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# Characterization of Process Efficiency Improvement in Laser Additive Manufacturing

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**Abstract**

Laser additive manufacturing (LAM) enables production of complex parts with good mechanical properties. Nevertheless, part manufacturing is still relatively slow and the process efficiency could be improved to achieve total breakthrough into series production. In this study, the process efficiency improvements via higher laser power and thicker powder layers are studied. Effect of the building parameters must be understood when increasing build rate. Track-wise and layer-wise manufacturing strategy involves different independent and dependent thermal cycles which all affect part properties.
Effects of the processing parameters such as speed and power on single-track formation are examined, since the part quality depend strongly on each single-track and layer. It was concluded that heat input has important effect on the penetration depth and possibility to melt thicker powder layers. These were noticed to be crucial for improving process efficiency.


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*Keywords:* additive manufacturing; process efficiency; single track; process parameters

## 1. Introduction

Laser additive manufacturing was developed in 1990s but only recently it has been considered as part of industrial revolution: manufactured parts can be used in various demanding industries such as medical, automotive and aerospace industries. Nowadays, the 3D printing hype has brought additive manufacturing closer to consumer

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products and it is noticed that the manufacturing process efficiency could be improved. The need of customized large scale production also pushes this technology into further developing the manufacturing process and its productivity. Laser additive manufacturing is a powder based process which allows designer to create parts being hard or impossible to manufacture with conventional methods. The possibility to optimize part weight and strength is also an advantage of this technology. Parts are built layer by layer as the laser beam melts the next layer on top of the previous one. Methods for process efficiency improvements are examined in this study, because it is very important to understand the effects of the process parameters in the manufacturing process in order to achieve building process without interruptions and high quality parts. Interaction of laser beam and powder material was also examined, as it is a fundamental issue to be able to understand basic nature of whole process and also this way understanding factors affecting process efficiency.

**Nomenclature**

| | | | |
|---|---|---|---|
| $V_{Process}$ | process velocity [$mm^3$/s] | $P$ | laser power [W] |
| $WDA$ | area of penetrated bead [$mm^2$] | $LT$ | layer thickness [mm] |
| $BW$ | bead width [mm] | $v$ | laser scanning velocity [mm/s] |
| $PD$ | penetration depth [mm] | $h$ | hatch distance [mm] |
| $ED$ | energy density [J/$mm^3$] | | |

## 2. Process efficiency

Research on additive manufacturing has been concentrated a lot in past years on new material qualification and implicating them into different industrial applications. This means that there are only few studies about process efficiency and build rate of LAM process and most of these are rather old or made by machine manufacturers R&D departments for their own purposes. At least there is only few of those articles publicly available as it is obvious that most of such development is done in companies but they are not available. For example, Meiners (1999) and Wagner (2003) have studied build rates in their doctoral theses. The process cycle time can be divided into primary and auxiliary process time in order to understand LAM process efficiency better. The primary process time consists the time that is needed in melting each layer of desired geometry. The auxiliary process time consists of operations, such as building plate lowering and powder spreading (Schleifenbaum et al., 2010; Kelbassa et al., 2012).

Studies found from literature (Kelbassa et al. (2012), Schleifenbaum et al. (2011)) are focused to investigating on the primary process time and increasing of build rate through that. This is because of processing time of large volume parts consists more than 80 % of the primary process time. Also several low volume parts can be counted into one large volume part which is placed on single building platform and manufactured simultaneously (Schleifenbaum et al., 2010). For this reason according to Schleifenbaum et al. (2010) build rate plays an important role in laser additive manufacturing. As this study also concludes, layer thickness, scanning velocity and hatch distance are affecting to build rate, as equation 1 shows. The scanning velocity and layer thickness are limited by the available laser power. The hatch distance is limited by the diameter of focused laser beam to be same as the beam diameter in order to achieve pore free structure (Buchbinder et al., 2011).

$$V_{Process} = LT \cdot v \cdot h \tag{1}$$

where, $V_{Process}$ process velocity,
$LT$ layer thickness,
$v$ laser scanning velocity,
$h$ hatch distance.

According to Schleifenbaum et al. (2011), one way to increase build rate is to equip LAM machines with higher power lasers in order to be able to increase layer thickness. It is also possible to increase the scanning velocity with increased laser power which leads to speeding up the building process. However, there is only limited potential to increase the build rate with only increasing laser power and scanning velocity, while keeping the beam diameter constant. When maintaining the beam diameter constant and increasing the laser power, the intensity increases also at the point of processing. This leads to higher evaporation rate and results in higher amount of spattering which has negative effect on the process.

