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Use of Direct Metal Laser Sintering for Tooling in High Volume Production

Joel W. Hendrickson
Utah State University

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By

Joel W. Hendrickson

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Approved:

Dr. Ling Liu
Major Professor

Dr. Thomas H. Fronk
Committee Member

Dr. Jason Quinn
Committee Member

UTAH STATE UNIVERSITY
Logan, Utah

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ABSTRACT

Use of Direct Metal Laser Sintering for Tooling in High Volume Production

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Joel W. Hendrickson, Master of Science

Utah State University, 2015

Major Professor: Dr. Ling Liu
Department: Mechanical and Aerospace Engineering

Metal 3D printing has caught the attention of many large industries. There have been stories of great success using metal 3D printing. Some of the largest industries to successfully use metal 3D printing are aerospace and medical. These industries have succeeded with metal 3D printing because of their need for light and complex parts. These success stories lead other industries to investigate how metal 3D printing or Direct Metal Laser Sintering (DMLS) can help them. Industries that are involved in high volume production ask how they can take advantage of the complexity and customization that is available with 3D printing. This report explores the feasibility of using metal 3D printing in high volume production applications.

There are many differences in 3D printed metal parts and parts made from traditional methods. The material properties of three DMLS materials are tested and compared to published values and wrought material in this report. Some of the material properties that are tested are: tensile strength, yield strength, Young's modulus, elongation-at-break, toughness, hermeticity, and hardness. Hydroburst of thin walled vessel and microstructure are also examined.

The comparison of these properties shows that the tensile strength, yield strength, Young's modulus, hardness and elongation-at-break for these three materials are the some order magnitude

as wrought material and published values. They do vary from expected results in some cases but they have relatively tight groupings.

In most cases the toughness of DMLS parts is 1/3 that of the wrought material, except for in the case of the maraging steel, the toughness of the DMLS part is three times higher than the wrought material.

The hermeticity and hydroburst results for the DMLS parts are as would be expected from the wrought material.

This report explains the specific design techniques that should be followed to get advantage in 3D printed parts. These techniques include understanding build orientation to reduce support structure, reduce build time and to maximize the parts per build. The geometry of the part can be modified to change how the part deforms while it is being built. A minimum wall thickness of .5 mm is recommended because of this.

There is an advantage in using DMLS for complex tooling in high volume production. With DMLS the complexity of the part is free, so it is often advantageous to create complexity by combining parts, making custom parts or making the part smaller or lighter weight. As people start-using DMLS for tooling in high volume production, these advantages will become clearer. This leads to a new way of thinking. Designers will have freedom to design parts that have never been possible before.

PUBLIC ABSTRACT

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Everyday people hear more and more about the amazing things that 3D printing technology does. 3D printers print everything from toys to clothing, from cars to guns. 3D printing has become more popular in the last few years. The wonders of 3D printing lead many people to believe that it can be used for just about anything.

3D printing has become popular over the last couple of decades. In the last few years that several leading companies have started to take a serious look at metal 3D printing. There are many advantages to printing with metal and some wonder if metal 3D printing will take over many of the current manufacturing processes.

This project explores many of the advantages and disadvantages, and the possibilities of using metal 3D printing in an everyday high volume production environment.

ACKNOWLEDGMENTS

I would like to acknowledge Autoliv for funding this project, including my colleagues in France, Dominique Legall and Yann Legall, who provided the data for the axial tension testing. I would also like to acknowledge the materials lab and test bay at Autoliv for helping with several of the test. I would also like to acknowledge Dr. Ling Liu who supported me in this project.

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1. INTRODUCTION

Printers no longer just print words on paper. In the last couple of decades, we have come a long way in developing the technology that allows printing 3D models. 3D printing with plastics started in the 1980s and continued to grow through the 1990s and 2000s. Metal 3D printing has become popular in the last 10 years.

There are many different methods of 3D printing. Direct Metal Laser Sintering (DMLS) is the most common method of printing metals. DMLS printers lay out a thin layer of powdered metal, and then sinter the desired areas with a laser. The printers repeat this process layer by layer until the part is completed.

This method of building metal parts is attractive to many industries. Complex parts that could never be machined, using traditional methods, are being printed. The aerospace industry uses this technology to minimize weight. Parts are designed to only have material in necessary locations. By doing this, the parts are usually much more complex, becoming a great fit for 3D printing. It is also common in the medical field for knee and hip replacements because of the complexity of the parts and the customization that is possible.

One question that many industries ask is, "can this new technology be used in high volume production?" The DMLS process is a slow and expensive process. It cannot compete with cheap stamped or formed production parts. DMLS seems to be more suited for low volume production, and for complex or custom parts where time is not as critical.

Even though high volume production cannot use DMLS for components, there are still options for using it for prototype parts or for tooling. Some of the advantages of DMLS are capability of creating complex parts, new way of thinking when designing tooling, and low weight, and cost savings can potentially be very significant when building many parts that are not easily machined. There are, however, many concerns that people may have as they start to consider using DMLS for tooling (strength, accuracy, consistency, cost, toughness, hermeticity, hardness, etc.) Mechanical properties of tooling in high volume production are generally very critical since tool failure can result in personal injury and/or line stoppage.

The main objective of this project is to explore how metal 3D printing can be used in high volume production. This is done by completing the following three objectives:

a) Test and compare mechanical properties of 3D printed metals to published results of 3D printed metals and those of wrought metal. The performance of any material depends on its properties. These properties need to be understood, so that the performance is understood. The properties depend on the structure, and the structure depends on its heat treat. The properties will be different for 3D printed parts because they have a different structure and heat treat.

b) Explore applications of metal 3D printing and the advantages and disadvantages of it. After the properties are understood, the applications of metal 3D printing can be determined.

c) Explore design techniques of metal 3D printing by designing parts that are advantageous for metal 3D printing. After advantageous applications of metal 3D printing are determined, design techniques specific to metal 3D printing need to be followed to get the biggest advantage out of metal 3D printing.

2. COMPARISON OF MECHANICAL PROPERTIES OF DIFFERENT METALS

It is necessary to understand the mechanical properties of metal 3D printed parts before designing any tooling. Designers of high volume production tooling, typically design tooling that machinists machine from wrought material. Suppliers of 3D metal printers often make the claim that the mechanical properties of a printed part are 90%-100% of those of the wrought material. The following sections show testing data on different materials to explain how the mechanical properties of a printed part compares to that of wrought material. In some cases, it confirms the claim of suppliers of metal 3D printing in others it does not.

2.1. Machine Selection

To complete these objectives, an EOS printer was chosen because they are one of the most common 3D printers throughout the world. Because of this, it was easy to find companies that use this kind of printer. These printers are used in the United States as well as France.

To choose a specific company, quotes were requested from several companies that use EOS DMLS printers. These companies include *Additive Manufacturing LLC., RTI Directed Manufacturing, Inc., Initial, and I3D Manufacturing. I3D Manufacturing*, out the The Dalles, Oregon, was chosen to print all of the parts that were tested in the United States. This company was chosen because they came back with the cheapest price of 3D printing and because EOS recommended them because of their many years of experience. *Initial* out of Seynod, France printed the DMLS parts for the uniaxial tensile tests with the same type of printer.

2.2. Material Selection

Three different materials that could potentially be used for tooling in production were studied. The three materials are: an aluminum alloy AlSi10Mg [1], Stainless Steel 316L [2] and MS 1 tool steel [3]. These materials were chosen because of the wide range of applications that they can be used for. A short description of the advantages of each is written below.

1) AlSI10Mg – good thermal and low weight considerations. Optimal for metal parts with thin walls and complex geometries

2) Stainless Steel 316 – good corrosion resistant, non-magnetic, stronger and tougher than aluminum

3) MS 1 – High strength, heat treatable steel used for tooling applications. The composition of MS1 corresponds to US classification 18% Ni Maraging 300. This material also has good corrosion resistance.

2.3. Uniaxial Tensile Tests

EOS has published several material properties for the materials that they have developed to be printed in their printers. Some of the critical properties are not published. Several tests were performed to verify the material properties that EOS reports and to test some of the material properties that are not reported.

The first test performed was a uniaxial tensile test. The picture below shows the setup of the tensile testing. An industrial engineering group at Autoliv, in France, performed this testing. The powder and the 3D printer are from the same company as for the parts that were built and tested in the United States. The 3D printer used in France was also an EOS M280.

Dog bone samples were printed out of several different materials including: AlSi10Mg, SS 316, and MS 1. A universal testing machine (Instron) applied a direct tension on these parts until failure. Extensometers measured the deformation of the samples with respect to time. From these data the tensile strength, yield strength and the modulus of elasticity were determined.

