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EFFECT OF MANUFACTURING PARAMETERS ON CIRCULAR RUNOUT OF SELECTIVE LASER MELTED METALLIC PARTS

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Abstract: In this study a detailed investigation is performed on size and shape accuracy of parts manufactured by selective laser melting. A previous study pointed out how geometric features of rectangular and circular parts substantially depends on manufacturing orientation of them on the tray. In our recent experiment series test specimen were manufactured with different manufacturing parameters from Ti6Al4V. Circular runout of cylindrical test parts were measured and analyzed as a function of manufacturing parameters. Quantitative expression for describing the comprehension between manufacturing parameters and circular runout gained by function fitting to experimental data.

Keywords: selective laser melting, Ti6Al4V, experiment series test specimen, manufacturing parameters

1. INTRODUCTION

Metal selective laser melting is an intensively developing branch of additive manufacturing technologies. Commonly used materials for wrought parts are available for selective laser melting.

Studies on effect of manufacturing parameters on quality of parts created by selective laser melting (SLM) technology is commonly reported in the international scientific literature. One of most important manufacturing parameters in this scope are layer thickness [2].

Before starting with manufacturing, preprocessing may substantially influence the accuracy of part. It is shown out how conversion parameters from CAD file to STL file makes a restriction for the geometrical accuracy of manufacturing process. [3]

Surface quality is mainly affected by part orientation inside the tray, hatch strategy, and the size of the part itself. Optimal strategy can be fitted to the certain part. [4]

Total energy input influences deformation of final part because of thermal expansion and shrinkage. While in case of complex shaped parts the amount of support substantially depend on the orientation of the part during the process, it is possible significantly improve size and shape accuracy by simple optimizing the orientation. [5] Recently simulation methods can be applied for design of optimal technological parameters and part orientation. [6] Shrinkage in direction of layer by layer advancing has been studied by a trivariable, three level experiment, and it has been shown out that laser power has the strongest effect to change in dimensions of the part in this direction. Dimension compensation has been proposed for improving size accuracy. [7] In case of internal channels, size accuracy can be improved by reorientation, shape compensation, parameter adaptation or redesign the part. [8] Other studies on the field of medicine and industry shows that questions of size and shape accuracy have to be handled with care, and theoretical end experimental investigations needed for achieving appropriate shape and surface quality. [9, 10, 11]

According to recent reviews additive manufacturing gain more and more field in production industry, and SLM technologies are accentuated in applications and development activities. [12, 13, 14]

In this paper an experiment series is published on a special geometrical feature of cylindrical parts, the circular runout. We used result communicated in the literature and all of our test specimens were manufactured in vertical position. Two experimental parameter was varied, the laser power and laser scan speed. Five different experimental setup was realized. Measurement data were evaluated by function regression, and empirical formulas were put down describing functional comprehension between experimental parameters and circular runout.

2. DESIGN OF THE CYLINDRICAL TEST SPECIMEN

Five series of test parts were manufactured. Each series involved 10 piece of parts with the same manufacturing parameters. 50 piece of test specimens were manufactured and measured altogether.

Nominal dimensions of cylindrical test specimens were 50 mm in length and 10 mm in diameter.

3. MANUFACTURING OF THE SPECIMEN

Test parts were manufactured with different manufacturing parameters. Specimens were manufactured by an EOS M290/400W additive manufacturing system. This is a „metal 3D printer”. We used Ti6Al4V material, which is commonly used in industrial and medical applications. Main advantages of this material is good mass-strength ratio, chemical durability and biocompatibility.

Orientation of the specimen on the tray was vertical. In a previous study we demonstrated that in case of horizontal align significantly larges shape and size errors can be measured. This is why we have chosen the better solution, the vertical orientation.

SLM process has many parameters which have to be set before starting through a software tool. There are parameter presets provided with the operating software of the additive manufacturing system. We applied the generally used preset, offered by the software so that we changed only two parameters listed below. Each other manufacturing parameters during SLM process were kept at default value. Layer thickness was left at value 0.03 mm, and hatch distance at 0.14 mm.

