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Process parameter optimization of dmls process to produce AlSi10Mg components

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Abstract. AlSi10Mg components were produced by Direct Metal Laser Sintering (DMLS) and its physical properties like density and mechanical properties ultimate tensile strength were measured. The experimental analysis showed that energy density and hatch spacing are the vital factors influencing the density of the components, the range of energy density for obtaining the best result was 42.40-63.25 J/mm³. The most important parameter effecting the Ultimate Tensile Strength (UTS) was Laser Power but Hatch Spacing also had an equal importance on the tensile strength but energy density analysis revealed that the highest energy density did not gave the least value of UTS as it was in the case of density. The optimum process parameter for both density and UTS was found to be a Laser Power of 330 W, Scan Speed of 1200 mm/s and Hatch Spacing of 0.15 mm.

1. Introduction

AlSi10Mg components has a very high strength to weight ratio because of which it is extensively applicable in aerospace and automobile industry [1,2]. The addition of silicon to aluminium increases the fluidity and decreases the solidification contraction. The addition of magnesium to the Al-Si alloy results in the formation of Mg₂Si precipitates enhancing its strength and also renders the alloy heat treatable. Additive Manufacturing produces components by adding one layer to the other, according to a 3-D CAD file. DMLS process is a powder bed fusion process which uses a heated build plate to aid in heat dissipation a powder layer the thickness of which is kept constant and is equal to the layer thickness is spread on the build plate by a recoater arm, a laser beam is used to sinter the powder. The most important parameters that influences the quality of the final parts in DMLS process are Laser Power, Hatch Spacing and Scan Speed [3]. The three most important parameters could be represented by a volumetric energy density function ϕ (j/mm³) [1,4] which is given as $\phi = p \div (h \times s \times z)$, where p =Laser Power, s=Scan Speed, h=Hatch Spacing and z =Layer Thickness [5,6]. These energy density model can be correlated to the mechanical properties of the components. In this paper Taguchi analysis was performed on tensile strength and ANOVA was performed on density of the manufactured AlSi10Mg components. The major drawback of DMLS process is that the optimum parameters for processing the same material varies from machine to machine, there are very few literatures available regarding the optimization of process parameter for the EOS INT M280 DMLS machine for sintering AlSi10Mg powder to get the best result for density and UTS. This paper would help in narrowing this gap.

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2. Material and method

The AlSi10Mg powder, the size of which ranges from 3-40 μ m as communicated by the provider EOS GmbH. The morphology of the powder is shown in figure 1 which shows that the particle shape is mostly spherical with smaller satellite particles attaching to the surface of the almost spherical particles, the flowability of the powder is primarily determined by the size and shape of the powder [7].

The chemical composition of the powder was also provided to us by EOS GmbH company and is given in the table 1.

Table 1. Chemical composition of powder.			
Element	Concentration (wt %)		
Si	10.7		
Mg	0.43		
Fe	0.17		
Mn	<0.01		
Cu	< 0.005		
Zn	< 0.002		
Ti	0.01		
Al	Balance		

The reflectivity and thermal conductivity values of Al is very high due to which high energy density is required for better densification and mechanical properties due to which laser power of 370 W was used. To investigate the interaction effect laser power was reduced to 330 W and 290 W. The use of high scan speed results in balling phenomenon depressing the density and surface finish [8] but increases the build rate whereas slow scan speed promotes oxide formation. With the increase in hatch spacing results in increase of gaps between the adjacent scan tracks and decrease in density.



Satellite particle

Figure 1. Morphology of the powder.

3. Manufacturing strategy

The DMLS process employs a laser beam to melt powder in the region of interest and components are produced by adding successive layers according to a 3D-CAD file [9]. The samples were manufactured in EOS INT M280 machine as shown in figure 2 which uses a laser power upto 400 W and a Yb fibre continuous laser beam. The building volume of the machine is 250×250×325 mm³. Rapid Prototype tool was used to convert the 3D-CAD file into Sliced Layer Interface (SLI) file, Magic software was used to build the support structure. Process Software (PSW) was used to vary the process parameter and for exposing the top view of the specimen to the laser beam for fabrication. The base plate is of Al

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the base plate was heated to a 165° C to aid in heat dissipation and to minimize internal stresses which are characteristics for DMLS parts [10]. The layer thickness was fixed at 30 µm, the recoater arm deposited the desired layer thickness of powder as the build plate was lowered until the components were fully fabricated. Alternating scan-strategy was employed. The as built components were kept at 300° C for 2 hours to relieve internal stresses and were polished to get the final component.