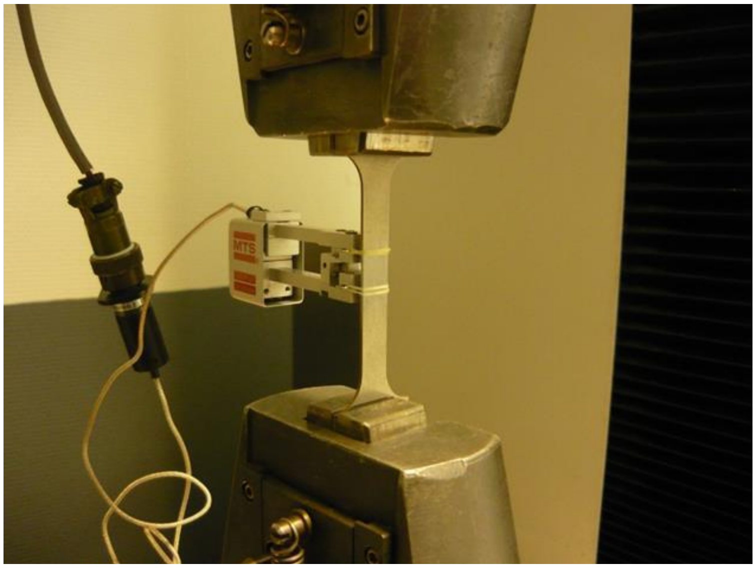

Figure 1. Tensile testing setup for DMLS parts

For each tensile test the displacement and the force was measured. Each material had samples that were printed both vertically and horizontally. The parts that were printed vertically were labeled as the Z-direction and parts that were printed horizontally were labeled as X/Y-direction. The tensile strength was tested in both of these directions for each one of these materials. For this study, we assume that the properties in the X-direction are the same as the Y-direction so these directions are not tested separately. The tensile data for AlSi10Mg in both directions is shown in Figure 4.

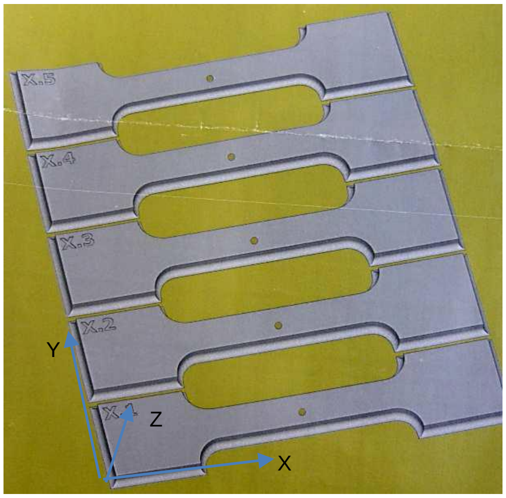

Figure 2. Tensile specimens printed in the horizontal direction (X/Y-direction)

Figure 3. DMLS tensile specimens printed in the vertical direction (Z-direction). Red represents support structure required.

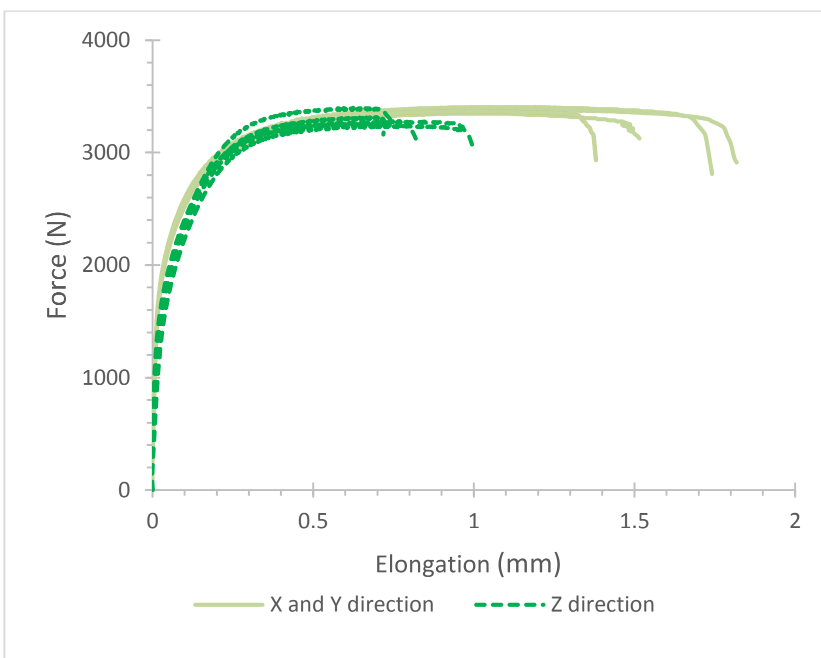

Figure 4. Tensile data for AlSi10Mg samples that were 3D printed

The ultimate tensile strength, yield strength, Young's modulus and the elongation-at-break were all extracted from the data found in Figure 4. These results were compared to the published values provided by EOS [1]. The results are also compared to aluminum 6061 [4], an aluminum alloy that is common and that would have similar material properties. The composition of these two alloys are different, but this comparison is still made to show how well the DMLS aluminum alloy compares to an alloy that is well known and commonly used.

Table 1 gives the properties and uncertainty bands, at 95% confidence, from the tensile tests. Because five samples were tested, one degree of freedom was used to calculate the standard deviation. This left four degrees of freedom to calculate the uncertainty using the t-distribution. The tensile strength and the yield strength results are half the published values [1]. The 3D printed aluminum is slightly stronger in the X/Y-direction than in the Z, but for most calculations, it would be reasonable to assume that the strength is equal in all directions and that this is an isotropic material.

Young's modulus was calculated by calculating the slope of the linear elastic portion of the curve at a 0.2% offset. The published values [1] for the Young's moduli are within the confidence interval of the tested parts.

The elongation-at-break was twice that of the published data [1]. The elongation-at-break of Al 6061 is within the confidence interval of that of the X/Y-direction [4].

By calculating the uncertainty, it is interesting to note that the tensile strength and yield strength have tight confidence intervals for the group of parts that were tested, but there are variables that were fixed in this study that cause these properties to vary from published results. Some possible variables are material lot, specific machine, and machine print parameters (i.e. laser power or speed). A follow-up study would be to test parts from different material lots, different machines and different machine parameters to see which variable causes the most variation.

	Tensile Strength (Mpa)	Yield Strength (Mpa)	Young's Modulus (Gpa)	Elongation-at-break
Printed AlSi10Mg – X/Y directions	230.7 +/- 2	136.8 +/- 2	75.4 +/- 5	15% +/-3%
Published value [1]	445.0	275.0	70.0	7%
Printed AlSi10Mg – Z direction	228.0 +/- 3	114.4 +/-5	67.6 +/- 28	9% +/- 2%
Published value [1]	405.0	230.0	65.0	4%
Aluminum 6061-T6 [4]	310	276	69	17%

Table 1. Material Properties of Aluminum Alloy

The tensile data for SS 316 is shown in Figure 5. This graph shows that the strength of SS 316 parts in the X/Y-direction are higher than in the Z-direction. This is because DMLS builds parts layer-by-layer. This data shows that for SS 316 the strength within a layer is stronger than the bond between the layers. This is important to understand when building parts. To increase accuracy of strength calculations, SS 316 should be treated as a transverse isotropic material. This phenomenon was not seen with the aluminum alloy because the strengths were so low, relative to the published data.

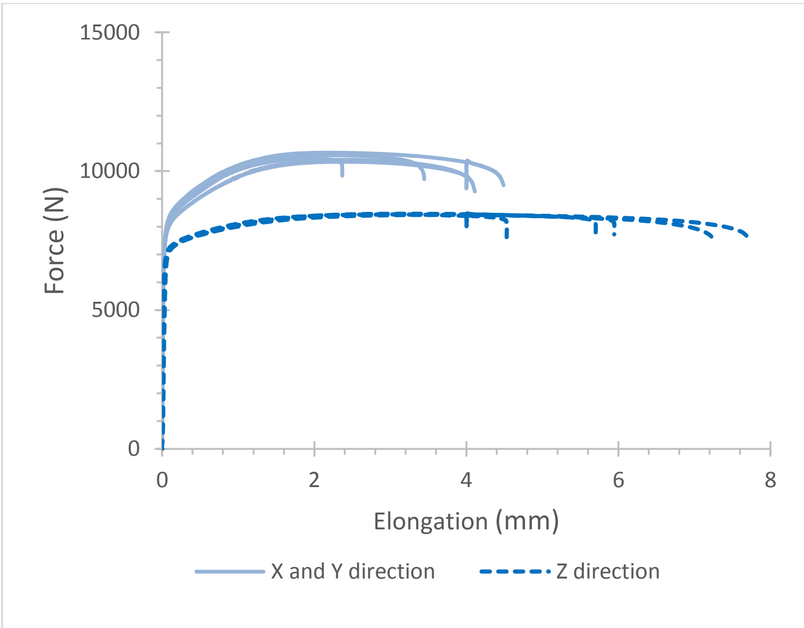

Figure 5. Tensile data for SS 316 samples that were 3D printed

Table 2 shows the tensile strength, yield strength, Young's modulus and elongation-at-break. The tensile strength and yield strength are within the tolerance of the published results [2] for the SS 316 parts that were tested. The tensile strength for the 3D printed parts is also similar to that of the wrought material [5], but the yield strength is higher. The plot in Figure 5 shows this in the elastic portion of the curve. In this case, young's modulus is slightly different from that of the published results and of the wrought material. The elongation-at-break is within the tolerance band of the published results, and similar to that of wrought material.

