Acta Materialia Transylvanica 6/1. (2023) 14–22.
DOI: Hungarian: https://doi.org/10.33923/amt-2023-01-03
English: https://doi.org/10.33924/amt-2023-01-03

Effect of Production Parameters on Impact Energy of Ti-6Al-4V samples Produced by Additive Manufacturing

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Abstract

Powder bed melting is an important additive manufacturing process. The process variants are gaining more and more space in the industry: especially in the industry that produces products made of special alloys with additive manufacturing. Selective laser melting is one variant of powder bed fusion processes. In this paper experimental study on impact energy of test specimens made from Ti-6Al-4V alloy, manufactured by selective laser melting is presented. Parameter setup of experiments are defined by design of experiment method, and an empirical formula is fitted to measured data. It is pointed out that impact energy is highly sensitive to manufacturing parameters studied here, and strong interactions are also observed. A formula is derived for costrained optimization on isoenergetic surfaces. Results can be applied for control of an important material property, impact strength of parts manufactured by selective laser melting.

Keywords*: powder bed fusion, selective laser melting, impact energy, scan speed, layer thickness.*

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1. Introduction

As a result of a revolution of scientific research and development started in the middle of 20th century and continuing also nowadays, additive manufacturing (AM) finds more and more place in practical applications and industry.

It may play many different role in the process of design, production and maintenance including prototyping, casting pattern and core making, manufacturing tools, jigs or fixtures (especially with complex shape), producing blanks, fabricating end-use parts, repairing of parts. It is remarkable that powder bed fusion technologies are recently applicable in the first five of the mentioned areas. According to predictions, three quarters of furnishing and equipment parts and half of engine parts are expected to be manufactured by AM technologies in the aircraft industry until 2050 [1]. Application of AM in medical industry can be classified into five fields: medical models, surgical implants, surgical guides, external aids and bio-manufacturing. The number of scientific publications on medical applications of AM show an exponential increase in last 15 years [2, 3]. AM technologies nowadays are applied mainly on high added value segments of industry in relatively small, but increasing quantity. Today AM is still an intensive field of research, industrial activity and business. Whilst several hundred AM technologies have been developed till now indicating creativity of experts and promising development potential of the area, there are some challenges to solve before AM turns into a widely spread and cost effective manufacturing technology. Development in several disciplines is needed for stronger utilization of this technology, such as education and knowledge management, more powerful softwares supporting design for AM, overcoming limits of bed size and speed of manufacturing, new ideas and procedures in quality management since features of products are highly dependent on manufacturing parameters and accidental fluctuations associated with them [4].

Quality management of additively manufactured products is an intensive area of research and development. While AM generally has the great advantage of manufacturing products directly from CAD models with almost arbitrarily complex geometry, it has some challenges in the field of quality and process repeatability [5, 6].

In this paper, experimental research is introduced on parts manufactured by metal selective laser melting (SLM). This is a powder bed fusion additive manufacturing technology applying a highly intensive laser beam for totally melting the metal powder layer by layer.

The main materials used for metal SLM are steel and titanium alloys. Interest in titanium alloys rose sharply around 2010 as they proved to be biocompatible. With all metals, application of SLM for ceramic and composite materials is increasingly studied [7].

Ti6Al4V is one of most frequently used titanium alloys in industry. This results from its excellent properties such as good mass-strength ratio, high corrosion resistance, being non magnetic and its biocompatibility. This material is often applied in the vehicle industry, especially aircraft parts manufacturing, marine applications, in medicine for medical implants, in nuclear reactor technology, and many other fields. This material is available in the form of stock for conventional technologies producing wrought parts, and also for additive technologies as metal powder. In this study we are interested in parts made of Ti6Al4V by an additive manufacturing technology.