Yadroitsev and Smurov (2010) concluded from their side that one way to study process efficiency of LAM is to examine single track formation which aim is to define energy density needed to melt the single tracks. Understanding of the mechanisms of single track formation in powder bed fusion (PBF) process gives basis for usage of wider range of commercially available powders and also basic knowledge to improve process efficiency by modifying the parameters of the building process (Yadroitsev and Smurov, 2010). According to study by Ciurana et al. (2013), energy density which is used in building process can be determined with equation 2.

$$ED = \frac{P}{v \cdot LT \cdot h} \quad (2)$$

where $ED$ energy density,
$P$ laser power,
$v$ laser scanning velocity,
$LT$ layer thickness,
$h$ hatch distance.

## 3. Aim and purpose of this study

Aim of this study was to determine the methods for LAM process efficiency improvements as it is very important to understand basic phenomena occurring during manufacturing process to achieve building process without process breaks. Uninterrupted process guarantees also high quality of end products, as each interruption causes a severe discontinuity to part being fabricated. Interaction of laser beam and powder material was also considered, as of it is such a fundamental understanding of process gives further aspect to analyze what are real factors affecting process efficiency. It was decided in this study to manufacture test pieces where input parameters such as laser power and scanning speed were varied and the formation and penetration of formed single tracks were studied. Test pieces were manufactured with two powder bead fusion systems. All of the test pieces were manufactured from EOS 17-4 PH stainless steel powder.

## 4. Experimental part

### *4.1. Model for interaction between laser beam and powder material*

The overall goal of this study was to be able to create preliminary model for interaction between laser beam and powder material in laser additive manufacturing of metallic materials. This way the knowledge of process efficiency during the LAM process can be improved and understanding gathered during study leads to deeper understanding of factors affecting process efficiency during the process. Piili (2013) created a model for interaction between laser beam and material in her thesis, and a modified model from that was created for this study. Fig. 1 presents this model for interaction between laser beam and powder material in LAM.

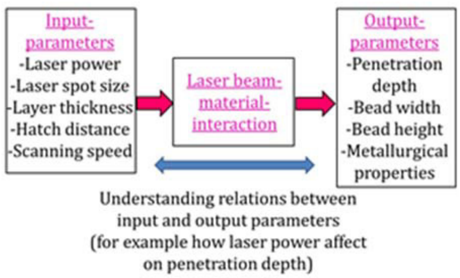


Fig. 1. Model for interaction between laser beam and powder material in LAM.

Aim to create interaction model introduced in Fig. 1 was to preliminary evaluate relation between input parameters to output parameters. If the dependency between them can be found out, preliminary equations describing this interaction between laser beam and powder material could be created. These equations could then act also as tool for rough evaluation of process efficiency. This study is first published study of a series of studies concentrating in understanding of interaction between laser beam and powder material. Aim in future is to study more closely single tracks with non-destructive methods such as x-ray imaging and laser spectrometer microscope, carry out further studies with various laser powers in order to see if there is correlation between the same energy density inputs with different laser powers and further analyze the formation of multiple tracks in order to achieve more accurate knowledge of the manufacturing process. This all enables further development of model for laser beam and material interaction and deepens understanding of basic phenomena occurring during laser additive manufacturing of metallic materials.

*4.2. Material*

Material used in this study was EOS StainlessSteel 17-4 PH stainless steel powder. Composition of this powder is similar to US classification 17-4 PH and European 1.4542 stainless steel materials. This type of material is widely used in engineering applications where high toughness, ductility and corrosion resistance is required. Suitable applications can be found for example from medical or mold making industry. The chemical composition of the material is shown in Table 1.