	Tensile Strength (Mpa)	Yield Strength (Mpa)	Young's Modulus (Gpa)	Elongation-at-break
Printed SS 316 – X/Y direction	692 +/- 15	497 +/- 10	248 +/-24	40% +/- 15%
Published value [2]	640 +/- 50	530 +/- 60	185	40% +/- 15%
Printed SS 316 - Z direction	582 +/- 5	464 +/- 20	163 +/-17	62% +/- 20%
Published value [2]	540 +/- 55	470 +/- 90	180	50% +/- 20%
SS 316L [5]	560	235	193	55%

Table 2. Material Properties for Stainless Steel 316

The tensile data for MS 1 tool steel is shown in Figure 6. The key differences shown by the graph are that the yield strength and tensile strength are higher in the x and y direction, but the elongation-at-break is higher in the z direction. For best results in calculations, this material should also be treated as a transvers isotropic material.

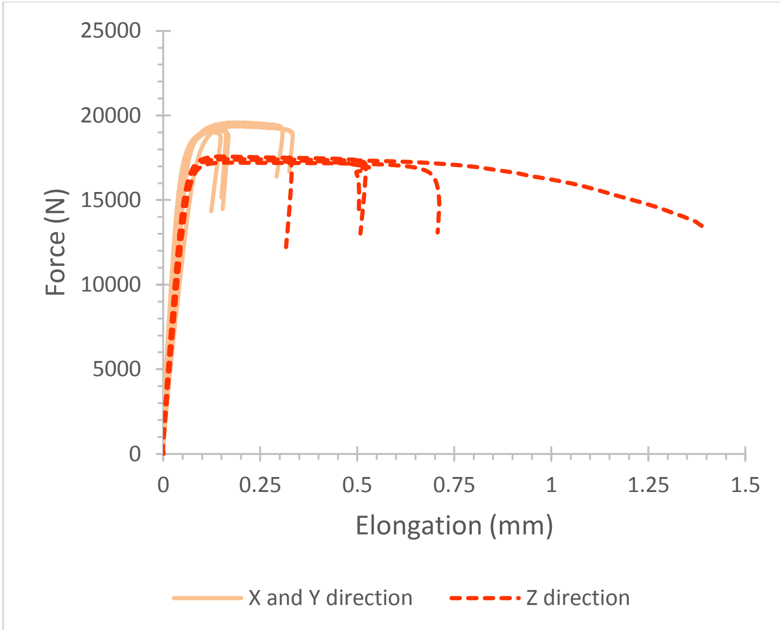

Figure 6. Tensile data for MS 1 samples that were 3D printed

Table 3 lists the tensile data for MS 1. The tensile strength, and yield strength are within or above the tolerance band of the published results [3], but significantly less than that of the wrought material [6]. The Young's modulus of the 3D printed material is similar to that of wrought material and the published results from EOS. The average elongation-at-break is only 2% in the x and y direction, but 7% in the z direction. This is compared to the published value of 8% +/- 3% and 12% for Maraging Steel C300.

	Tensile Strength (Mpa)	Yield Strength (Mpa)	Young's Modulus (Gpa)	Elongation-at-break
Printed MS 1 – X/Y direction	1310	1245	208	2%
Published value [3]	1100 +/- 100	1000 +/-100	180 +/- 20	8% +/- 3%
Printed MS 1 – Z direction	1127	1084	175	7%
Published value [3]	1100 +/- 100	1000 +/- 100	180 +/- 20	8% +/- 3%
Maraging Steel C300 [6]	2035	2000	195	12%

Table 3. Material Properties for Maraging Tool Steel

The tensile data of one specimen from each material and each printed direction was graphed in Figure 7. This is used to show a comparison for the different materials. The MS 1 has significant higher strength than the SS 316 or the aluminum alloy, but the SS has significantly higher elongation-at-break than MS 1. From looking at this curve, it appears that SS 316 should have similar if not higher toughness than MS 1 because of the size of the area under the curve. This will be verified with a Charpy impact test.

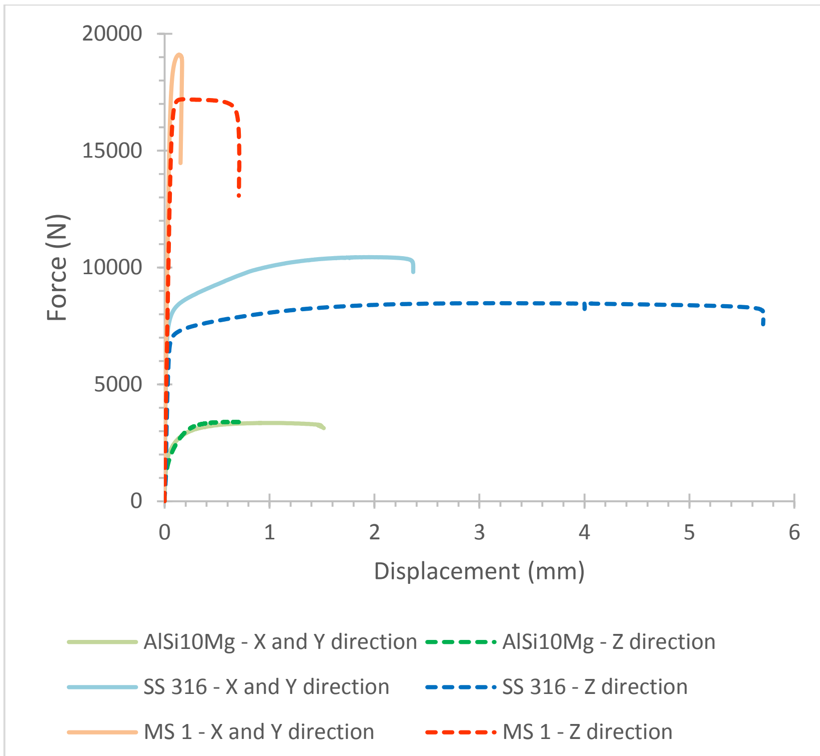

Figure 7. Tensile data comparison of different materials samples that were 3D printed

2.4. Toughness

The published results from EOS show that the 3D printed AlSi10Mg has similar yield strength and tensile strength to that of a commonly used aluminum, such as Al 6061-T6. It also shows how similar SS 316 is to wrought materials. It however, does not publish any toughness information. It is hard to find impact tests of 3D printed materials. Understanding the toughness of these materials is critical to knowing how these materials can be used.

The toughness of these materials was tested with a Charpy impact test. Standard ASTM E23 specimens were used. The parts were 10 mm x 10 mm x 55 mm, with a 2 mm notch cut out. The notch could have been 3D printed into these samples, but in an attempt to keep as many variables as constant as possible, the parts were printed, then the notch was cut out. All parts were built in the vertical orientation as shown in Figure 8. A 50 J impact tester was used for each of these tests.

The three different types of 3D printed metals were all tested along with an Al 6061-T6 sample that was machined. By testing this aluminum sample, it verified that the test setup used was correct and would give similar results to published Charpy impact results. The Charpy impact test results are shown below.

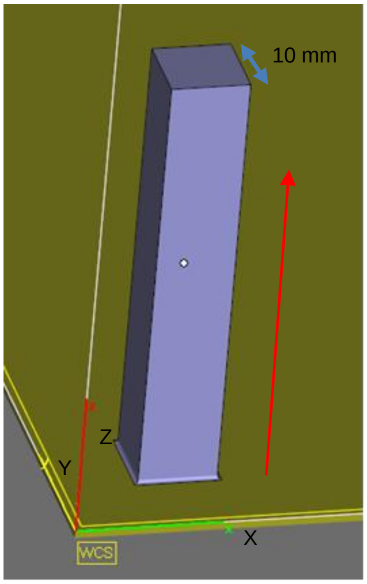

Figure 8. Build orientation of Charpy impact test specimens. Red line shows the build direction.