SLM is a widely applied technology for processing Ti6Al4V material. This is the technology which has the most industrial application mainly in aeronautical and biomedical areas, and attracts salient research attention because of its versatility. Besides the advantages of SLM it has three main challenges when it is applied to Ti6Al4V powder. Firstly, besides high material strength, manufactured parts have the feature of relatively low ductility. It correlates with high cooling rate during the SLM process, which results in martensitic material structure. Secondly, a challenge is the presence of microstructural defects such as balling and porosity greatly affecting fatigue resistance of parts. The third challenge is the presence of residual stresses in as-built parts derived from high temperature rates and gradients during the manufacturing process. All of the above challenging problems depend on a high number of parameters, since the entire SLM manufacturing process can be characterised by more than a hundred technical data However there are three parameters which play a special role in how material features develop in SLM: laser power, laser scanning speed and layer thickness. While these three challenging problems substantially impact how parts can be used in practice and industry, extensive research work is in progress currently on this area [8, 9]. Usually, post-processing is also required for achieving appropriate quality. For medical applications different post-processing treatments can be applied such as sandblasting, carborundum disc polishing or ultrasonication in isopropyl alcohol [10, 11].

Features of materials manufactured by SLM do not depend directly on a single process parameter, rather, on a combination of them. So when the aim is to investigate how those depend on manufacturing parameters, a multivariable study is necessary.

Impact energy is a material feature standing in strong relationship with ductility. In this paper we present our experimental research results on impact energy of Ti6Al4V specimens as a function of laser power, laser scanning speed and layer thickness.

2. Material and samples

2.1. Material

In our experiments samples were built from Ti6Al4V (TC4, Ti64) alloy material melted from EOS Titanium Ti64ELI powder. Chemical composition of this powder can be characterized as 5.5-6.75 wt% Al, 3.5-4.5 wt% V the balance is composed of Ti, and some elements like O, N, C, H and Fe are guaranted to be under a certain low limit. This is a Grade 25 titanium alloy, with reduced content of oxygen, nitrogen, carbon and iron, containing extra low interstitials (ELI), ensuring higher ductility and improved fatigue resistance related to Grade 5 Ti6Al4V materials. This is why it is suitable for medical implants and devices. The size of metal alloy powder particles varies in the range of 20-80 micrometers according to the data sheet [12].

2.2. Sample preparation

Test specimens were manufactured by an EOS M290/400W additive manufacturing machine, which implements selective laser melting of metal powders. Selective laser melting is a layer by layer additive manufacturing technology, which has two key steps: a coating of metallic powder is formed on a plate or tray, then a laser beam fuses the metal powder selectively in areas belonging to the part being fabricated. This is accomplished in a closed chamber filled with an inert atmosphere. The main parameters of this process are layer thickness, hatch distance, laser power and laser (scanning) speed, but there are several other parameters controlling properties of gas flow, laser beam, scanning pattern, motion of actuators, thermal state of the chamber and others. Parameters usually vary depending on which region of the model is just built, that is internal (infill), bottom, top or some edge of it. Operating software of machines offer default parameter setup, and can also be changed by the user.

The shape of the samples was identitcal to a standard 10×10×55 mm Charpy impact test (or V-notch test) specimen (standard: MSZ EN ISO 148-1:2017 The specimens were manufactured in a laid position so that notches were on the top side.

Each test specimens was manufactured in the same orientation. This is highly important in the case of manufacturing technologies comprising special directions in space leading to anisotropy either in microstructure or material properties of the produced part. We performed a preliminary study with 5-5 test pieces for impact energy. We found that there was a 19.57% difference between mean values for specimens produced in standing and laid position. As expected, the smaller impact energy value belongs to the standing position, because in this case fractures grow along layers melted onto each other, that is layers separate from each other during the process of breaking. In the case of test parts manufactured in the laid position, when the notch is on the top side, layers have to split when the specimen breaks.

In our study the effect of production parameters on impact energy is investigated. Because there are a large number of manufacturing parameters, we selected three that are highly important: infill laser power (*P*), infill laser speed (*u*) and layer thickness (*t*). The main default values of them are summarized in **Table 1**.

It is important to emphasize that hatch distance (*h*), which is also an essential parameter, was kept constant in this study with a default value $h = 0.14\,\mathrm{mm}$.

Three levels of each of those were taken into account in our experiment plan. Levels are not equidistant, but are calculated proportionately with a multiplicative factor of 1.2. **Table 2** shows values of varied production parameters in experiments.