Two manufacturing parameters varied were infill laser speed and infill laser power. Table 1 shows values of them for the five different test specimen series. The third column of the table shows specific energy input (e, energy input into a volume unit during a unit time, second), which can be calculated as follows:

$$e = \frac{E}{V}$$

$$E = P \cdot 1s$$

$$V = u \cdot 1s \cdot h \cdot t$$

where notations are listed below: e : specific energy input [J/mm^3], P : infill laser power [W], E : total energy input in 1 second [J], V : total volume scanned in 1 second [mm^3], u : infill laser speed [mm/s], t : layer thickness [mm], in this study always t=0.03 mm, h : hatch distance [mm], in this study always h=0.14 mm.

Table 1. SLM manufacturing parameters and energy inputs in our experiments

Code of parameter setup	infill laser speed, u [mm/s]	infill laser power, P [W]	energy input, e [J/mm^3]
1	1200	233,33	46,30
2	1000	280,00	66,67
3	1440	336,00	55,56
4	1000	233,33	55,56
5	1200	280,00	55,56

Parameter sets 3,4 and 5 ensures the same energy input.

4. EXPERIMENTAL SETUP AND MEASUREMENT RESULTS

Particle size of metal powder from which SLM process makes the specimen is 20-60 micrometer. Microscopic observations proved that raw surface of manufactured parts is highly complex and uneven in the magnitude of particle size that is approximately. This implies that we can expect a natural noise in measured data in this magnitude. Consequently a gauge was eligible for the measurements.

It may surprising, but raw surface resulted from manufacturing of a selectively leaser melted part is not rigorously defined. This is why powder particle are bonded it the surface in some different ways. The strongest bond is total melting, in this case original shape of the powder particle cannot be recognized. The second strongest way of bonding is partial melting, in this case some part of powder particle remained unmelted, but other part melted in the body of the part. Next way of bonding is adhesive interaction between an unmelted dust and the surface of part which is formed by thermal effects, but does not mean a continuous material link. Strength of adhesive fixing depends on temperature and time duration of the thermal effect what the particle suffered. So adhesive links of particles vary in strength continuously from the relatively strong almost-melted state to zero. And eventually there are powder particles what are not bonded anyway, only stayed on the surface like a pollution. From this point of view one may argue about what particles can be considered to really belong to the surface and what not, and what kind of particle removal process can be called „cleaning”, and what as „subsequent machining”.

Before measurement remainder of metal powder and loosely bonded particles were cleaned from specimens by compressed air. It means that morphological elements stayed on the surface were fixed either by total or partial melting or by adhesive forces strong enough to resist removing effect of compressed air flow. We think that any stronger particle removal method on the surface could be considered as an additional machining (a subsequent surface modification), and would prevent us to measure what we really wanted.

Each test specimen was measured in 5 plane, diameter was measured in each plane in 3 directions. Test specimens have individual code, which refers to the manufacturing parameter set. For example test specimens manufactured with 1st parameter set have codes according to the following scheme: 1-1, 1-2, ...,1-10.

Table 2 shows all data measured and calculated for specimen 1-1. What we can see is that measured diameters differ from each other in the magnitude of 0.01 mm. It is highly important that no trend can be observed between mean values of different measurement planes. It is valid for all test parts investigated. It means that there is no vertical tapering in the diameter of a specimen.

Table 2. Measured and calculated data for a single specimen

		directions of diamater measurements			mean
specimen code	planes	1	2	3	
1-1	1	9,88	9,92	9,93	9,91
	2	9,91	9,92	9,89	9,91
	3	9,91	9,94	9,97	9,94
	4	9,93	9,91	9,90	9,91
	5	9,93	9,93	9,95	9,94
	mean [mm]	9,92			
	standard deviation [mm]	0,02295			

In the followings we present value of each test specimen and their average amongst the 10 specimen belonging to the same set of manufacturing parameters.

