Mechanical and Physical Properties of AlSi10Mg Processed through Selective Laser Melting

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Abstract - In the past few decade, Additive Manufacturing (AM) has become popular and substantial to manufacture direct functional parts in varieties industrial applications even in very challenging like aerospace, medical and manufacturing sectors. Selective Laser Melting (SLM) is one of the most efficient technique in the additive Manufacturing (AM) which able to manufacture metal component directly from Computer Aided Design (CAD) file data. Accuracy, mechanical and physical properties are essentials requirement in order to meet the demand of those engineering components. In this paper, the mechanical properties of SLM manufactured AlSi10Mg samples such as hardness, tensile strength, and impact toughness are investigated andcompared to conventionallyhigh pressure die cast A360 alloy. The results exposed that the hardness and the yield strength of AlSi10Mg samples by SLM were increased by 42% and 31% respectively to those of conventionally high pressure die cast A360 alloy even though without comprehensive post processing methods. It is also discovered that AlSi10Mg parts fabricated by SLM achieved the highest density of 99.13% at the best setting parameters from a previous studyof 350 watts laser power, 1650 mm/s scanning speed and hatching distance 0.13 mm.

Keywords-Additive Manufacturing; AlSi10Mg; Mechanical Properties; Selective Laser Melting

I. INTRODUCTION

Selective Laser Melting (SLM) is one of the best technique in the additive Manufacturing (AM) which able to produce metal component with a single step process by following the Computer Aided Design (CAD) file data. Contrasting by conventional subtractive machining methods, SLM produced parts by a layer construction process, whereas thin layers of material are deposited/solidified, intricately, stacked on top of another. The layer information originates from 2-D cross sections of a 3-D CAD model. The fabrication process replications continue from bottom to top until the product is completed [1]–[4]. With the development of SLM over the past decade, the demand of the complex and new customize products on the market can be complied and simultaneously reduced the production time and manufacturing costs. Furthermore, SLM techniques are categorized green manufacturing by recycling the powder material that leads to zero wastage within the processes.In the AMpowder bed technique as illustrated inFig. 1. The piston raisedthe powder dispenser platform within the range of the thickness layer that been specified and then the re-coater arm distributed a layer of powder on top of the powder bed.A laser beam then melts and fuse the layer of powder metal, referring to the generated slice. After fabricating a layer was completed, the build piston will lower down the build platform and the following layer of powder is spread. The fabrication process repetitions continue from bottom to top until the part is completed.

The SLM process is controlled by the set of parameters demonstrated in Table I that has a great influence on the quality of the final part [5]. The foremost build parameters involved in the process of the process are laser power, scanning speed, hatch spacing, and layer thickness.Scanning strategy and building atmosphere also contribute as a significant factor to ensure the fabricated part goes form good to superior quality. There are many investigations and experiments work can be discussed in the current literature about the properties of laser sintered parts considering these parameters to enhance microstructure and mechanical properties parts of different materials [5]–[8].

From powders to full dense metal component with excellent physical and mechanical properties, high quality of surface roughness and good part build accuracy are the main aim of the most investigations and experiments work. The effect of parameters and variation scanning strategies and orientations on mechanical properties have been investigated by many researchers [6], [7], [9]–[11]. Besides the effect of processing parameters for instance laser power, scan speed and hatching distance, powder characteristics are of important concern. The size, shape, particles distribution and chemical composition of the powder have a strong influence in the melting and fusing activity. Powders with low oxygen, content high flow rate and high packing density are preferred [6], [12]–[14] .