Energy input (e, [W/mm^3]) is a highly characteristic feature of a selective laser melting process. As seen from the unit, the production parameter commonly named “energy input” is a more precise specific power input, or indeed power density, and is the laser energy irradiated into 1 mm^3 volume of material in 1 second. It can be calculated from manufacturing parameters by the following formula:

$$e = \frac{P}{u \cdot 1s \cdot t \cdot h} \tag{1}$$

Here the meaning of proportionately selected levels can be understood, because in this way we have many different parameter sets with equal energy input (e) as **Tables 2** and **3** show, so we have an additional opportunity for evaluating experimental data taking into account this significant derived parameter. A full factorial experiment would consist of $3^3 = 27$ different parameter setup. This is a large number, so we decided to plan an orthogonal fractional factorial experiment with a 9 experimental parameter setup according to **Table 3**. This fractional factorial experiment plan is derived from Taguchi’s $L_9(3^4)$ orthogonal plan array by deleting fourth column **[13]**.

Table 1. *Names, notation and default values of four important parameters of the SLM process in the case of our additive manufacturing system*

Name of the parameter	Notation	Default value
laser power	*P*	280 W
laser scanning speed	*u*	1200 mm/s
layer thickness	*t*	0.03 mm

Table 2. *Levels of varied factors in experiments*

Factor	level -1	level 0	level 1
P (W)	233.33	280	336
u (mm/s)	1000	1200	1444
t (mm)	0.025	0.030	0.036

Table 3. *Parameter setup of partial factorial experiment plan, and energy input values belonging to those*

	Infill laser power [W]	Infill laser speed [mm/s]	Layer thickness [mm]	Energy input [W/mm^3]
A	233.33	1200	0.03	46.296
B	280	1000	0.03	66.667
C	336	1440	0.03	55.556
D	336	1200	0.025	80.000
E	233.33	1000	0.025	66.667
F	280	1440	0.025	55.556
G	280	1200	0.036	46.296
H	336	1000	0.036	66.667
I	233.33	1440	0.036	32.150

For comparison and control of results, samples were manufactured with an additional three parameter set, involving default parameter setup (*J*), as shown in **Table 4**. Five pieces of test specimens were produced for each parameter setup.

3. Results and evaluation

3.1. Experimental results

The Charpy impact test were performed according to standard MSZ EN ISO 148-1:2017. We applied Charpy impact test equipment PSW 15 with maximum impact energy 15 J and scale constant 0.1 J. There is a single exception; the sample series denoted as A, because the impact energy of that sample exceeded 15J. For this reason, in this case, we had to apply larger test equipment; the PSW 300. This is why the impact energy data in row A have only two siginificant figures. In this paper we use *K* as notation for impact energy. the unit of impact energy is the Joule (J) in this paper. Measurement results are summarized in **Table 5**.

Each experiment consisted of 5 measurements. This means that 5 test specimens manufactured with the same parameter setup were broken. Then, the mean value and standard deviation of impact energy were calculated. In our experiments standard deviations have relatively small values.

3.2. Evaluation of the measurement results

The impact energy is considered as a function of experimental factors. In our case:

$$K = K(P, u, t). \tag{2}$$

Our first goal was to find an empirical formula for this function. In our case an interpolation technique was appropriate, because we sought a formula, which adequately approximates measured impact energy values within the experimental parameter domain. Using a polynomial interpolation function is straightforward because of the nature of the phenomenon we study. Order of interpolation has to be determined so that we avoid overfitting. Now we have 12 measured data, it implies that the third order approximation was too high in order. Consequently we supposed a second order polynomial formula for interpolation as follows:

$$\begin{aligned} K(P,u,t) &= a_0 + a_1P + a_2u + a_3t + a_4P^2 \\ &+ a_5u^2 + a_6t^2 + a_7Pu + a_8Pt + a_9ut \end{aligned} \tag{3}$$

Table 4. *Three additional parameter setup for comparison*

	Infill laser power [W]	Infill laser speed [mm/s]	Layer thickness [mm]	Energy input [W/mm³]
J	280	1200	0.03	55.556
K	233.33	1000	0.03	55.555
L	280	1000	0.025	80.000

Table 5. *Summary of measurement results. Sample series codes (column 1), measurement results in J units (columns 2-6), mean values and standard deviations (columns 7 and 8 respectively).*

