

INVESTIGATING FEATURE FORMATION BY THERMOPLASTIC FORMING OF
ZIRCONIUM BASED BULK METALLIC GLASS ON STAINLESS STEEL MOLDS

By

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LIST OF ABBREVIATIONS

BMG	Bulk metallic glass
SEM	Scanning electron microscope
XRD	X-Ray diffractometer

Abstract of Thesis Presented to the Graduate School
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A relatively new material, bulk metallic glass is an amorphous metal that has mechanical properties that surpass aluminum and steel alloys. These enhanced properties allow this material to be considered in many applications ranging from microelectromechanical systems (MEMS) to structural uses, to electronics. Because of the ability to be thermoplastically formed, metallic glasses can be molded into complex shapes that conventional metals cannot achieve. The limiting factors for production for metallic glasses at this time include their cost and the ease of forming large shapes all while keeping a completely amorphous structure.

This thesis focuses on the formation of features on the order of 200 μ m that were machined into a stainless steel mold. A total of three zirconium based metallic glass alloys were chosen and their ability to form small intricate features on stainless steel molds during molding was evaluated. A load frame fitted with heaters was utilized to enable the thermoplastic forming of metallic glass alloys in a laboratory setting. The reactivity between the metallic glass and the mold as well as the atmosphere is observed and evaluated. Along with this, the alloys require a relatively high cooling rate to achieve their vitreous nature. To determine crystallinity, an X-ray diffractometer was

used and a scanning electron microscope (SEM) was utilized to examine the formed features. The molds were examined with an SEM to analyze the wear associated with the molding of the alloys.

CHAPTER 1 INTRODUCTION

Background on Metallic Glass

History

The concept behind metallic glasses began in the 1950s when an idea was devised through thermodynamics and kinetics that if a molten metal or metallic alloy is cooled quickly from a liquid, the amorphous structure that was present in the liquid would remain since the alloy would not have sufficient time to crystallize [22]. It was suggested that an alloy, consisting of metals with different crystal structures, would aid in slowing down the kinetics to stay amorphous upon rapid quenching from a liquid. It was theorized that since there would be no crystalline structure, there would be no slip planes or dislocations. This would increase the strength of the alloy and would warrant it to be used in structural applications. In 1960, Duwez created the first metallic glass by quenching a Au-Si liquid alloy to form an amorphous solid [1]. Following this discovery, lead based ternary alloys were produced to allow for the liquid alloy to be cooled slower but still achieve an amorphous structure [1]. By adding metals with different crystal structures, melting temperatures and atomic sizes, the kinetics of the liquid are slowed down enough to allow for the production of a metallic glass when cooled at a fast enough rate. These alloying additions create a lower temperature eutectic point for the system, suppressing the melting temperature [1]. During this research, the discovery of a glass transition temperature was made in these alloys [2]. Further research was performed in the following decades that resulted with easy to form metallic glasses and the realization that they could have far reaching engineering implications. In the 1990s, Peker and Johnson created a quinary alloy, Vitreloy 1, which

consists of Zr-Ti-Cu-Ni-Be, which could be cast several centimeters in thickness, which lead to the term bulk metallic glass [3]. The dimensions of bulk metallic glass can be increased by either increasing the cooling rate or by slowing the kinetics, since both resisting crystallization. Continuing research has led to alloys with increasing critical casting thicknesses because of a decreased critical cooling rate to lock in the amorphous structure, furthering their applications [4].

The first techniques to create metallic glass produced samples that had minimal use for structural parts. Atomization was one of these processes. Atomization involved melting an alloy and forcing the melt through a nozzle that separated the liquid stream into small droplets, almost like a mist [21]. These droplets would spray into a chilled atmosphere and would cool quickly enough to stay amorphous. What is left is a powder of fine metallic glass particle. Another technique is splat forming [21]. This involved imparting a liquid drop of alloy onto a chilled copper plate. The drop would “splat” onto the plate and cool quickly, leading to a metallic glass flake [21]. One other way was called melt spinning. A chilled copper wheel was spun around and liquid metal was poured onto the wheel [21]. The liquid would cool quickly and exit off of the wheel as a thin sheet [21].

Values of BMG in Production

Metallic glasses can be thermoplastically formed just like a polymer. If heated to a certain temperature, they will become viscous and will flow under a load, allowing them to be pressed into a mold with a desired shape. The viscosity of the liquid is temperature dependant and can vary by orders of magnitude when heated [7].

Essentially, metallic glasses are supercooled liquids, leading to this property.

Thermoplastic molding may be able to cut down on start-up costs for a company looking

to use metallic glasses for their part [7]. This process is inhibited by the cooling rates necessary to resist crystallization and a proper cooling system will be necessary to reach the critical cooling rates necessary. The cast parts can also contain defects caused by the high velocity flow of the material into the mold cavities [5].

Another benefit is the ability to obtain net shape forming and good surface finishes on these alloys [6]. The lack of a phase transformation from a liquid to a solid results in no change in volume associated with the transformation [22]. The amorphous qualities of the metallic glass lead to thermal expansion coefficient of less than 0.5% [7]. This means that when molding a piece, it will retain its dimensions after the cooling process. Little to no secondary machining would be needed to achieve proper dimensional tolerances on the molded part [7]. Metallic glasses are known to replicate a molding surface very well. They are able to replicate micrometer and nanometer features. If the molding surface is highly polished then the molded piece will be as well. Even the smallest machine marks can be reproduced so care has to be involved to make the molds properly. This quality of metallic glass also allows less secondary processing to improve the surface finish after molding since the mold dictates the surface finish.

Many mechanical properties of metallic glasses are superior to that of common commercial metals such as steel and nickel. Metallic glasses exhibit an increased tensile strength, ultimate tensile strength, hardness and a higher elastic limit [8]. Many of these improved properties arise from the fact that in the amorphous structure, dislocations do not form in addition to this, there is no slip plane so shear of the material is inhibited, leading to increased mechanical properties [9]. These enhanced properties make metallic glass a good choice for a part that has a load applied to it. These alloys

also possess increased resistance to corrosion and are electrically conductive [7,10].

Many of the alloys contain elements, including beryllium that are oxygen getters and this leads to a resistance to oxidize at elevated temperatures [11]. Beryllium is toxic when in a powder form so it must be decided if alloys containing this element can be used.

Challenges in Production

During molding, the alloy is subjected to elevated temperatures, which can cause corrosion. The titanium in many alloys is insufficient to prevent corrosion by itself and it needs to be with another oxygen getter to provide enough protection [11]. To prevent oxidation in non-beryllium containing alloys, a controlled atmosphere must be involved. This can be achieved by placing a chamber around the molding apparatus and backfilling this space with an inert gas such as argon. This would eliminate the problem of oxidation in the non-beryllium containing alloys. In a production process, the use of a controlled atmosphere can reduce the efficiency of the process. Each molding attempt would require a backfilling of argon and a subsequent removal of argon to extract the part from the mold and set up a new molding attempt. This would slow the system down and will increase the cost to produce the parts. Another reason to use a controlled atmosphere is because as the concentration of dissolved oxygen increases in the alloy, the amount of time to process before crystallization occurs decreases because of the increased propensity for nucleation, leading to crystallization. [12]. With a controlled atmosphere, more time can be taken to mold and cool the part than if the process was performed in regular atmosphere conditions.

Metallic glass alloys need to be cooled quickly from their molding temperature in order to achieve an amorphous structure. Each alloy has a critical cooling necessary to keep its amorphous nature [7]. Cooling systems in the molding system can be

implemented to reduce the heat right after molding to ensure that the critical cooling rate is achieved.

Mold compatibility with the alloy poses a problem for processing as well. Reactions between the mold and the alloy can lead to problems that will make the molded part useless. Crystallization can occur, usually on the mold surfaces first, in the alloy when it is held too long at the molding temperature. Making all surfaces of the mold smooth and polished can minimize this problem. At molding temperatures, diffusion in the alloy and mold can lead to diffusion bonding between the parts, ultimately fusing them together. Diffusion of elements from the mold into the metallic glass can also lead to compositional changes in the metallic glass. This would ultimately change the properties of the alloy in the diffusion layer and could also cause crystallization. This crystallization can lead to permanent mold deformation and a rejection of the molded part. To prevent this, tests must be performed to confirm that in a production process, there will be no reaction between the mold and the metallic glass that would compromise either the part or the mold.

Problems Associated with Crystallinity

Crystallinity in this alloy is unwanted and adversely affects the properties that are associated with metallic glasses. A significant degree of crystallinity prior to molding will result in a failed molding attempt since the alloy will not become viscous when subjected to an elevated temperature. When unable to flow, damage to the mold will occur when a load is applied. This introduces a problem for the surface finish of a molded piece. Metallic glass can replicate a surface very well when molded and the presence of crystallization on the surface inhibits this property and causes a dull finish on the molded piece. The different crystallographic grains on the surface reflecting light

differently cause this dull finish. When the crystalline nature is produced after or during molding, the mechanical, electrical and corrosion properties that are desired in the alloy no longer exist.