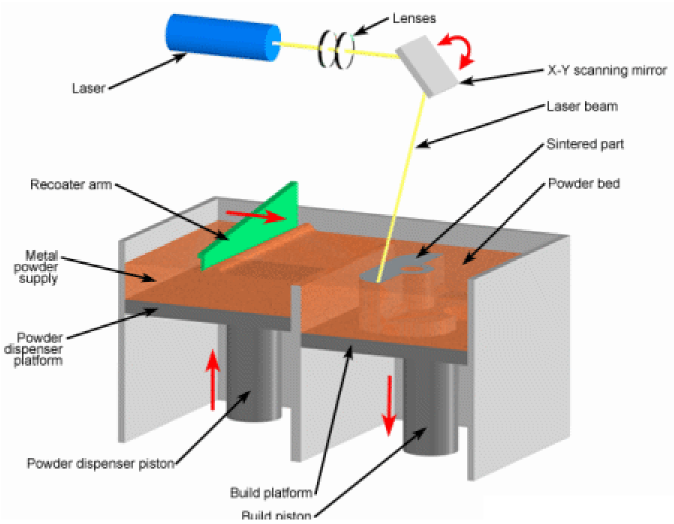

Fig. 1: A schematic diagram of the AM powder bed technique machine

Aluminium-Silicon alloys are very light metal with strength to weight ratio and characterized with high strength, good weld-ability and exceptional corrosion resistanceAttributable to their attractive combination of mechanical properties and high thermal conductivity at low weight, Al-Si alloys has been used in a large number of applications such as automotive, aerospace and moulding industries [3], [15]–[18]. By adding magnesium in aluminium-silicon alloys will extended the mechanical properties and increase the modulus of elasticity and ductility properties. AlSi10Mg, the alloy being used in this experiment, contains 0.3 to 0.5 wt% Mg and can be hardened through a specific heat treatment to enhance the mechanical properties [19], [20]. Furthermore, due to the near-eutectic composition of Al and Si which is resulted to a small solidification range, make the SLM process relatively easy compared to high strength aluminium alloys such as the 7000 series [21], [22].

TABLE 1. Controlling parameters in SLM process [5]

Process Parameter			
Laser-related	**Powder-related**	**Scan-related**	**Temperature-related**
• Laser power • Spot Size • Pulse Duration • Pulse frequency	• Particle size • Particle shape & distribution • Powder bed density • Layer Thickness • Material properties	• Scan Speed • Scan Spacing • Scan Pattern	• Powder bed temperature • Powder feed temperature • Temperature uniformity

The main aim of this paper is to investigate the density/porosity,surface roughness and mechanical properties such ashardness, tensile strength and Impact toughness of AlSi10Mg samples produced by SLM and compare those properties to the conventional high pressure die cast A360 alloy. The results will be used to predict and to facilitate the manufacturing process for mould fabrication and other automotive applications.

II. MATERIAL AND EXPERIMENTS

A. Material

Besides the effect of processing parameters, the size, shape, particles distribution and chemical composition of the powder have a significant influence in the melting and fusing activity. The chemical composition of the AlSi10Mg powder which was supplied by LPW Technology Ltd is shown in Table II. In this research work, the powder was sowed on a double-sided carbon tape and softly shaken to assure a thin layer of powder being left on the sample block. The morphology and the size of the powder were examined using Field Emission Scanning Electron Microscope (FESEM, JSM-7600F) micrograph.

TABLE II. Chemical composition of the investigated AlSi10Mg alloy (Wt. %)

Cu	Fe	Mg	Mn	N	Ni	Pb	O	Si	Sn	Ti	Zn	Al
0.05	0.10	0.39	0.01	0.20	0.01	0.01	0.11	10.00	0.01	0.15	0.1	Bal

B. Experimental works

The SLM system SLM 125 HL (SLM Solutions),was used to manufacture all samples in this study. The machine system is equipped with a 400 W fibre laser with 80 µm laser beam spot and has a build chamber of 125 × 125 × 125 mm as shown in Fig. 3. Argon is used as inert gas in the build chamber. The stripe scanning strategy with 45° orientation and 90° rotated incrementally no the next layer was used. The platform building was maintain at 150°c to avoid the build samples from warping due to non-uniform thermal expansion at elevated temperature. The thickness layer of the powder was constant at 30μm by lowering the build platform. An aluminium platform is placed on the building platform (XY table) and levelled.

In order to manufacture all test samples in optimum physical and mechanical properties, this experiment was conducted using the best setting parameters from previous study, wherebyone factor at a time (OFAT) approach has been used. A laser power of 350W, a scan speed of 1650mm/s and a hatching distance of 0.13 mm was used to manufacture 8 test cube samples with dimensions of 10mm×10mm × 10mm have been built to examine the microstructure of the top and side surface using Scanning Electron Microscope (SEM). The same samples are used to measure the density and porosity. Archimedes method was used to determine the relative density of the material by comparing the weight in air and distilled water. The relative density of the material is expressed in % relatively to the materials' theoretical density of 2,68g/cm^3[6], [11].

