An Investigation of Process Variables Influencing Fatigue Properties of Components Produced by Direct Metal Laser Sintering

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Abstract
Direct Metal Laser Sintering (DMLS) is one of the methods in layered manufacturing technologies by which metal powder can be directly used to produce both prototype and production tools. Fatigue strength is one of the important mechanical properties for the functional application of DMLS parts. This study was carried out to determine the optimum process parameters influencing the fatigue cycles to failure of DMLS components. Sintering speed, scan spacing, post-contouring speed, infiltration and hatch type are the process parameters taken up for the study. Statistical design of experiments using Taguchi's orthogonal array was employed for this study. Experimental data obtained were analysed using analysis of variance (ANOVA). From the results, it is found that one of the process parameters, sintering speed affects the fatigue properties of parts produced by this technology to a significant extent.

Keywords: *Layered manufacturing, DMLS, Taguchi Method, Fatigue*

1 Introduction

Direct Metal Laser Sintering is an emerging technique in layered manufacturing to form metallic parts without intermediate tooling. It is also a promising method for direct production of functional parts. The method involves progressive sintering of successive layers of metal powder conforming to the geometry of successive slice of CAD models to realize the components with shorter lead time. Metal powders commercially available for DMLS process are Direct Steel and Direct Metal. Direct steel is a steel-based powder, where as Direct Metal is bronze based. Direct Metal powder is used to carry out the experiments in this study. Since this process is suitable for lot manufacturing of components it is felt that there is a need for a quantitative study of process variable on the mechanical properties mainly the fatigue cycles to failure. This paper reports the work carried out on DMLS process to find the contribution of process parameters on the fatigue properties of parts.

In DMLS, there are number of input parameters that can be controlled and varied to obtain desirable qualities in sintered components. An experimental study on DMLS process with material mixture of nickel, bronze and copper- phosphide material is carried out and dimensional accuracy, surface roughness, impact toughness, hardness and strength of parts were measured. Methods for improving the parts quality accuracy, hardness wear resistance are also discussed [1]. Density, surface roughness, tensile strength, hardness and microstructure evaluation were carried out on direct rapid tooling using liquid phase laser sintering of multi component metallic powders (mixture of Fe, Cu, C, MO & Ni). Manufacturing parameters such as laser-power, scan rate, powder characteristics are taken into account for rapid tooling [2]. Selection of process parameters is important for better mechanical properties for metal sintered parts [3-4].

A parameter optimization study using DMLS to improve strength of parts produced is reported [5]. An analysis using ANOVA was used for DMLS components to find the influencing factor on surface roughness and wear properties [6-7].Taguchi technique was used to find the process parameters influencing the quality of parts produced by fused deposition modelling [8-9]. Taguchi L8 experimental design was used to study optimization of process parameters of SLS process [10]. Application of Taguchi philosophy is applied for optimization of welding variables thereby integrating statistical techniques into the engineering process [11]. Components manufactured by DMLS using optimized process parameters were used to carry out a functional test on a real time application [12]. It is to be noted that not much work has been carried out about the fatigue properties of metallic components manufactured using DMLS. The above survey of literature reveals that improvements in mechanical properties are possible in layer manufacturing using metal sintering and that layered manufacturing can be a promising alternative for lot production of mechanical components for functional application. A parametric optimization study using Taguchi method is carried out in the present study.

2 Process details

Experiments were carried out on EOSINT M250 laser sintering machine, developed by EOS Gmbh of Munich, Germany. The machine produces components by Direct Metal Laser Sintering process (DMLS). Parts produced by this technology is 95% dense and of relatively good strength. Therefore it has been used for production of moulds and inserts. Basic principle of this process is to fabricate net-shape metal parts in one single process. Components are built directly and fully automatically from metal powder without any polymer binders, which ensures high speed and accuracy as well as practically no shrinkage. During the process, a thin layer metal powder is spread over a previously sintered layer and cross-sectional area of the product is processed with laser scanning. To improve the fatigue properties of metallic components produced by DMLS, process parameters with appropriate levels that will give a better values for fatigue strength has to be found out. Also the quality characteristics have to be identified before selecting the factors. Process parameters selected for studying the influencing factor on fatigue properties of sintered components in this study are sintering speed, scan spacing, hatch type, post-contouring speed and infiltration.