The formation of a crystalline structure forms in the alloy when three things happen either individually or together. The first is when the alloy is heated to above its crystallization temperature. This temperature is determined using a DSC and can be avoided during molding [14,15]. Above the crystallization temperature, the kinetics of the alloy are fast enough to enable nucleation and growth of crystals upon cooling [16]. The second way is to cool the alloy at a slower rate than the critical cooling rate. A slow rate will allow atomic movements and will result in nucleation of crystals. A slow cooling rate is an issue during the drop molding process of the alloy. The drop mold and hearth are two separate pieces and do not form a good contact to one another. This results in a poor heat transfer between the two pieces. When the molten alloy drops into the mold, the cooling rate is thus reduced and can be slow enough to cause crystallization in parts of the alloy, usually towards the top of the drop mold where the most heat is contained. Each alloy of metallic glass has different crystallization temperatures and critical cooling rates. To avoid crystallization of the alloy, this temperature must not be exceeded. The third way to cause crystallinity in these alloys is to allow oxygen into the composition. This can occur if the metal is at an elevated temperature in ambient atmosphere, which occurs during molding. The higher the concentration of oxygen, the less time available to work and mold the metal before crystallization occurs. The presence of oxygen at high temperatures can lead to oxidation of the piece. Oxidation ruins the surface finish and thus makes the use of metallic glass less desirable.

The choice of alloy is important since oxygen can be absorbed into the alloy at high temperatures. Some metallic glass alloys contain beryllium, which helps to reduce this problem. Beryllium is an oxygen getter so when the alloy is subjected to elevated temperature, the oxygen will preferentially be attracted to the beryllium and will prevent a shortened processing time as well as surface corrosion. Unfortunately, beryllium is a toxic material so it is undesirable to choose a beryllium containing alloy for use in a product that would be used by people. Most beryllium containing alloys have a lower critical cooling rate than an alloy deficient of beryllium. Because of this, keeping an alloy amorphous after molding is more difficult and requires the use of a quench tank rather than a platen cooling system that is attached to the load frame. In a mass production based operation, this issue would need to be addressed with a better system to cool the alloy post-molding.

Motivation

This research will focus on forming features approximately 200 μm in size in two beryllium containing alloys and one non-beryllium containing alloy and investigating whether molding and demolding can be achieved with a stainless steel mold for production processes. The features machined in the mold will be measured after each molding attempt to record deviations in dimensions. Reactions of the alloys, during molding, with the mold and the atmosphere will be also evaluated to determine if they affect the molding process.

CHAPTER 2 PROCEDURES

Alloys Used

Three zirconium based alloys were chosen for the molding of bulk features. The alloys were chosen based on their mechanical properties as well as on the critical cooling rates and crystallization temperature. The alloys were Vit 1 ($Zr_{41.2}Be_{22.5}Ti_{13.8}Cu_{12.5}Ni_{10}$), Vit DH ($Zr_{35}Ti_{30}Be_{27.5}Cu_{7.5}$) and Vit 106a ($Zr_{58.5}Cu_{15.6}Ni_{12.8}Al_{10.3}Nb_{2.8}$) [7,23]. In order to keep an amorphous structure in the these alloys, the part must be rapidly cooled from the liquid at a rate from $1^{\circ}C$ to $10^{\circ}C$ per second, deemed the critical cooling rate. The critical cooling rates of these alloys are low enough so that an amorphous structure can be obtained simply by quenching in water directly after molding.

Preparation of the Alloy

Arc Melting and Creating the Alloy

The alloys were obtained and produced from outside sources. Each alloy was created from high purity powders to reduce impurities. A bell jar arc furnace was used to melt the powders. The chamber of the arc melter was backfilled with argon to minimize the amount of oxygen present prior to melting the alloy. A titanium getter was struck with an arc and melted prior to melting the alloy to remove any residual oxygen in the chamber that would compromise the alloy. A copper water chilled hearth was used to cool the molten alloy as quickly as possible to prevent crystallization. The final alloy was in the shape of a small button that is a result of the hemispheres machined into the hearth to allow the pooling and consolidation of the melt.

Creating the Proper Dimensions

A low speed diamond saw was used to section the arc melted button of metallic glass into 3.5 to 5.5 g pieces. A copper drop mold, Figure 2-1, has a channel for casting to fit that amount of material in the mold.



Figure 2-1. Copper drop mold containing a casted piece of metallic glass [7]

Two drop molds were used to melt the alloy into the desired shape. The first drop mold had the melted alloy sitting above the water chilled hearth, separated by the drop molds copper lining about 5 mm thick as seen in Figure 2-1 above. The second drop mold had a through cut that allowed the melted alloy to directly touch the hearth during cooling. The second drop mold was created for Vit 106a, which required a faster cooling rate to ensure an amorphous structure. Similar to before, the chamber of the arc melter was backfilled with argon 3 times and a titanium getter was used to ensure the oxygen concentration in the chamber was minimal. To ensure a high rate of cooling, the copper water chilled hearth was used.

Steel Mold and the Load Frame

Steel Mold

The material chosen for the mold was a 316 stainless steel. Stainless steel was chosen for its relatively cheap cost and corrosion resistance. The mold was a cylinder 25mm in diameter and 6.3 mm thick made from stainless steel. On one face of the mold, a design was machined into it as seen in Figure 2-2 and 2-3. The design was simply four fingers, each with a channel and hemisphere machined into them.

