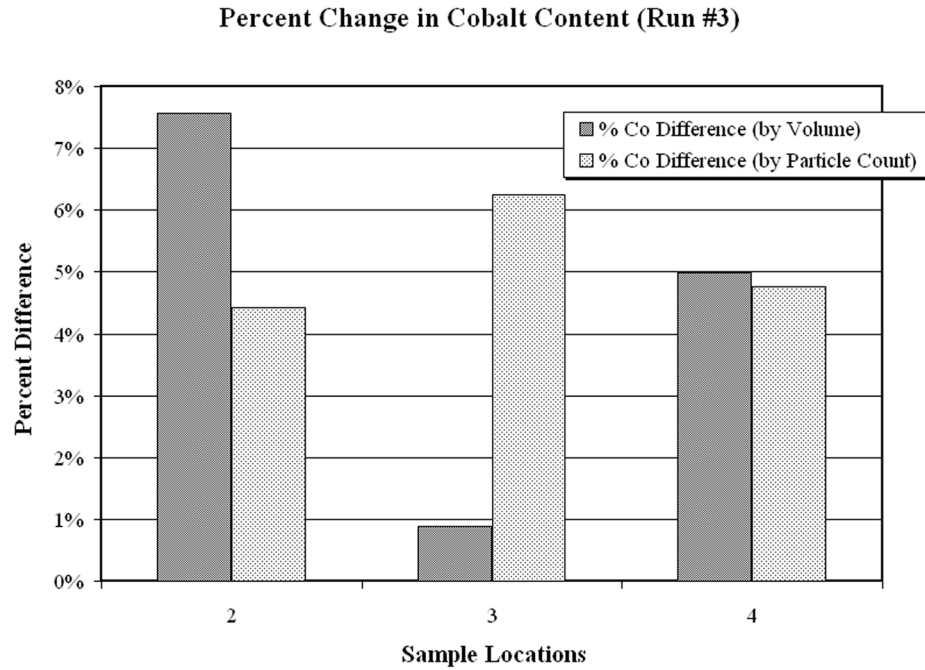


Figure 5.10: Change in Cobalt Content from Location 1 for Run 3

5.3.1 Part Fabrication in Air

The first attempted part fabrication was performed in air during the development of the atmospheric control subsystem and the integration of the powder delivery subsystem. This test was performed as a baseline to measure the impact of the developing shield gas system on part quality. Additionally, it was also performed to complete the debugging of the system and determine if any additional work was required to complete the workstation in addition to the shield gas system.

Since this work was performed during the installation of the powder delivery subsystem, it was necessary to manually mix and deposit the FGM in the part cylinder during processing. Four blends of powder were mixed using a roller mixer. Mixture components consisted of a straight blend of small spherical cobalt particles with larger

Cobalt Content (%)	Layer Numbers
40	1 – 35
30	35 – 70
20	70 – 105
10	105 – 145

Table 5.2: Blend Layer Assignments

angular particles of tungsten carbide.

Using the software developed for file conversion, the stereolithography file of the drill bit insert was modified for use on the multiple material workstation. (Ref. Section 4.3.4). First, the file was sliced and a `.mtg` file was generated with the Tool 4 hardware. This file was found to contain approximately 150 layers assuming a default layer thickness of 0.127 mm (0.005 in). During file generation, scan vector spacing was set to a small value of 0.00381 mm (0.00015 in).

The four material blends were assigned to the layers in such a manner as to increase tungsten carbide in the vertical direction (Ref. Table 5.2). This would result with the highest tungsten carbide content at the tip of the drill bit insert. Scanning parameters were developed to generate a drill bit insert approximately 12.7 mm (0.5 in) in diameter. A scanning speed (SS) was set at 16 and laser controlling current was set at a mid-range value of 25 mA. In order to properly center the resulting component on the part cylinder, an iterative process was used to determine the necessary offset parameters, δx and δy . These parameters were found to be $\delta x = -0.75$ and $\delta y = -1.0$. Prior to laser sintering, a powder bed was deposited on the part cylinder with an approximate depth of 12.7 mm (0.5 in).

A manual procedure was used to build up the part. First, the current layer was scanned using the appropriate sliced layer from the part file. Next, a small amount of the correct material blend was manually deposited to one side of the part cylinder. The part cylinder was lowered the correct amount and then the powder was smoothed

across the part cylinder with a straight edge, due to the lack of an available powder roller which was installed with the powder delivery subsystem.

Initial attempts at part fabrication focused on a high energy approach in which the primary goal was the generation of a fully developed melt pool. It was theorized that the fully developed melt pool would lead to lower values of porosity and better material properties. In addition to this approach, a lower energy scanning method was also examined. This method was examined to determine the overall effect on part quality in an air environment with a reduction in laser energy input.

Initial attempts at part fabrication given the previous laser parameters did not yield satisfactory results. The primary problem observed was the development during scanning of thick layers on the order of 0.508 mm (0.02 in). Given these thick layers and an observed lack of complete melting, energy density was increased via a decrease in scanning speed to $SS = 10$.

The use of the thicker layers will cause a elongation of the insert in the vertical direction since the file was originally created with the assumed default layer thickness. Since the layer thickness cannot be changed on the Tool 4 hardware during part file generation, the solution to this problem was to run every fourth layer in the part. Thus, Table 5.2 must be modified (Ref. Table 5.3). The use of thicker layer negatively impacts the accuracy of the sidewalls for the drill bit insert. Additionally, the generation of the file on the Tool 4 hardware generates layers in which scan vectors of neighboring layers are rotated 90° . During initial attempts at scanning, it was observed that this alternating pattern produced better results then a static pattern of scan vectors. In order to capture an alternating pattern of scan vectors, both even and odd layer numbers were selected as show in Table 5.3.

Results from the high energy scanning procedure indicated a loss of surface geometry and the development of problems during processing which frequently forced a termination of the build. The high laser energy input necessary to generate the melt pool caused excessive thermal growth of the insert sidewalls into the surrounding loose

Cobalt Content (%)	File Layer Numbers	Part Layer Numbers
40	4	1
40	7	2
40	12	3
40	15	4
40	20	5
40	23	6
40	28	7
40	31	8
40	36	9
40	39	10
30	44	11
30	47	12
30	52	13
30	55	14
30	60	15
30	63	16
30	68	17
30	71	18
30	76	19
20	79	20
20	84	21
20	87	22
20	92	23
20	95	24
20	100	25
20	103	26
20	108	27
20	111	28
10	116	29
10	119	30
10	124	31
10	127	32
10	132	33
10	135	34
10	140	35
10	143	36
10	148	37

Table 5.3: Updated Blend Layer Assignments

powder. This thermal growth resulted in poor sidewall geometry.

Additionally, during fabrication, green cobalt oxides (CoO) were observed to form at the edges of the melt pool due to oxidation reactions with the surrounding air. These oxides undergo a volume expansion during formation and would form a raised ring about the melt pool during fabrication. This effect became more developed as the build proceeded due to increased surrounding bed temperatures from the stored thermal energy contained the partly fabricated insert. The build up of the oxides also lead to an increase in layer thickness as the part was fabricated. It became necessary to increase the layer thickness in order to prevent shifting of the part during the manual smoothing procedure. As layer thickness increased, a lack of through-thickness melting developed in which the sintering layer was not fully melted through and bonded to the previous layer. This effect lead to weak parts and delamination of the parts at layer boundaries in some cases. The presence of cobalt oxides at the layer boundaries also was a contributing factor in the delamination.

Results from the low energy density scanning procedure indicate a more acceptable surface geometry. In general, thermal growth was reduced resulting in a more uniform and straight sidewall profile (Ref. Figure 5.11). Additionally, cobalt oxide formation was reduced resulting in less delamination and thinner layers. However, porosity in the part was much more evident with this build technique.

Results of these tests indicate the need for enhanced atmospheric processing capabilities. As expected, attempts to fabricate components in air lead to a number of problems arising from oxidation of the melt pool. In general, these problems become more severe as the build proceeds due to increasing temperatures in the powder bed. During the build process, the powder delivery and scanning systems operated correctly. No major mechanical problems developed during part fabrication. However, following some of the initial builds and cleaning of the machine, it was evident that a routine tear-down of the workstation for cleaning and maintenance procedures will be necessary. Such activities are an expected and normal part of the operation of an experimental

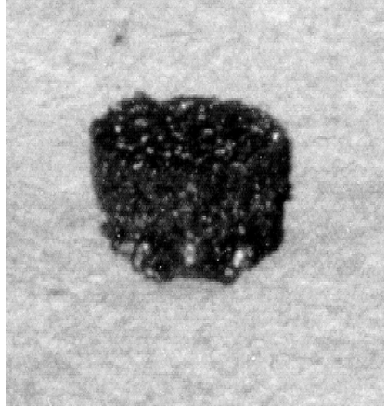


Figure 5.11: Partial Drill Bit Insert with Low Energy Density

workstation.

5.3.2 Part Fabrication with Shield Gas

Following the development and fabrication of the shield gas subsystem, additional part fabrication runs were conducted. These tests were conducted to gauge the degree of improvement in part quality as a result of addition of a shield gas subsystem. In particular, it was desired to determine if the oxidation present in the previous runs was alleviated with the use of a shield gas. Additionally, these tests served as a means to test the integrated powder delivery subsystem for correct operation.

The workstation powder hoppers were prepared and loaded with powder. Due to limitations in the amounts of available powder, only the top half of the drill bit insert containing the cone was fabricated for these runs. A build table of voltages for the powder hoppers was developed for use during processing (Ref. Table 5.4). In the table, the file layer number refers to the number of the layer in the part file that was scanned, while the actual layer number refers to the actual layer number in the resulting part. As the case in the previous section (Ref. Section 5.3.1), the part file was generated with a default layer thickness of 0.127 mm (0.005 in) while the actual part had much thicker

File Layer Number	Actual Layer Number	Co Hopper Voltage	WC Hopper Voltage
71	1	4.00	2.00
82	2	3.75	2.25
91	3	3.50	2.50
102	4	3.25	2.75
111	5	3.00	3.00
122	6	2.75	3.25
131	7	2.50	3.50
142	8	2.25	3.75
149	9	2.00	4.00

Table 5.4: Build Planning Table

layers of 1.27 mm (0.05 in). The layer numbers in the part file were selected at every tenth layer in order to generate a drill bit insert of the correct length and aspect ratio. Additionally, layer numbers were selected with alternating even and odd numbers to generate an alternating pattern of scan vectors between subsequent layers (Ref. Section 5.3.1).

Thicker layers were selected for these experiments due the presence of the powder roller. A manual powder smoothing technique was used for the previous work in the air processing environment. This technique is much more robust with respect to part shifting then powder smoothing using a roller subsystem. The powder roller is more forceful in the spreading of the powder and will cause part shifting much more easily then a manual technique. Additionally, the use of high energy densities and the tendency of the layers to thicken during oxidation presented additional factors for the selection of relatively thick layers during processing.

The initial ratio of the voltages sent to the powder hoppers at the bottom of the part was set to a 2:1 ratio of Co:WC. This ratio of voltages was varied in a linear fashion to a ratio of 1:2 of Co:WC at the top of the part. During these part fabrication runs, high energy densities ($SS = 10$) were utilized in order to better determine the

File Layer Number	Actual Layer Number	Co Hopper Voltage	WC Hopper Voltage
72	1	4.00	2.00
71	2	4.00	2.00
72	3	4.00	2.00
71	4	4.00	2.00
82	5	3.75	2.25
91	6	3.50	2.50
102	7	3.25	2.75
111	8	3.00	3.00
122	9	2.75	3.25
131	10	2.50	3.50
142	11	2.25	3.75
149	12	2.00	4.00

Table 5.5: Build Planning Table with Anchor Layers

extent of oxide formation.

Initial scanning attempts resulted in layer growth due to oxidation and part shifting leading to run termination. An anchor strategy was utilized in which a number of layers were run at the start of the build to form a stabilizing mass. The use of these layers ensure a lack of part shifting and generate a solid mass of sintered material. The seventy-first layer of the part file was selected for scanning to generate the anchor mass. The presence of the previously sintered material reduces the sensitivity of the part to shifting due to part / roller interference (Ref. Table 5.5).

During part fabrication, oxide formation was somewhat reduced compared to runs in air (Ref. Figure 5.12). However, oxides were still observed and layer thickness was also observed to increase. The increases in layer thickness lead to part / roller interference and associated part shifting. This behavior required an interactive alteration of layer thickness during fabrication. Increased layer thickness lead to a lack of complete through-thickness melting for some layers. Resulting part delamination were also present, but at a reduced rate compared to previous runs in air. In general, some



Side View



Top View

Figure 5.12: Cone Section of Insert Fabricated Under Shield Gas

improvement was observed with a shield gas system, however, optimal part quality will require one of two approaches.

First, relatively low energy densities could be utilized resulting in a relatively porous part with low levels of oxide formation. Part yields would be relatively high with few cases of part delamination following processing. However, the use of this procedure would require a post-processing step in which another material is used to infiltrate and fully densify the drill bit. A second approach would consist of future developments in the atmospheric control subsystem to allow greater control of oxidation formation. A reduction in partial pressure of oxygen in the processing environment would allow the use of greater energy densities, which would reduce the accompanying levels of porosity.

5.3.3 Conclusions

In closing, the primary thrust of the development of the multiple material workstation has focused on powder delivery. This aspect of the workstation is the primary

differentiating feature of the system from traditional SLS. As such, powder delivery represented the primary innovative and unique work performed during the development of the multiple material workstation. Testing of the powder bed for desired material ratios indicates a variability on the order of 10% to 15%. While this value is not acceptable for a production or commercial device, it is deemed reasonable for a first generation workstation.

Atmospheric control is an obvious area of concern for the workstation and additional work is required in this area to bring the process up to the level currently present in other research on traditional SLS processes. Atmospheric control has traditionally been an area of concern in selective laser sintering and significant work has been done in the field to improve the atmospheric control of the process in order to improve part quality. Due to the presence of this previous work, the initial efforts in the project focused on the development of powder delivery hardware and the other more critical subsystems making up the overall process. The needed atmospheric control improvements for the multiple material workstation are similar to the previous work with some potential unique problems arising from the multiple material features of this process.

Chapter 6

Modeling of the WC-Co System: Single Layer Case

6.1 Problem Definition and Boundary Conditions

Development of the bond graph model first requires a through description of the problem and the associated boundary equations. Figures 6.1 and 6.2 presents our case of interest, namely, the sintering of a single layer sample containing a gradient of material composition. Sintering conditions are assumed to be performed under a high vacuum with significant powder bed pre-heat in order to duplicate the experimental results presented previously. Additionally, it is assumed that the material of interest duplicates our tungsten carbide / cobalt material system.