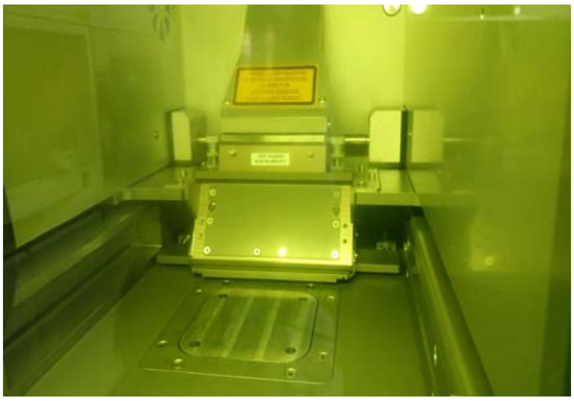

Fig. 3: Build chamber SLM system SLM 125 HL

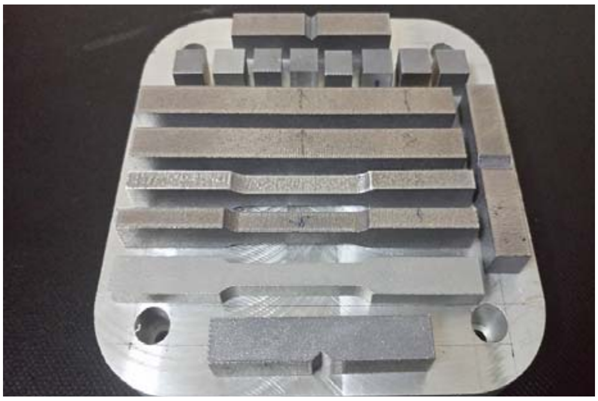

Fig. 4: The arrangement of samples on the SLM platform

To determine the mechanical properties, hardness test, tensile test, and Charpy impact test were performed. The value of the hardness tests were determine using Shimadzu HMV-2T E under the load of 2.942 N (HV0.3). The measurement was taken from the top and side surface on ten different location supporting the general characterization of the microstructure.Tensile test samples using the ASTM E8 standard with the 25 mm gauge length were directly built on the platform in the x-z axis. Precision machining and polishing by abrasive papers were carry out on the gage length to improvise the surface quality. A Gotech testing machine with 0.5 mm/s test speed was used to measure the mechanical properties.Samples for transverse rupture strength test were prepared according to the ASTM E23 Type A. Fig. 4 shows the samples built by the SLM process.

III. RESULTS AND DISCUSSION

C. Morphology of AlSi10Mg Powder Particles

Fig. 5 shows the Field Emission Scanning Electron Microscope (FE-SEM) micrograph of AlSi10Mg powder as in received conditions. The AlSi10Mg particles are not spherical and size ranges from 5 to 50 µm. The appearance of the particles are very irregular morphology, with many small irregular satellite particles agglomerated to the big particles creating some clusters of about 60 to 80 µm, and this could be detrimental for the final density of the SLM parts, considering that the layer thickness employed in this research is of 30 µm. Regardless of the irregular powder morphology, the powder had an acceptable flowability and Hauser's ratio for SLM.

(a) (b)

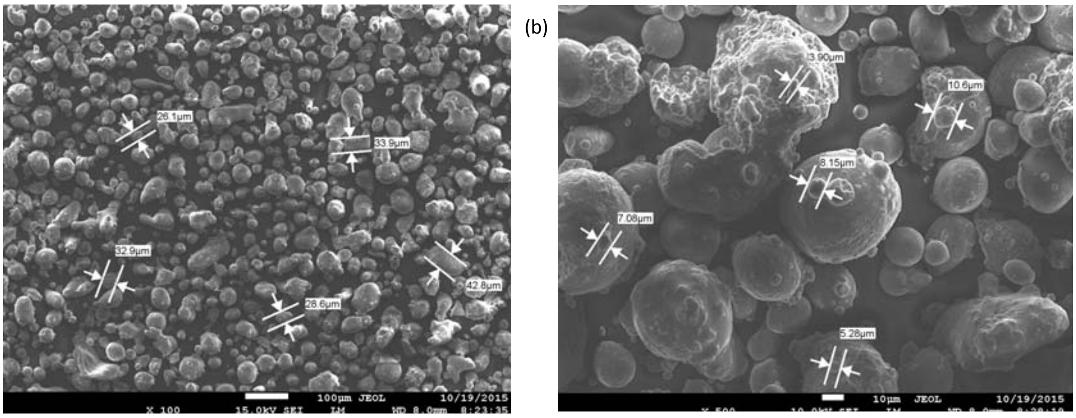

Fig. 5 shows the Field Emission Scanning Electron Microscope (FESEM, JSM-7600F) micrograph of AlSi10Mg powder (x100(a)& x500(b))

In Fig. 6a and 6b shows the SEM micrograph of top surface and the side surface of Y direction of the samples produced by SLM with the laser power of 350W, scanning speed of 1650mm/s and 0.13 mm hatching distance. Both surfaces are almost smooth but the laser scanning tracks are visible especially on the side surface shows more of the wavy layers. Due to the surface tension effect, the formation of metallic balls occurred during the laser melting process.