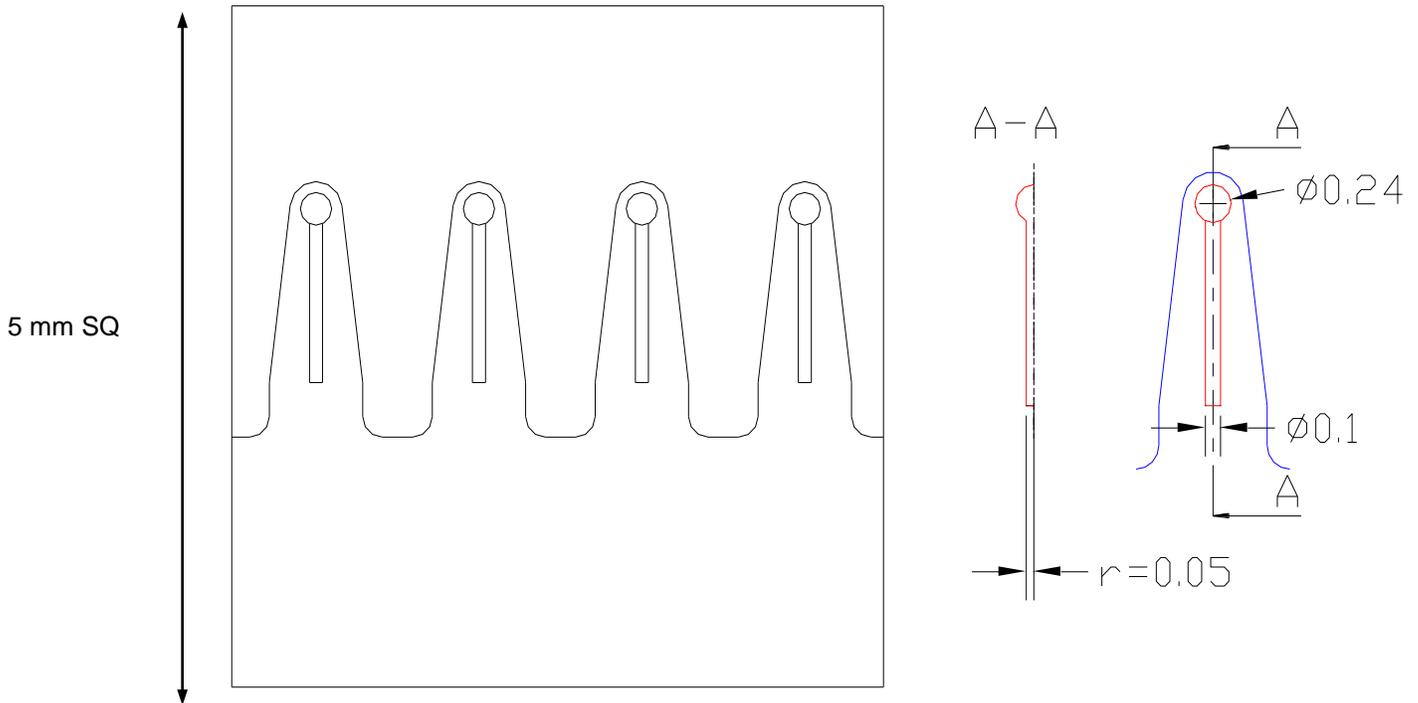


Figure 2-2. Schematic of the molding features to be machined into a mold

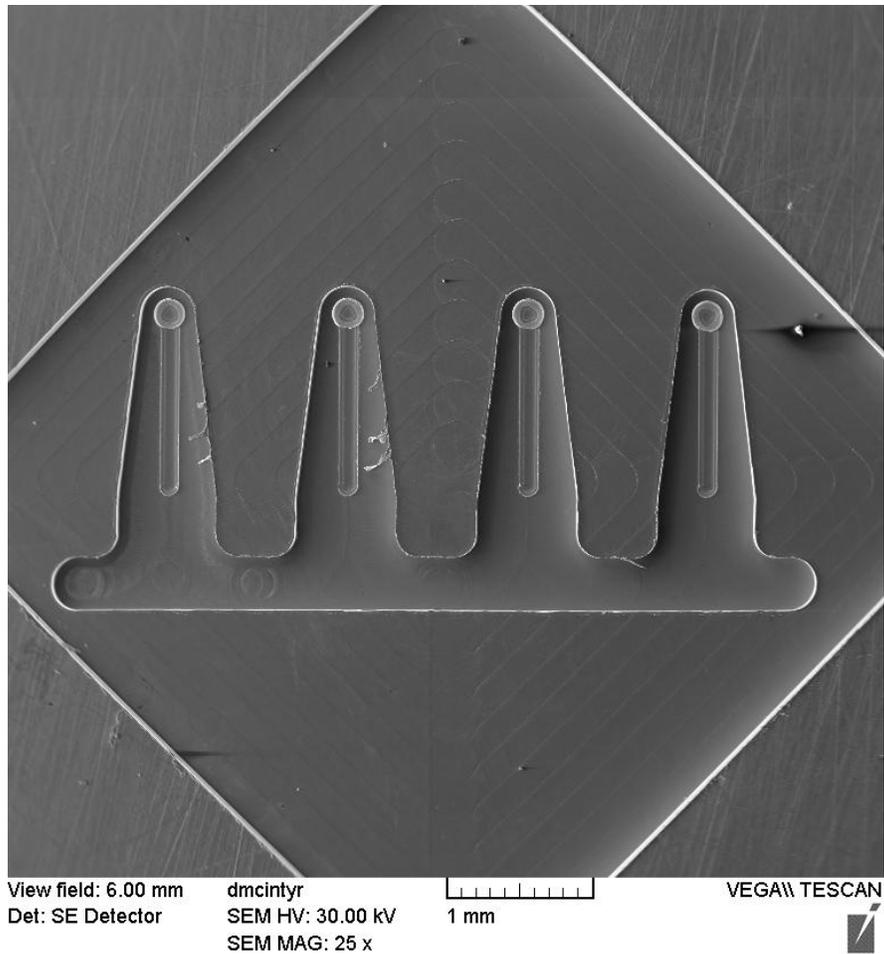


Figure 2-3. SEM image of the mold design that was machined into a stainless steel

Load Frame

The load frame as seen in Figure 2-4 was capable of applying a maximum load of 5000 N. The load frame was first build by Jeff Bardt for his research to develop a similar process for silicon molds [7]. The top and bottom platens contain cartridge heaters inside of them and the whole setup is demonstrated in Figure 2-5. The heaters provide adequate heating to the platens, which then heat metallic glass into a viscous enough state to be pressed into a mold. The time necessary to bring the platens and

molding pieces to a proper operating temperature is approximately 60 seconds. This relatively quick time to heat up reduced the opportunity for both corrosion and any reactivity that can exist between any of the molding materials and the metallic glass. A load of 2000 N was applied to the mold at the designated temperature of around 350° C, depending on the alloys glass transition temperature. The amount of pressure was load controlled so when the metallic glass alloy starts to flow, a constant pressure was applied, which allows a uniform flow of the alloy into the mold [7]. There were 4 parts accompanying the mold that were used to ensure proper alignment and pressure from the load frame on the metallic glass and the mold as seen in a simplified Figure 2-6. Essentially, the mold and metallic glass were placed onto a platen and a ram directed the force down onto these pieces for molding.



Figure 2-4. Load frame setup showing platens and water cooling system [7]

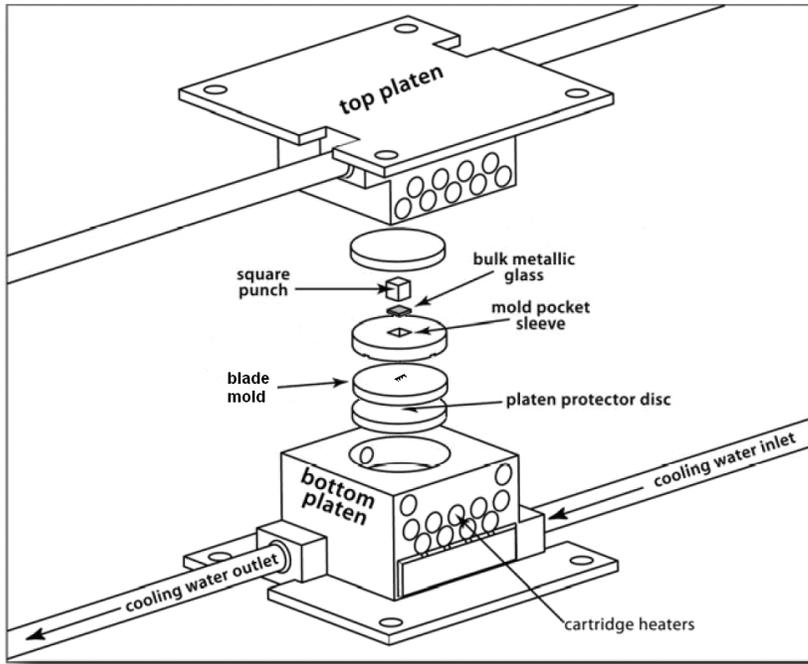


Figure 2-5. Schematic of the parts used with the load frame for molding [7]

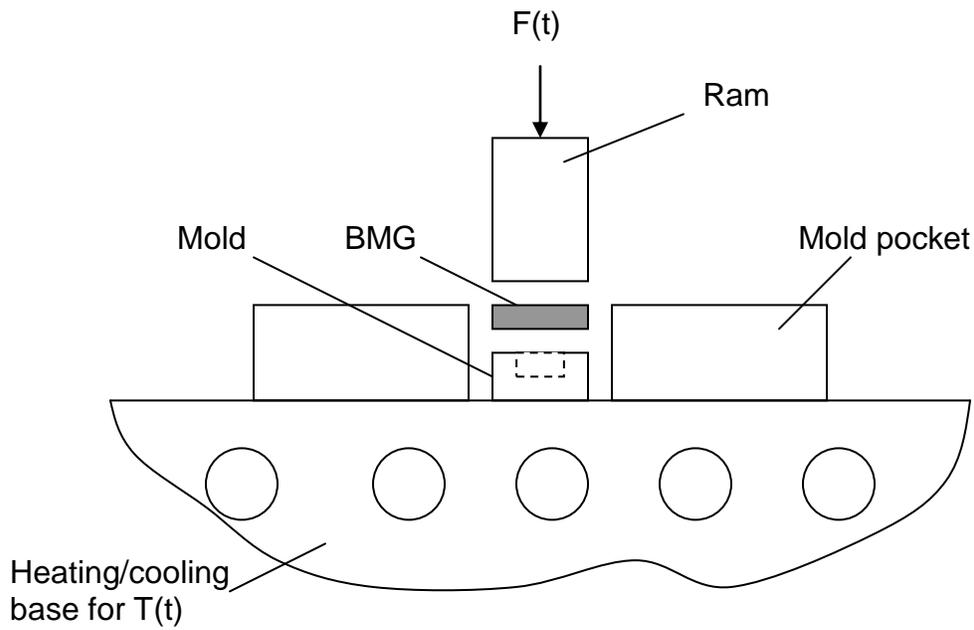


Figure 2-6. Cross sectional view of the molding setup [7]

A water cooling system was implemented into the top and bottom platen to provide sufficient cooling to keep the alloy amorphous. The cooling system starts when the load is removed after the molding has finished. If a faster cooling rate than can be achieved by the system is needed, the mold and accessories can be quickly dropped into a water filled quench tank. The cooling rate for the quench tank is much greater than the cooling system, which is seen in comparing Figure 2-7 and 2-8. The cooling system results in a maximum cooling rate of approximately $0.87^{\circ}\text{C}/\text{sec}$. The water quench rate is essentially instantaneous and thus cannot be quantified.