Sample code	1	2	3	4	5	Mean value	Standard deviation
A	18.0	18.0	16.0	16.0	16.0	16.8	1.10
B	15.0	13.7	14.6	11.9	13.9	13.8	1.19
C	10.2	10.3	10.7	10.2	11.4	10.6	0.51
D	8.4	8.2	10.1	8.9	8.3	8.8	0.79
E	11.0	9.8	8.6	9.5	10.2	9.8	0.88
F	12.7	10.0	11.3	10.8	11.6	11.3	1.00
G	12.8	14.2	12.6	13.0	14.3	13.4	0.81
H	11.3	11.7	11.3	11.1	10.6	11.2	0.40
I	11.3	10.2	10.2	11.7	12.2	11.1	0.90
J	11.4	9.6	10.4	12.1	11.7	11.0	1.02
K	11.2	10.3	10.6	11.3	9.8	10.6	0.63
L	10.3	9.1	9.0	8.6	8.9	9.2	0.65

Multiplicative parameters $a_0 \dots a_9$ have derived dimensions so that, after evaluation of this formula unit of the result, let be J (Joule). For example

$$[\mathrm{a}_0] = \mathrm{J}, \qquad [\mathrm{a}_1] = \frac{\mathrm{J}}{\mathrm{W}} = \mathrm{s}$$

and so on. In the following we will not deal with and will not indicate dimensions of the $a_0 \dots a_9$ iparameters, because we believe that writing out those would make formulas and tables unnecessarily unperspicuous.

We applied Scilab software for determining $a_0 \dots a_9$ parameters in the function of *K*. These parameters were to ensure that difference between values of K and the measured data is as small as possible. In Scilab, the OPTIM function can be used for nonlinear optimization. It requires definition of the function to be optimized, its gradient as another vector function, and some parameters controlling the convergence of the algorithm. Our task is a general nonlinear optimization with a single, smooth objective function, without constraints. OPTIM uses L-BFGS method for optimization **[14]**.

As result of nonlinear optimization we obtained the following function for *K*:

$$\begin{aligned} K(P,u,t) = {} & -70{,}745933 - 0{,}0008086\,P \\ & + 0{,}1064481\,u + 1329{,}3723\,t \\ & - 0{,}0001446\,P^2 - 0{,}0000315\,u^2 \\ & - 93{,}507847\,t^2 + 0{,}0000201\,Pu \\ & + 0{,}908954\,Pt - 1{,}1531936\,ut \end{aligned} \tag{4}$$

Values of the multiplicative parameters in this formula show how strongly a factor (*P*, *u*, *t*) and interaction of factors (*Pu*, *Pt*, *ut*) influence impact enegy (*K*). The larger the multiplicative parameter, the more sensitive the impact energy is for factor or the interaction it multiplies. So we can get a „compass” for control of impact energy of the material fused in our SLM machine. The empirical trivariate function defined by the formula (4) is demonstrated on **Figure 1**.

Only one thing obscures this picture. This is the significant difference in magnitude of factors *P*, *u* and *t*. Scanning speed in mm/s units is 5 orders of magnitude larger than layer thickness in mm units. This implies that a small change in *u* creates a great shift in *K*, but a small change in *t* results in far smaller effect if those have the same multiplicative factor. In other words multiplicative parameters are not comparable if the factors they multiply are not in the same order of magnitude.

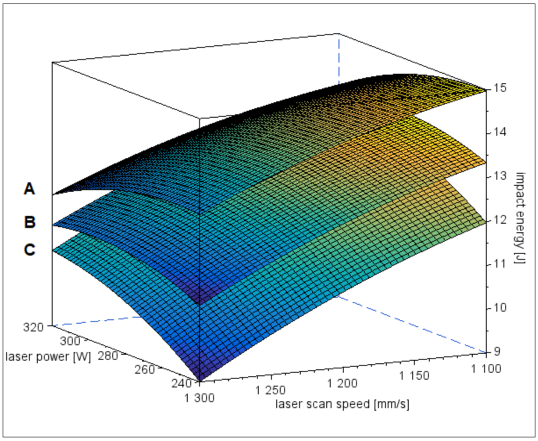

Figure 1. *Graph of empirical formula (4). Three different surfaces belong to different layer thickness values: A: t = 0.036 mm, B: t = 0.03 mm, C: t = 0,025 mm.*