First, we define our system of interest as the melt pool which gradually moves into regions of unsintered powder and leaves a resulting region of solidified material. This system has a number of different boundary conditions which determine the rates of heat transfer from the melt pool and determine sintering behavior. These boundary conditions are dependent upon material composition and thus change as one moves along the material gradient. Additionally, a perpendicular versus parallel orientation of the scan vectors to the gradient of material composition also presents distinctly different

boundary conditions to be considered. Specifically, the parallel orientation results in different material compositions on front and back of the advancing melt pool, while the perpendicular orientation has a consistent material composition in these regions.

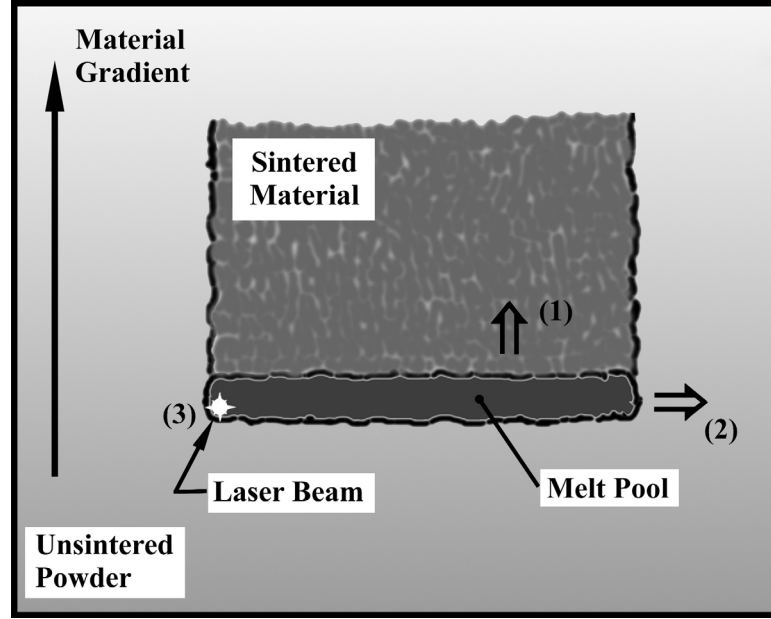


Figure 6.1: Melt Pool Heat Transfer Modes: Top View

Four primary modes of heat transfer are used to model the problem and are indicated by the numbers in Figures 6.1 and 6.2. Conduction from the melt pool can occur along two different routes. First, heat may flow back along the solidified material as it cools (Number 1; Figures 6.1 & 6.2). Additionally, heat may also flow into the unsintered powder surrounding the melt pool (Number 2; Figures 6.1 & 6.2). It has been observed that this region consists of a heat-affected zone which surrounds the melt pool and consists of partially sintered powder. Beyond this region, we have the loose unsintered powder found traditionally in the part cylinder.

Heat transfer by conduction through the unsintered powder occurs by a number of different methods (Ref. Figure 6.3) [48]. Assuming a lack of flow of gas through the powder bed, four primary methods of heat flow may be observed and are indicated

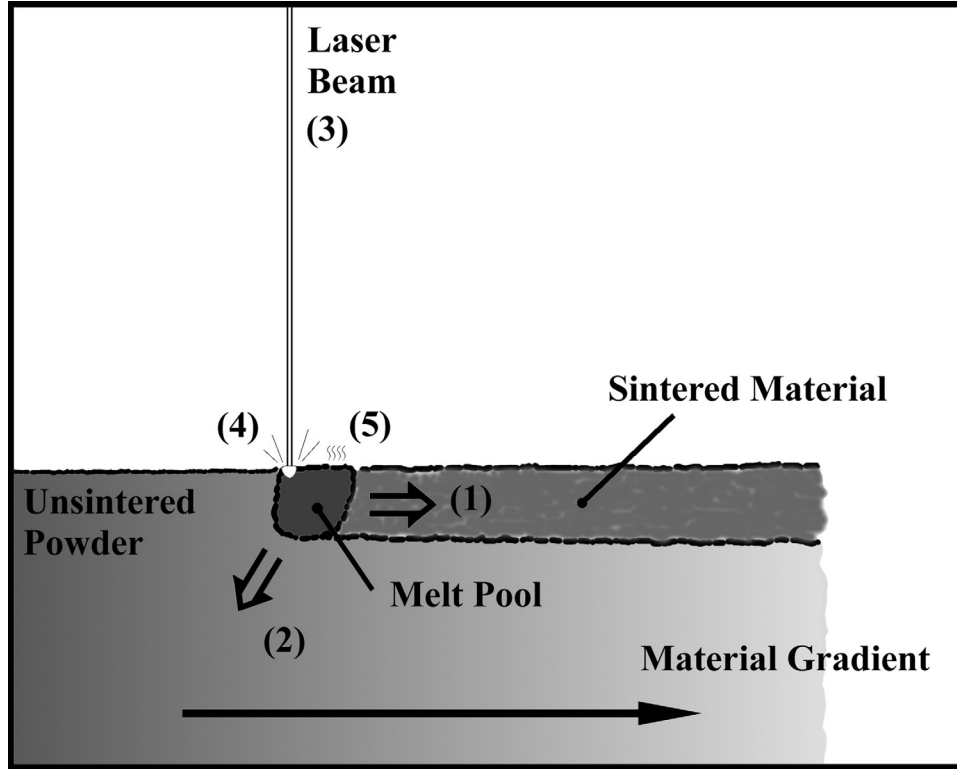


Figure 6.2: Melt Pool Heat Transfer Modes: Side View

in Figure 6.3 as before. First, we have conduction within a given particle (Number 1; Figure 6.3). We may also have thermal conduction between particles through the contact surfaces of the two particles (Number 2; Figure 6.3). Third, radiant heat transfer may occur between the surfaces of two particles (Number 3; Figure 6.3). Finally, we may also have radiant heat transfer between neighboring voids in the powder bed (Number 4; Figure 6.3).

The primary source of heat flow into the melt pool arises from the optical coupling of the melt pool and the scanning laser beam (Number 3; Figures 6.1 & 6.2). Thermal energy is also utilized to cause a phase change of solid powder into a liquid form in the melt pool.

In addition to these primary modes, other, less significant modes of heat transfer

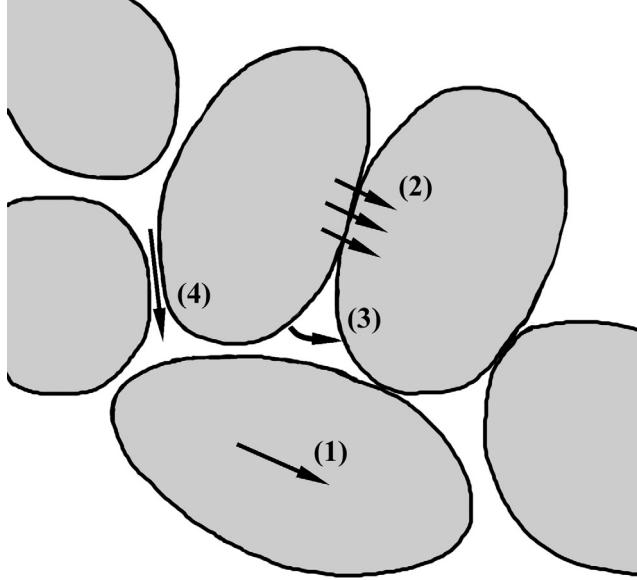


Figure 6.3: Heat Transfer Modes in the Powder Bed

also exist. First, the melt pool will tend to radiate heat to the chamber walls (Number 4; Figure 6.2). Secondly, some evaporation of the melt pool can be expected to occur when processing under a high vacuum (Number 5; Figure 6.2). The thermal energy required to drive this phase change represents a loss to the system and reduces heat which could be used to maintain melt pool temperature and melt additional powder. In addition to the thermal energy used to drive the evaporative phase change, heat is carried away from the melt pool system by the escaping vapor. Finally, we need not consider convective heat transfer from the melt pool due to our earlier assumption of a high vacuum processing environment.

Thus, the primary boundary conditions of interest are 1) Thermal conduction into the sintered material, 2) Thermal conduction into the unsintered powder, 3) Thermal irradiation of the melt pool by the laser beam, 4) Thermal irradiation of chamber walls by the melt pool, and 5) Mass transfer of vapor from melt pool due to excessive heating.

6.2 Bond Graph Development

6.2.1 Description of Bond Graph Variables

The first step in our modeling effort consists of the development of a bond graph which describes and represents the physical behavior of the situation described above. A cursory examination of our problem reveals that it is primarily a problem of modeling thermal and chemical effects. This specific characteristic of the problem, when coupled with its general nature require the extensive use of multi-port **R** and **C** elements in the bond graph. While these elements can accurately describe the behavior of complex systems such as ours, the development of system state equations becomes much more complex compared to the extensive use of single port bond graph elements.

The initial bond graph of our system is present in Figure 6.4. This bond graph is roughly divided into two broad areas. To the left of the graph, we have a **0** junction that represents the common temperature of the melt pool. This junction is connected to a number of different multi-port **R** elements that describe the behavior of the various thermal flows into and out of the system. In our graph, we have **R** elements for: 1) Heat flow from the laser beam, 2) Thermal interaction with the unsintered powder, 3) Thermal interaction with the solidified (sintered) material, and 4) Radiant thermal interaction with the chamber walls.

To the right of the graph, we have a multi-port **C** element that describes the effects of material flows into and out of the melt pool. At a basic level, the multi-port **C** describes the energy that is stored in the melt pool. The material flows into and out of the melt pool are divided into three categories which are represented by three corresponding effort sources. These three categories are: 1) Melting of unsintered powder by the advancing melt pool, 2) Solidification of the trailing edge of the melt pool, and 3) Loss of material due to vaporization of the melt pool.

The variables used in this bond graph are presented below followed by a brief description of the nature of each variable.

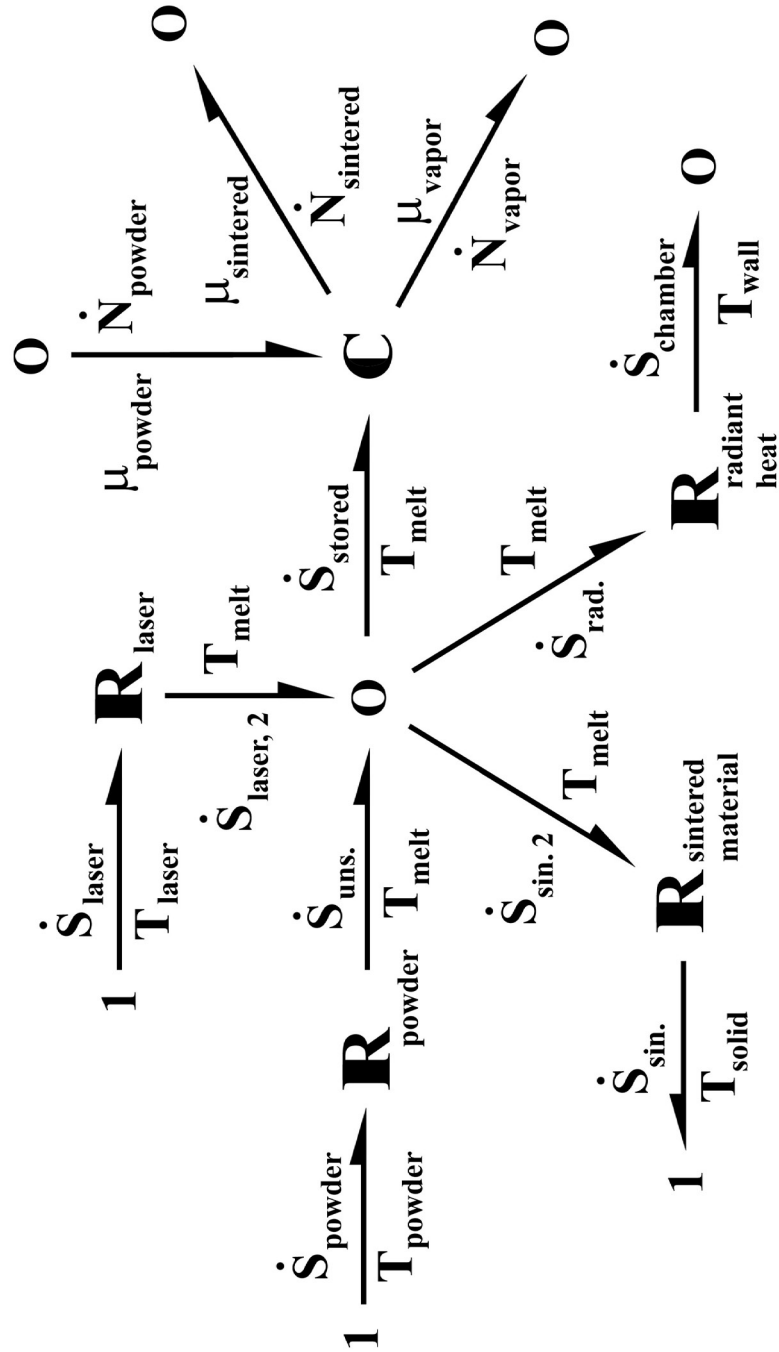


Figure 6.4: Bond Graph Representation

- $T_{melt} \equiv$ Temperature of melt pool.
- $S_{stored} \equiv$ Entropy stored in melt pool due to laser energy input.
- $T_{laser} \equiv$ Temperature of laser beam ($\sim$ temperature of plasma in laser).
- $S_{laser} \equiv$ Entropy associated with laser beam.
- $S_{laser, 2} \equiv$ Entropy added to melt pool by laser beam.
- $T_{powder} \equiv$ Temperature of unsintered powder bed.
- $S_{powder} \equiv$ Entropy associated with unsintered powder bed.
- $S_{uns.} \equiv$ Entropy transferred to unsintered powder (thermal growth).
- $T_{solid} \equiv$ Temperature of sintered material.
- $S_{sin.} \equiv$ Entropy associated with sintered material.
- $S_{sin., 2} \equiv$ Entropy transferred to sintered material via heat transfer.
- $S_{rad.} \equiv$ Entropy transferred to chamber walls via radiative heat transfer.
- $S_{chamber} \equiv$ Entropy associated with chamber walls.
- $T_{wall} \equiv$ Temperature of inside surface of chamber walls.
- $\mu_{powder} \equiv$ Potential of unsintered powder.
- $N_{powder} \equiv$ Moles of unsintered powder.
- $\mu_{sintered} \equiv$ Potential of sintered material.
- $N_{sintered} \equiv$ Moles of sintered material.
- $\mu_{vapor} \equiv$ Potential of vapor from melt pool.
- $N_{vapor} \equiv$ Moles of vapor from melt pool.