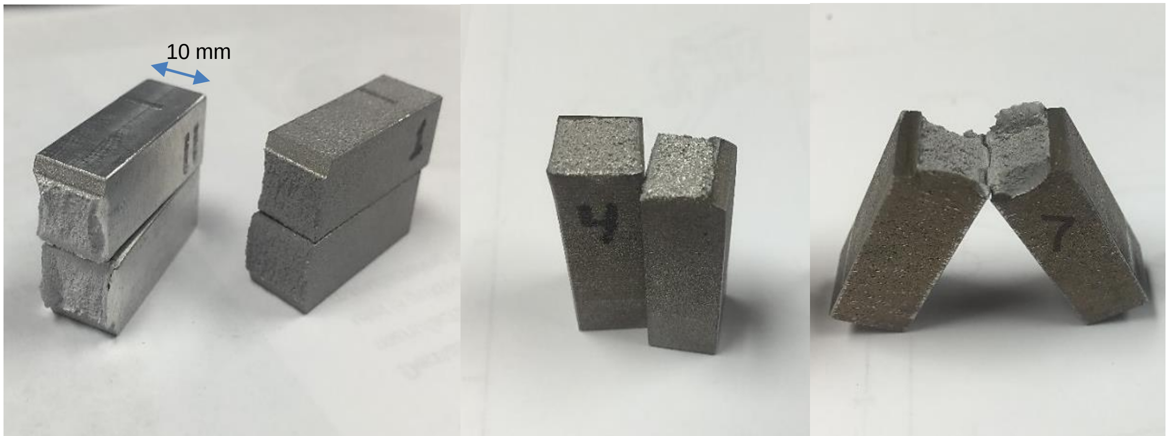

Figure 9. Charpy impact test specimens from left to right: Al 6061-T6, 3D printed AlSiMg10, 3D printed SS 316, and 3D printed MS1

The only Charpy impact value that EOS publishes is that of MS 1 [3]. The MS 1 sample that was tested, resulted in similar toughness to that of the published result, but significantly higher than that of wrought material [6]. The tradeoff between strength and toughness is seen in these data. The strength of 3D printed Maraging tool steel is half that of the wrought material but the toughness is over double. This can be an advantage for 3D printed MS 1. Although, 3D printed MS 1 should not be used in the same situations as Maraging steel because the strength is less. It opens up opportunities to use 3D printed MS 1 in tooling applications where you need fairly high strength, but you need more toughness than could be achieved with Maraging steel C300.

The tradeoff of strength vs toughness is seen again in the Charpy impact results for AlSi10Mg and SS 316. Even though these two materials have similar strength to that of wrought materials, the toughness is significantly less. In both cases, the toughness was about one third of that of wrought materials [5] [7].

	Printed Total Energy (J)		Similar Wrought Material Total Energy (J)		Similar Wrought Material
	Tested	Published	Tested	Published	
AlSi10Mg - Z direction	7.75	NA	22	22 [7]	Al 6061-T6
SS 316 - Z direction	41.2	NA		103 [5]	SS 316 L
MS 1 - Z direction	47.2	45 +/- 10 [3]		17 [6]	MS C300

Table 4. Charpy impact results for 3D printed standard 10mm x 10mm x 55mm samples with a 2mm notch

2.5. Hardness

To measure the hardness all samples were cut and polished. A transverse hardness test was used to take five different hardness values. The average of the transverse hardness tests are shown in Table 5. The hardness values of MS 1 and SS 316 were measured using a 500-gram load. And the hardness value of the aluminum alloy was taken using a 200-gram load. All hardness values were measured in Vickers (HV).

The hardness values for Alsi10Mg and MS 1 are relatively close to the published values (within 20%). The hardness for stainless steel is 36% higher than the published value. The heat treat that occurs from printing the SS makes the hardness higher as well as the yield strength. The published values for the three materials are similar to that of the wrought material.

	Hardness Measurements (HV)	Published Hardness (HV)	Similar Material Hardness (HV)	Similar Material (HV)
AlSi10Mg	103	120 [1]	107 [4]	Aluminum 6061
SS 316	222	163 [2]	152 [5]	SS 316L
MS 1	373	344 [3]	353 [6]	MS C300

Table 5. Hardness values of 3D printed materials in Vickers (HV)

2.6. Hydro-burst and Leak Rate

As people learn about 3D metal printing, a concern that is brought up is how the parts will react to differential pressures. Some of the questions that people have are: How does the burst strength compare to materials we are familiar with when pressurized to failure? Will 3D printed metal parts hold a vacuum? What is the leak rate of gasses through the material? Tests were performed to answer these questions.

Thin walled parts were made to test the hermetic tightness of 3D printed parts and to test the hydro-burst strength. These parts had a 0.5 mm wall thickness because this is as small as most 3D printing companies would recommend printing to get accurate results. By going to the smallest recommended thickness, this becomes a good margin condition to see how hermetic 3D printed parts can be. These parts were be closed cylinders with a threaded hole on one end with an O-ring groove to seal on the machine. The cross section of these parts can be seen in Figure 10. Figure 10 also shows that these parts were all built in a vertical orientation. These parts were checked on an Alcatel helium leak detector that creates a vacuum inside of the part then measures the amount of helium that can be pulled through the material. The outside of the parts were flooded with helium to ensure that sufficient helium is used.

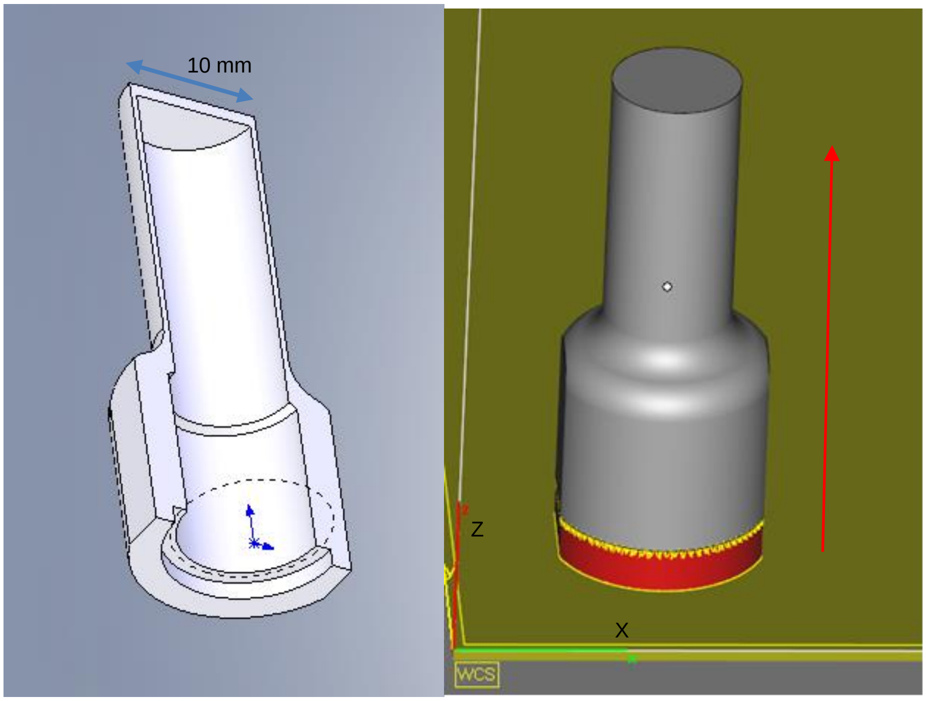

Figure 10. Cross section of hydro-burst part (left) and build orientation of hydro-burst part (right). Red area represents support structure required and the red arrow represents the build direction.

When leak checked, these parts all leaked at a leak rate of $1*10^{-8}$ mbar*l/sec. This leak rate is at the lower limit of the machine's measurement capability (i.e. It is suspected that the parts may actually leak at a lower rate and this measurement is due to small leaks through the machine). This level of tightness is as tight as one would expect from machined parts.

Because the parts are designed with a thin wall, they can be dimensioned such that they can be assumed thin walled cylinders. This will make it easier to calculate the expected burst results given the tensile strength. This should also drive the hydro-burst failures into the cylinder portion of the part. These parts were tested on a 50 KSI hydro-burst machine. The hydro-burst results are recorded in Table 6. The actual burst pressure was recorded along with the calculated burst pressures. The calculated burst pressures were found using the hoop strength equation for a thin walled cylinder,

$$Hoop\ Stress = \frac{Internal\ Pressure * Radius}{Wall\ Thickness} \tag{1}$$

The tensile strength in the X/Y direction was used in these calculations. This equation generally assumes that the wall thickness is about one-tenth the radius of the cylinder. In this equation, the hoop strength is set equal to the tensile strength the internal pressure is calculated. In this case, the parts do not meet the one-tenth rule since the radius is 5 mm. Nevertheless, they are close enough to calculate accurate burst pressures. All parts failed in the cylindrical portion of the parts, but the failure of the part made out of MS 1 extended into the axial portion of the part (Figure 11).