Bonding of structural metal powder and binder metal powder at temperature below melting point of binder metal powder causes sintering process using a laser source. Speed of laser beam at which laser sinters is referred to as sintering speed. Movement of laser beam within the contour to produce solidified material in a specified path with a proper spacing is known as scan spacing. Scan spacing that is equal to laser beam diameter sinters the metal powder once and that of less than beam diameter causes a second direct heating of metal powder layer. Usually a regular pattern is followed by laser beam known as hatch pattern. In the present study two commonly used types of hatch patterns, unsorted and shifted type are taken up. In unsorted hatch pattern, laser beam moves along the path and progresses along X-direction with specified scan spacing and in second layer, laser beam moves along specified path in Y-direction alternatively. In case of shifted hatch pattern, in each layer, hatch structure is shifted by half scan spacing depending on activation in both X and Y axis. In first and second layer (both X and Y) laser beam path is similar to that of unsorted type. In third and fourth layers, laser beam is shifted by half scan spacing depending on previous layers. This process is repeated for X-and Y direction alternatively. Laser scan spacing and hatch pattern can play an important role in heat transfer through powder layer. Scanning of contour boundary in the final stage of sintering is known as post contouring speed. Since parts manufactured are not fully dense, infiltration can be carried out to fill the pores present. This is usually carried out using epoxy resin.

3 Design of experiments using Taguchi technique

Design of Experiments is a highly effective method to optimize process parameters, where multiple factors are involved. Design of experiments using Taguchi [13] approach was adopted to reduce the number of trials. Since DMLS process is expensive, it is necessary to select an orthogonal array with minimum number of trials. From Taguchi's standard orthogonal array, L8 modified array is selected for conducting the experiment. It is a multi level experiment. As sintering speed, scan spacing, hatch type, post contouring speed and infiltration are the factors considered in this experiment; certain levels have to be selected for each factor. A minimum of two levels is required to evaluate the factors effect. Maximum and minimum levels for factors are identified in the case of two-level experiment. Table 1 shows the developed orthogonal array table. Experiments were carried out with five factors. First factor has a four level combination and remaining factors have two levels. Sintering speed ranges from 250mm/s to 550mm/s with an increment of 100mm/s. As mentioned earlier, unsorted and shifted are the two types of hatch patterns selected. Post contouring speed selected was 300 and 500 mm/s. Four of the eight specimens manufactured were infiltrated.

4 Testing procedure

4.1 Specimen preparation

A three dimensional model of the required part is modeled using CAD software. Model is then converted to. STL file format. This .STL file is given as an input to the machine, which gets converted into .STL (Sliced file) by Machine software.

Table 1: Developed modified L8 orthogonal table

Trial	Sintering Speed (mm/s)	Scan Spacing (mm)	Hatch Type	Post Contouring Speed (mm/s)	Infiltration
1	250	0.25	Unsorted	300	Yes
2	250	0.35	Shifted	500	No
3	350	0.25	Unsorted	500	No
4	350	0.35	Shifted	300	Yes
5	450	0.25	Shifted	300	No
6	450	0.35	Unsorted	500	Yes
7	550	0.25	Shifted	500	Yes
8	550	0.35	Unsorted	300	No

Bed surface of the machine is cleaned and homing is done. Homing is a process in which machine is restarted, piston moves up and comes down for cleaning and then powder is brushed up again. Nickel- bronze powder is loaded on bed surface of the machine. Powder bed is leveled, which is done manually and partly by the machine. Process parameters are set in the control panel of DMLS machine. Fabrication chamber is maintained at a temperature just below melting point of powder so that heat from laser need only elevate the temperature slightly to cause sintering. A laser traces the pattern of first layer, sintering it together. Platform is lowered by height of next layer and powder is reloaded using a roller. This process is repeated until part is complete. Sintered parts of different process parameters along with the base plate are taken out carefully. Eight different cylindrical sintered components of 18mm produced were taken to EDM wire cutting machine to remove the final part from base plate. As mentioned earlier, four components are infiltrated with epoxy resin. Epoxy resin is applied on the component and then it is placed in oven for two hours for equal distribution of heat. These components were machined to test specimens as per ASTM standard for fatigue testing. Photograph of the specimen is shown in Figure 1.