6.3 Development of State Equations

Following the development of the bond graph, the next step in our modeling effort is the derivation of the governing state equations of our system. For a bond graph utilizing single port elements, this is a relatively straightforward process, while the addition of multiple port elements adds some complexity to this process. Our approach will first derive the basic equations for the resistive multi-port elements (the **R**-elements), followed by a similar process for the capacitive multi-ports (**C**-elements) and then finally completed by collecting these equations into a set of formal state equations.

6.3.1 Constitutive Equations for R-Elements

The first element to consider describes the radiative transfer of energy from the laser to the powder bed (denoted by $\mathcal{R}_{laser}$). For this element, we have the effort on the input bond denoted as $\dot{S}_{laser}$ and on the output bond as $\dot{S}_{laser, 2}$. Similarly, for the flows, we have on the input bond, T_{laser} and on the output bond, T_{melt} .

Use of the basic heat transfer equations for the radiative mode with our designated variables yields the constitutive laws for this element.

$$\dot{S}_{laser} = A_{laser} F_{laser/melt} \sigma \left\{ \frac{T_{melt}^4 - T_{laser}^4}{T_{laser}} \right\} \quad (6.1)$$

$$\dot{S}_{laser, 2} = A_{melt} F_{melt/laser} \sigma \left\{ \frac{T_{melt}^4 - T_{laser}^4}{T_{melt}} \right\} \quad (6.2)$$

where

- $\sigma = 5.67 \times 10^{-8} \frac{\text{W}}{\text{m}^2 \text{K}^4} \equiv \text{Stephan - Boltzmann constant}$
- $A_{laser} \equiv \text{Spot size at laser exit}$
- $A_{melt} \equiv \text{Spot size on powder bed}$
- $F_{laser/melt} \equiv \text{Radiation shape factor between laser exit and laser spot on bed}$
- $F_{melt/laser} \equiv \text{Radiation shape factor between laser spot on bed and laser exit}$

The next step in the development is to determine how one may calculate the radiation shape factors. $F_{laser/melt}$ can also be defined as the fraction of laser radiation that leaves laser exit and strikes laser spot on the powder bed. If we assume that the aperture of the focusing lens captures 100% of the laser beam, then 100% of the radiation that leaves the laser exit is delivered to the laser spot on the bed.

Is this a valid assumption? The beam diameter at the lens location was calculated to be 14 mm where the term beam diameter refers to the diameter of an aperture through which 87% of the laser radiation passes. The lens diameter was specified to be 38.1 mm [1.5 in.]. Given that we know that 87% of the energy passes through an aperture of 7 mm radius, we can iteratively calculate the standard deviation of the Gaussian beam profile as 4.6 mm. Then, using statistical confidence intervals, one calculates that 99.95% of the beam will pass through an aperture with a radius of 19.05 mm.

Given that our assumption is reasonable, we can then state that

$$F_{laser/melt} = 1 \quad (6.3)$$

Additionally, we can use the following property of radiation shape factors to find the corresponding factor ($F_{melt/laser}$)

$$A_{melt}F_{melt/laser} = A_{laser}F_{laser/melt} \quad (6.4)$$

which yields

$$F_{melt/laser} = \frac{A_{laser}}{A_{melt}} \quad (6.5)$$

The next element to consider describes the conductive transfer of heat from the melt pool to the surrounding powder bed (denoted by $\mathcal{R}_{powder}$). For this element, we have the effort on the input bond denoted as $\dot{S}_{powder}$ and on the output bond as $\dot{S}_{uns.}$. Similarly, for the flows, we have on the input bond, T_{powder} and on the output bond, T_{melt} .

Use of the basic heat transfer equations for the conductive mode with our designated variables yields the constitutive laws for this element.

$$\dot{S}_{powder} = \frac{K_{powder}A_{powder}}{L_{powder}} \left\{ \frac{T_{powder} - T_{melt}}{T_{powder}} \right\} \quad (6.6)$$

$$\dot{S}_{uns.} = \frac{K_{powder} A_{powder}}{L_{powder}} \left\{ \frac{T_{powder} - T_{melt}}{T_{melt}} \right\} \quad (6.7)$$

where

- $K_{powder} \equiv$ Thermal conductivity of unsintered powder
- $A_{powder} \equiv$ Area of contact between melt pool and unsintered powder
- $L_{powder} \equiv$ Distance from melt pool boundary to region in powder where T_{powder} is constant.

The last term described above (L_{powder}) is a simplification of the actual situation. This description assumes that heat flows from two distinct bodies, the melt pool at (T_{melt}) and the unsintered powder bed at (T_{powder}). In actuality, the difference in temperatures sets up thermal gradients that extend into the melt pool and affect its fluid behavior and also extend into the unsintered powder to cause thermal growth of the part.

The next element to consider describes the conductive transfer of heat from the melt pool to the previously sintered material (denoted by $\mathcal{R}_{sintered}$). For this element, we have the effort on the input bond denoted as $\dot{S}_{sin., 2}$ and on the output bond as $\dot{S}_{sin.}$. Similarly, for the flows, we have on the input bond, T_{melt} and on the output bond, T_{solid} .

Use of the basic heat transfer equations for the conductive mode with our designated variables yields the constitutive laws for this element.

$$\dot{S}_{sin., 2} = \frac{K_{sin. mat.} A_{sin. mat.}}{L_{sin. mat.}} \left\{ \frac{T_{melt} - T_{solid}}{T_{melt}} \right\} \quad (6.8)$$

$$\dot{S}_{sin.} = \frac{K_{sin. mat.} A_{sin. mat.}}{L_{sin. mat.}} \left\{ \frac{T_{melt} - T_{solid}}{T_{solid}} \right\} \quad (6.9)$$

where

- $K_{sin. mat.} \equiv$ Thermal conductivity of the sintered material
- $A_{sin. mat.} \equiv$ Area of contact between the melt pool and the sintered material

- $L_{sin. mat.} \equiv$ Distance from melt pool boundary to region in powder where T_{solid} is constant.

Note that the issues described above for L_{powder} also exist for $L_{sin. mat.}$.

The final element to consider describes the radiative transfer of heat from the melt pool to the external environment, which in this case consists of the interior chamber walls (denoted by $\mathcal{R}_{radiant heat}$). For this element, we have the effort on the input bond denoted as $\dot{S}_{rad}$ and on the output bond as $\dot{S}_{chamber}$. Similarly, for the flows, we have on the input bond, T_{melt} and on the output bond, T_{wall} .

Use of the basic heat transfer equations for the radiative mode with our designated variables yields the constitutive laws for this element.

$$\dot{S}_{rad} = A_{melt pool} F_{melt/wall} \sigma \left\{ \frac{T_{melt}^4 - T_{wall}^4}{T_{melt}} \right\} \quad (6.10)$$

$$\dot{S}_{chamber} = A_{chamber} F_{wall/melt} \sigma \left\{ \frac{T_{melt}^4 - T_{wall}^4}{T_{wall}} \right\} \quad (6.11)$$

where

- $A_{melt pool} \equiv$ Area of exposed melt pool surface
- $A_{chamber} \equiv$ Area of interior chamber walls
- $F_{melt/wall} \equiv$ Radiation shape factor between melt pool and chamber wall.
- $F_{wall/melt} \equiv$ Radiation shape factor between wall and melt pool.

As before, we seek to determine the radiation shape factors in terms we can calculate. $F_{melt/wall}$ can also be described as the fraction of radiation leaving the melt pool surface that strikes the interior surface of the chamber. Since the chamber completely encloses the melt pool, we can say

$$F_{melt/wall} = 1 \quad (6.12)$$

Then, using as before the basic relationship between areas and shape factors, we find that

$$F_{wall/melt} = \frac{A_{melt\ pool}}{A_{chamber}} \quad (6.13)$$

At this point, we now have developed the constitutive equations for the R-elements in our bond graph. Our next step consists of a similar development for the capacitive elements.

6.3.2 Constitutive Equations for C-Elements

For our capacitive elements, we face a slightly different problem than the resistive elements described above. First, we only have one element, however, this element possesses four bonds so that the equations describing this element are more complex. Additionally, the constitutive relationships for this element are much more specific than those presented above, which represent the classical heat transfer modes. The capacitive relationships to be developed are more focused with respect to our modeling effort and will require a more formalized and involved development process.

First, in a generalized sense, we have a set of equations in which a set of rates of change of material and one rate of change of entropy ($\dot{N}_{powder}$, $\dot{N}_{sintered}$, $\dot{N}_{vapor}$, and $\dot{S}_{stored}$) must be described in terms of the state variables of the capacitive multi-port (μ_{powder} , $\mu_{sintered}$, μ_{vapor} , and T_{melt}).

$$\dot{N}_{powder} = f_1(\mu_{powder}, \mu_{sintered}, \mu_{vapor}, T_{melt}) \quad (6.14)$$

$$\dot{N}_{sintered} = f_2(\mu_{powder}, \mu_{sintered}, \mu_{vapor}, T_{melt}) \quad (6.15)$$

$$\dot{N}_{vapor} = f_3(\mu_{powder}, \mu_{sintered}, \mu_{vapor}, T_{melt}) \quad (6.16)$$

$$\dot{S}_{stored} = f_4(\mu_{powder}, \mu_{sintered}, \mu_{vapor}, T_{melt}) \quad (6.17)$$

where f_i is a generalized function which must be defined. Given the presence of the chemical potentials as state variables, it is likely that the modeling process will require

an examination of the Gibbs free energy of the system based on the formal definition of the chemical potential as follows

$$\mu_i = \left(\frac{\partial G}{\partial n_i} \right)_{T, P, n_j, \dots} \quad (6.18)$$

where μ_i represents an increase in the free energy of the system due to an infinitesimal addition of the species i , per mole of i added, with the addition made at constant temperature, pressure, and numbers of moles of all other species present [27].

Also, we can state a simple relationship between the rates of flow of the materials in our systems based on a simple conservation of mass as follows

$$\dot{N}_{melt} = \dot{N}_{powder} - \dot{N}_{sintered} - \dot{N}_{vapor} \quad (6.19)$$

where $\dot{N}_{melt}$ is the rate of increase (or decrease) in the number of moles of melt. This equation basically states the change in the number of moles of melt is determined by the difference between the rate at which powder is melted and the rate at which the melt solidifies and is vaporized.

Another equation of some potential applicability to our modeling effort defines the change in entropy due to the phase change of the powder from a solid to a liquid melt.

$$\Delta S_{melting} = \frac{\Delta H_{melting}}{T_{melting}} \quad (6.20)$$

where

- $\Delta S_{melting} \equiv$ Increase in entropy due to the melting of a given amount (x moles) of solid material (species i).
- $\Delta H_{melting} \equiv$ Amount of heat needed to melt x moles of species i (also known as the latent heat of fusion of species i).
- $T_{melting} \equiv$ Melting temperature of species i .

Note that the term $\Delta H_{melting}$ is not equivalent to the chemical potential of the powder, μ_{powder} . The potential of the powder is the change in the overall Gibb's free

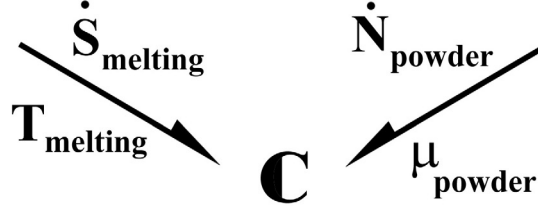


Figure 6.5: Proposed Bond Graph Modification: Additional Multi-port **C** Bonds

energy of the system due to the addition of the powder on a per molar basis, while the latent heat of fusion is concerned only with the energy required to affect a phase change in a given material.

However, this equation seems to lead to a potential lack of precision regarding our bond graph as it is developed so far. First, we have the introduction of unsintered powder, with some given potential, to our system which changes the Gibb's free energy. Additionally, we also have a melting process in which the powder changes from a solid to a liquid with an accompanying increase in entropy. The current bond graph is relatively unclear in distinguishing between these two processes and produces some confusion (for example, does the chemical potential described previously refer to the potential of the powder or the melt?).

It would seem that the bond graph needs some additional structures to distinguish between these physical phenomena. Two potential structures can be suggested. The first of these structures is to simply add two additional bonds to the currently existing multi-port **C** to represent the effect of the phase change (Ref. Figure 6.5). The second of the proposed structures would consist of a bond representing the phase change (with $\dot{S}_{melting}$ and $T_{melting}$ variables) which feeds into a multi-port **R** which is then connected to the multi-port **C** by a chemical potential bond (Ref. Figure 6.6).

An examination of Equation 6.74 can be used to lead to a relationship between $\dot{S}_{melting}$ and $\dot{N}_{powder}$. First, we can recast Equation 6.74 to explicitly denote the volume



Figure 6.6: Proposed Bond Graph Modification: Additional Multi-port **R** Element

of species i which is melted (V_{melted}).

$$\frac{S_{melting}}{V_{melted}} = \frac{H_{melting}}{V_{melted} T_{melting}} \quad (6.21)$$

Next, we can introduce a melting rate term to each side.

$$\frac{S_{melting}}{V_{melted}} \frac{V_{melted}}{t} = \frac{H_{melting}}{V_{melted} T_{melting}} \frac{V_{melted}}{t} \quad (6.22)$$

An examination of the bond graph reveals that that the melting rate term is another expression of the rate at which unsintered powder is melted and enters the system ($\dot{N}_{powder}$). Substitution of this term with simplification of the left hand side of Equation 6.22 yields the following.

$$\frac{S_{melting}}{t} = \frac{H_{melting}}{V_{melted} T_{melting}} \dot{N}_{powder} \quad (6.23)$$

$$\dot{S}_{melting} = \frac{\Delta H_{melting}}{T_{melting}} \dot{N}_{powder} \quad (6.24)$$

Equation 6.24 then relates the entropy produced by the phase change to the rate of powder melting and would seem to be applicable to the proposed multi-port **R** element described above. Based primarily on the usefulness of the result above and need to model entropy generating processes (such as a phase change) by a multi-port **R** element, the bond graph shown in Figure 6.4 is modified to include the additional proposed elements (Ref. Figure 6.7).