(a) (b)

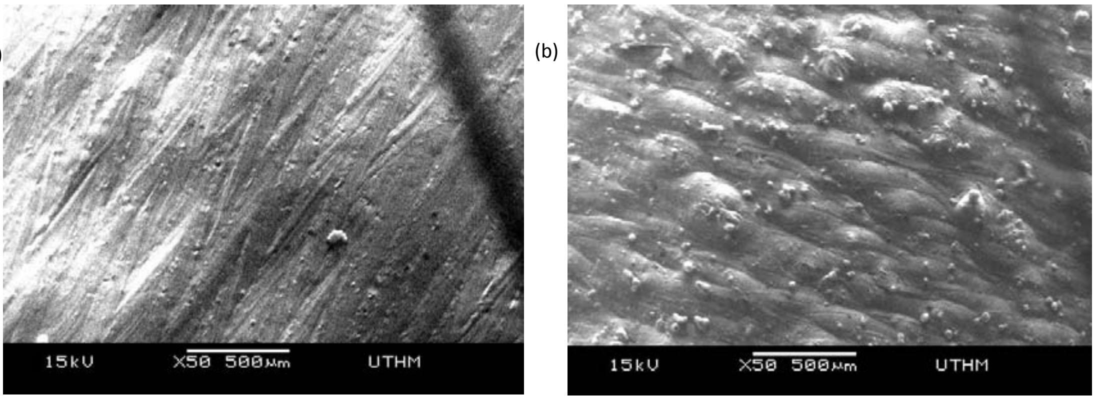

Fig. 6: SEM micrograph of the (a) top surface (b) side surface of the AlSi10Mg samples by SLM (laser power: 350W; scanning speed: 1650 mm/s, hatching distance: 0.13 mm.

D. Density and porosity

In Table III listed the values ofmeasured density and relative density that have been obtained by Archimedes method. Eight samples using the optimized parameters from a previous study that resulted in a maximal density permitted to achieve the optimum mechanical properties of AlSi10Mg samples produced by SLM.A uniform relative density can be found in this experiment with the highest value of 99.13% in the sample 4.In order to promote the optimum mechanical properties of AlSi10Mg parts produced by SLM, the density can be further increased to 99.8% by re-melting every layer with the same parameters, but alternating directions over 90°[5].

TABLE III. Density measurement by Archimedes method

Nr. Sample	Weight in AIR(A)	Weight in WATER (B)	Water Tempt (°C)	Water density	Measured Density	Theoretical Density	Relative Density %
1	2.549	0.956	30.2	0.995	2.654	2.68	99.034
2	2.576	0.966	29.6	0.995	2.656	2.68	99.108
3	2.562	0.960	29.1	0.995	2.656	2.68	99.109
4	2.564	0.961	29.1	0.995	2.656	2.68	99.132
5	2.561	0.961	28.5	0.996	2.653	2.68	99.013
6	2.553	0.958	28.5	0.996	2.654	2.68	99.030
7	2.600	0.975	28.4	0.996	2.654	2.68	99.054
8	2.551	0.957	28.3	0.996	2.654	2.68	99.032

The percentage of the Volume fraction porosity can be calculated due to the uniformly dense samples, it ranges from 0.8% to 0.9%, so it is certainly low and this will enhanced the mechanical properties of the samples. Fig. 7a and 7b shows the porosity microstructure of the top and side surface of sample 4.