Water Cooling System Temperature Profile

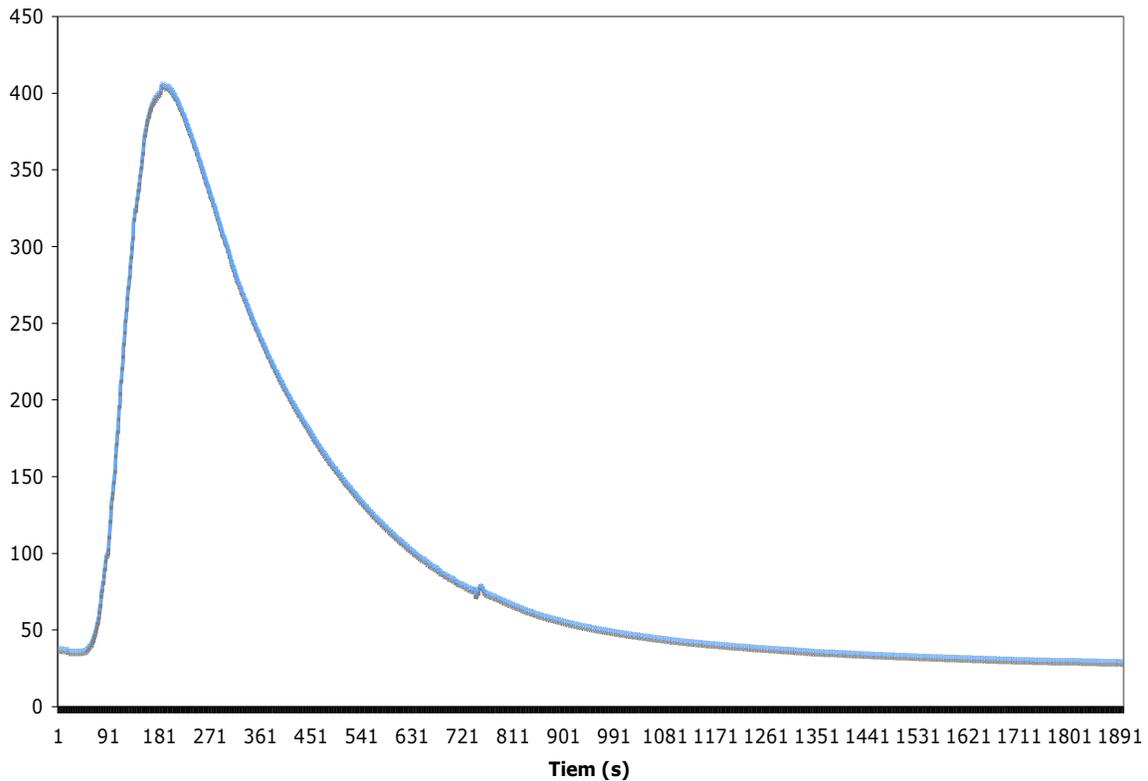


Figure 2-7. Water cooling system temperature profile during a test

Water Quenching Temperature Profile

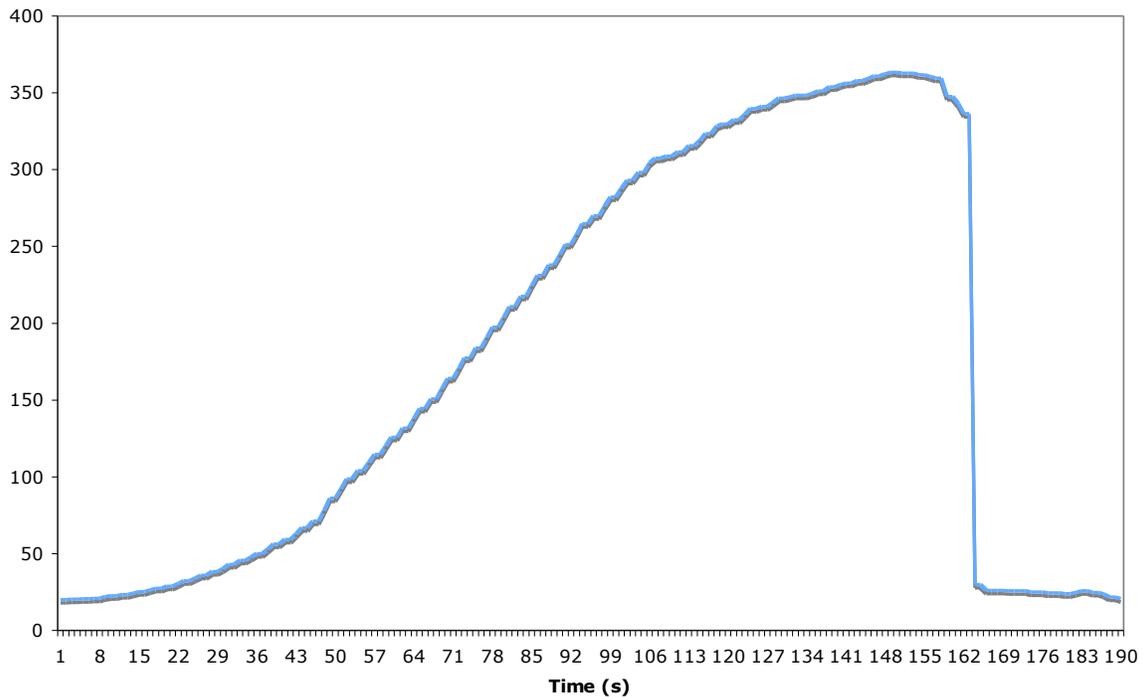


Figure 2-8. Water quenching temperature profile during a test

Measuring Mold Wear

SEM Analysis

A scanning electron microscope (SEM) was used to obtain secondary electron images of the mold that were then analyzed and measured to determine any changes of dimension. The SEM was operated at 30kV at a pressure of less than 5×10^{-5} mbar. The mold was analyzed prior to molding and repeatable measurements were recorded. These measurements were taken after each successive molding of the alloy. The amount of deformation caused by molding of Vit DH was analyzed for this process and a total of four measurements were taken to measure deformation and they are represented as a yellow line in Figures 2-9 to 2-12.

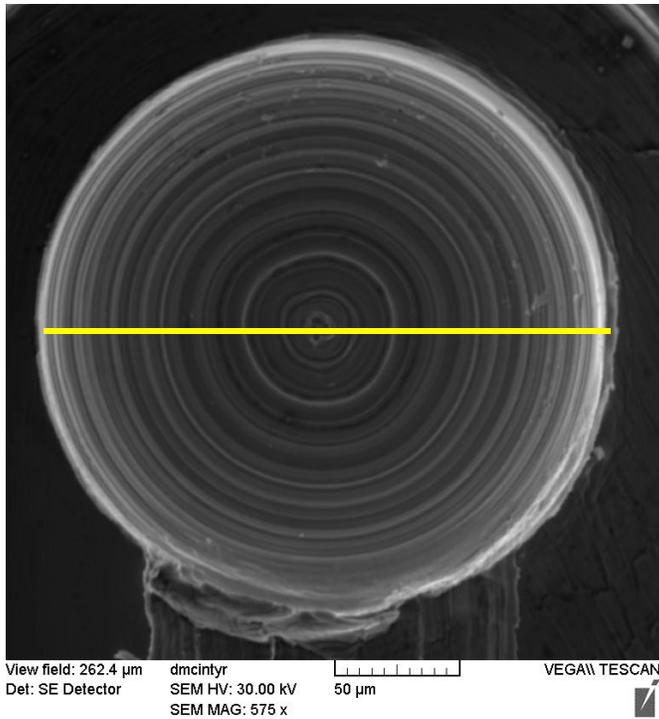


Figure 2-9. SEM secondary electron image illustrating the measurement taken for circle diameter

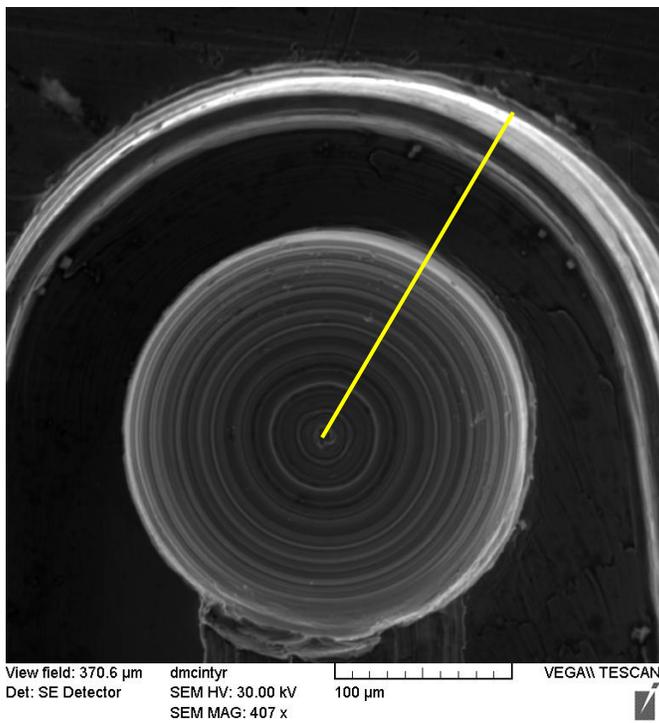


Figure 2-10. SEM secondary electron image illustrating the measurement taken for finger radius

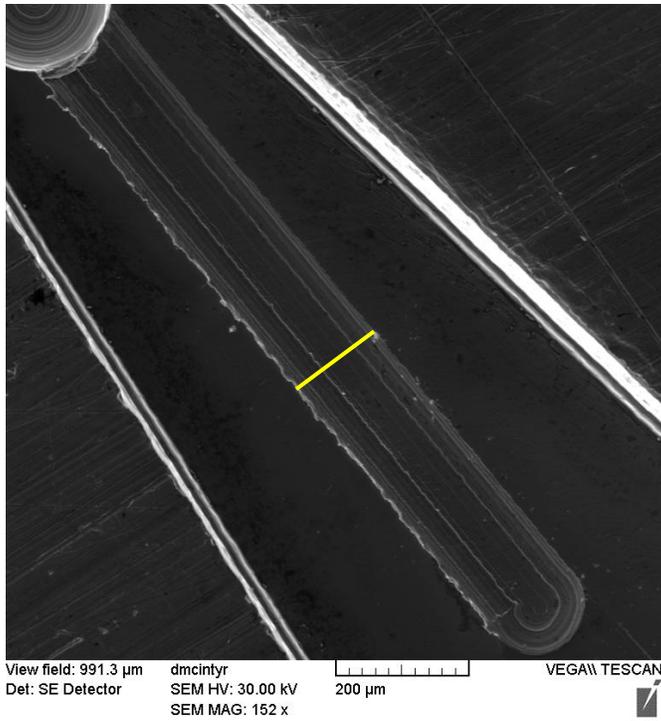


Figure 2-11. SEM secondary electron image illustrating the measurement taken for channel width



Figure 2-12. SEM secondary electron image illustrating the measurement taken for finger width

Determining Crystallinity

To ensure the alloy used in the molding process was completely amorphous, the samples were scanned in a powder X-Ray diffractometer (XRD) before and after the molding process as shown in Figures 2-13. In circumstances that show post-molding crystallinity like in Figure 2-14, the temperature used during molding can be altered to ensure an optimum molding temperature for that specific alloy.