The revised bond graph introduces a number of new variables to our developing model, which are described below. Also, an examination of the new variables and

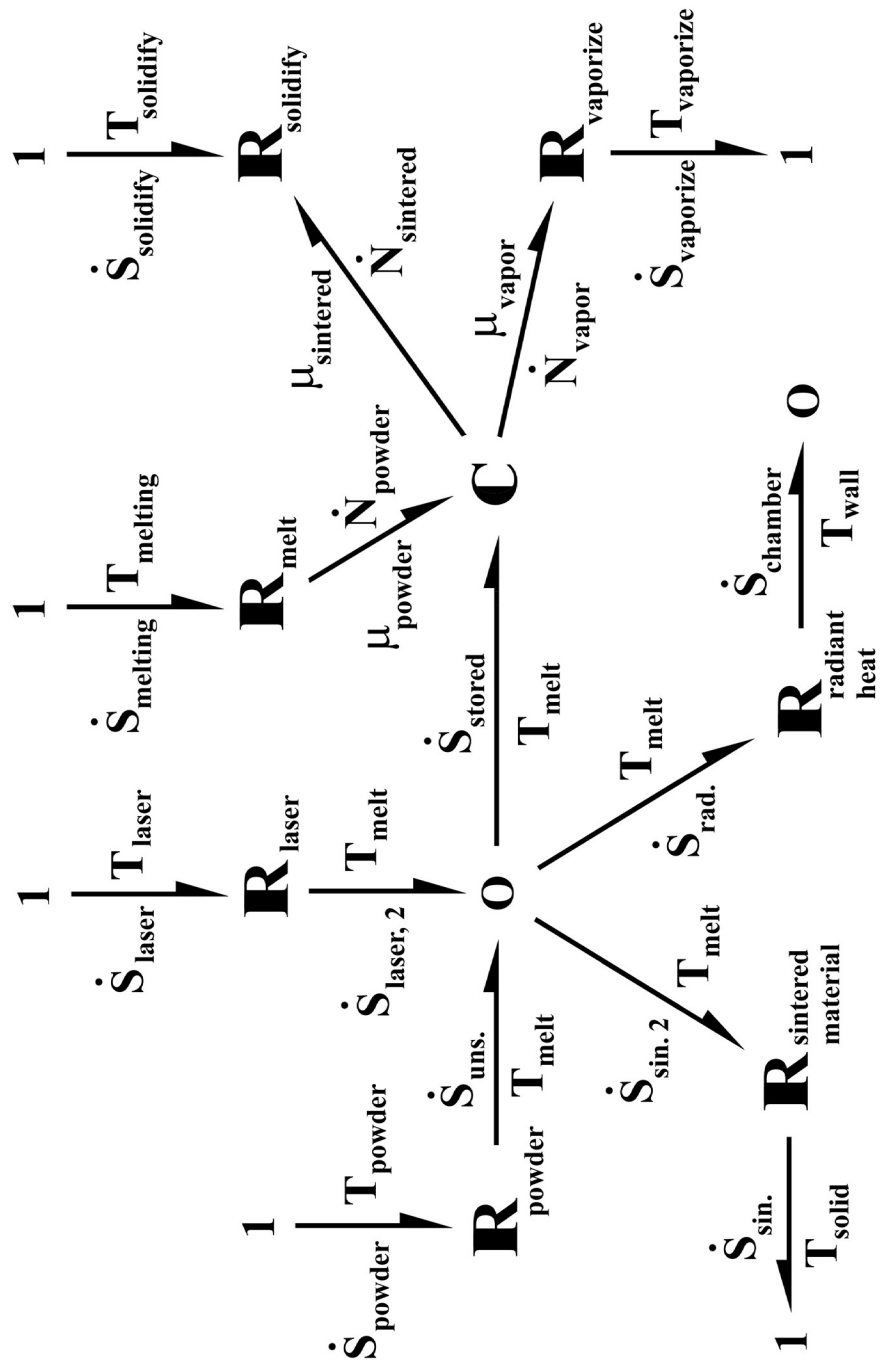


Figure 6.7: Revised Bond Graph Representation

revised bond graph reveal the presence of a number of different temperatures. Thus, our previous assumption of a melt pool with a single temperature has been expanded to include multiple temperatures. It was found to be necessary to include these different temperatures to describe the physical processes driving the phase changes which define the boundaries of our system and which so strongly influence our modeling effort. These different temperatures will also generate a number of other physical effects which were described above (thermal gradients in the melt pool, for example). The contribution of these other effects to the behavior of the system will not be modeled by this effort, which limits the effects of the multiple temperatures in the melt pool to the phase changes at the system boundaries.

- $S_{melting} \equiv$ Entropy change due to the melting of powder into liquid form
- $T_{melting} \equiv$ Melting temperature of the powder at the leading edge of the melt pool
- $S_{solidify} \equiv$ Entropy change due to the solidification of the melt pool
- $T_{solidify} \equiv$ Solidification temperature at the trailing edge of the melt pool
- $S_{vaporize} \equiv$ Entropy change due to vaporization of the melt pool
- $T_{vaporize} \equiv$ Vaporization temperature of the melt pool

Of some interest to our specific investigation is the melting temperature of the powder mixture. For traditional SLS, this value is simply a constant, however, for our multiple material case, this value changes based on the current ratio, or blend, of powder at the leading edge of the melt pool. A similar phenomena exists for the vaporization and solidification temperatures described above. The changes in these values will effect the model and the behavior of the melt pool as it moves over the powder bed in a unique fashion from traditional SLS.

Since our model now assumes different temperatures in the melt pool, we can see that one of the primary factors influencing the potential of different material flows

into the melt pool is the temperature at the different locations of the phase changes. These different temperatures at the melting, vaporization, and solidification regions is the main driving force behind these phase changes. At first, this seems to make the use of potentials in our bond graph problematic, however, the potentials can be realized to be primarily functions of temperature as well as other system variables. Thus, the potentials can be thought of as driving the phase changes.

Based on our assumption of different temperatures, we must redo equations 6.14 thru 6.17. These equations now become the following.

$$\dot{N}_{powder} = f_1(\mu_{powder}, \mu_{sintered}, \mu_{vapor}, T_{melting}) \quad (6.25)$$

$$\dot{N}_{sintered} = f_2(\mu_{powder}, \mu_{sintered}, \mu_{vapor}, T_{solidify}) \quad (6.26)$$

$$\dot{N}_{vapor} = f_3(\mu_{powder}, \mu_{sintered}, \mu_{vapor}, T_{vaporize}) \quad (6.27)$$

$$\dot{S}_{stored} = f_4(\mu_{powder}, \mu_{sintered}, \mu_{vapor}, T_{melt}) \quad (6.28)$$

An examination of the model reveals that the rates of material flow through each of the respective phase changes is controlled by the potential of the liquid melt at the different regions of the melt pool. Therefore, we can define a series of dimensionless ratios that describe the relative strength of one phase change versus another. The use of these dimensionless ratio will provide additional insight into the model. The ratios are defined as:

$$\alpha = \frac{\mu_{sintered}}{\mu_{powder}} \quad (6.29)$$

$$\beta = \frac{\mu_{vapor}}{\mu_{powder}} \quad (6.30)$$

$$\gamma = \frac{\mu_{vapor}}{\mu_{sintered}} \quad (6.31)$$

These ratios are primarily functions of temperature since the relative temperature differences in different regions of the melt pool drive the potentials. Note also that the ratios are also functions of time since the temperature profile of the melt pool changes with time.

These ratios are controlled by complex physical properties of the fluid melt pool which consist of thermal and fluid interactions. These interactions include fluid flow in the melt pool driven by the effects of natural convection, buoyancy, and surface tension forces. Additionally, chemical reactions in the melt pool and at the surface of the pool also exert an influence on the fluid and thermal properties of the pool.

Due to the complex nature of these effects, a purely theoretical modeling of these melt pool behavior is highly difficult and may result in significant deficiencies. A more productive and accurate method is to attempt to determine the defined ratios in an empirical manner. This method would most likely consist of collecting temperature data of the melt pool and other experimental measurements and then use this data to set initial values of the ratios defined above. These initial ratio values would be used to solve the model and produce a set of preliminary results. A tuning strategy would then be utilized to vary the ratios around the first, initial approximation and bring the model results into closer agreement with the observed behavior of the melt pool.

In conclusion, the use of the defined ratios and an empirical strategy would allow the determination of the constitutive equations of the **C** multi-port. The resulting constitutive equations can then be combined with the rest of the bond graph state equations described above to yield the desired theoretical model.

6.4 Melt Pool Kinetics: Effects on Homogenization

One of the primary problems which may be encountered in the use of functionally gradient materials is the possibility of homogenization of the gradient by the melt pool. A sufficiently steep gradient will produce a gradient of cobalt concentration across the melt pool. Sufficient movement of the liquid cobalt within the melt pool could cause cobalt migration in which the cobalt moves the high concentration region to regions of lower cobalt concentration. This effect would tend to blur the gradient and, if sufficiently strong, would eliminate the gradient and homogenize the melt pool so that the desired gradient is eliminated.

This effect is primarily driven by the time scales of two different processes: solidification in SLS and the cobalt migration process. Rapid solidification of the melt pool will maintain the desired gradient in the resulting sintered material, however, slow solidification times relative to cobalt migration time scales will provide sufficient time for homogenization and elimination of the gradient. Therefore, the primary issue of consideration is the relative magnitude of the time scales of the solidification and cobalt migration processes.

6.4.1 Research Investigations

Of additional consideration is the fact that the size of the melt pool can be controlled to some extent by scanning strategies and is generally determined by part and/or feature size. For large parts with simple features, it is desirable to have a relatively large melt pool as it tends to speed up the sintering process. For this case, homogenization of the gradient may be a significant problem. For a part with a large number of small features, the melt pool size must be controlled to a small size in order to allow the proper representation of the small features. For this case, homogenization of the melt pool may be less problematic since a gradient would still exist at the scale of the size of the melt pool.

First, we need to determine the time scales associated with solidification in the SLS process. In traditional applications (such as casting) solidification can be a relatively slow process. However, due to the small volume of the melt pool, solidification in the SLS process normally occurs relatively rapidly. Due to the rate of cooling, very little undercooling occurs. Thus, solidification is predicted to occur epitaxially [51].

In general, the transformation of liquid melt to a solid involves two steps. First, nucleation by a cluster of atoms occurs. This process requires energy to develop a liquid solid interface. However, this process also creates a certain amount of solid which is at a lower energy state than the surrounding liquid. The total energy change can be described by

$$\Delta G_T = 4\pi R^2 \gamma + \frac{4}{3}\pi R^3 \Delta G_V \quad (6.32)$$

The γ term denotes the surface energy required to form the interface and prevents nucleation, while the ΔG_V term (which is always negative) describes the free energy change when the liquid melt becomes a solid. It can be shown that nucleation is unfavorable unless a critically sized nucleus, R^* , is formed. This value can be shown by differentiation of Eq. 6.32 with respect to particle radius to yield

$$R^* = \frac{-2\gamma}{\Delta G_V} \quad (6.33)$$

Once the nucleus has formed, additional atoms are added to the surface, allowing the nucleus to grow and create a solidification front. However, for our case, we already have a large number of surfaces for nucleation to initiate on due to the presence of the solid, unmelted WC particles. These particles allow heterogeneous nucleation to occur in our system. These particles act as a large number of nucleation sites and help to remove the energy barrier present in homogeneous nucleation. Thus, nucleation is enhanced and solidification rate is increased [28].

Previous work has been examined in which SLS has been used for the sintering and consolidation of nanostructured tungsten carbide-cobalt composites. Nanostructured materials are fabricated, normally in particle form, to have extremely small grain sizes on the order of a few hundred atoms in diameter. The extremely small grains are desired because they improve the material properties (wear resistance, for example). However, this type of material does not lend itself well to traditional sintering techniques which require exposure to high temperatures for long periods of time. This lengthy exposure leads to rapid grain growth and a loss of the desired material properties. It has been shown that SLS processing of these types of materials can be performed without a degradation in material properties due to rapid consolidation rates possible with SLS [14]. The rapid cooling rates of the SLS process causes the material to solidify before the grains have a chance to grow. While this work does not directly discuss the

issue of cobalt migration, it does tend to illustrate the rapid solidification times of SLS compared to traditional sintering processes.

Video microscopy of the SLS process has been used as part of a study to examine the wetting behavior of metals in a direct SLS process developed at the University of Texas at Austin. An examination of this work reveals typical SLS solidification times in the range of 3 to 15 seconds [16]. Therefore, we see that SLS consolidation and solidification occurs at a relatively rapid rate.

Next, we consider the problem of cobalt migration and attempt to determine the time scales of this process. The first process to consider which may lead to cobalt migration is diffusion. A diffusion flux can be defined as

$$J = \frac{M}{At} \quad (6.34)$$

in which J is the diffusion flux, M is the mass of material which diffuses through the substance, A is the cross-sectional area, and t is the elapsed diffusion time. For steady-state diffusion in a single direction, the flux is proportional to the concentration gradient expressed as

$$J = -D \frac{dC}{dx} \quad (6.35)$$

where D is known as the diffusion coefficient and C is the concentration gradient. The negative sign indicates that the direction of diffusion is down the concentration gradient, from high to low concentration. This equation is known as Fick's First Law.

The more complex case of non-steady diffusion results in Fick's Second Law given as

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} \left(D \frac{\partial C}{\partial x} \right) \quad (6.36)$$

Both the species of material diffusing and the diffusing medium affect diffusion rates. Additionally, temperature strongly influence diffusion rates. However, an examination of the literature indicates that diffusion fluxes are very small and occur on very long time scales. Diffusion times of several hours are common [58].

Thus, it is very unlikely that diffusion will lead to any significant homogenization of the FGM gradient during time scales normally associated with SLS processing. However, we still must be concerned with convective and gravity driven fluid currents in the melt pool which could lead to undesired homogenization.

Cobalt migration has been observed as a problem in the liquid phase sintering of WC-Co FGM materials. In an examination of FGMs for use as mining tools bits, graded drilling tools were produced by sintering multilayered green bodies from cold-pressed stackings of powder layers. Liquid-phase sintering was used to achieve pore-free materials. It was observed that the initial compositional gradients partly vanished due to melt redistribution [40].

Additionally, Berg illustrated the need to control time and temperature during HIP processing to mitigate the effects of cobalt migration. HIP times were approximately one hour which indicates the possibility that observed cobalt migration may be associated with relatively long time scales used for HIP processing [10].

Finally, Colin, et al. examined the issue of homogenization (cobalt migration) in WC-Co cermets. Mixtures of 10, 20, or 30 wt % cobalt were cold-pressed in a steel die. Each layer was cold pressed to achieve a flat surface and then a final cold-press of 1263 MPa was performed for the three layers. These layers were then liquid-phase sintered at 1353 C for 15 minutes. Interfaces between layers remained visible, however, a complete homogenization of the structure was observed for a sintering time above 30 minutes.

Additionally, two layer structures of 10/20 wt % cobalt and 20/30 wt % cobalt were developed with the cold-pressing process. Microhardness profiles were developed for these samples which indicated a partial homogenization had occurred in samples sintered for 20 minutes at 1345 C (Ref. Figure 6.8). The interface for the transition zone still remains visible even with a relatively long sintering cycle of 20 minutes (compared to SLS processing times). Also, the 20/30 wt % cobalt ratio appears to be more stable and resistant to homogenization.