Nondimensionalization is a common means for transforming physical quantities into a form in which they become more comparable. It is worth substituting the *P*, *u* and *t* factors with a dimensionless variable and at the same time rescale multiplicative parameters. Let us introduce the following dimensionless variables:

$$x_P = \frac{P}{280\,W},\, x_u = \frac{u}{1200\,m/s},\, x_t = \frac{t}{0.03\,mm}. \tag{5}$$

We can say that we normalize variables to their default values. Nondimensionalized variables have dimensionless value 1 if *P*, *u* and *t* have the default value. For example $x_P = 1$ if $P = 280$W, and $x_P = 1{,}2$ if $P = 336$W. This means that in our experiments values of all the three process parameters correspond to one of the values 0.8, 1 or 1.2 of dimensionless parameters. Multiplicative prameters $a_0 \ldots a_9$ are rescaled as:

$$\begin{gathered} b_0 = a_0,\, b_1 = a_1 \cdot 280\,W,\, b_2 = a_2 \cdot 1200\,\frac{m}{s}, \\ b_3 = a_3 \cdot 0{,}03\,mm, \qquad b_4 = a_4 \cdot (280\,W)^2, \\ \ldots, \\ b_7 = a_7 \cdot 280\,W \cdot 0{,}03\,mm \\ b_8 = a_8 \cdot 1200\,\frac{m}{s} \cdot 0{,}03\,mm. \end{gathered} \tag{6}$$

All of the new parameters $b_0 \ldots b_9$ have the same unit as *K*, that is the Joule. After nondimensionalization we have the following interpolation formula:

$$\begin{aligned} & K(P,u,t) \\ & \quad = -70{,}745933 - 0{,}226397\,x_P \\ & \quad + 127.73777\,x_u + 39.881168\,x_t \\ & \quad - 11.340299\,{x_P}^2 - 45.311942\,{x_u}^2 \\ & \quad - 0.0841571\,{x_t}^2 + 6.7491589\,x_P x_u \\ & \quad + 7.6352133\,x_P x_t - 41.51497\,x_u x_t \end{aligned} \tag{7}$$

In the formula (7) the coefficients are comparable. In first order terms the coefficients of laser scan speed and layer thickness are 100 times larger than those of laser power. In pure second order, member layer thickness has two magnitudes smaller weight than the other two. In interaction terms $x_u x_t$ has the largest coefficient, but $x_P x_u$ and $x_P x_t$ also have notable weight. From this overview we can conclude that each of three manufacturing parameters *P*, *u* and *t* has an effect on impact energy, none of them is negligible, but they stand in different mathematical relation with it.

3.3. Constrained optimization of the impact energy along an izoenergetic surface

Energy input, in other words power density, is an important feature of selective laser melting (SLM) technology. Several phenomena are strongly dependent on it, like thermal gradients during the manufacturing process, thermal stresses and deformations, and some accompaniment as balling and splatter. However it is not straightforward that there is direct relationship between energy input and a phenomenon or feature. When SLM technology is optimized, many times, multiple conditions are to be fulfilled, or at least minimized or maximized. In such a situation a constrained task may arise: to change the manufacturing parameter keeping energy input constant so that a special feature of the manufactured part, (such as impact energy), changes.

Our experimental parameter setup was developed so that many of those can be featured with same power density (energy input, e) value. We use this for investigating how impact energy depends on laser power density during the manufacturing process. According to **Tables 3** and **4** we can identify which experimental setups have identical energy input. This is summarized in **Table 6**.

In field of our three varied manufacturing parameter (laser power, laser scan speed and layer thickness) Formula (1) defines a surface for each value of energy. Such surfaces are called isoenergetic surfaces. The equation of these surfaces can be derived by rearrangement:

$$t = \frac{P}{u \cdot 1s \cdot e \cdot h} \tag{8}$$

Figure 2 shows izoenergetic surfaces belonging to values in first column of **Table 6.** Each experimental setup corresponds a point on some of these surfaces.