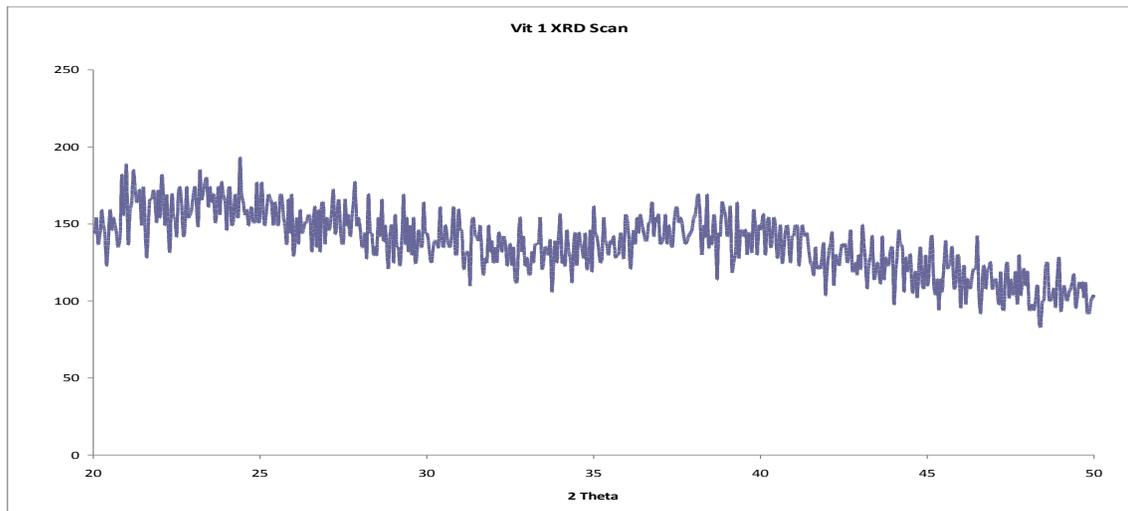


Figure 2-13. XRD scan of Vit 1 showing a highly amorphous piece of bulk metallic glass

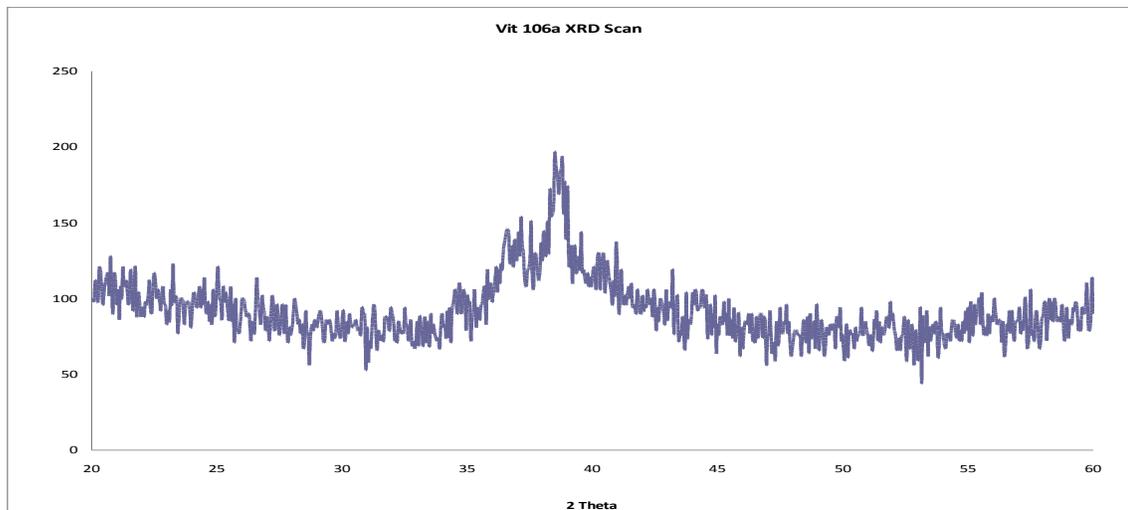


Figure 2-14. XRD scan of Vit 106a showing a crystalline peak

CHAPTER 3 RESULTS AND DISCUSSION

The Formation of Small Features

The two beryllium containing metallic glasses replicated micrometer sized features. An example of this can be seen in Figure 3-1 showing micrometer sized machine marks replicated on a molded piece of Vit DH alloy. A successful molding of the feature is seen in Figure 3-2 where the entire piece molded except for one hemisphere on one finger. This was the result of a lack of material and not a failure to mold. These two alloys also remained amorphous through molding, confirmed by a XRD scan shown in Figure 3-3.

Vit 106a, the non beryllium containing alloy, was also able to form the features in the mold, but the molding was unsuccessful because the alloy crystallized during molding. A XRD scan demonstrating crystallinity in Vit 106a after molding is shown in Figure 2-14. Altering the molding temperature to prevent crystallization in the alloy was unsuccessful.

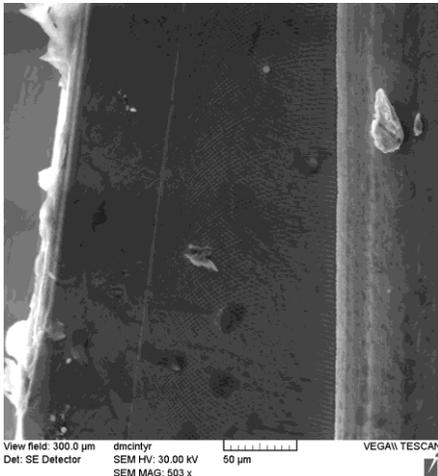
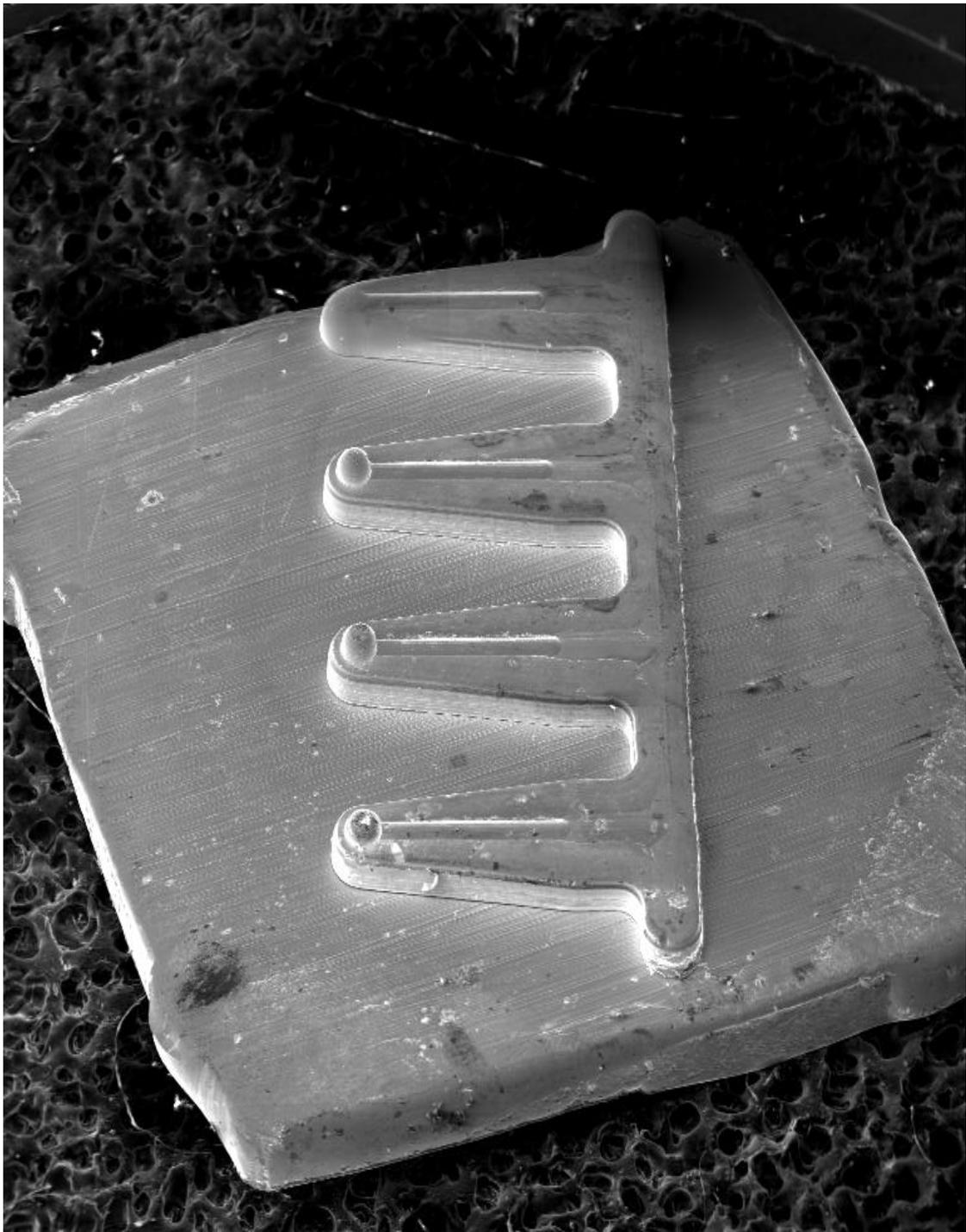
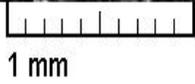