Material	Burst Pressure (MPa)	Calculated Burst Pressures (MPa)
MS 1	135.1	131.0
SS 316	59.8	69.2
AlSi10Mg	26.0	23.0

Table 6. Hydro-burst results for 3D printed parts.

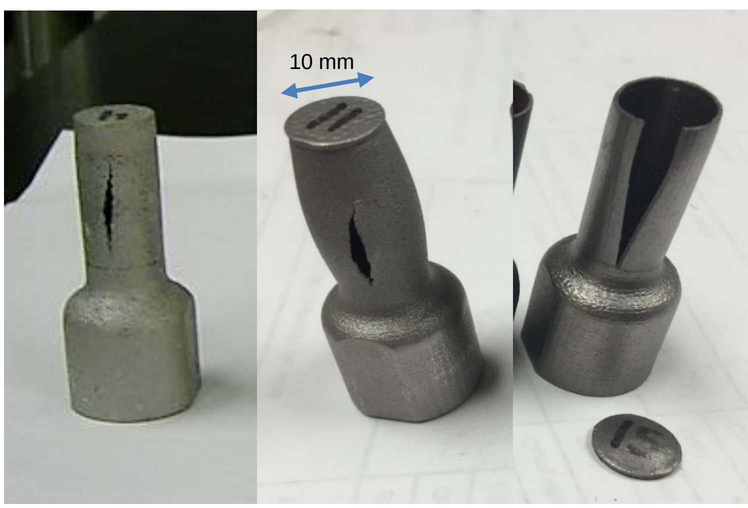

Figure 11: Hydro-burst failure modes from left to right: 3D printed AlSi10Mg, 3D printed SS 316, and 3D printed MS 1

The images of the fracture surfaces are shown in Figure 12, Figure 13, and Figure 14. These figures show that the failures are consistent with ductile overloads due to the micro-voids on the fracture surfaces. If they were brittle failures, they would be more faceted.

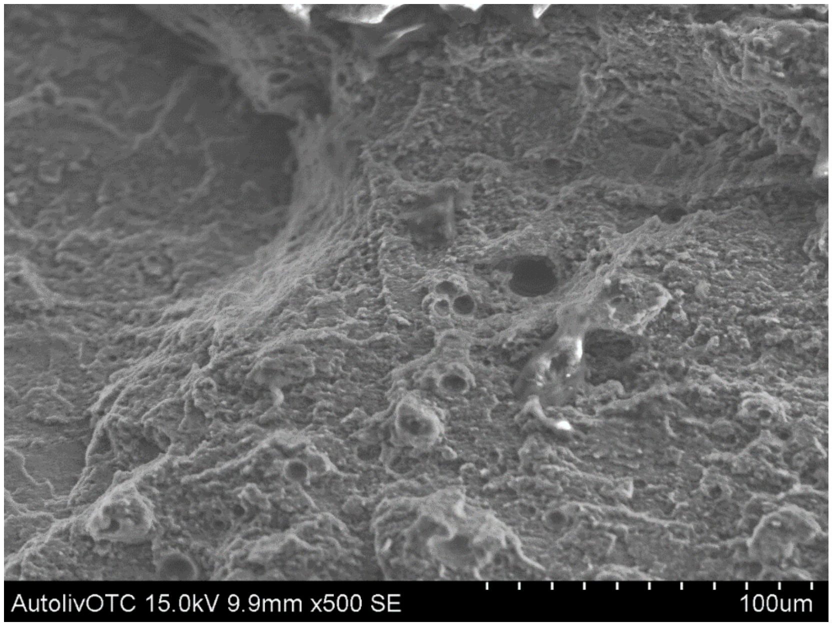

Figure 12. Fracture surface for 3D printed AlSi10Mg

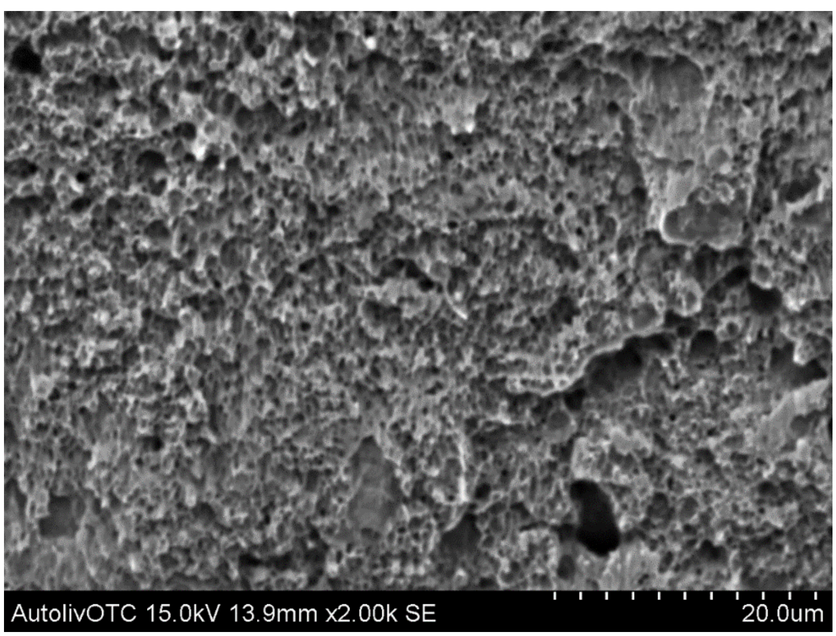

Figure 13. Fracture surface for 3D printed SS 316

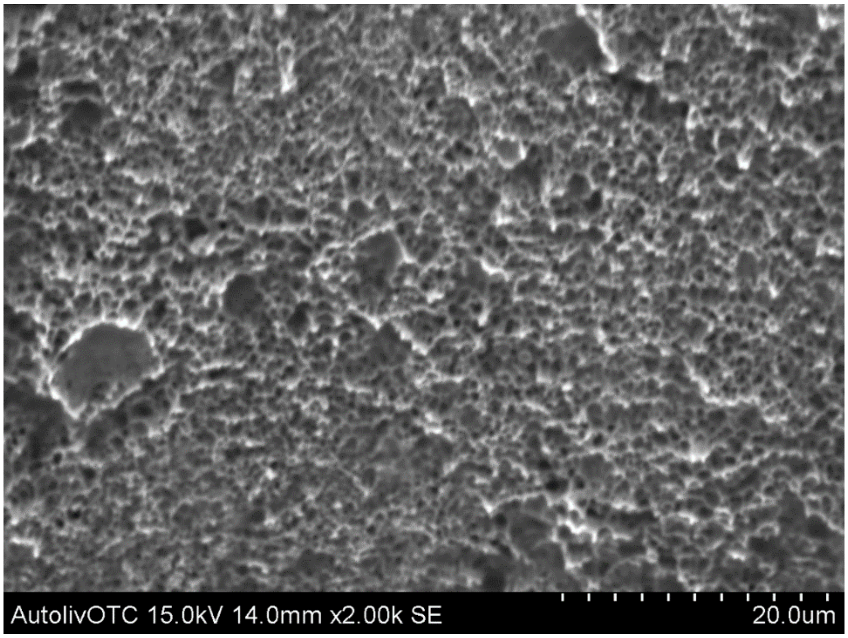

Figure 14. Fracture surface for 3D printed MS 1

2.7. Microstructure

One part, from each of the materials, was cut and polished to look at the microstructure of the 3D printed material. The microstructure images are shown in Figure 15, Figure 16, and Figure 17.

The aluminum microstructure (Figure 15) shows what appears to be boundaries between the grains that were deposited and sintered together. Figure 16 and Figure 17 cover a bigger area (Note the scale on the images). It appears that these images also show similar grain boundaries. The sintered grains have good contact that allows the strength and hermetic tightness to be the same as wrought material, but the toughness generally suffers from it.