Figure 2. Manufacturing chamber of the DMLS machine.

4. Experimental design

In our study three levels of laser power, scanning speed, hatch spacing was chosen. The levels of the process parameter are shown in table $2.L_9$ orthogonal array design of experiment (doe) was developed demonstrated in table 3.

Table 2. Level of dmls process.					
Level	Level LASER POWER,LP SACAN SPEED,SS				
	(W)	(mm/s)	SPACING,HS (mm)		
1	370	1400	0.19		
2	330	1300	0.15		
3	290	1200	0.11		

Specimen number	LP(W)	SS(mm/s)	HS(mm)
1	370	1200	0.11
2	370	1300	0.15
3	370	1400	0.19
4	330	1200	0.15
5	330	1300	0.19
6	330	1400	0.11
7	290	1200	0.19
8	290	1300	0.11
9	290	1400	0.15

To perform the parameter optimization for density,9 samples of dimensions 10 mm×10 mm× 10 mm were manufactured according to the parameter combination in the orthogonal array L_9 .

To optimize the parameter for tensile strength, horizontal samples were manufactured as shown in figure 4.

The dimension of the sample prepared were according to ASTM E8-00 as demonstrated in figure 3.



Figure 3. Tensile test Specimen Specification as per ASTM E8-00 (All dimensions are in mm). The horizontal as built specimen for tensile strength is shown in Figure 3.

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Figure 4. As built component.

The density of the samples was calculated by Archimedes Principle [11] which is given by the following equation.

$$Density = \frac{Ma}{Ma - Ml} \times \rho l$$
(1)

Where Ma= Mass in air (gm), Ml= Mass in liquid (gm), ρ l= Density of liquid (ethanol) in gm/cm³, Density in (gm/cm³). Relative Density (RD) of the samples was calculated by considering the theoretical density as 2.67 gm/cm³ and was expressed in percentage, the ultimate tensile strength value is also listed in table 4.

Specimen number	LP (W)	SS (mm/s)	HS (mm)	Energy density	Relative density	UTS
				(J/mm ³)	(%)	(MPa)
1	370	1200	0.11	93.43	95.88	309
2	370	1300	0.15	63.25	99.25	305
3	370	1400	0.19	46.36	98.50	292
4	330	1200	0.15	61.11	99.63	335
5	330	1300	0.19	44.53	99.25	319
6	330	1400	0.11	71.42	96.25	300
7	290	1200	0.19	42.40	98.87	279
8	290	1300	0.11	67.60	97.00	297
9	290	1400	0.15	46.03	99.25	315

5. Doe analysis for density

In any powder bed fusion process components, density is the most important factor as it is detrimental for the mechanical properties of the component. The analysis of variance (ANOVA) was carried out for determining the most influencing parameter on density. The ANOVA result is tabulated below.

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TABLE 5. ANOVA result for density.					
SOURCE	DF	ADJ SS	ADJ MS	F-VALUE	P-VALUE
LP	2	0.000356	0.000178	4.00	0.200
SS	2	0.000289	0.000144	3.25	0.235
HS	2	0.011022	0.005511	124.00	0.008
ERROR	2	0.000089	0.000044	-	-
TOTAL	8	0.011756	-	-	-
\mathbf{D} \mathbf{D} $(1')$					

R-sq R-sq(adj)

99.24% 96.98%

DF- Degree of freedom; ADJ SS- Adjusted sum of squares; ADJ MS- Adjusted mean squares; F- Statistical test; P- Statistical value.