Figure 1: Photograph of the specimen

4.2 ***Fatigue testing***

A single point loading rotating beam cantilever type fatigue-testing machine at a frequency of 50 Hz (3000 rpm) was used for fatigue testing. Real life operating conditions of rotating parts is possible with a rotating beam fatigue testing. All tests were carried out in atmospheric condition as per the standard for rotating beam fatigue testing. Eight specimens were tested to establish the number of cycles to failure. Bending moment (Mb, N mm) applied to specimens was determined for a load of 4 kg and bending stress (σb) was calculated using the formula $\sigma b = 32\ Mb/\pi d^3$.

5 Results and discussions

In order to study the effect of process parameters on fatigue strength of components, an analysis was carried out using statistical method-ANOVA using MiniTab Software. This technique helps to determine, process parameter that is statistically significant and also the contribution of each process parameter to output characteristics. Analysis was undertaken and influence of process parameters on fatigue was elucidated. All the eight components manufactured were tested for fatigue cycles to failure and measured values are shown in table 2. fatigue strength for lower values of sintering speed and components which are infiltrated, whereas scan spacing, hatch type and post contouring speed selected did not seem to have any significant effect on fatigue strength. Main effect plot of mean fatigue cycles verses process parameters are shown in Figure 2.

Table 2: Fatigue testing results

Trial No.	Fatigue Cycles
1	59241
2	35921
3	37959
4	46018
5	31690
6	40788
7	29746
8	22165

Analysis of measured data was carried out using ANOVA. Process variable which influences more on fatigue cycles to failure was found out. Table 3 shows the results of process variables influencing fatigue cycles to failure of DMLS components. Calculation was carried out to find the percentage contribution of variables and error for selected process parameters on fatigue cycles to failure. Result indicates that sintering speed and infiltration have a substantial effect on fatigue strength compared to other process parameters. Fatigue test carried out on layer manufactured samples indicated higher fatigue strength for lower values of sintering speed and components which are infiltrated, whereas scan spacing, hatch type and post contouring speed selected did not seem to have any significant effect on fatigue strength. Main effect plot of mean fatigue cycles verses process parameters are shown in Figure 2.

Table 3: ANOVA results for fatigue testing

Process Parameters	Degree of Freedom (V)	Sum of Squares (SS)	Variance (SS/V)	F-test	% contribution
Sintering Speed (mm/s)	**1**	**498803188**	**498803188**	**77.22**	**56.28**
Scan Spacing (mm)	**1**	**23612192**	**23612192**	**3.66**	**2.66**
Hatch Type	**1**	**35187660**	**35187660**	**5.45**	**3.97**
Post Contouring Speed (mm/s)	**1**	**27011250**	**27011250**	**4.18**	**3.04**
Infiltration	**1**	**288696421**	**288696421**	**44.69**	**32.57**
Error	**2**	**12918553**	**6459277**		
Total	**7**	**886229264**			