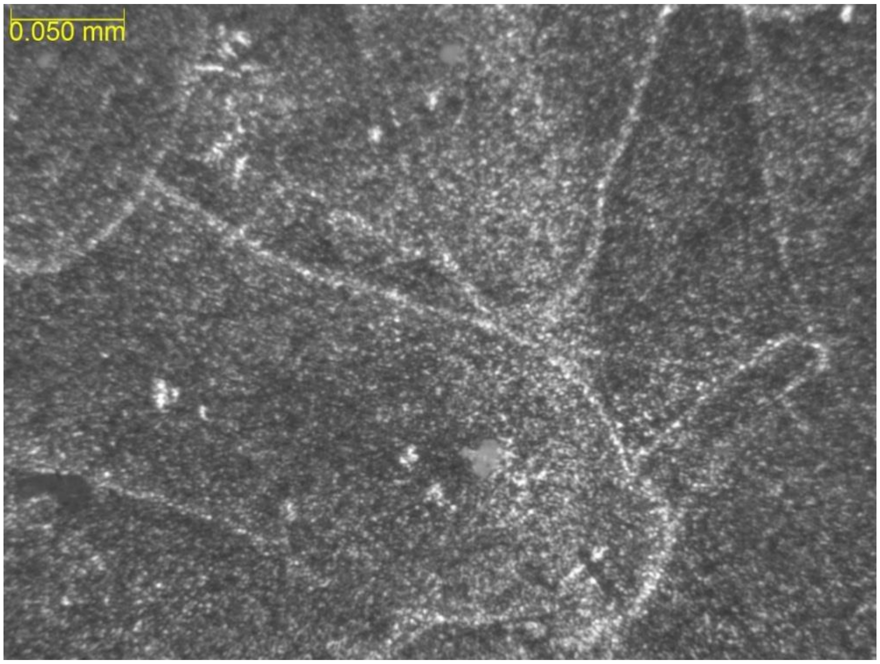

Figure 15. Microstructure of 3D printed AlSi10Mg

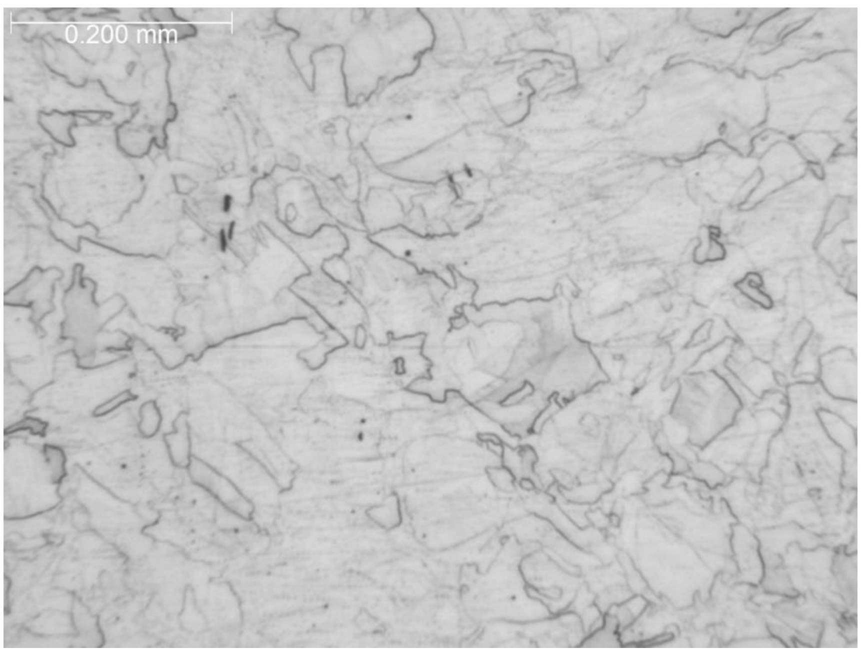

Figure 16. Microstructure of 3D printed SS 316

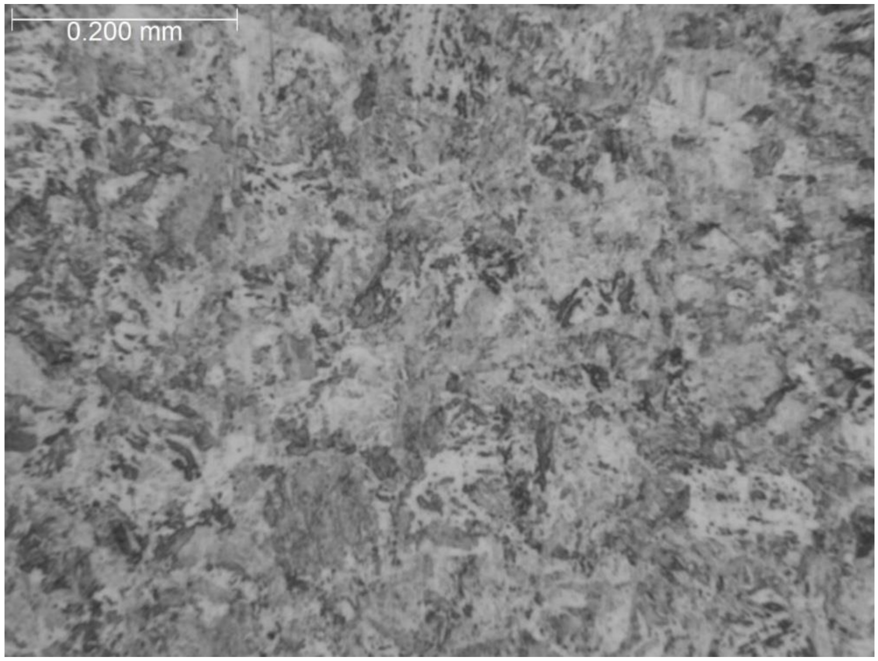

Figure 17. Microstructure of 3D printed MS 1

3. APPLICATIONS FOR METAL 3D PRINTING

3D printing can be used for many different applications. When thinking about where 3D printing can be used there are three different types of models that can be made, including:

1) A model that has the required size and shape of a specific part - "Looks like" model.

2) A model that has the required function of a part - "Works like" model.

3) A model that has the required form and function - "Looks like" and "Works like" model

"Looks like" models are used to build prototypes for display. Sales representatives, to show off what a manufactured part would look like, can use these models. Engineers can also use them to look at possible problems with fit-up, failure points and processing concerns. A lot can be learned from a product by having a 3D model that you can handle. Typically, a "looks like" model would be printed out of plastic due to the cost of printing metals, but may be printed out of metal if the desired weight and appearance need to be of metal.

"Works like" models are the most common models for metal 3D printing. Metals are much stronger than plastics. Metal parts can be printed to create parts that have a desired advantage over machining parts.

When designing complex tooling it can be much cheaper than machining parts. This is especially true for small parts that use very little material. When designing for 3D printed metal parts, it is good to remember that complexity of the part is free; it is the material and the print time that costs money. Money can also be saved when using metal 3D printing to combine tooling – One piece of tooling could take the place of several pieces that are joined. This makes it so there is less weight, less components, and less assembling required.

Another advantage of 3D metal printing is one can design tooling how it really should be designed and not be constrained by machining requirements.

Sometimes prototype parts need to both look like the real part and work like it. This is the third model that can be used. This is one of the big advantages of metal 3D printing – parts can be made to look and work like the parts you need them to.

4. DESIGN TECHNIQUES FOR METAL 3D PRINTING

When designing metal 3D printed parts, a different way of thinking is required. Because 3D printing of metals is new, many people that design parts are unfamiliar with the design process, the cost, and the applications of metal 3D printing. To understand the pros and cons, different tools were designed and built with 3D printed metals, which could replace production and prototype tooling.

The following case studies will demonstrate the different design techniques of metal 3D printing. These case studies demonstrate some of the advantages and limitations of metal 3D printing. Several things about designing for metal 3D printing were learned during these case studies. Although this report does not include all of the tricks for designing for 3D metal printing, it demonstrates some key advantages and limitations of printing with 3D metal parts.

4.1. Case Study 1 – Orient tool and ball feed

The first tool that was designed was a tool that has multiple functions. It contains a mechanism in it that causes a pin to come up to orient a part then the pin must go down and the whole part must move out of the way. While the part is in its forward position and the pin is up, a small ball is also fed through the tooling into a pocket below it. This assembly of parts is currently in production (Figure 18). The goal is to use metal 3D printing techniques to make it simpler, more robust and less expensive.

The first thing that was examined is how six components on the existing assembly could be reduced to just one single component when 3D printed.

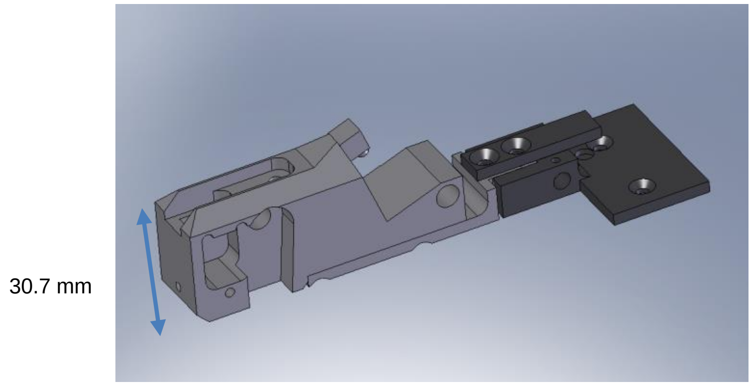

Figure 18. Current production orient tool and ball feed that is examined for benefits from metal 3D printing

When designing 3D printed parts complexity is free, but it is the material and the build time that cost money. The first shot at designing this 3D part was created with the end goal in mind and only adding material where necessary. This part can be seen in Figure 19.