Figure 3-1. SEM secondary electron image showing machine marks replicated on a molded piece of metallic glass



View field: 6.00 mm
Det: SE Detector

dmcintyr
SEM HV: 30.00 kV
SEM MAG: 25 x



VEGA\\ TESCAN


Figure 3-2. An SEM secondary electron image of a successful molding of bulk metallic glass. The top finger not molding a hemisphere was a result of a lack of material and not a failed molding

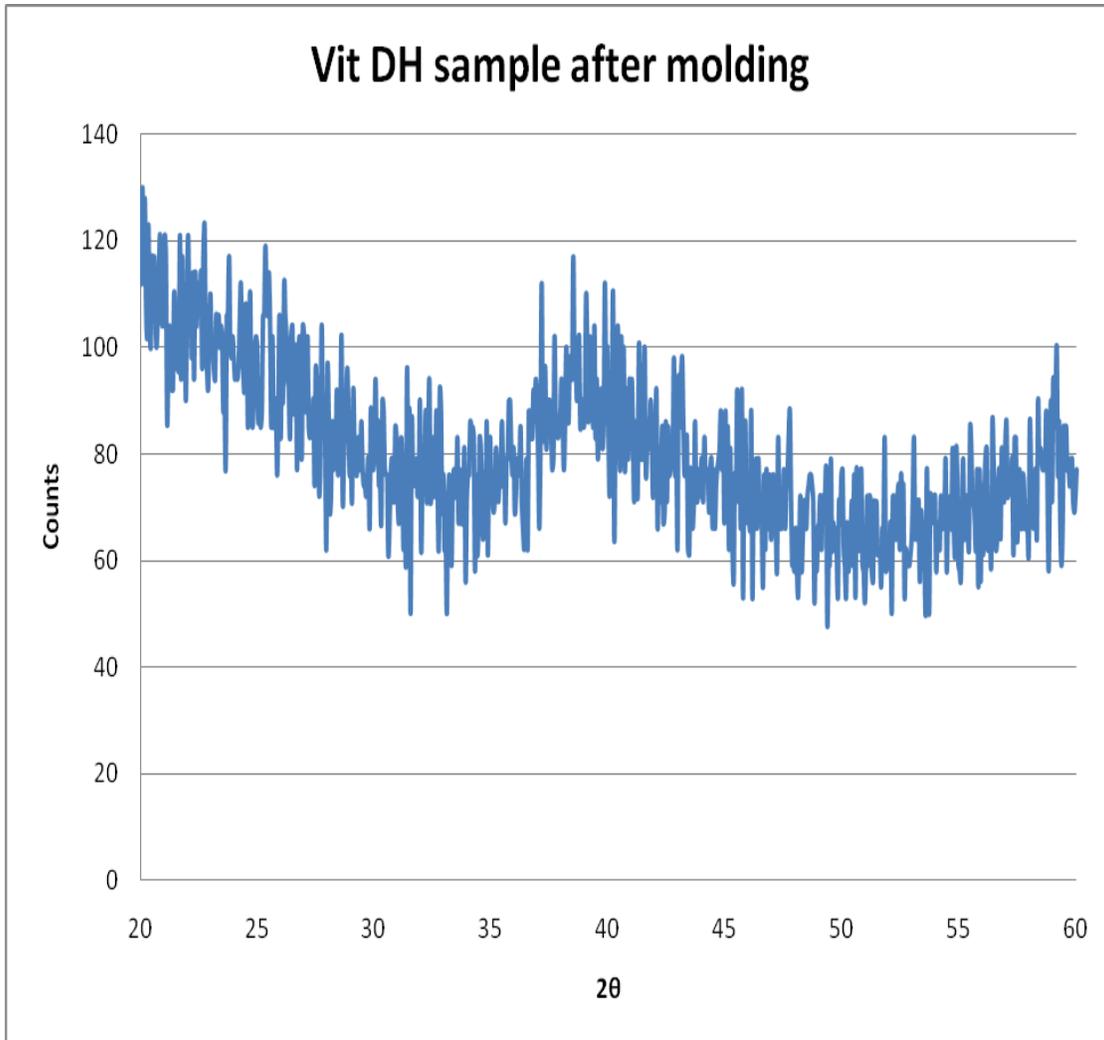


Figure 3-3. An XRD scan of the Vit DH alloy after molding illustrating the retained amorphous structure.

Corrosion of Metallic Glass During Molding

The alloys that contained beryllium were not susceptible to oxidation during molding. Vit 106a formed a visible surface oxide during molding. An example of surface oxidation can be seen in the optical microscope image in Figure 3-4, which was a molded sample of Vit 106a. As a comparison, Figure 3-5 is a molded sample of Vit DH, which shows a polished metallic surface. The molding was partially successful for

Vit 106a in that the features were formed but the layer of oxide negatively affected the surface finish and compromised the part.

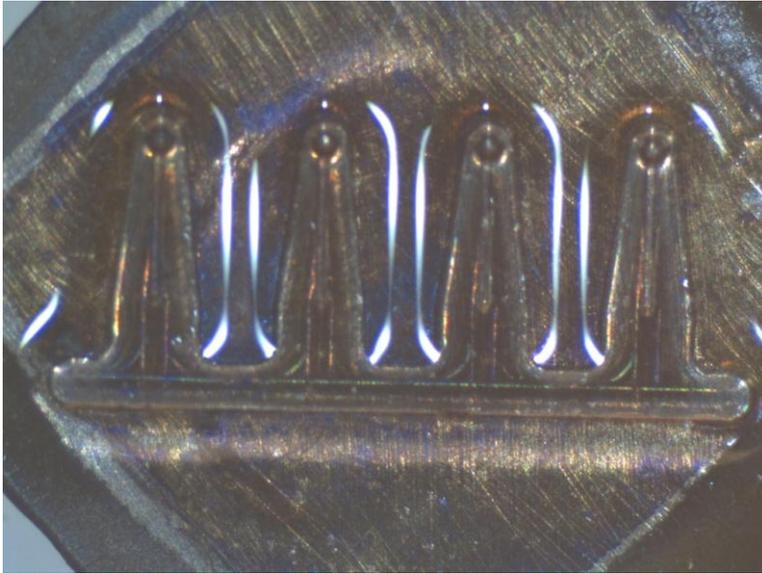


Figure 3-4. Optical microscope image of a molded Vit 106a piece with surface corrosion



Figure 3-5. Optical microscope image demonstrating the good surface finish of the Vit DH alloy

Wear on the Molds Caused by Thermoplastic Molding

The stresses and strains associated with molding the metallic glass were not sufficient to cause significant changes in the dimensions of the molds even after multiple molding attempts with Vit DH, as seen in Figure 3-6 to 3-9.

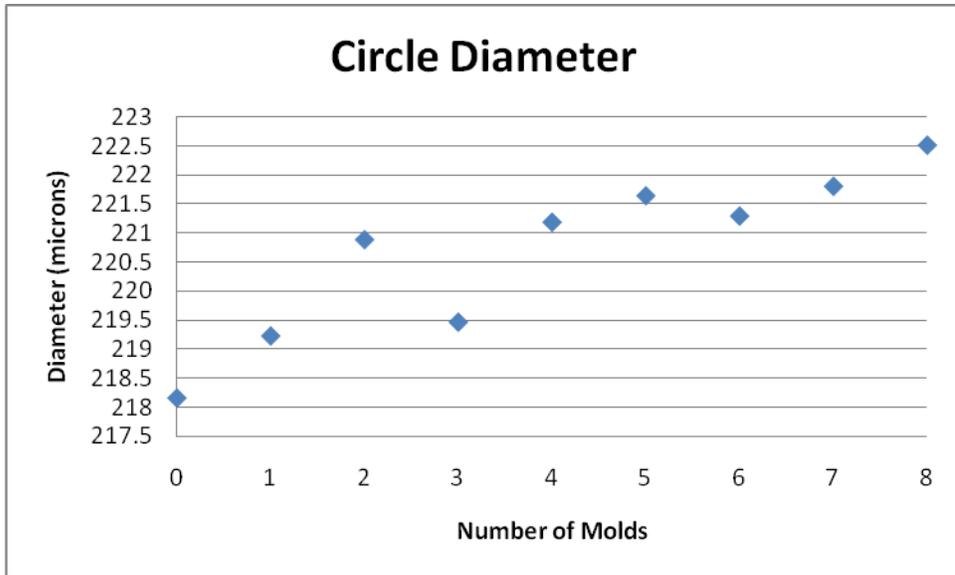


Figure 3-6. Circle diameter dimensional changes with respect to molding attempts of Vit DH