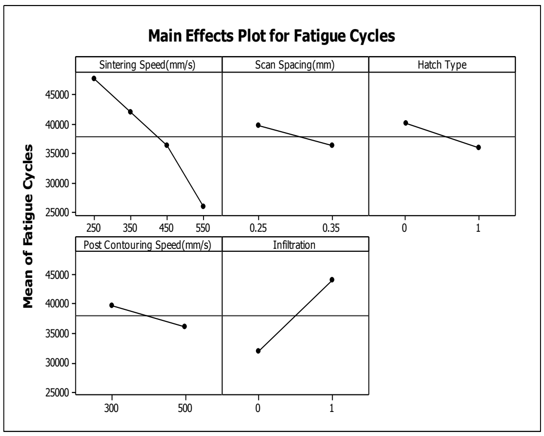

Figure 2: Main effect plot of fatigue cycles Vs process parameters

In order to check the influence of various process variables, parts were built with a minimum value of sintering speed of 250 mm/s and a post contouring value of 300 mm/s. Again sintering speed selected was 500 mm/s, post contouring speed as 300 mm/s and a scan spacing of 0.35 and fatigue cycles to failure was determined. From previous test it was observed that for sintering speed of 550 mm/s and a lower value of scan spacing of 0.25 and higher value of post contouring of 500 mm/s, value of fatigue cycles to failure was lower. Sintering speed was further reduced to 350 mm/s and a scan spacing of 0.35 and a lower value of post contouring speed, fatigue cycles to failure was more than previous test. It is evident that there is no much variation in fatigue cycles to failure values by changing values of post contouring speed, scan spacing and hatch type. Multiple regression analysis was used to develop a mathematical model using first order polynomial by least square fit (Equation 1).

$$Z = a_o + a_1 x_1 - a_2 x_2 - a_3 x_3 + a_4 x_4 - a_5 x_5 \quad (1)$$

$$Fatigue = 79939.4 - 70.626x_1 - 34360x_2 - 4194.5x_3 - 18.375x_4 + 12014.5x_5 \quad (2)$$

Where Z is response or output, x_i are factors or variables. The expression contains linear terms in x_1, x_2 to x_5. The terms a_i are constant coefficients.

To realise the relation between response and input factors, constant coefficients need to be determined for fatigue properties using the equation 2. Response surface is plotted for major process parameters influencing fatigue strength. Figure 3 shows response surface plot of fatigue strength with sintering speed and infiltration. When a lower value of sintering speed and is selected for manufacturing the part and infiltrated, better values of fatigue cycles to failure is obtained. Higher the sintering speed and components without infiltration is more prone to fatigue failure. Effect of other selected process parameters is negligible. By these plots, identification of the range of sintering speed and infiltration on fatigue cycles to failure is easier.

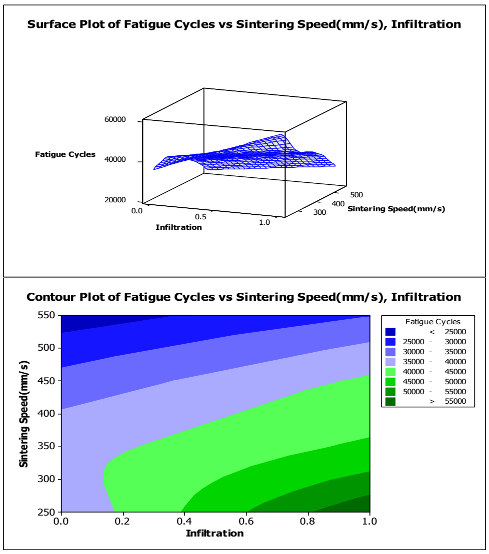

Figure 3: Surface and contour plot of fatigue cycles Vs sintering speed and infiltration

6 Conclusions

A number of test specimens (manufactured by DMLS technology) were evaluated to determine influence of process parameters on the fatigue cycles to failure. ANOVA was used to determine the process parameter that is statistically significant and also the contribution of each process parameters to the output characteristics was evaluated. Herein the analysis was carried out, and influence of process parameters on fatigue cycles to failure was ascertained. It can, therefore, be concluded that sintering speed and infiltration have a major influence on fatigue strength. Other selected process parameters do not have much influence. Also these studies provide a much better understanding of physical phenomena that occurs during such processes. This helps in developing processing strategies for minimizing structural defects and also towards maximizing mechanical properties of manufactured parts so that these rapid prototyped parts can be used for functional application.

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