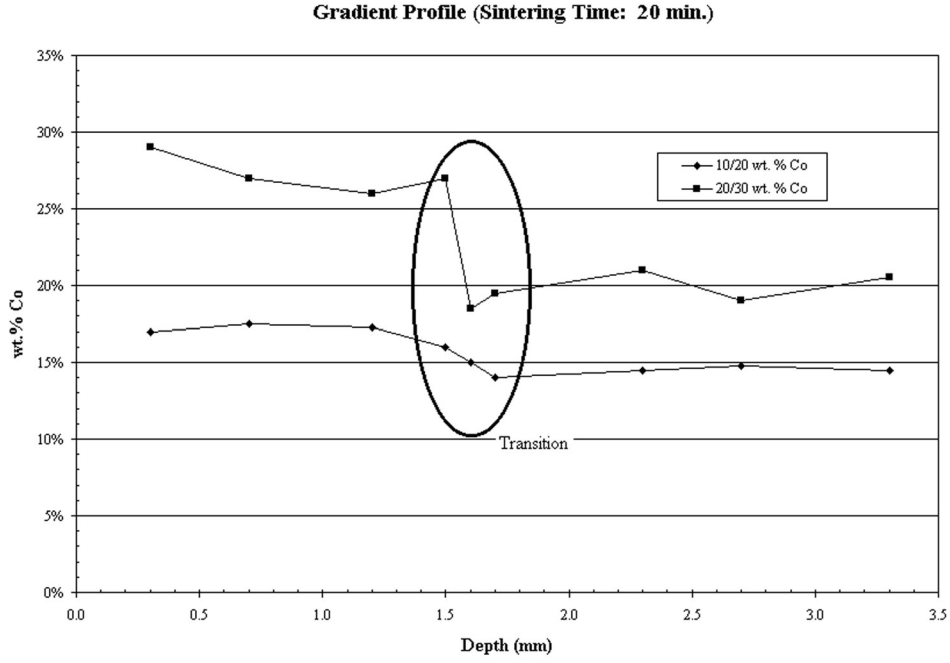


Figure 6.8: Concentration Profiles for 10/20 and 20/30 Wt % Cobalt Sintered for 20 Minutes [13]

Homogenization was more pronounced for a longer sintering time of 2 hours at 1345 C. The 10/20 wt % cobalt ratio has homogenized to approximately 15 wt % cobalt, however, the transition zone for the 20/30 wt % cobalt ratio still remains visible (Ref. Figure 6.9). Thus, we see that even with a two hour sintering cycle, those gradients with higher ratios of cobalt still remain distinct.

Finally, we shall return to our single layer work presented earlier in this paper and examine the gradient profiles for evidence of homogenization (Ref. Figure 3.13). An examination of this plot reveals some differences between the predicted and measured values of % cobalt for low values of cobalt. This could be due to migration of cobalt from regions of cobalt-rich material. However, it must be realized that the image analysis process used to determine the values of % cobalt contained subjective processes

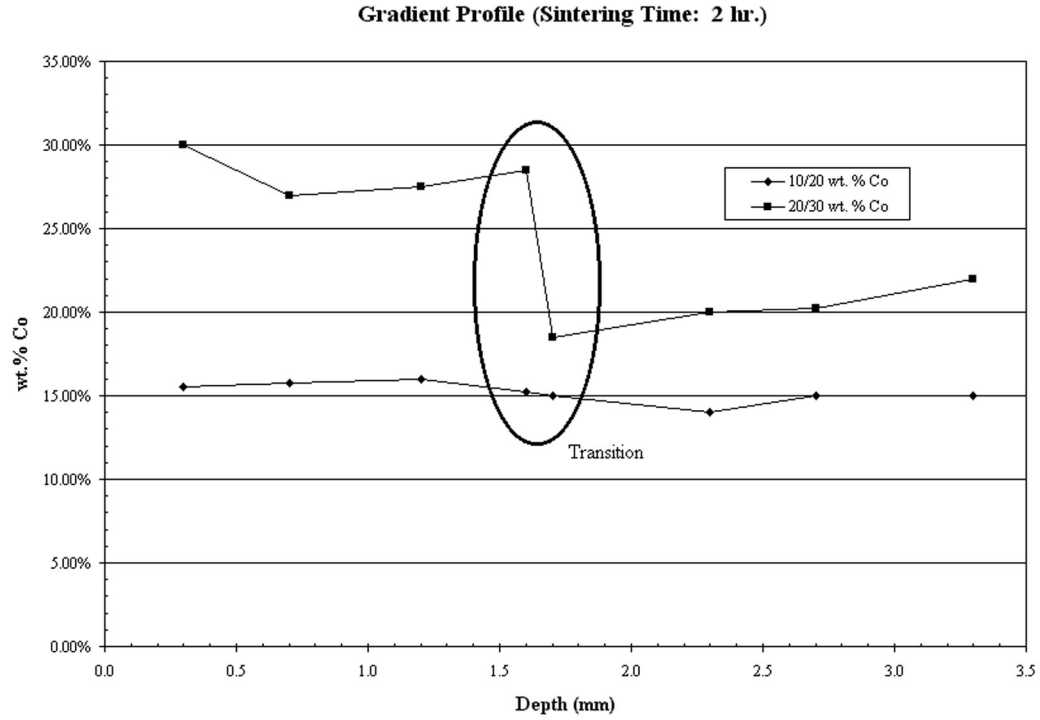


Figure 6.9: Concentration Profiles for 10/20 and 20/30 Wt % Cobalt Sintered for 2 Hours [13]

which easily could have driven errors into the process and caused some uncertainty in the results which could also explain the differences noted above. Additionally, homogenization of the sample, by its definition, must also tend to reduce the high values of % cobalt so that the cobalt-rich and cobalt-poor regions are driven toward equilibrium. An examination of the plot reveals a high degree of accuracy for the larger values of % cobalt. The errors are biased on one side of the theoretical curve and therefore suggest a consistent measurement error rather than cobalt migration.

Based on these results, it appears that the time scales required for cobalt migration range from 20 minutes up to 2 hours. Traditional solidification times for SLS processes typical range in the seconds (3 to 20 seconds). Based on these results, cobalt

migration is of concern when used with traditional liquid-phase sintering. However, given the rapid consolidation rates with SLS, cobalt migration is not seen as a significant processing issue in the future development and use of FGMs in SLS.

6.4.2 Modeling Investigation

As a final check of this potential issue, simple models will be used to calculate the solidification and cobalt migration times and then compared to the results presented above. The first model will be used to calculate the solidification times. This model will use the melt pool as a control volume and will then consider the heat flow out of the system to determine solidification times. Note that no laser input is assumed and that the pre-existing melt pool is allowed to cool down. Basically, this model will be a simplified version of the more complex and complete bond graph model presented earlier. This simplified version will then be used to generate equations describing the cooling rate of the melt pool and generate an approximate solution. The primary boundary conditions through which the heat is removed from the cooling melt pool will be through the surrounding powder bed and the top surface of the pool. The cooling process of the melt pool will be considered in two separate steps. First, the cooling of the melt pool to the solidification temperature (the melting point of cobalt) must be examined. This is required due to the fact that the melt pool will be heated beyond the melting temperature. The second step then addresses the time required for the melt pool at the solidification temperature to dump sufficient heat (or entropy) to undergo a phase change and convert into a solid form. The modeling effort for the first step is the more complex of the two, since the temperature of the melt pool is changing which affects the rates at which heat is transferred from the melt pool via radiative and conductive paths. For the second step, the amount of entropy to remove from the system is a set amount based on the size of the melt pool and the rate of heat flow is also constant since the temperature of the pool will remain at the melting point of cobalt during the phase change.

The second model will be used to calculate the time scales required for the cobalt migration process. This model will assume a small control volume in the interior regions of the melt pool. The mass transfer properties of this small volume will be addressed to examine the rate at which mass (in the form of liquid cobalt) will move into and out of this control volume. The primary methods for mass transport for this model are currently assumed to be diffusion and fluid flow of molten cobalt, which will be assumed to be driven by convective buoyancy forces. Traditional modeling methods will be used to generate equations that will then be solved to yield approximate rates of mass transfer from the control volume. These mass transfer rates can then be used to determine the time frames required for significant cobalt migration to occur.

Solidification Model

The first step in the development of the solidification model is the simplification of the fully developed bond graph for our specific problem (Ref. Figure 6.7). Considering a cooling melt pool with only heat flow via conductive and radiative paths yields the following simplified bond graph (Ref. Figure 6.10). For this simplified model, we have a capacitive storage element which represents the stored thermal energy in the melt pool. As the melt pool cools, this thermal energy is dissipated through two resistive elements which represent the conduction of energy into the powder bed and radiation of heat from the surface of the melt pool.

The variables used in this bond graph are presented below followed by a brief description of the nature of each variable.

- $T_{melt} \equiv$ Temperature of melt pool.
- $T_{powder} \equiv$ Temperature of unsintered powder bed.
- $S_{powder} \equiv$ Entropy associated with unsintered powder bed.
- $S_{uns.} \equiv$ Entropy transferred to unsintered powder (thermal growth).

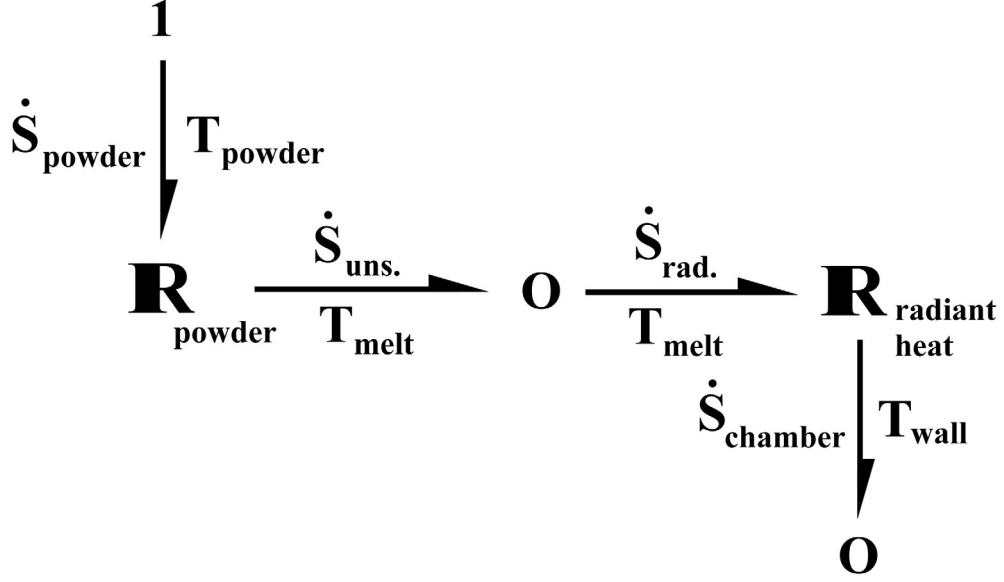


Figure 6.10: Bond Graph: Solidification Model

- $S_{rad.} \equiv$ Entropy transferred to chamber walls via radiative heat transfer.
- $S_{chamber} \equiv$ Entropy associated with chamber walls.
- $T_{wall} \equiv$ Temperature of inside surface of chamber walls.
- $S_{stored} \equiv$ Entropy stored in melt pool.

Next, we derive the constitutive equations for the bond graph presented above. Following this derivation, we will combine these equations to yield the state equations for our model.

The first element to consider describes the conductive transfer of heat from the melt pool to the surrounding powder bed (denoted by $\mathcal{R}_{powder}$). For this element, we have the effort on the input bond denoted as $\dot{S}_{powder}$ and on the output bond as $\dot{S}_{uns.}$. Similarly, for the flows, we have on the input bond, T_{powder} and on the output bond, T_{melt} .

Use of the basic heat transfer equations for the conductive mode with our designated variables yields the constitutive laws for this element.

$$\dot{S}_{powder} = \frac{K_{powder} A_{powder}}{L_{powder}} \left\{ \frac{T_{powder} - T_{melt}}{T_{powder}} \right\} \quad (6.37)$$

$$\dot{S}_{uns.} = \frac{K_{powder} A_{powder}}{L_{powder}} \left\{ \frac{T_{powder} - T_{melt}}{T_{melt}} \right\} \quad (6.38)$$

where

- $K_{powder} \equiv$ Thermal conductivity of unsintered powder
- $A_{powder} \equiv$ Area of contact between melt pool and unsintered powder
- $L_{powder} \equiv$ Distance from melt pool boundary to region in powder where T_{powder} is constant.

The last term described above (L_{powder}) is a simplification of the actual situation. This description assumes that heat flows from two distinct bodies, the melt pool at (T_{melt}) and the unsintered powder bed at (T_{powder}). In actuality, the difference in temperatures sets up thermal gradients that extend into the melt pool and affect its fluid behavior and also extend into the unsintered powder to cause thermal growth of the part.

The final element to consider describes the radiative transfer of heat from the melt pool to the external environment, which in this case consists of the interior chamber walls (denoted by $\mathcal{R}_{radiant\ heat}$). For this element, we have the effort on the input bond denoted as $\dot{S}_{rad}$ and on the output bond as $\dot{S}_{chamber}$. Similarly, for the flows, we have on the input bond, T_{melt} and on the output bond, T_{wall} .

Use of the basic heat transfer equations for the radiative mode with our designated variables yields the constitutive laws for this element.

$$\dot{S}_{rad} = A_{melt\ pool} F_{melt/wall} \sigma \left\{ \frac{T_{melt}^4 - T_{wall}^4}{T_{melt}} \right\} \quad (6.39)$$

$$\dot{S}_{chamber} = A_{chamber} F_{wall/melt} \sigma \left\{ \frac{T_{melt}^4 - T_{wall}^4}{T_{wall}} \right\} \quad (6.40)$$

where

- $A_{melt\ pool} \equiv$ Area of exposed melt pool surface
- $A_{chamber} \equiv$ Area of interior chamber walls
- $F_{melt/wall} \equiv$ Radiation shape factor between melt pool and chamber wall.
- $F_{wall/melt} \equiv$ Radiation shape factor between wall and melt pool.