Now we derive from equations (4) and (6) a formula for impact energy along an isoenergetic surface. We eliminate layer thickness (*t*) from (4) by substituting (6):

$$\begin{aligned} K(P,u,e = constant) &= -70,745933 - 0.0008086\,P \\ &+ 0,1064481\,u + 1329,3723\,\frac{P}{u \cdot 1s \cdot e \cdot h} \\ &- 0,0001446\,P^2 - 0,0000315\,u^2 \\ &- 93,507847\left(\frac{P}{u \cdot 1s \cdot e \cdot h}\right)^2 + 0,0000201\,Pu \\ &+ 0,908954\,\frac{P^2}{u \cdot 1s \cdot e \cdot h} \\ &- 1,1531936\,\frac{P}{1s \cdot e \cdot h} \end{aligned} \tag{9}$$

As mentioned earlier, in our investigation, hatch distance h is also constant. This is a bivariate function of laser power (*P*) and laser scan speed (*u*). Here we note that at the place of formula (8) another variable could also be expressed, and eliminated, so impact energy along an isoenerget-

Table 6. *Experimental setups with same energy input*

Energy input, e, (W/mm³)	Codes	Number of them
32.150	I	1
46.296	A, G	2
55.556	C, F, J, K	4
66.667	B, E, H	3
80.000	D, L	2

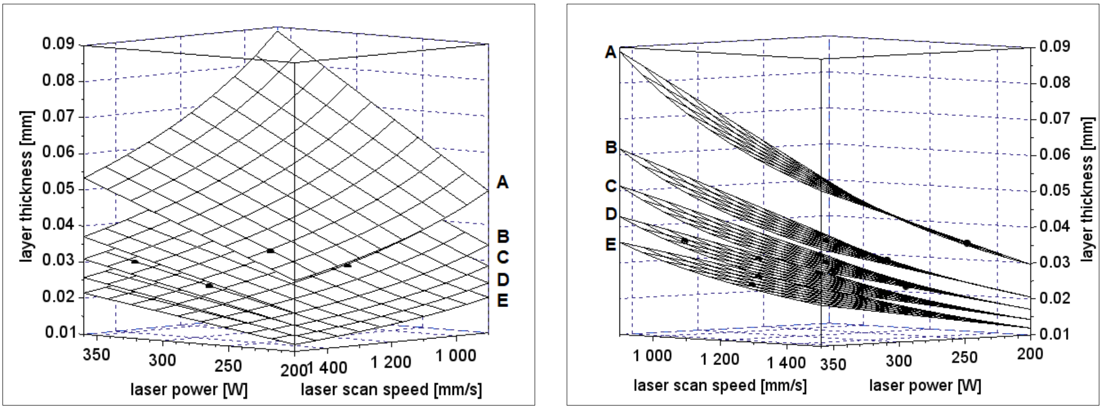

Figure 2. *Isoenergetic surfaces in the space of three manufacturing parameter varied in our experiments. A: 32.150 W/mm³, B: 46.296 W/mm³, C: 55.556 W/mm³, D: 66.667 W/mm³, E: 80.000 W/mm³, black dots indicate experimental setups, each dot belongs to one of the isoenergetic surfaces, both parts of the figure show the same diagram from different views.*

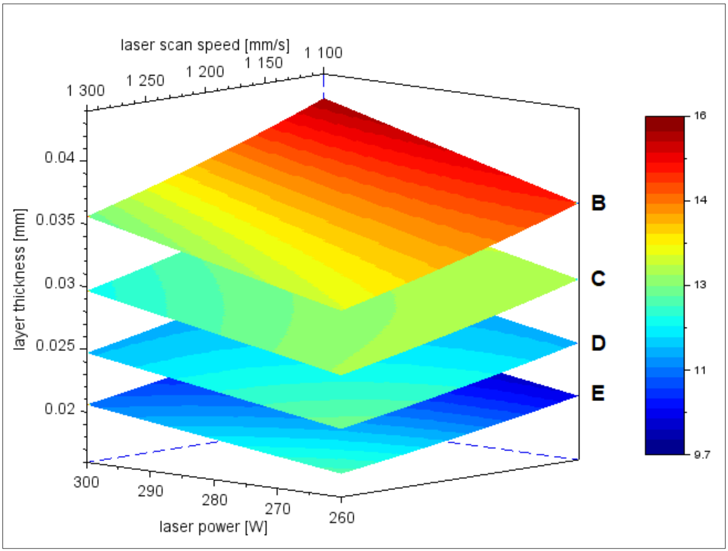

Figure 3. *Impact energies computed from formula (4) on isoenergetic surfaces in the space of three manufacturing parameters varied in our experiments. Isoenergetic surfaces belong to power densities: B: 46.296 W/mm³, C: 55.556 W/mm³, D: 66.667 W/mm³, E: 80.000 W/mm³. Impact energy in [J] units is visualized by colors, the legend shows the color codes.*