(a) (b)

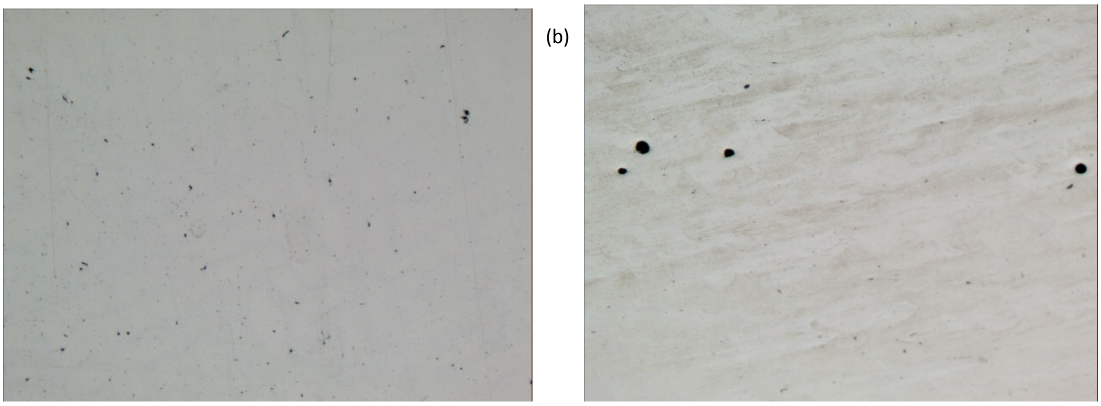

Fig. 7: The porosity microstructure of the (a) top surface (b) side surface of sample 4.

E. Mechanical properties

Hardness is well known as an initial indication for mechanical properties. By using the Micro-Vickers hardness testing machine, the measurements were performedon 10 different location of the top surface (x-y direction) and side wall surface (y-z direction) to all the 8 test cube samples as mentioned in heading 3 with dimensions of 10mm ×10mm × 10mm of each cube. The mean value of hardness on both surfaces direction is reported in table 4.

Ultimate Strength, 0.2% Yield Strength and Elongation in % obtained from the tensile tests using ASTM E23 standard,total 3 samples were examined for the AlSi10Mg processed through SLM in x-z direction at optimized parameters. The mean values for 3 tested results were taken and presented in Table IV while the stress-strain curve for them is shown in Fig. 8. The Ultimate Strength, 0.2% Yield Strength and Elongation in % from tensile test ofHigh pressure die cast (HPDC) alloyA360F, HDPC alloy A360T6[23]and from the other SLM processed AlSi10Mg Samples experiment using X-Y and Z building direction[24]are also listed for reference and comparison purpose with this research work. Both HPDC alloysare considered to give the optimum mechanical properties for mould manufacturing through the casting processes only. This is the reason to examine the mechanical properties for AlSi10Mg alloy processed through SLM in x-z direction for further investigation and practicability in the mould manufacturing and other automotive applications.

TABLE IV. Mechanical properties of SLM AlSi10Mg samples and HPDC alloy A360F and HDPC alloy A360T6

Material	Direction	0.2%Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation at Break (%)	Hardness (HV)	Impact energy (J)
AlSi10Mg	X-Z	242 ± 5	412 ± 2	6.34 ± 0.3	139 149	2.5 ± 0.5
A360F[23] A360T6[23]	-	160-185 285-330	300-350 330-365	3-5 3-5	95-105 130-133	2.5-3.0
AlSi10Mg[24]	X-Y Z	-	391 ± 6 396 ± 8	5.55 ± 0.4 3.47 ± 0.6	127	3.94 ± 0.5 3.69 ± 0.4

Both measurement from the top surface (x-y direction) and side wall surface (y-z direction) of the Vickers hardness is higher than HPDC alloy A360F and HDPC alloy A360T6. The enhancement of the Vickers hardness value is about 32% for top surface (x-y direction) & 42% for side wall surface (y-z direction)while 4% and 12% enhancement compared to HPDC alloy A360F and HDPC alloy A360T6 respectively.The 0.2% yield strength value of the AlSi10Mg samples produced by SLM is 31% higher when compared to HPDC alloy A360F, but 27% lower from the HDPC alloy A360T6, whereas the value of the ultimate tensile strength for SLM AlSi10Mg samples is higher whencompared to the both HPDC alloys. The elongation is nearly 2% higher comparable to the HPDC alloys in both conditions. This is also been proven by [24]in his experiment using the same material processed through SLM in x-y & z direction having almost the same trends of results when comparing to both HPDC A360F and A360T6 alloys,however; a slightly lower results of mechanical properties whencompared to this research work. This is because of processing the samples in x-zbuilding direction and the value of density of the tested sample in this work is also higher at almost 1%.