As before, we seek to determine the radiation shape factors in terms we can calculate. $F_{melt/wall}$ can also be described as the fraction of radiation leaving the melt pool surface that strikes the interior surface of the chamber. Since the chamber completely encloses the melt pool, we can say

$$F_{melt/wall} = 1 \quad (6.41)$$

Then, using as before the basic relationship between areas and shape factors, we find that

$$F_{wall/melt} = \frac{A_{melt\ pool}}{A_{chamber}} \quad (6.42)$$

The final equation to be derived consists of the constitutive equation for the **C** element. For this element, we seek to find the functional relationship between the temperature of the melt pool (our effort) and the entropy stored in the melt pool (our displacement). We begin with the basic Gibb's equation

$$du = \frac{\partial u}{\partial s} ds + \frac{\partial u}{\partial v} dv = T ds - P dv \quad (6.43)$$

For our case, the liquid melt pool is not effected by changes in pressure so we can solve for ds to yield

$$ds = \frac{1}{T} du = \frac{1}{T} c_p dT \quad (6.44)$$

where we have introduced the specific heat to capture the relationship between entropy and internal energy. Note for our modeling effort, we may use either c_p or c_v since we are examining a liquid, we will continue with the c_p term. Integrating yields

$$s - s_0 = \int_{T_0}^T \frac{1}{T} c_p dT = c_p \ln \left[\frac{T}{T_0} \right] \quad (6.45)$$

where c_p is assumed to be constant and s_0 is defined as the entropy of the system at standard, or reference, conditions. Next, we can solve this equation for the temperature.

$$T = T_0 \exp \left[\frac{s - s_0}{c_p} \right] \quad (6.46)$$

Finally, we can replace the intensive s with the extensive S for the entropy and introduce our bond graph terminology to yield.

$$T_{melt} = T_0 \exp \left[\frac{S_{stored} - S_0}{M c_p} \right] \quad (6.47)$$

where

- $T_0 \equiv$ Reference or standard temperature
- $S_0 \equiv$ Entropy defined at standard conditions
- $c_p \equiv$ Specific heat of the liquid cobalt
- $M \equiv$ Mass of melt pool

This completes the development of the constitutive equations for our solidification bond graph. Next, we seek to develop the state equation for our system. Since we have one energy storage element, the **C** element, we will have only one state equation and one state variable, S_{stored} . Our state equation will have the form of

$$\dot{S}_{stored} = f(S_{stored}) \quad (6.48)$$

We will also introduce an intermediate variable to ease the calculations to follow. From Equation 6.47 above

$$\beta = \frac{S_{stored} - S_0}{M c_p} \quad (6.49)$$

so that Equation 6.47 becomes

$$T_{melt} = T_0 e^\beta \quad (6.50)$$

The first step in our development is to sum about the **O**-element from the solidification bond graph (Ref. Figure 6.10).

$$\dot{S}_{stored} = \dot{S}_{uns.} - \dot{S}_{rad} \quad (6.51)$$

Next, substitute Equations 6.38 & 6.39 into Equation 6.51 to yield

$$\begin{aligned} \dot{S}_{stored} = & \frac{K_{powder} A_{powder}}{L_{powder}} \left\{ \frac{T_{powder} - T_{melt}}{T_{melt}} \right\} \\ & - A_{melt\ pool} F_{melt/wall} \sigma \left\{ \frac{T_{melt}^4 - T_{wall}^4}{T_{melt}} \right\} \end{aligned} \quad (6.52)$$

where we can assume that $F_{melt/wall}$ is assumed to have a value of 1. Next, we substitute Equation 6.50 into the equation above to yield

$$\begin{aligned} \dot{S}_{stored} = & \frac{K_{powder} A_{powder}}{L_{powder}} \left\{ \frac{T_{powder} - T_0 e^\beta}{T_0 e^\beta} \right\} \\ & - A_{melt\ pool} \sigma \left\{ \frac{T_0^4 e^{4\beta} - T_{wall}^4}{T_0 e^\beta} \right\} \end{aligned} \quad (6.53)$$

Finally, we can simplify to reach the state equation.

$$\begin{aligned} \dot{S}_{stored} = & \frac{K_{powder} A_{powder} T_{powder}}{L_{powder} T_0 e^\beta} - \frac{K_{powder} A_{powder}}{L_{powder}} - \\ & A_{melt\ pool} \sigma T_0^3 e^{3\beta} + \frac{A_{melt\ pool} \sigma T_{wall}^4}{T_0 e^\beta} \end{aligned} \quad (6.54)$$

$$\begin{aligned} \dot{S}_{stored} = & -A_{melt\ pool} \sigma T_0^3 e^{3\beta} + \left\{ \frac{K_{powder} A_{powder} T_{powder}}{L_{powder} T_0} + \frac{A_{melt\ pool} \sigma T_{wall}^4}{T_0} \right\} e^{-\beta} \\ & - \frac{K_{powder} A_{powder}}{L_{powder}} \end{aligned} \quad (6.55)$$

where our state variable S_{stored} is contained within our intermediate term β .

Next, we need to determine and/or approximate values for the various coefficients used in our model. This values will be based primarily on tabulated values for cobalt or approximations from the previous descriptions of the single layer experiments.

First, we can set the reference entropy for cobalt [27].

$$S_0 = 0.217 \frac{\text{J}}{\text{K}} \quad (6.56)$$

Next, we must determine the approximate mass of the melt pool. First, we can assume dimensions from the experimental results. These dimensions can be used to determine the volume, which is then used with the density to determine the mass. From Section 3.1.2, we assume the melt pool will occupy approximately one third of the length of the resulting sample coupon. This results in the following dimensions:

$$\begin{aligned} \text{Width} &= 12 \text{ mm} \\ \text{Depth} &= 4 \text{ mm} \\ \text{Height} &= 1 \text{ mm} \end{aligned} \quad (6.57)$$

From these dimensions, the volume of the melt pool can be calculated to be

$$V_{\text{melt pool}} = 48 \text{ mm}^3 = 4.8 \times 10^{-8} \text{ m}^3 \quad (6.58)$$

With a density of cobalt of 8900 kg/m^3 , the mass of the melt pool is found to be [1]

$$M = \rho V_{\text{melt pool}} = 4.27 \times 10^{-4} \text{ kg} \quad (6.59)$$

Note that this approximation does not take into effect the presence of the tungsten carbide. However, to assume the melt pool is 100% cobalt will yield longer solidification times and is thus an overly conservative and acceptable approximation.

Next, we must determine the correct value for the specific heat of cobalt, c_p . This was found from tabulated values to be [2]

$$c_p = 421 \frac{\text{J}}{\text{kg K}} \quad (6.60)$$

We find the area of the melt pool from the dimensions given above to be

$$A_{\text{melt pool}} = 48 \text{ mm}^2 = 4.8 \times 10^{-5} \text{ m}^2 \quad (6.61)$$

Additionally, the Stephan–Boltzmann constant and reference temperature are given by

$$\sigma = 5.67 \times 10^{-8} \frac{\text{W}}{\text{m}^2 \text{K}^4} \quad (6.62)$$

$$T_0 = 298 \text{ K} \quad (6.63)$$

Next, we must approximate the conductivity of the powder bed. First, we locate the conductivity of cobalt metal in its basic state from tabulated values [3]

$$K_{\text{metal}} = 100 \frac{\text{W}}{\text{m K}} \quad (6.64)$$

After we have determined this value, we must modify it to account for the effect of the powder bed. We will use the following fitting equation to modify our value of the conductivity [30]

$$K_{\text{powder}} = K_{\text{metal}} (1 - nP) \quad (6.65)$$

where n = fitting parameter ≈ 2.5 and P = porosity ≈ 0.3 . Use of these values yields the following value of powder conductivity

$$K_{\text{powder}} = 25 \frac{\text{W}}{\text{m K}} \quad (6.66)$$

Next, we must approximate the L_{powder} term, which describes the distance of the thermal gradient from the melt pool out into the surrounding powder bed. At a distance of L_{powder} , the temperature of the powder has fallen to the average powder bed temperature. We will assume that L_{powder} is the same as the depth of the melt pool. From the dimensions given above,

$$L_{\text{powder}} = 4 \text{ mm} = 0.004 \text{ m} \quad (6.67)$$

The A_{powder} term, which describes the area of the powder bed through which heat can flow via conduction can be found from the dimensions given above by

$$A_{\text{powder}} = \text{Front and Back} + 2 \text{ Sides} + \text{Bottom} \quad (6.68)$$

to yield

$$A_{\text{powder}} = 80 \text{ mm}^2 = 8 \times 10^{-5} \text{ m}^2 \quad (6.69)$$

Finally, the temperature of the powder and the wall are both assumed to be at the pre-heat temperature.

$$T_{powder} = T_{wall} = 998 \text{ K} \quad (6.70)$$

This completes the development of numerical values for the various coefficients in our state equation. The last step to complete before development of our MatLab model consists of the determination of the initial conditions of our state variable. Basically, this consists of calculating the initial entropy contained in the melt pool when cooling and solidification begins.

Our process is to assume an initial temperature between the melting point and vaporization points of cobalt and then use this temperature to calculate the initial entropy, S_i . Solving Equation 6.47 for S_i yields

$$S_i = Mc_p \ln \left\{ \frac{T_i}{T_0} \right\} + S_0 \quad (6.71)$$

where we have introduced the initial temperature, T_i . Let us assume that T_i is approximately 75% of the vaporization temperature of cobalt. With a vaporization temperature of 3200 K, T_i is found to be [3]

$$T_i = 2400 \text{ K} \quad (6.72)$$

which is approximately half way between the melting and vaporization points of cobalt. Using this value in Equation 6.71 yields

$$S_i = 0.592 \frac{\text{J}}{\text{K}} \quad (6.73)$$

Note that this value is based just on the temperature change from the reference state to T_i . We must also add in another term to account for the increase in entropy of the melt pool due to the phase change from a solid to a liquid which has increased the entropy an additional amount. We will define this additional entropy term as $S_{phase \Delta}$ which is given by

$$S_{phase \Delta} = \frac{\Delta H_{melting}}{T_{melting}} M \quad (6.74)$$

where $\Delta H_{melting}$ is the latent heat of melting for cobalt. This can be found from tabulated values to be [4]

$$\Delta H_{melting} = 2.75 \times 10^5 \frac{\text{J}}{\text{kg}} \quad (6.75)$$

Using this value and the melting point of cobalt (1768 K) in Equation 6.74 yields [5]

$$S_{phase \Delta} = 6.64 \times 10^{-2} \frac{\text{J}}{\text{K}} \quad (6.76)$$

Finally, we can define a new initial entropy which includes both the entropy due to temperature over the reference state and the entropy due to phase change as

$$\begin{aligned} S_{i, total} &= S_i + S_{phase \Delta} \\ &= 0.658 \frac{\text{J}}{\text{K}} \end{aligned} \quad (6.77)$$

Now, we are ready to develop our MatLab script. First, we convert our state equation parameters into alternate terms for use in the script, as presented in the list below.

- $S_{stored} \Rightarrow y$
- $\dot{S}_{stored} \Rightarrow dy$
- $S_0 \Rightarrow So$
- $M \Rightarrow M$
- $c_p \Rightarrow Cp$
- $A_{melt pool} \Rightarrow Ameltpool$
- $\sigma \Rightarrow sigma$
- $T_0 \Rightarrow To$
- $K_{powder} \Rightarrow Kpowder$
- $L_{powder} \Rightarrow Lpowder$

- $A_{powder} \Rightarrow \text{Apowder}$
- $T_{powder} \Rightarrow \text{Tpowder}$
- $T_{wall} \Rightarrow \text{Twall}$
- $\beta \Rightarrow \text{beta}$

The script defines our state equation as a function (`solid`) which is called by an `ode45` command that is manually entered in the command window. Plotting of the resulting data is also performed via manually entered commands. First, the values of the coefficients are assigned to the corresponding terms. Next, a number of intermediate terms are defined in order to simplify the final state equation. Finally, the formal state equation completes the script (Ref. Section 6.4.2).

MatLab Script

```
function dy = solid(t,y)

% Assign coefficient values

So = 0.217;
M = 4.27e-4;
Cp = 421;
Ameltpool = 4.8e-5;
sigma = 5.67e-8;
To = 298;
Kpowder = 25;
Lpowder = 0.004;
Apowder = 8e-5;
Tpowder = 998;
Twall = 998;
```

```

% Define intermediate term
beta = (y - So) / (M * Cp);

% Define additional coefficient terms

A = -Ameltpool * sigma * (To^3);
B = (Kpowder * Apowder * Tpowder) / (Lpowder * To);
C = (Ameltpool * sigma * (Twall^4))/To;
D = (Kpowder * Apowder) / Lpowder;

% State equation

dy = A * exp(3 * beta) + (B + C) * exp(- beta) - D;

```

Execution of this model results in the following plot which indicates the decrease in entropy of the melt pool (Ref. Figure 6.11). Note that the entropy corresponding to the melting temperature of cobalt has been indicated on the plot. This is necessary because the model above is only accurate for temperatures above the melting point since the temperature and entropy of the melt pool are related. As stated previously, once the temperature drops to the melting point of cobalt, a phase change is initiated in which entropy and temperature are no longer related. The time required for the melt pool to cool to the solidification temperature can be determined from the plot. This time will be added to the time required for solidification to yield the total time for cooling and solidification. The time required for cooling to the solidification temperature is very rapid (< 1 sec) which agrees with the previous results from our literature research (Ref. Section 6.4.1).