ic surface can be expressed as a function of *P* and *t*, or *t* and *u*. We continue with formula (9).

Figure 3 shows impact energy as a function of laser power and laser scan speed along isoenergetic surfaces belonging power density values involved in first column of **Table 6.**

The isoenergetic surface belonging to 32.150 W/mm^3 was omitted because we have only one experimental point on it, and possibly that has the highest interpolation error.

It can be observed that the power density itself does not bear a direct relation with impact energy. This means that power density can not be applied as a control quantity when the ductility or the brittleness of a part has to be ifluenced. Indeed, the special parameter triplet of laser power, laser scan speed and layer thickness have to be used.

However it is possible to describe the impact energy as a function of three important manufacturing parameters, and give an expression of it along isoenergetic surfaces.

4. Discussion

It can be observed that the experimental factors laser power, laser scanning speed and layer thickness influence significantly the impact energy of the specimen, and impact energy of specimens manufactured with default values (denoted with *J* in **Table 4**) is placed near the middle of the range of measured values.

Impact energy of samples with code A is salient. We repeated the experiment, and got the same result. This indicates that there is a substantial change in internal structure of the material as the triplet of studied process parameters approaches towards parameter setup A. It seems to be worthy of a deeper study.

The empirical formula gained by interpolation on experimental data must be handled with care, because this can give acceptable approximation within the small part of the domain around the center point of parameter variation. Our results may be extended by a future experimental work with a larger number of experimental setups. In the case of a larger number of measurements, order of interpolation can also be increased without overfitting. A full third order interpolation in case of three variables needs at least 20 measurement points, possibly more.

Formula (4) shows that impact energy is far from a linear function of laser power, laser scan speed and layer thickness even within a small parameter window. Pure second order and interaction terms also have significant coefficients.

The complex nature of SLM (and generally additive manufacturing) technology can be presumed behind non-linear behaviour. The impact energy is substantially influenced by material porosity, metallographic microstructure, surface quality and residual stress state. All of these features depend on manufacturing parameters.

5. Conclusions

The impact energy of samples manufactured by selective laser melting (SLM) was measured by V-notch impact test. Test specimens were manufactured with different process parameters. Three manufacturing parameters, the laser power, the laser scanning speed and the layer thickness were varied, while the hatch distance and other parameters were kept constant. Experimental parameter setups were constructed by fractional factorial design of the experiment.

The measurement results show significant difference. Least mean value is 8.8 J, while highest mean value is 16.8 J, which is more than double the previous. This indicates that the impact energy is a material property, which is highly sensitive for manufacturing parameters investigated in this study.

A quantitative trivariate empirical formula was fitted onto experimental data by interpolation procedure. This is a second order polinomial formula. It can be observed that pure second order and interaction terms have notable coefficiency, which means that impact energy is a strongly nonlinear function of production parameters.

A formula was derived for calculating impact energy along isoenergetic surfaces. Here isoenergetic means that parameter triplets represented by points of the surface are associated with the same energy input (power density).

While the impact energy is a highly important material feature, this empirical formula may be a useful tool to pre-indicate or optimize it as a function of SLM process parameters.

Acknowledgements

This work was supported by the application project GINOP-2.2.1-15-2017-00055 entitled „Research on osteosynthesis of implants and development of trabecular structures by application of additive manufacturing” cofunded by European Union and Hungarian Government.

Authors express thanks to Biomechanical Laboratory at University of Debrecen for manufacturing test specimens, and Material Test Laboratory at University of Nyíregyháza for measurements in the frame of project mentioned above.

This project was supported by the Scientific Council of the University of Nyíregyháza.

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