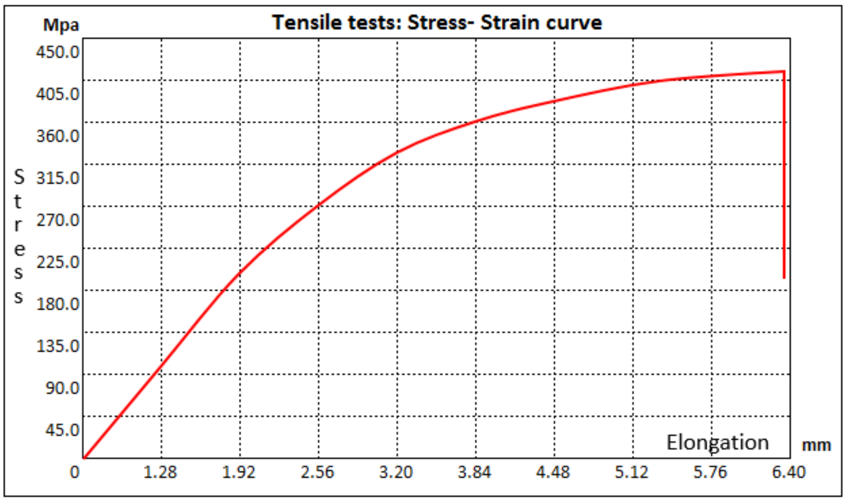

Fig. 8: Stress-Strain curves for SLM AlSi10Mg Samples built along X-Z direction

While theresult of charpy impact energy of this research workis still comparable to both HPDC alloys,however; a lower value by 32% noticed whencompared to [24]research work. From the experimental result, it can be observed that the AlSi10Mg samples produced by SLM in x-z direction possessed greater mechanical properties then to the HPDC alloy A360F and HDPC alloy A360T6 and can be concluded that it can be practically employed for the mould manufacturing and other automotive applications.

IV. CONCLUSION

After characterization and analysis of the powders' size, morphology and chemical composition through to the assessment of mechanical properties of AlSi10Mg SLM as-fabricated samples, it can be determined that:

1. The AlSi10Mg powders employed in this study are spherical and irregular in shape with an average size of 5 to 50 µm, but very fine particles with a diameter lower than 10 µm tend to agglomerate, developing bigger clusters of irregular shape. These clusters can poorly affect the flowability of the powders. Sieving process is compulsory needed before starting the SLM process.
2. Density evaluation of samples indicates a measurement of 99.13% relative density. Microscopic observations show that porosities are very small, on the order of 5 to 20 µm.
3. In comparison to the properties of a the HPDC alloy A360F and HDPC alloy A360T6, AlSi10Mg SLM samples show very high values of hardness, yield strength, ultimate tensile strength and elongation at break, while for the Charpy impact energy test, there is comparable although with a slightly lower value.
4. The AlSi10Mg samples of this research work produced by SLM in X-Z direction possessed greater mechanical properties then to the HPDC alloy A360F and HDPC alloy A360T6 and can be concluded that it can be practically employed for the mould manufacturing and other automotive applications whereby will tremendously decrease the manufacturing cost.

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REFERENCE

[1] C. Y. Yap, C. K. Chua, Z. L. Dong, Z. H. Liu, D. Q. Zhang, L. E. Loh, and S. L. Sing, "Review of selective laser melting: Materials and applications," Appl. Phys. Rev., vol. 2, no. 4, 2015.
[2] X. Yan and P. Gu, "A review of rapid prototyping technologies and systems," CAD Comput. Aided Des., vol. 28, no. 4, pp. 307–318, 1996.
[3] S. Rahmati, "Direct rapid tooling: a review of current research," Compr. Mater. Process., vol. 10, no. 2, pp. 303–344, 1998.
[4] K. V. Wong and A. Hernandez, "A Review of Additive Manufacturing," ISRN Mech. Eng., vol. 2012, pp. 1–10, 2012.
[5] N. T. Aboulkhair, N. M. Everitt, I. Ashcroft, and C. Tuck, "Reducing porosity in AlSi10Mg parts processed by selective laser melting," Addit. Manuf., vol. 1–4, pp. 77–86, 2014.
[6] D. Manfredi, F. Calignano, M. Krishnan, R. Canali, E. P. Ambrosio, and E. Atzeni, "From powders to dense metal parts: Characterization of a commercial alsimg alloy processed through direct metal laser sintering," Materials (Basel)., vol. 6, no. 3, pp. 856–869, 2013.
[7] M. Krishnan, E. Atzeni, R. Canali, D. Manfredi, F. Calignano, E. P. Ambrosio, and L. Iuliano, "On the effect of process parameters on properties of AlSi10Mg parts produced by DMLS," Rapid Prototyp. J., p. manuscript accepted, 2014.
[8] N. Raghunath and P. M. Pandey, "Improving accuracy through shrinkage modelling by using Taguchi method in selective laser sintering," Int. J. Mach. Tools Manuf., vol. 47, no. 6, pp. 985–995, 2007.
[9] S. Siddique, M. Imran, E. Wycisk, C. Emmelmann, and F. Walther, "Influence of Process-Induced Microstructure and Imperfections on Mechanical Properties of AlSi12 Processed by Selective Laser Melting," J. Mater. Process. Technol., vol. 221, pp. 205–213, 2015.