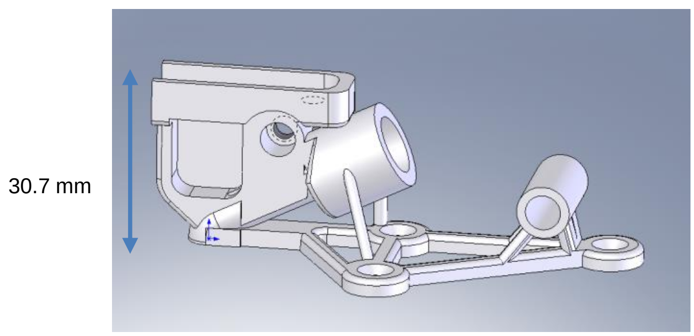

Figure 19. 3D printed orient tool and ball feed Rev A

Another concern of the existing assembly is the internal dimensioning of the part. The path through the part (as seen in Figure 20) is to feed a small steel ball through. The concern is that in order to create this tunnel, the part has to be drilled from both directions. Sometimes the holes do not line up exactly right and the ball can be stuck in the middle of the tooling. By 3D printing this part, a smooth transition can be designed, that would allow the ball to go through consistently (Figure 21).

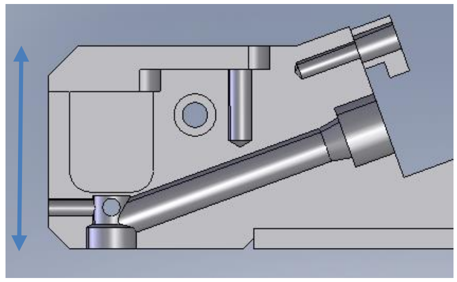

Figure 20. Cutaway view of current orient tooling assembly

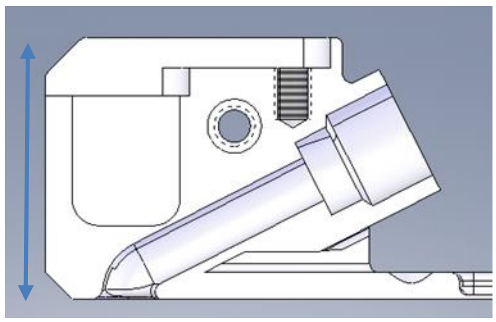

Figure 21. Cutaway view of metal 3D printed part

After designing the first iteration of the orient tooling, I3D Mfg. engineers brought up that by building the part designed, it would create many support structures. Support structures are needed to support the part as it is being built. Because the parts are built from the bottom up, overhanging parts need to be supported as they are being built. Support structures can also be used to keep parts from deforming from the internal strengths.

Typically parts can be self-supporting (They do not need support structure) if the overhang is 45º or less. If there is more of an overhang than that then the support structures have to be used. It is a common misconception that support structures are easy to remove. With plastic 3D printing, the support structures are often made from a different material that can be broken off with your fingers or that dissolve when placed in a specific solution. Metal 3D printing, however, uses the same material that the part is printed with. They are often removed with a file, by machining or use of a wire EDM.

By examining all of the overhanging sections in Figure 19, one can see that there would be large number of support structures that would be very difficult to remove. A second revision of this part was designed to minimize the amount of support structures needed, and would allow them to be removed much more easily. See Figure 22 for the second revision of this part.

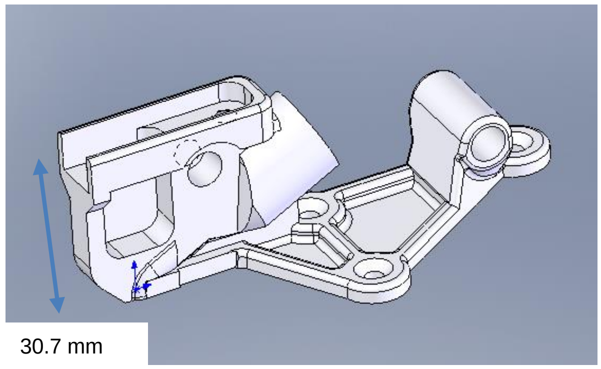

Figure 22. 3D printed orient tool and ball feed Rev B

This part was designed so that if it is built at a 45º angle then almost every angle on the part is at 45º or less. This creates much less support structure, and makes it much easier to remove. Figure 23 shows the build orientation and the required support structure (shown in red).

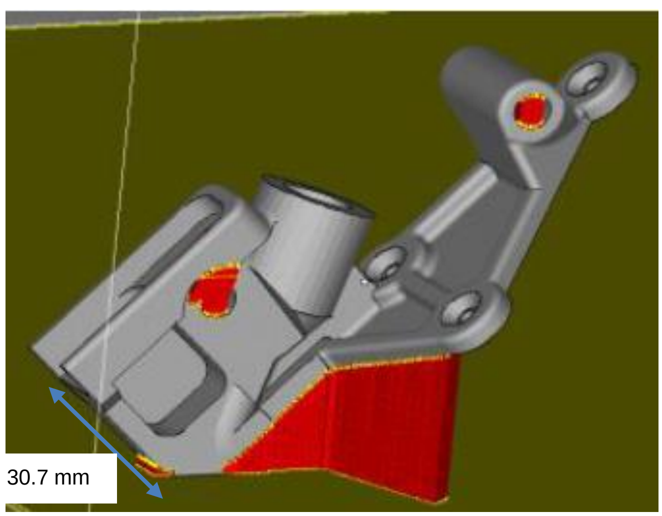

Figure 23. Support structure for 3D printed tool Rev B

By building this part along the 45º direction, as shown in Figure 23, it makes the part taller, which increases the time it takes to build this part because the part is built one layer at a time starting at the bottom. This increased build time makes the part more expensive if only one part is made. It also makes it so that more parts will fit on a build plate, which makes the build time per part less. Therefore, to reduce cost per part, the build plate should be as full as possible even if it adds a little extra height.

Rev B of this part was built out of SS 316 because it needed to be non-magnetic. There were a few concerns when the final part arrived. The first concern was that there were a couple key areas that the dimensions were not correct. The slot on the top of the part had closed a little due to the strengths in the parts. The Engineers at I3D MFG thought that they could control this better by controlling the printing parameters. The hole through the part that the ball goes through had also shrunk just a little which made it hard for the ball to go through. This was fixed by designing the hole to be a little bigger.

Rev C of this part was designed to fix these concerns. One of the bolt holes was moved as well so that the part would function better and to reduce the amount of support structure required. The view of the build orientation and support structure is shown in Figure 25.

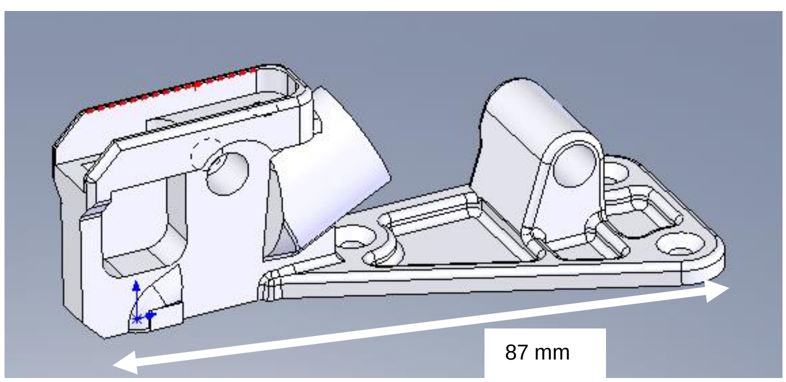

Figure 24. 3D printed orient tool and ball feed Rev C

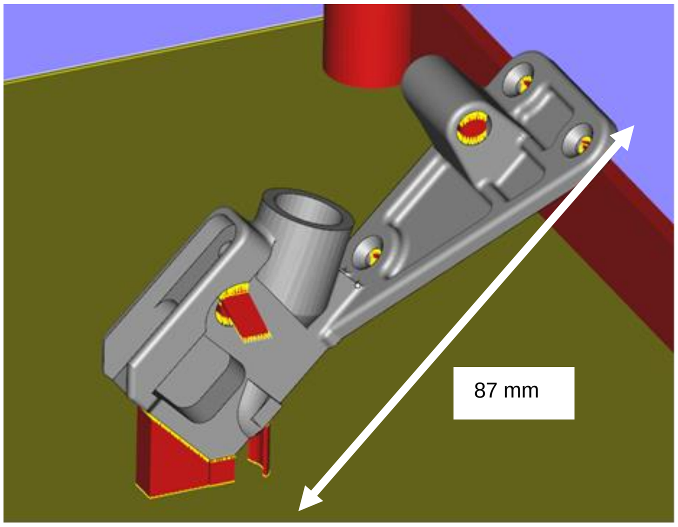

Figure 25. Support structure for 3D printed tool Rev C

There were two problems with the way Rev C printed. The first concern was obvious as soon as it was built. By increasing the diameter of the internal hole, that the ball goes through, it made the wall thickness below the recommended minimum wall thickness. This made the part crack when it was being built. When designing metal 3D parts the minimum recommended wall thickness is usually 0.5mm.