Next, we must calculate the time required for the entropy contained in the melt pool to be removed from the melt pool so that solidification may occur. For this phase

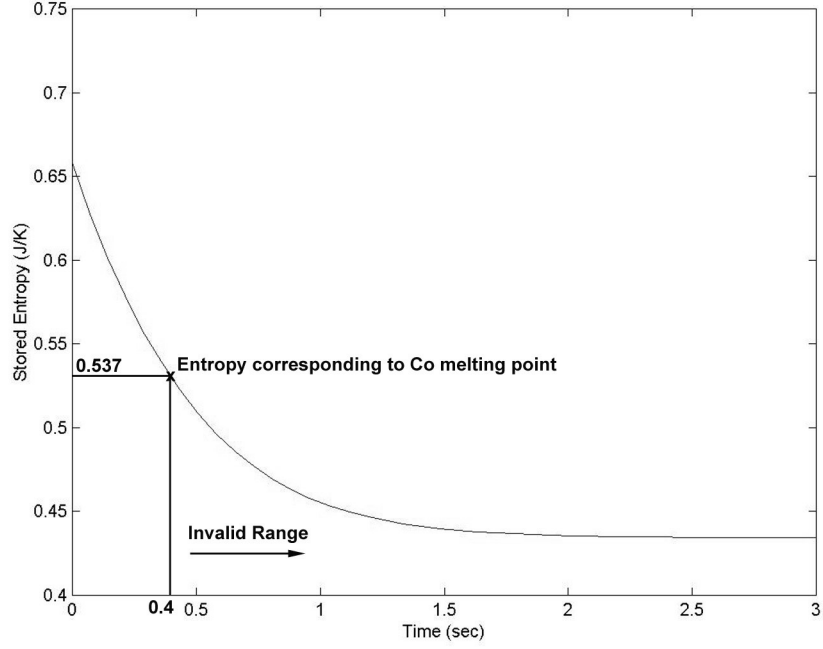


Figure 6.11: Cooling of Melt Pool: Entropy vs. Time

change, the temperature of the melt pool becomes constant and the rate at which the heat leaves the pool via the conductive and radiative modes becomes a constant. To calculate this constant rate, we can take Equation 6.52 and input our values for the coefficients determined above.

$$\begin{aligned}
 \dot{S}_{stored} &= \frac{K_{powder} A_{powder}}{L_{powder}} \left\{ \frac{T_{powder} - T_{melt}}{T_{melt}} \right\} \\
 &\quad - A_{melt\ pool} F_{melt/wall} \sigma \left\{ \frac{T_{melt}^4 - T_{wall}^4}{T_{melt}} \right\} \\
 &= 0.232 \frac{\text{J}}{\text{K s}}
 \end{aligned} \tag{6.78}$$

We have already calculated the energy stored in the melt pool due to phase change (Ref. Equation 6.76). Then, the time required for the melt pool to solidify can

be found as follows

$$\begin{aligned} t_{solidify} &= \frac{S_{phase} \Delta}{\dot{S}_{stored}} \\ &= 0.286 \text{ sec} \end{aligned} \tag{6.79}$$

Finally, the total time required for solidification including both the cooling of the melt pool to the melting point of cobalt and the solidification of the melt pool can be found to be

$$t_{total} = 0.4 + 0.286 = 0.686 \text{ sec} \tag{6.80}$$

These results indicate a cooling time of less than one second, which is considerably faster than the times predicted from the literature review. The most likely explanation is that the process used to adjust the conductivity of the powder was inaccurate, such that the conductivity of the powder bed is much lower than assumed in the model. In any case, the model does agree with the literature in that solidification times for the SLS process occur very rapidly and is orders of magnitude faster than the 20 minutes required for noticeable cobalt migration and homogenization.

Cobalt Migration Model

Finally, we will model the migration of cobalt in a cooling melt pool in order to confirm the time scales seen in the literature for this process. For the key assumption of a cooling melt pool with no laser energy input, we can assume that diffusion is the primary method of transport of the cobalt which leads to homogenization. Thus, based on this assumption, we have only one physical mode to examine for the process of cobalt homogenization. This simplified situation drives one away from the use of bond graph models for this effort. Additionally, the energy based nature of bond graph modeling does not necessarily lend itself to the modeling of mass flows via a diffusion transport mode.

Therefore, the modeling of cobalt migration will be limited to the solution of Fick's second law which will provide an assessment of how the concentration of cobalt

will change with respect to time and distance along the functional gradient.

We see from Fick's second law that the concentration is a function of time and distance which fulfills the following partial differential equation

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x} \left\{ D \frac{\partial C}{\partial x} \right\} \quad (6.81)$$

We will use the classical solution for this equation with the assumption of a semi-infinite solid. While this solution is not completely representative of our physical problem, all of the necessary assumptions are conservative; that is, they would tend to produce higher diffusion rates than would be experienced in our case. Thus, diffusion times with the semi-infinite solid assumption will always be shorter when compared to our case. If diffusion times are found to be of the same time scales as those observed in the literature for homogenization, we can be assured that the time scales for our specific problem will be of the same magnitude if not greater.

This observation allows us to use the classical solution for diffusion and avoid the complexities associated with a numerical solution of Equation 6.81. The first assumption necessary for the use of the classical solution is a semi-infinite solid with a surface concentration held at a constant value. This assumption will generate higher diffusion rates and shorter diffusion times than our case since the semi-infinite solid assumes that the far end (at infinity) will never be reached by any of the diffusing cobalt so that it acts as a sink. In our case, the region of low concentrations of cobalt will increase in concentration to reach the homogenization concentration value. As the this concentration value increases, the rate of diffusion will tend to slow as the homogenization value is approached.

Likewise, the assumption of a constant surface concentration will act as a source and supply a never-ending supply of cobalt at a consistently high potential. For our case, the region of high cobalt concentration will decrease as homogenization proceeds, thus the high potential will decrease and the rate of diffusion will again slow as homogenization is approached.

The second assumption necessary to use the classical solution requires an initial,

constant (with respect to x) concentration (C_0) at $t = 0$. We will chose this initial concentration to be the low value of cobalt concentration used in our single layer experiment, which is approximately 12% cobalt. Similarly, we will use the high value of our cobalt concentration (100% cobalt) as our constant (with respect to time) surface concentration. These assumptions will create a large, discrete change in concentration at the high concentration boundary condition. This assumption will also tend to produce higher diffusion rates with a large sudden change in concentration versus the blended concentration gradient present in our actual problem.

These assumptions then lead to the following boundary conditions necessary for the application and use of the classical solution to be presented later. Note that with these boundary conditions, the distance variable, x , is defined as zero at the high concentration boundary condition and increases toward the far end of the solid.

$$\begin{aligned} \text{For } t = 0, C &= C_0 \text{ at } 0 \leq x \leq \infty \\ \text{For } t > 0, C &= C_s \text{ at } x = 0 \\ C &= C_0 \text{ at } x = \infty \end{aligned} \tag{6.82}$$

These boundary conditions and the assumptions described above lead to the following solution for the diffusion equation (Ref. Equation 6.81).

$$C_x = \{C_s - C_0\} \left\{ 1 - \operatorname{erf} \left\{ \frac{x}{2\sqrt{Dt}} \right\} \right\} + C_0 \tag{6.83}$$

where

- $C_0 \equiv$ Initial concentration at $t = 0$.
- $C_s \equiv$ Concentration at surface (high concentration boundary condition)
- $C_x \equiv$ Concentration at distance x and time t .
- $\operatorname{erf} \equiv$ Gaussian error function.
- $D \equiv$ Diffusion coefficient

Using this equation, we can determine how the concentration of the cobalt varies as a function of time and distance along the gradient. Additionally, we can also set a value of distance, x , that is relevant to our problem and then observe how the cobalt concentration at this distance varies as a function of time. Based on these observations, we can determine the time required for cobalt homogenization and compare to the time scales observed in literature.

However, we need to more properly define the diffusion coefficient, D . First, we must account for reduction in effective diffusion paths due to the presence of the tungsten carbide particles. This effect on diffusion coefficient is accounted for by a tortousity scaling factor.

$$D = \tau D_0 \quad (6.84)$$

where D_0 is the diffusion coefficient through the bulk material and τ is the tortousity coefficient. The tortousity is formally defined as

$$\tau = \left[\frac{L_e}{L} \right] \quad (6.85)$$

where L is the straight-line path used by diffusion and L_e is the effective diffusion path length. The tortousity is always less then one and usually varies between 0.5 and 0.7 [6].

Next, we can determine the bulk diffusion coefficient, D_0 , as a function of the activation energy for diffusion and the temperature [58].

$$D_0 = D_{00} \exp \left\{ \frac{-Q_d}{RT} \right\} \quad (6.86)$$

where

- $D_{00} \equiv$ Temperature independent diffusion coefficient
- $Q_d \equiv$ Activation energy for diffusion
- $R \equiv$ Gas constant
- $T \equiv$ Temperature at which diffusion occurs

Finally, we can use the following simple rule to calculate the activation energy [11].

$$Q_d = 140T_{melting} \quad (6.87)$$

where $T_{melting}$ is the melting point of cobalt.

Next, we must determine the coefficients to be used in the equations described above. First, as described above, we will choose the values of the surface cobalt concentration, C_s , and initial uniform cobalt concentration, C_0 , to be

$$\begin{aligned} C_s &= 1.0 \\ C_0 &= 0.12 \end{aligned} \quad (6.88)$$

We will choose the tortousity to be

$$\tau = 0.5 \quad (6.89)$$

The temperature independent diffusion coefficient, D_{00} , was found to be [22]

$$D_{00} = 1.5x10^{-4} \frac{\text{m}^2}{\text{s}} \quad (6.90)$$

We can find the activation energy with a melting point of cobalt of 1768 K to be

$$Q_d = 2.475x10^5 \frac{\text{J}}{\text{mol}} \quad (6.91)$$

The gas constant is defined as

$$R = 8.31 \frac{\text{J}}{\text{mol K}} \quad (6.92)$$

Finally, we will choose the temperature at which diffusion occurs as the initial temperature used for the solidification model above. The actual temperature at which diffusion occurs will actually decrease the melt pool cools. However, we will assume a conservative case and choose the highest value for the temperature which will tend to cause higher predicted diffusion rates.

$$T = 2400 \text{ K} \quad (6.93)$$

Use of these values in Equation 6.86 yields the following value.

$$D_0 = 6.118x10^{-10} \frac{\text{m}^2}{\text{s}} \quad (6.94)$$

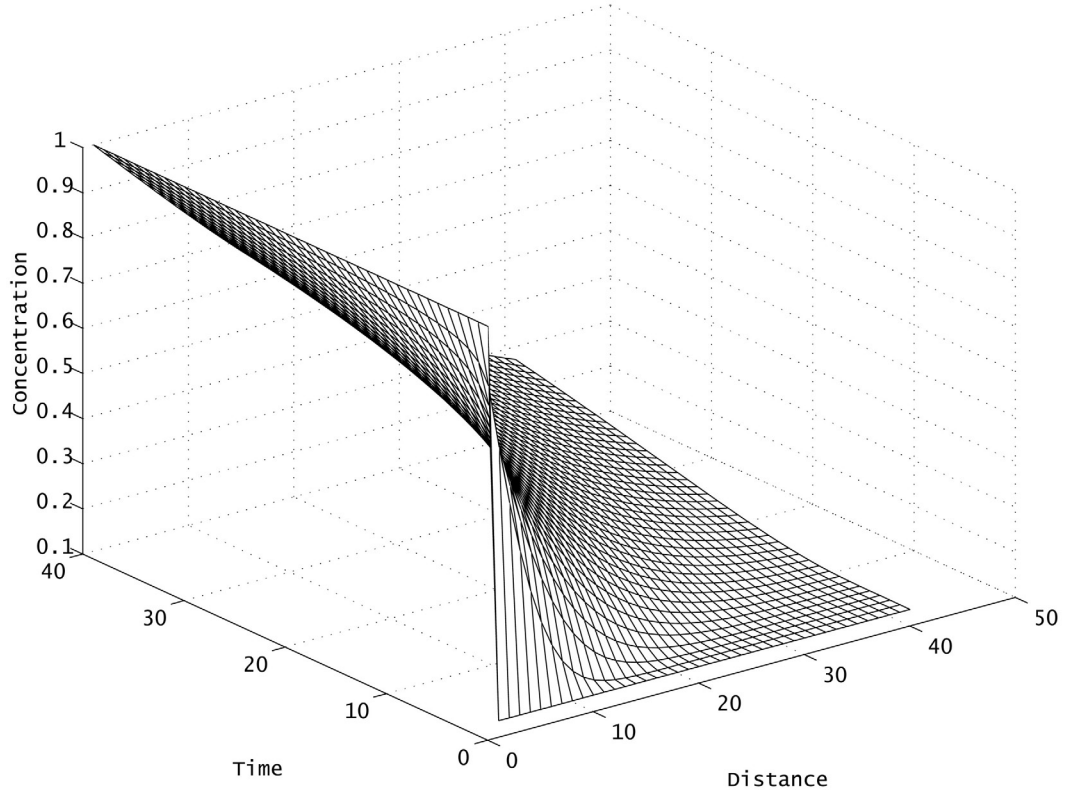


Figure 6.12: Cobalt Concentration as a Function of Time and Distance

The final value of the diffusion coefficient can be found using the value above with our chosen tortousity in Equation 6.85 to yield

$$D = 3.059 \times 10^{-10} \frac{\text{m}^2}{\text{s}} \quad (6.95)$$

This value of D is then used in Equation 6.83 to determine C_x as a function of time and distance. The resulting surface was plotted to show the decay of cobalt concentration with distance and time (Ref. Figure 6.12). We are specifically interested in the change with respect to time of the cobalt concentration at a distance equivalent to the width of the melt pool. To examine this specific distance, we set $x = 0.004$ m and then plot the change in concentration as a function of time (Ref. Figure 6.13).

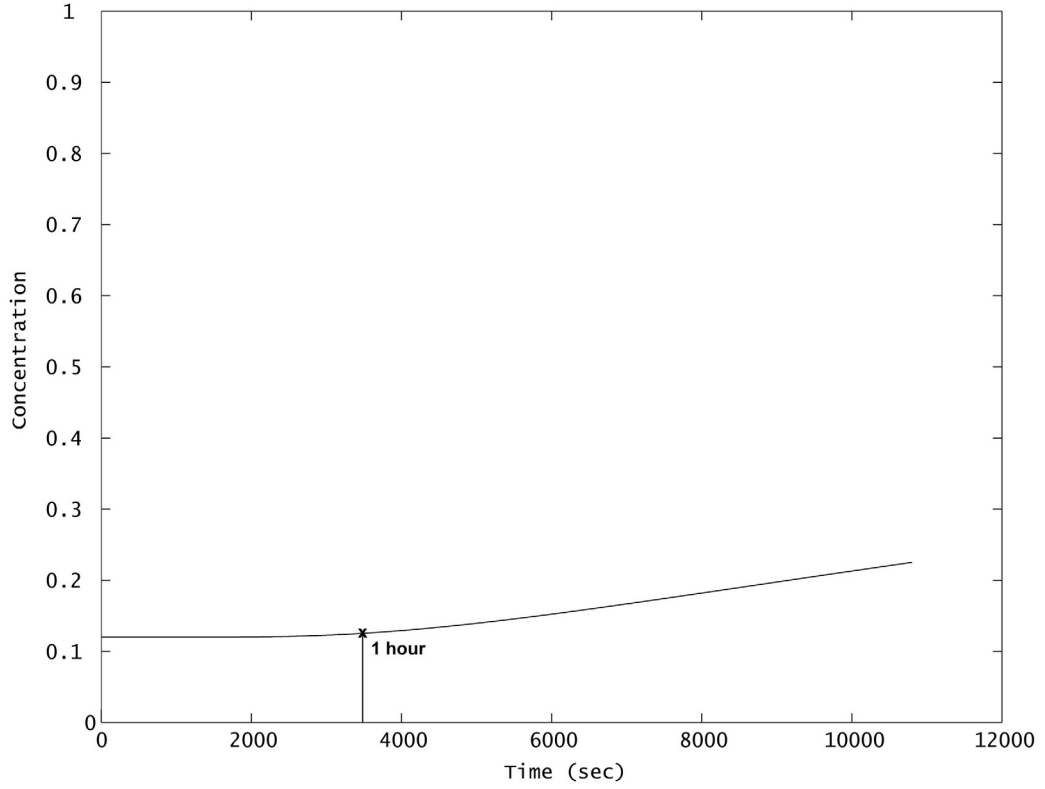


Figure 6.13: Cobalt Concentration as a Function of Time at $x = 0.004$ m

Based on Figure 6.13, we can see that the concentration changes very slowly with time. After 1 hour, the concentration has only increased from 0.12 to approximately 0.15. Homogenization of the melt pool would require the concentration to rise to approximately 0.5. An examination of Figure 6.13, this would require several hours of diffusion to occur. The literature presented previously predicts homogenization in approximately 20 minutes. Therefore, our model predicts slower diffusion times than in the published literature.