[10] F. Calignano, D. Manfredi, E. P. Ambrosio, L. Iuliano, and P. Fino, “Influence of process parameters on surface roughness of aluminum parts produced by DMLS,” Int. J. Adv. Manuf. Technol., vol. 67, no. 9–12, pp. 2743–2751, 2013.
[11] R. Canali, “Study, development and characterization of aluminum based materials by additive manufacturing Part 2,” pp. 0–58, 2015.
[12] E. Louvis, P. Fox, and C. J. Sutcliffe, “Selective laser melting of aluminium components,” J. Mater. Process. Technol., vol. 211, no. 2, pp. 275–284, 2011.
[13] Y. Wang, J. Bergström, and C. Burman, “Characterization of an iron-based laser sintered material,” Mater. Sci. Eng. A, vol. 513–514, no. C, pp. 64–71, 2009.
[14] E. Brandl, U. Heckenberger, V. Holzinger, and D. Buchbinder, “Additive manufactured AlSi10Mg samples using Selective Laser Melting (SLM): Microstructure, high cycle fatigue, and fracture behavior,” Mater. Des., vol. 34, pp. 159–169, 2012.
[15] B. Vandenbroucke and J.-P. Kruth, “Selective laser melting of biocompatible metals for rapid manufacturing of medical parts,” Rapid Prototyp. J., vol. 13, no. 4, pp. 196–203, 2007.
[16] D. Manfredi, F. Calignano, E. P. Ambrosio, M. Krishnan, R. Canali, S. Biamino, M. Pavese, E. Atzeni, L. Luliano, P. Fino, and C. Badini, “Direct Metal Laser Sintering: An additive manufacturing technology ready to produce lightweight structural parts for robotic applications,” Metall. Ital., vol. 105, no. 10, pp. 15–24, 2013.
[17] M. Rivette, P. Mognol, and J.-Y. Hascoët, “Method to obtain hybrid rapid tools with elementary component assembly,” Rapid Prototyp. J., vol. 19, no. 2, pp. 77–87, 2013.
[18] a. Simchi, “Direct laser sintering of metal powders: Mechanism, kinetics and microstructural features,” Mater. Sci. Eng. A, vol. 428, no. 1–2, pp. 148–158, 2006.
[19] S. Menargues, E. Martín, M. T. Baile, and J. A. Picas, “Materials Science & Engineering A New short T6 heat treatments for aluminium silicon alloys obtained by semisolid forming,” Mater. Sci. Eng. A, vol. 621, pp. 236–242, 2015.
[20] J. Rajabi, G. Branch, J. Rajabi, E. Alibeiki, G. Branch, M. Nekoei, S. Branch, M. Rajabi, G. Branch, M. R. Meschian, and M. Branch, “MODELING THE T 6 HEAT TREATMENT OF Al-Mg-Si ALLOY BY,” vol. 2, no. 3, pp. 114–119, 2012.
[21] E. O. Olakanmi, “Direct selective laser sintering of aluminium alloy powders,” no. November, 2008.
[22] N. Read, W. Wang, K. Essa, and M. M. Attallah, “Selective laser melting of AlSi10Mg alloy: Process optimisation and mechanical properties development,” Mater. Des., vol. 65, pp. 417–424, 2015.
[23] “CSIRO Light Metals Flagship Technical data sheets for heat treated aluminium high pressure die castings,” 2008.
[24] K. Kempen, L. Thijs, J. Van Humbeeck, and J.-P. Kruth, “Mechanical Properties of AlSi10Mg Produced by Selective Laser Melting,” Phys. Procedia, vol. 39, pp. 439–446, 2012.

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