Table 3a. Diameter mean data for specimens and for manufacturing parameter sets

code	diameter mean [mm]	code	diameter mean [mm]	code	diameter mean [mm]
1-1	9.92	2-1	9.91	3-1	9.99
1-2	9.91	2-2	9.99	3-2	9.94
1-3	9.92	2-3	9.88	3-3	9.94
1-4	9.93	2-4	9.93	3-4	9.92
1-5	9.95	2-5	9.90	3-5	9.94
1-6	9.96	2-6	9.91	3-6	9.93
1-7	9.95	2-7	9.90	3-7	9.97
1-8	9.96	2-8	9.90	3-8	9.93
1-9	10.05	2-9	9.94	3-9	9.94
1-10	9.94	2-10	9.94	3-10	9.93
all mean	9.95	all mean	9.92	all mean	9.94

Table 3b. Diameter mean data for specimens and for manufacturing parameter sets

code	diameter mean [mm]	code	diameter mean [mm]
4-1	9.94	5-1	9.96
4-2	9.94	5-2	9.98
4-3	9.94	5-3	10.01
4-4	9.95	5-4	9.96
4-5	9.96	5-5	9.99
4-6	9.95	5-6	10.01
4-7	10.00	5-7	9.97
4-8	9.95	5-8	9.96
4-9	9.90	5-9	9.94
4-10	9.90	5-10	9.99
all mean	9.94	all mean	9.98

Shape of manufactured specimens were characterized by circular runout. It has been measured according to standard, by a digital micrometer.

Table's 4a and 4b lists circular runout data for each specimen and mean values for groups of specimens belonging to the same manufacturing parameter set.

Table 4a. Circular runout data for each specimen and mean value for manufacturing parameter sets

specimen code	circular runout (mm)	specimen code	circular runout (mm)	specimen code	circular runout (mm)
1-1	0,04	2-1	0,07	3-1	0,05
1-2	0,06	2-2	0,04	3-2	0,05
1-3	0,05	2-3	0,05	3-3	0,04
1-4	0,05	2-4	0,06	3-4	0,06
1-5	0,04	2-5	0,05	3-5	0,06
1-6	0,04	2-6	0,07	3-6	0,05
1-7	0,05	2-7	0,06	3-7	0,04
1-8	0,06	2-8	0,04	3-8	0,05
1-9	0,06	2-9	0,04	3-9	0,05
1-10	0,04	2-10	0,05	3-10	0,05
1-11	0,06	2-11	0,04	3-11	0,06
1-12	0,05	2-12	0,04	3-12	0,05
mean	0,0500	mean	0,0508	mean	0,0508

Table 4b. Circular runout data for each specimen and mean value for manufacturing parameter sets

specimen code	circular runout (mm)
4-1	0,07
4-2	0,06
4-3	0,05
4-4	0,06
4-5	0,05
4-6	0,05
4-7	0,07
4-8	0,05
4-9	0,06
4-10	0,07
4-11	0,05
4-12	0,06
mean	0,0583

specimen code	circular runout (mm)
5-1	0,08
5-2	0,08
5-3	0,07
5-4	0,07
5-5	0,07
5-6	0,06
5-7	0,07
5-8	0,07
5-9	0,08
5-10	0,06
5-11	0,06
5-12	0,06
mean	0,0692

5. EVALUATION OF EXPERIMENTAL DATA

Diameter data presented in Tables 3a-b are comparable with those published in our previous work [1]. In this experiment series samples 5-1 … 5-10 made with the same orientation (vertical) and manufacturing parameters (h=0.14 mm, u=1200 mm/s, P=280W, t=0.03 mm) as X16 … X20 in paper [1], where mean value of diameter measurements is 10.00 mm, in this study 9.98 mm. This is a good agreement. In this study mean values for all other manufacturing parameter sets are 9.95 mm or less.

This demonstrates that size accuracy depends on not only orientation but also on manufacturing parameters.