Our model assumes that all mixing occurs as a result of diffusion and does not consider other causal factors of mixing, including bulk flow of the liquid. Fluid flow could be driven in the melt pool due to convective (or buoyancy) forces generated by

the large thermal gradients present in the cooling melt pool. It is most likely that the slower diffusion times predicted by our model is due to the lack of consideration of this effect in the model development.

In any case, both the model and the literature predict the cobalt migration process to occur on a minutes to hours time scale. Given the fact that the solidification literature and model are also in agreement with a solidification process time scale of seconds, it is apparent that cobalt migration and loss of functional gradients is not seen as a significant processing issue in the future development and use of FGMs in SLS.

Chapter 7

Conclusions and Recommendations for Future Work

7.1 Conclusions

We have observed that the functional requirements of a given component are dependent upon the spatial location in or on the surface of the component. In order to fulfill these functional requirements, the material properties arising from the material composition must be properly chosen. Thus, we arrive at an abstract problem statement: *How to control the spatial variation of material properties in a component to match the corresponding spatial variation in functional requirements?* The traditional solution to this problem for components with conflicting functional requirements has been the separation of the component into two mating components and then the use of various bonding techniques to connect the two components. The various problems with the traditional techniques have been presented and multiple material Rapid Prototyping processes have been identified as having the potential to overcome these difficulties and solve the abstract problem statement.

An extension of SLS to include multiple materials, Multiple Material Selective Laser Sintering (M²SLS) was identified as the specific RP technology to develop as a potential solution for our problem. Additionally, Functionally Gradient Materials (FGMs) fabricated by the M²SLS process represents an example of the functionally optimized component of interest. A tungsten carbide / cobalt drill bit insert component from the petroleum drilling field has been identified as a specific industrial component to narrow the scope of the design process. Thus, we arrive at a hypothesis of our more specific problem statement: *The desired matching of material properties to functional requirements may be achieved by the fabrication of drill bit inserts containing functional gradients with the Multi-Material Selective Laser Sintering (M²SLS) process.*

Next, additional background information was collected and presented to more fully understand the state of the art in the fabrication of FGM components with various technologies. First, a brief history of the development of SLS was presented for those readers unfamiliar with this technology. Then, a review of recent developments in the general fabrication of FGMs was presented which revealed a strong bias toward recent research developments in Japan and Europe. Recent developments regarding the potential application of newly developed RP technologies was also presented. Finally, a review of proposed ideas for the use of material gradients in WC / Co drill bit inserts indicates a long standing recognition of the need for functional grading in these components.

A series of feasibility experiments were conducted to gain further insight into physical processes underlying the laser sintering of material gradients, generate design knowledge for the development of the M²SLS process, and prove the feasibility of the proposed hypothesis. A number of alternative methods for the manual fabrication of FGMs were presented. Of these methods, two were chosen for further investigation. Next, the fabrication procedure used to create a number of single layer samples was presented with the corresponding parameters chosen for the fabrication runs and the nature of the FGM which was manually developed for the samples. Similarly, the

fabrication procedure for a corresponding set of experiments for multiple layer samples was also presented. A brief description of the workstation used for these runs and associated workstation parameters were also presented. Following the fabrication runs, a microstructural analysis of the resulting samples was performed. A simple visual examination of the results indicates the presence of an FGM of WC content.

Next, image analysis techniques were described which allowed an empirical determination of the relative change in material composition along the FGM in the fabricated samples. Microhardness values were measured at different locations along the FGM to determine the nature of the gradient of material properties. The resulting material property data was then presented in graphical form and various conclusions were drawn regarding the sintering behavior and part quality due to changes in scanning speed and FGM / scan vector relative orientations.

Following the completion of the feasibility experiments, design and development of the M²SLS workstation was initiated. First, system level design was performed to determine the general functional capabilities of the system based on the nature of the FGM to fabricate. Due to cost and timing constraints, initial system design focused on the development of a workstation capable of fabricating a 1-D FGM in the vertical direction. Powder storage and mixing are the primary distinguishing characteristics of this system from traditional SLS, thus, the design and development of this subsystem was performed off-line from the rest of the machine development. A series of conceptual designs were developed, followed by the selection and fabrication of a simple alpha prototype. Following simple testing of this system, a fully functional powder delivery subsystem was developed and then tested for functional performance. Results for repeatability, uniformity, and accuracy were found to be within acceptable limits.

The first significant subsystem developed for the primary workstation was the laser scanning system. A 0.5 kW CO₂ laser was donated and installed in a lab which was selected for future development of the M²SLS workstation. A description of this hardware and associated principles of operation are presented including the cooling,

electrical, and gas subsystems. The two primary operating modes of the laser are presented which consists of raw and recycled gas modes. Laser operator controls are also presented with suggested start-up procedures.

Next, the various optical components along the beam path are also presented, including the laser table and frame used as basis for the overall machine design. A series of steering mirrors are used to direct the beam down the length of the table where collimating and focusing hardware are used to direct the beam into the laser scanning heads. Some simple formulas used to specify this hardware based on desired operating spot size are also presented. Next, a description of the laser scanning head and associated controller are presented with basic operating principles. File conversion software developed to properly format part build files are also provided. Lastly, a concise operating procedure for these subsystems is presented to aid future users of the system.

The next major assembly presented consists of the powder plate, part cylinder, and accompanying actuator hardware. The various components, their dimensions, and fabrication process are presented for this subassembly. Additionally, an actuator was selected to drive the part piston based on developed specifications. An accompanying controller was also selected and then used as the basis for the development of a Labview virtual instrument which allows control of the actuator from the dedicated PC. The design and development of a counter-rotating powder roller subassembly is also presented. An appropriate actuator-rail system was selected and purchased to translate the roller and stabilize the end of the powder roller head at the end of its stroke. A dedicated PC was selected and installed with the other control hardware in a large electronic cabinet to centralize the electronic and control hardware of the system.

Finally, a simple shield gas box was developed to assist in the pooling of the gas for improved processing atmosphere. This box was also used as a structural support for the integration of the powder delivery subsystem into the overall M²SLS workstation hardware. The development and fabrication of this box is presented, along with the process used to integrate the powder delivery hardware. The mounting of this hard-

ware required some minor modifications to the frame of the overall system, followed by the fabrication and installation of powder flow chutes to transfer the powder from the hopper to the mixing impeller. A simple bottle of shield gas and nozzle fixture was also fabricated to allow the introduction of shield gas into the enclosure.

The processing atmosphere used during sintering strongly effects the resulting part quality, as evidenced by previous work with traditional SLS. A number of different atmospheric processing hardware variants are presented with accompanying considerations of cost and timing. Some simple tests were performed with different atmospheres to experimentally examine the effects of processing atmosphere on part quality. The results of these tests, with the financial constraints of the project, were used as the basis for the selection of the appropriate design variant and determination of the nature of the future development of the workstation.

During the off-line development of the powder delivery subsystem, the performance of this system was empirically measured. However, following the integration of this system, it was desired to determine the effect of the roller transfer of the powder on the given composition of the powder deposited by the mixing chamber. A series of samples were collected from the powder bed and from a location near the powder deposition site. Digital images of the resulting samples were then collected and examined to determine the ratio of the two constituent materials. An analysis of the results are presented with accompanying graphs of the data. Conclusions were drawn from this data which indicate that the experimental noise introduced by the roller transfer is less significant than that introduced by the powder mixing system and thus does not increase the variability in the mixture composition introduced to the powder bed.

Following the completion of the workstation, some very simple, initial efforts were conducted to fabricate sample components. Given the limited nature of the thermal and atmospheric processing subsystems, poor part quality was expected. First, parts were fabricated in air and the details of this fabrication process are presented. A number of observations are presented, including the primary conclusion that, as ex-

pected, attempts to fabricate components lead to large levels of oxidation and very poor part quality. Next, sintering was conducted under a shield gas atmosphere to fully test the workstation and determine the extent of part quality improvement due to the shield gas system. Some minor improvements in part quality were observed, but overall part quality still remained very poor.

7.2 Originality and Contributions

I have extended the basic SLS process to include the processing of multiple material components. Specifically, I have developed a fabrication process to allow the development of components containing functional gradients for the matching of desired material properties to functional requirements.

7.2.1 Fabrication of First FGM Components with SLS

The fabrication of the samples resulting from the previously described feasibility experiments represent, to the best of my knowledge, the first and only FGM samples created with the traditional SLS process. Thus, this part of this work represents a unique investigation into the behavior of FGMs during a laser sintering process. As an initial investigation of the fabrication of FGMs via SLS processing, these initial experiments open the door to further investigations of this field and represent a new method of fabricating FGM components.

7.2.2 Demonstration of Control of Material Properties

The testing of the feasibility study samples reveals the material properties of the sample have been controlled via a control of the material composition of the sample. As such, this work represents an attempt to control the material properties of an SLS produced sample via control of material composition. This pioneering investigation demonstrates and validates the potential of SLS to produce unique components in which the material

properties are controlled to vary over the surface and inner volumes of the component. Additionally, this work indicates that the basic physical process of laser sintering underlying SLS allows the control of the spatial variation of material properties.

7.2.3 Development of a M²SLS Workstation

My work in the design and development of the M²SLS workstation is a physical embodiment of a significant enhancement of the current SLS process. Through this work, the new M²SLS process possesses a significantly enhanced ability to fabricate components consisting of multiple materials, a functional ability beyond the traditional SLS process. As a result of first initial steps, new and unique components may now be fabricated from the SLS process which was not possible before my efforts. This work has opened up a large field of new and unique research possibilities within the field of selective laser sintering which were not present before my work. With further development work from this initial beginning, entirely new components may be possible from the SLS process, components which are currently very difficult to fabricate with existing technologies.

7.3 Recommendations for Future Work

7.3.1 Fabrication and Testing of Components

The first step is to more fully understand the operation of the current embodiment of the M²SLS workstation from an empirical approach. This would be performed by the development and execution of a full Design of Experiments (DOE) in which the various operating parameters, including processing atmosphere, of the workstation would be empirically related to final part quality. In order to effectively measure final part quality, an efficient process to examine the gradients of material composition needs to be developed. Additional, one or two relevant material properties of interest must be selected and corresponding methods of measuring the variation of these properties also needs to be developed. These methods would then be used to measure the resulting

fabricated components for gradients of material composition and material properties. Finally, fabricated drill bit inserts would be functionally tested in conditions similar to those experienced in service in order to quantify any improvements in the functional performance of the drill bit inserts.

7.3.2 Integrated LabView Driven Control System

In order to enhance the sophistication and ease of use of the workstation, a master control program needs to be developed which allows the user to control all of the hardware systems of the workstation from the PC. The Labview programming environment is recommended for this effort due to compatibility with existing control software, ease of development, and the ability to develop simple and easy to use virtual instruments for interaction with the user. Additionally, a more sophisticated control software would also allow the workstation to operate in a more automated mode so that constant observation of the machine would be reduced.

7.3.3 Design Decision for Next Level of Atmospheric Control

One of the primary recommendations regards the further development of the atmospheric control subsystem beyond the current primitive shield gas system. A more detailed timing and financial analysis of the three subsystem design variants needs to be performed. Some additional testing regarding the impact of processing atmosphere upon part quality may be performed, however, this relationship is well understood due to previous work on the direct sintering of metals [16]. Finally, the financial and timing constraints for the future development of the workstation must be determined and additional efforts expended to secure additional funding if the constraints are found to be excessive. Finally, this information must be summarized and then used as the basis for a design decision regarding the future development of this subsystem. Based on the preliminary examination of this subject in this work, a gradual development of the processing atmosphere is recommended (Ref. Section 5.1.1).

7.3.4 Design and Development of Improved Atmospheric Control

Following the selection of the correct design variant, the enhanced processing chamber must be designed and then fabricated. Other necessary hardware must be specified and purchased. Following delivery and fabrication of all necessary components, an assembly and testing phase must be completed. This design and development process must also correlate with other subsystem functionality so that the full functionality of the entire system is not degraded. This process may require the redesign and/or alteration of other workstation subsystems.

7.3.5 Space Optimized Design of Powder Delivery Subsystem

As a part of this process, it is recommended that the current powder delivery subsystem be redesigned with the specific design goal of a significant reduction in the size of this hardware. The current design variants under consideration for the atmosphere processing subsystem all have a direct and strong relationship between financial cost and interior volume. Thus, a design effort to reduce the space occupied by the powder delivery subsystem will reduce the implementation cost for all design variants and provide enhanced processing capabilities within the financial constraints. Following the redesign, fabrication of the new powder delivery hardware would be performed, followed by installation into the workstation. Note that this process must be tied closely to any ongoing design efforts to alter the processing enclosure.

7.3.6 Develop Ability to Grade within a Given Layer: 3D FGM

The other major functional improvement recommended for the workstation is an enhancement of the process and hardware to allow the automated graded of material composition within one layer. This functional ability, when coupled with the current system, would allow the fabrication of a fully three dimensional material gradient. This recommended work would require a complete redesign of the current powder delivery system. The current system could serve as a potential design variant, however, it is rec-

ommended that a full conceptual design of the powder delivery subsystem be performed. Following the conceptual design, the traditional development process would be followed consisting of detail design, fabrication, installation and assembly, and functional testing. As before, this modification must function with the currently existing subsystems to prevent redundancies in the design process. Another significant area of expected effort in this modification is the development of more advanced control methods to allow the precise deposition of powder necessary to develop an intra-layer material gradient.

7.3.7 Robust Linkage between Computer Model and Control System

Lastly, more advanced computer software at the machine level should be developed to allow the rapid and efficient conversion of current and developing multiple material computer models into specific machine commands used to drive the various hardware systems in the workstation [46]. This software should be able to process a number of different models and should also allow a minimal number of simple operations to the model to allow the resolution of final build issues.

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This dissertation was typeset with L^AT_EX 2_ε¹ by the author.

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