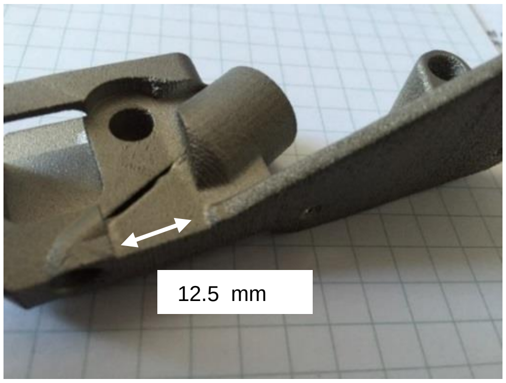

Figure 26. Crack in 3D part, Rev C, due to small wall thickness

The other concern from this part was the “volume jump” at the end of the part (Figure 27). By going from a thin area to a thick area, the end of the part curls up as indicated by the arrow in Figure 27. The solution to this was to decrease the volume in that area as shown in Figure 28

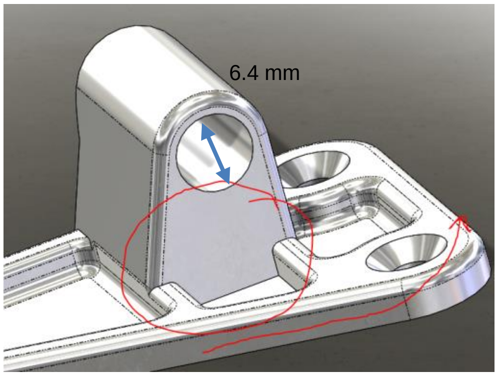

Figure 27. Volume jump of 3D printed part. The red circle shows the area with higher volume and the red arrow shows how the end of the part tended to curl up.

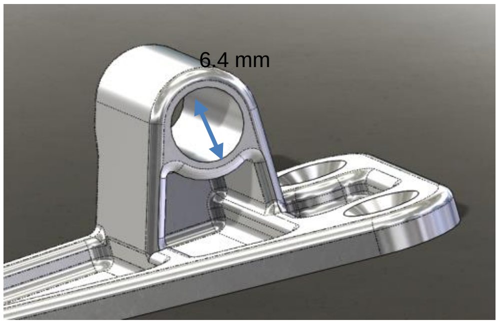

Figure 28. Volume jump solution

The final part of is shown in Figure 29. Several iterations were done on this part to make it a good candidate for metal 3D printing.

Figure 29. 3D printed orient tool and ball feed Rev D

The final cost of this part is $750.00 if only one part is made, but if 100 parts are ordered the cost is reduced to $247.50 per part. Combined total for the six parts that are machined today to create this assembly is $1,069.93. Even though metal 3D printing is much more expensive than machining for simple parts, this shows an example of how metal 3D printing can be much less expensive by building multiple parts, combining parts and making complex geometries.

4.2. Case Study 2 – Vacuum Press Tool

The second case study is to build a prototype tool that is used to install a small cylindrical foil into another part. MS 1 is used for this part so that it can be heat treated if necessary to reduce the wear. This part requires the use of a vacuum to hold the foil in place until it is pressed into the part. This tool requires several different parts. Two of the parts can be combined and kept much smaller by 3D printing them. For the vacuum to work there has to be an internal cavity. If these parts were machined, the internal cavity would have to be machined in one part, and then it would have to be closed off by the other part.

By 3D printing this part, the cavity can be created inside of the part. When creating internal cavities in 3D printed parts one needs to remember how the part is built. Parts are built by laying down one layer of powder at a time then sintering it together in the appropriate locations. If an internal cavity is created there needs to be a way to get the powder out of the part. In this part, the powder can be removed through the hole that connects to the vacuum hole.

Because there is no way to access the internal cavity of this part to remove support structure, it needs to be designed so that no support structure is required. This is done by putting a 45º at the top of the internal cavity of the part, which makes it self-supporting (see area marked with circle in Figure 30).

The build orientation was determined before this part was designed. By building the part as shown in Figure 30 there is no support structure needed for this part.

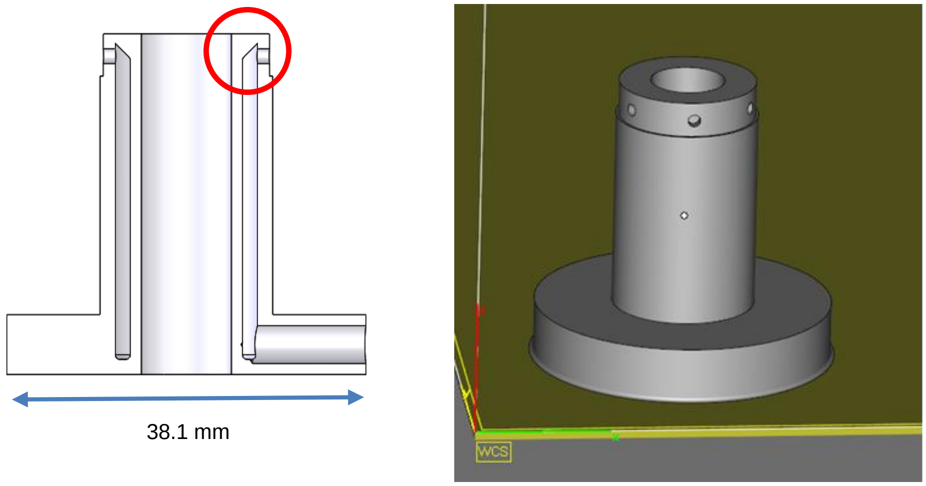

Figure 30. Cross section and build orientation with required support structure (none required) of vacuum press tool. The red circle shows the 45º angle overhang that makes support structure unneeded.

5. SUMMARY

Mechanical tests of AlSi10Mg, SS 316 and MS 1 3D printed materials show that, while not always the same as wrought materials, if the properties are understood, metal 3D printed parts can be built to meet the strength requirements of specific parts. Some of the major findings include:

1) The tensile strength (230 MPa in both directions tested) and yield strength (137 MPa in X/Y direction and 114 MPa in Z direction) for aluminum was about half of the published results, but Young's Modulus was similar in both directions. The Elongation at break was nearly twice the published results.

2) The tensile tests for SS 316 resulted in similar properties to those of published results and to wrought SS 316L. There was however a bigger difference in properties in the parts from the two different print orientations. The tensile strength in the X/Y direction was 692 MPa but in the Z-direction, it was 582 MPa. Tensile strength and yield strength results were within 10% of published value. The yield strength for SS 316 is double that of the wrought material at 235 MPa.

3) For MS 1, the yield strength and tensile strength are similar to the values published by EOS. This is, however, half that of wrought material of Maraging steel C300.

4) The toughness of AlSi10Mg and SS 316 is not published by EOS, but when tested it resulted in about a third of the toughness as wrought material. The printed MS 1 had over twice the toughness of the wrought material.

5) The hardness values and hermetic tightness of 3D printed materials are similar to what would be expected with wrought materials. The hydro burst values of printed metals are predictable given the material properties of the specific metal are known.

6) There was a lot of deviation of the parts tested to the published values. This means there is an unknown variable that affects the strength of this printed metal. Some possible variables are material lot, specific machine, and machine print parameters (i.e. laser power or speed). A follow-up study would be to test parts from different material lots, different machines and different machine parameters to see which variable causes the most variation.

7) When the accuracy of the material properties of a 3D printed part is critical to the design and robustness of that part, it is recommended that test specimens, with which these critical properties can be tested, be built in the same build.

This report has also shown many of the applications of metal 3D printing. The main advantage of 3D metal printing comes from making complex parts. 3D metal printing cannot just replace machined parts. Parts that are normally machined have been optimized to make the machining as simple as possible while still meeting the parts function. These parts have not been optimized to make them as simple for metal 3D printing since the build orientation of the part was not considered, the support structures were not considered and the height of the part probably was not considered.

Some of the limitations in designing for metal 3D printing are support structure removal; orientation of part during build; angles of features to avoid support structure; and specific dimensions that may cause problems (i.e. volume jump, thin wall, tight tolerances). However, when these limitations are considered, metal 3D printed parts can be very advantageous.

Designers and Engineers everywhere should be aware of the possibilities of metal 3D printing. Metal 3D printing is nowhere near the point where it can be used for all tooling in a high volume production, but it is a technique that should be considered and used where it makes sense. Metal 3D printing opens up doors that can make tooling much cheaper, more robust, and simpler to make. Parts can be built with metal 3D printing that could never be made before.

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