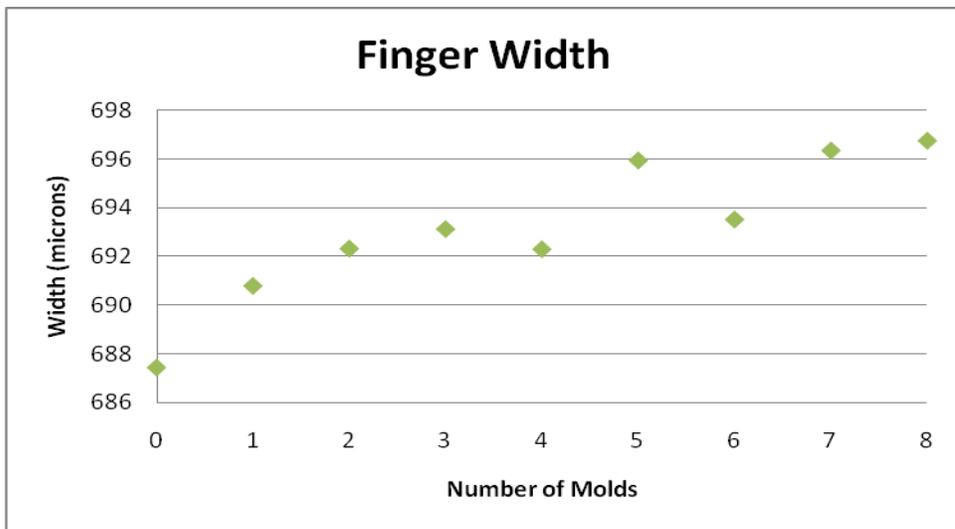


Figure 3-7. Finger width dimensional changes with respect to molding attempts of Vit DH

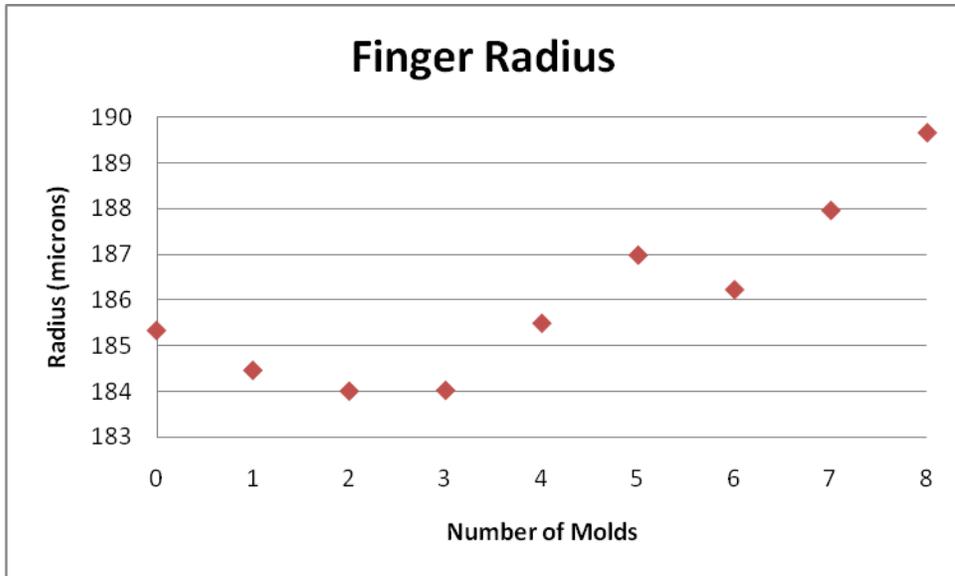


Figure 3-8. Finger radius dimensional changes with respect to molding attempts of Vit DH

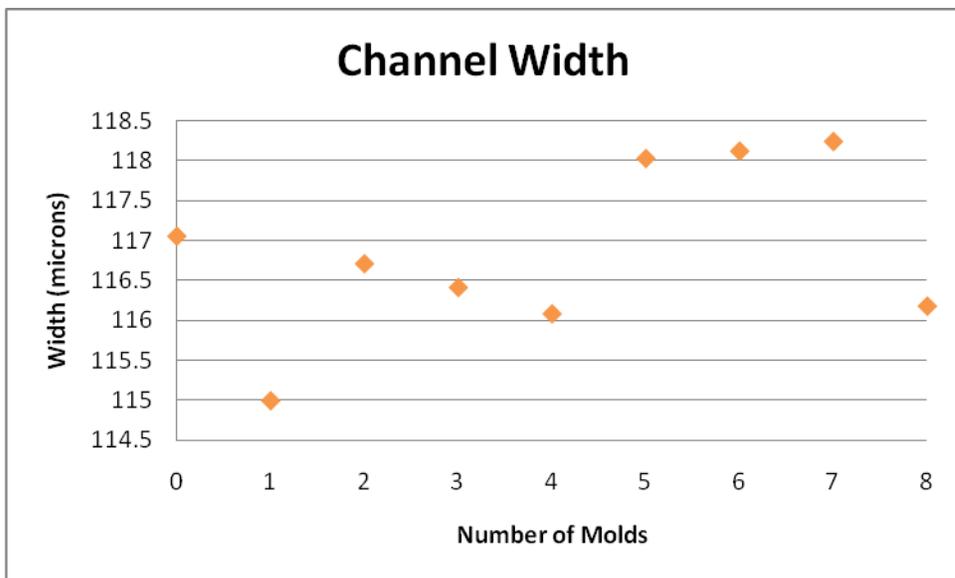


Figure 3-9. Channel width dimensional changes with respect to molding attempts of Vit DH

The change in dimensions of the mold during the molding of Vit DH is on the order of 1-3%. The amount of deformation is relatively low and demonstrates that multiple

molding attempts can be performed before the mold is determined to be unusable because of dimensional considerations.

The water-cooling system on the load frame was tested with a sample of Vit DH to determine if the cooling rate was sufficient to prevent crystallization. The XRD scan after molding showed a definite crystalline peak, signifying that the water cooling system does not cool the metallic glass faster than the critical cooling rate for that alloy.

The de-molding of the part also presents some difficulties and an example of a failed demolding is presented in Figure 3-10. Many times during the molding of, because of the complex design of the mold, the metallic glass will be frictionally bound to the mold. A relatively large force must be applied to the metallic glass in order to separate it from the mold. During this mechanical process forces are imparted onto the mold causing plastic deformation on the relatively soft stainless steel, an example of this is shown in Figure 3-11. Along with frictional effects, diffusion bonding occurred with the mold and metallic glass. Because of the high temperatures involved, the kinetics are increased and diffusion between the viscous metallic glass and the stainless steel mold walls can occur. The result is the inability to remove the sample from the mold.

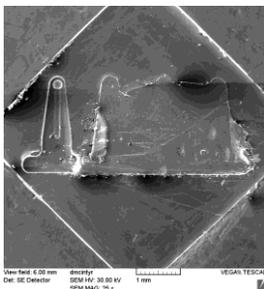


Figure 3-10. SEM secondary electron image of a failed demolding attempt. Part of the metallic glass did not separate from the mold because of a lack of material