Mean values of diameter (d) varies by experimental parameters infill laser power (P) and infill laser speed (u), so diameter can be considered as a bivariate function d=d(P,u). Now an empirical formula can be constructed by function fitting to mean values.

We applied least squares method, and used an implementation in Scilab software.

Result of approximation is the following formula:

$$\begin{aligned} d(P,u) = &-0.0607888\,P + 0.0129847\,u \\ &+ 0.0001055\,P^2 \\ &- 0.0000065\,u^2 \\ &+ 0.0000054\,P\,u \\ &+ 10.725048\ [\mathrm{mm}] \end{aligned}$$

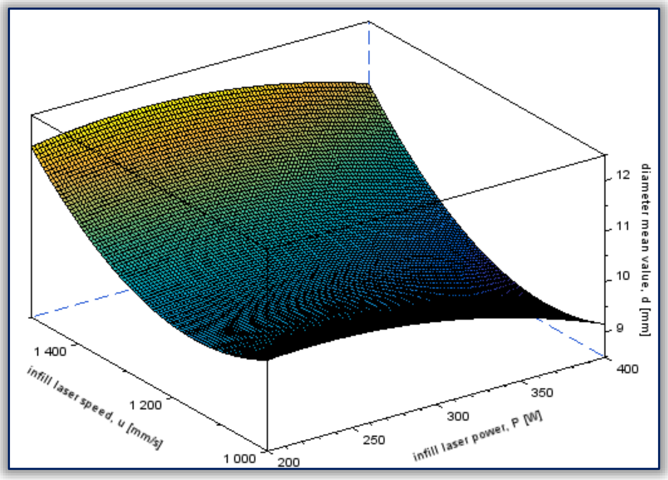

Figure 1. Diameter mean values as function of infill laser power and infill laser speed

An empirical formula for radial runout mean values (r) also can be gained by least squares method function approximation:

$$\begin{aligned} r(P,u) = &-0.0010936\,P + 0.0000844\,u \\ &- 0.0000042\,P^2 \\ &- 0.0000004\,u^2 \\ &+ 0.0000029\,P\,u \\ &+ 0.1870961\ [\mathrm{mm}] \end{aligned}$$

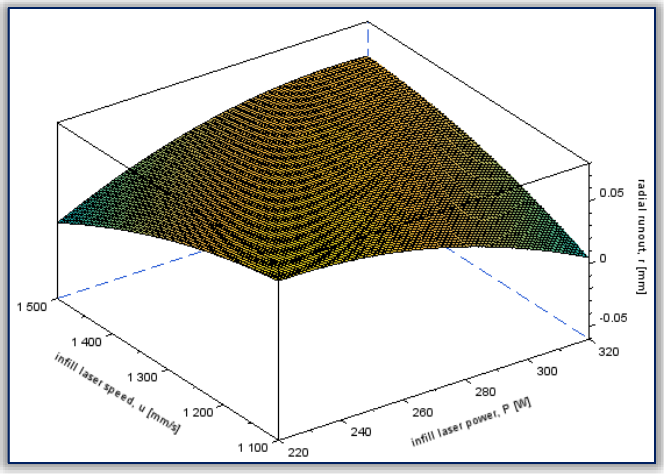

Figure 2. Radial runout mean values as function of infill laser power and infill laser speed

6. CONCLUSIONS

Effect of two important manufacturing parameters of selective laser melting were studied on geometric properties of fabricated parts. These two parameters were infill laser power and infill laser speed. Cylindrical test parts were manufactured and two geometric features were studied: diameter and radial runout. Empirical formulas were constructed by least squares method fitting onto mean values calculated from measurement data.

Empirical formulas show that geometric features investigated are nonlinear functions of two most important manufacturing parameters. Additionally those show different behaviour by studied manufacturing parameters.

For detailed description of these two functions a study with more samples is necessary. In case of optimization of a product by such kind of parameters a composite index composed from the two bivariate function is necessary.

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