Inference that can be drawn from the ANOVA table is that Hatch Spacing is the principal parameter affecting the relative density of the components with a p-value of 0.008 less than 0.05 [12]. The interaction plot for Relative Density in figure 5 shows that an interaction effect between laser power of 370 W and 290 W can be observed for scan speed 1200 mm/s to 1300 mm/s,whereas an interaction effect between 290 W and 330 W,290 W and 370 W for scan speed ranging from 1300 mm/s to 1400 mm/s.For hatch spacing between 0.11 mm to 0.15 mm relative density is more sensitive to laser power and scan speed.



Figure 5. Interaction plot for Relative Density (%).

6. Process parameter optimization for rd

It can be observed that the optimum process parameter to obtain maximum relative density in our study which is 99.63% is laser power of 330 W,scan speed of 1200 mm/s and hatch spacing of 0.15 mm with a energy density value of 61.11 J/mm³. For very high energy density of 93.43 J/mm³ the least

relative density value was observed which could be attributed to the evaporation and vaporization of the powder leading to pore formation [13].

The effect of energy density on relative density can be seen from figure 6 an energy density range can also be obtained denoted by the rectangular box for getting the best results which ranges from 42.40 J/mm³ to 63.25 J/mm³ to obtain relative density from 98.5% to 99.63%, hatch spacing of 0.15 and 0.19 mm lies in the window.



Figure 6. Influence of Energy Density (ED) on Relative Density (RD).

7. Tensile strength analysis

Tensile testing was carried out in INSTRON 5582 with a strain rate of $10 \times E^{-3} s^{-1}$. Taguchi analysis was performed on the results. The signal to noise (S/N) ratio larger the better characteristics was used to evaluate the effect of each parameter on the tensile strength [14,15].

The S/N ratio output table for ultimate tensile strength is given below.

TABLE 6. Signal to Noise ratio result (larger is better).				
LEVEL	LP(W)	SS(mm/s)	HS(mm)	
1	49.42	49.74	49.58	
2	50.04	49.72	50.05	
3	49.63	49.64	49.46	
DELTA	0.61	0.10	0.59	
RANK	1	3	2	

From the table it is clear that laser power is the most influencing factor followed by hatch spacing which is equally important as not much difference in the delta value which decides the rank. The interaction plot in figure 7 reveals an interaction among the parameters. It can be observed that there is an interaction effect between laser power of 330 W and 290 W also for laser power 370 W and 290 W interaction is observed for scan spacing 1300 mm/s to 1400 mm/s. For laser power 370 W and 290 W and for 370 W and 330 W an interaction effect is seen for hatch spacing 0.11 mm to 0.15 mm. For hatch spacing 0.15 mm to 0.19 mm an interaction effect is seen among the different scan speeds.



Figure 7. Interaction effect plot for UTS (MPa).

8. Process parameter optimization for uts

The optimum process parameter for obtaining the best result for ultimate tensile strength is LP of 330 W, SS of 1200 mm/s and HS of 0.15 mm which also yielded the best result for Relative Density but the least RD value did not show the minimum UTS value.

9. Microstructural investigation

The figure 8 shows the porosity of the specimen 1 in table 4 which had the least relative density of 95.88 %. Due to very high energy density it resulted in vaporization of the material resulting in a large number of irregularly shaped pores (a majority of them is marked in the figure) which led to the depression of the density of the sintered specimen, a Scanning Electron Microscope(SEM) was operated at 15KV to get the image.



Figure 8. SEM image showing the porosity.

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10. Conclusion

In this study the manufacturing of AlSi10Mg components was carried out by DMLS process by varying the process parameters primarily Laser Power, Scan Speed and Hatch Spacing and they were optimized to get the best result for density and ultimate tensile strength by using ANOVA and Taguchi analysis. The main conclusions that can be drawn are as follows.

- The most important process parameter affecting relative density was found to be Hatch Spacing, whereas for UTS it was Laser Power but Hatch Spacing also had an important influence.
- The optimum process parameter for both density and UTS was found to be the following process parameter of LP 330 W, SS 1200 mm/s and HS of 0.15 mm.
- The highest energy density of 93.43 J/mm³ which gave the least relative density value did not gave the least value for UTS rather it was energy density of 67.6 J/mm³ which provided the least UTS value, which suggests that the UTS values of the samples are not solely depended on the density of the components. Fracture surface analysis need to be carried out to understand the effect of density and energy density on the UTS value.

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