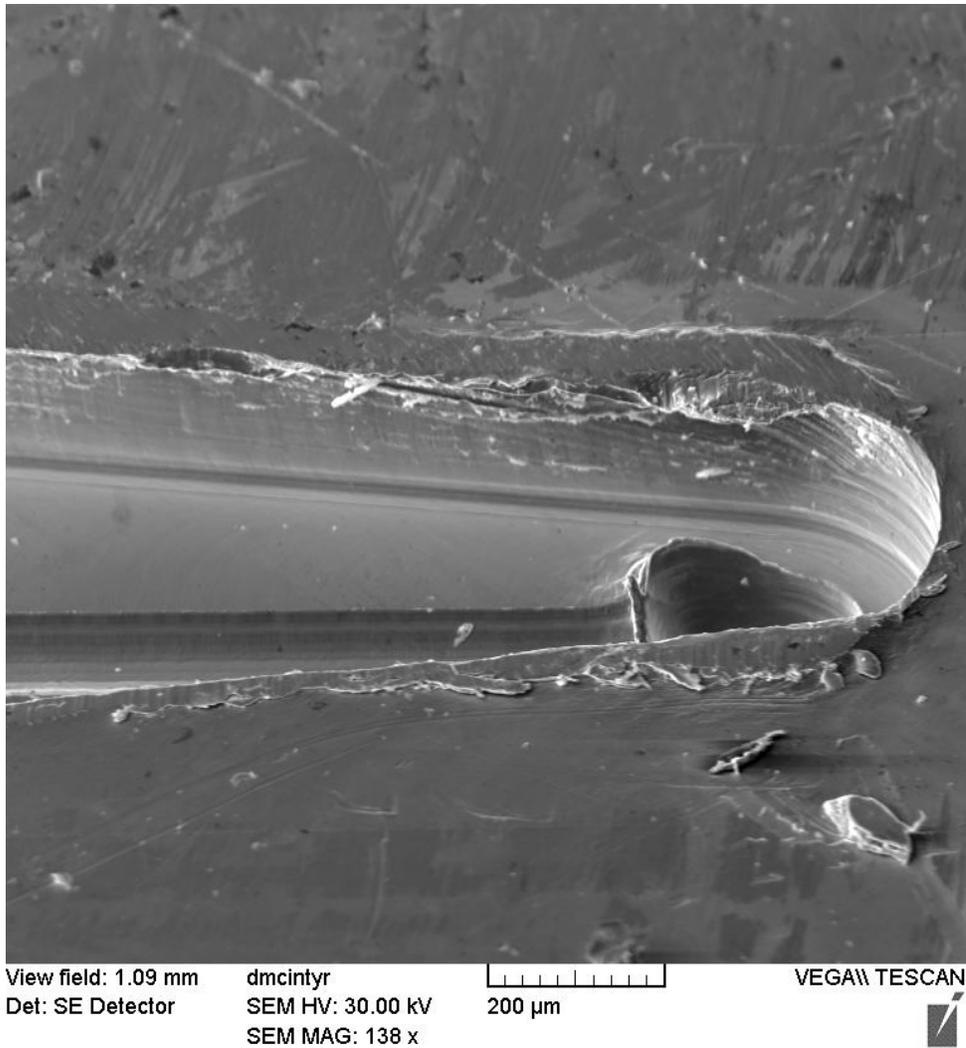
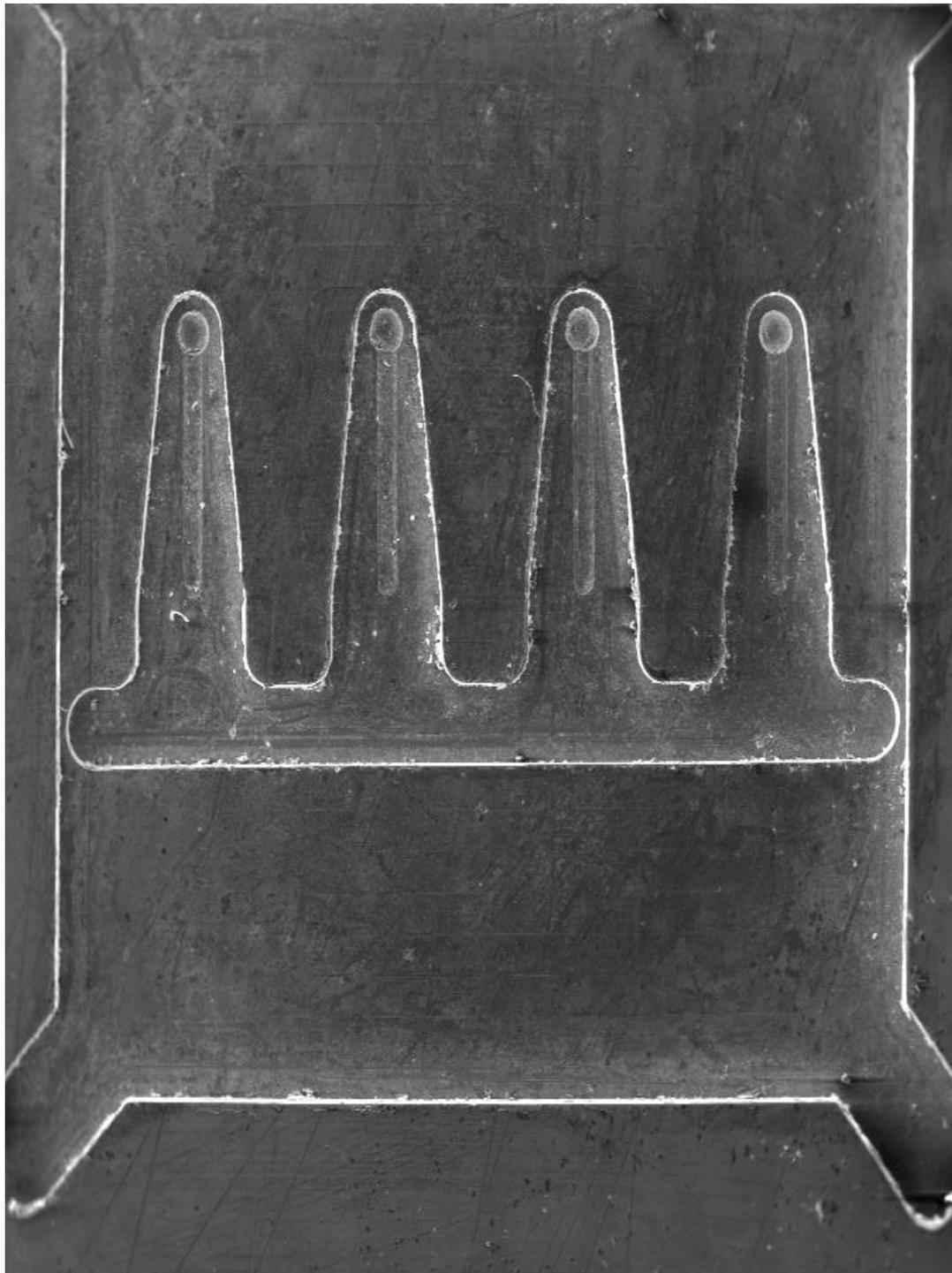


Figure 3-11. SEM secondary electron image showing an angled view of a mold finger demonstrating the amount of deformation after a failed molding attempt

Lubrication was suggested to prevent difficulties in the de-molding process. The lubrication used was a boron nitride aerosol. Characterization of the BN particles found that particles as large as 10 μ m in diameter existed. The surface finish on the part was negatively influenced by the lubrication because it interfered with the ability of the metallic glass to replicate the surface of the mold, which is visible in Figures 3-12 and 3-13.



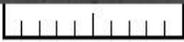
View field: 6.00 mm dmcintyr  VEGA\\ TESCAN
Det: SE Detector SEM HV: 30.00 kV 1 mm
SEM MAG: 25 x 

Figure 3-12. SEM secondary electron image showing the rough surface after a BN aerosol was used as a lubricant



View field: 500.0 μm dmcintyr
Det: SE Detector SEM HV: 30.00 kV
SEM MAG: 302 x

100 μm

VEGA\\ TESCAN

Figure 3-13. SEM secondary electron image of the rough surface after the use of a BN aerosol lubricant

CHAPTER 4 CONCLUSION

Metallic glasses provide enhanced performance over many of their metallic counterparts such as steel and aluminum. While metallic glass alloys are relatively expensive and more difficult to fabricate, they are able to be formed into smaller parts. Compared to common load bearing metals such as steel and aluminum, metallic glasses generally have a higher yield strength, ultimate tensile strength, a lower Young's modulus and higher elongation. Parts as small as MEMS can be created with metallic glasses that provide improved mechanical properties over the mechanical fatigue limitations of the other materials used in the devices [17,18]. The corrosion properties of these alloys trump common metals as well. The oxygen getters common in the composition of many metallic glasses protect against oxidation of the alloy.

Metallic glasses also possess the ability to be thermoplastically formed using common procedures of vacuum die and suction casting [5,20]. At elevated temperatures, these alloys flow viscously and this property allows the alloy to be processed in a similar manner to polymers that have been made in this manner for many years. Because of the viscous flow of the material, the molding of complex parts can be achieved. Such parts would be too hard or expensive to produce with common processing techniques for crystalline metals. In addition, metallic glass alloys inherently have a relatively low coefficient of thermal expansion and do not change phase, so there is no change in volume during molding. Because of this, net shape parts can be molded in one step and will not have to be machined down to proper dimensional tolerances. This means a higher efficiency and lower cost for production. Furthermore, these alloys are able to replicate features and surfaces very well. While molding, if the

design in the mold is highly polished then the metallic glass surface will be as well, reducing any secondary finishing.

The molding of the three zirconium based metallic glass alloys in ambient atmosphere using 316 stainless steel molds was investigated to determine the feasibility in a production process. Mold part feature reproduction and mold wear was monitored and characterized for 8 molding attempts with Vit DH, a beryllium containing alloy.

The features that were molded with Vit 1 and Vit DH showed ease of release, reproducibility and minimal mold wear. Molding attempts with Vit 106a, a beryllium free alloy, were unsuccessful due to crystallization and oxidation of the sample. Molding of the two beryllium containing alloys was successfully demonstrated in an ambient atmosphere while molding attempts with the beryllium alloy was unsuccessful.

The amount of wear from the molding process on 316 stainless steel molds was not a significant issue when molding Vit DH. Stainless steel is a viable mold material for the thermoplastic forming of metallic glass. When the proper molding temperatures are used, the amount of wear on the mold after each molding attempt was between 1% and 3%. This is suitable for a large production run where the most uses out of a single mold is needed for the cost efficiency. Another benefit to metallic glass processing is the fact that simple alloys such as stainless steel or nickel can be used as mold materials, making the process even more cost efficient. To reduce the overall wear on the mold and extend its lifetime, lubrication can be used to aid in the de-molding process. The issues with using lubrication are surface finish and reactivity with the alloy. While molding on the micron scale, the smallest particle of contamination from the lubrication can cause adverse affects on the surface finish of the part. Elements in the alloy can

also react with certain elements in the lubrication and can create unwanted phases that can negatively affect the properties of the alloy.

Future work on these alloys includes research into non-beryllium containing alloys that do not oxidize under elevated temperatures and have a large processing window. This would eliminate the need for a controlled atmosphere around the molding apparatus and will cut costs to produce parts in a production run. The use of a controlled atmosphere will also be examined. Research into the causes of crystallization and oxidation in beryllium free alloys will be investigated to explore a solution. The load frame will be setup to allow for an argon containment unit around the platens and mold to eliminate oxidation. A process to automate the molding and de-molding, all while allowing the use of the controlled atmosphere chamber will be evaluated. These processes will be further researched as to whether they influence the amount of mold wear caused by molding and de-molding of the part.

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BIOGRAPHICAL SKETCH

Daniel McIntyre was born in 1987 in Boynton Beach, Florida to Kenneth and Barbara McIntyre. He lived his whole life in south Florida until his graduation from Atlantic High School when he then moved to Gainesville, FL to attend college at the University of Florida. Daniel graduated the University of Florida with a Bachelor of Science in materials science and engineering in May of 2005. He then joined Dr. Gerald Bourne for graduate school at the University of Florida where he is scheduled to complete his Master of Science degree in December of 2010.