Table 1. Material composition of EOS 17-4 PH.

| Material | Fe | Ni | Mo | Cu | Cr | Mn | Si | C | P | S | O | N | Nb |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Composition [%] | 73.7 | 4.2 | 0.4 | 3.9 | 15.8 | 0.7 | 0.7 | 0.01 | 0.02 | 0.01 | 0.04 | 0.14 | 0.29 |

*4.3. LAM equipment*

Laser additive manufacturing systems used in this study consists of laser unit, process chamber and process control computer. Two different LAM systems are used in this study. These LAM systems are equipped with 200 W and 400 W fiber laser sources. LAM equipment with 200 W fiber laser source is located in Laboratory of Laser Material Processing of Lappeenranta University of Technology (Finland). This modified research equipment is similar to EOS EOSINT M-series device and it is equipped with IPG YLS-200-SM-CW fiber laser and Scanlab hurrySCAN 20 scanner. This laser unit produces 200 W power at a wavelength of 1070 nm and the focal length is 400 mm. The LAM system with 400 W fiber laser source is located to EOS Finland in Turku (Finland). This equipment is commercially available EOS EOSINT M280 system.

*4.4. Geometry of the test pieces*

It was decided to manufacture single track test pieces by altering heat input to be able to determine the effect of heat input on the single track formation and penetration depth. These single tracks were made on top of 20 x 40 x 15 mm bulk piece. The 3D model of single track test piece is shown in Fig. 2.

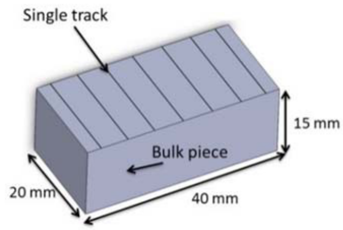

Fig. 2. 3D model of the single track test piece.

*4.5. Analysis equipment*

Polished sections were made from the manufactured test pieces so that the pieces were first cut half in longitudinal direction and then polished. The sections were polished with Struers TegraPol 31 grinding/polishing machine. Etching of the test pieces was first made with Kalling’s 2 reagent. After first etching the single tracks were not visible enough to analyze them. It was decided to etch the test pieces again with Fry’s reagent. However, even after etching with Fry’s reagent, the outlines of the beads were not clear and visible, so it was decided to etch the single track test pieces once more with electro etching using again Kalling’s 2 reagent as etchant. Table 2 shows the compositions of the etchants and the etching times.

Table 2. Composition of etchants and etching times.

| | Kalling's 2 reagent | Kalling's 2 reagent (electro etching) | Fry's reagent |
|---|---|---|---|
| Cupric chloride $CuCl_2$ | 5 g | 5 g | 5 g |
| Hydrochloric acid HCl | 100 ml | 100 ml | 40 ml |
| Ethyl alcohol $C_2H_5OH$ | 100 ml | 100 ml | 25 ml |
| Water | - | - | 30 ml |
| Etching time | 10 s | 10 s | 5 s |
| Current | - | 0.6 A | - |
| Voltage | - | 10 V | - |

The polished sections were photographed with Infinity camera coupled with Olympus optical microscope. The imaging software was i-Solution Lite. The penetration depth, width and height of the bead of the single tracks were measured with AxioVision LE64 microscopy software.

## 5. Experimental procedure

### *5.1. Parameters of single track experiments*

Basic parameters of this process are marked as $St_0$ in table 3. The parameters were then varied by keeping the laser power as constant of 200 W in tests performed at LUT Laser and 325 W tests made at EOS Finland. The scanning speed was then altered so that energy density also varies. Table 3 shows building parameters in single track tests executed at LUT Laser. The energy densities were maintained the same between tests in LUT Laser and in EOS Finland.

Table 3. Building parameters in single track tests performed at LUT Laser with laser power of 200 W.

| Parameter | $St_{-3}$ | $St_{-2}$ | $St_{-1}$ | $St_0$ | $St_1$ | $St_2$ | $St_3$ |
|---|---|---|---|---|---|---|---|
| Laser power [W] | 200 | 200 | 200 | 200 | 200 | 200 | 200 |
| Scan speed [mm/s] | 1600 | 1400 | 1200 | 1000 | 800 | 600 | 400 |
| Layer thickness [mm] | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Laser spot size [mm] | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Energy density [$J/mm^3$] | 63 | 71 | 83 | 100 | 125 | 167 | 250 |
| Laser interaction time [s] | $6.3*10^{-5}$ | $7.1*10^{-5}$ | $8.3*10^{-5}$ | $1*10^{-4}$ | $1.3*10^{-4}$ | $1.7*10^{-4}$ | $2.5*10^{-4}$ |

Similarly, the single track tests were made in EOS Finland in Turku. Table 4 shows parameters in single track tests fabricated at EOS Finland.

Table 4. Building parameters in single track tests manufactured at EOS Finland with laser power of 325 W.

| Parameter | $St_{-3}$ | $St_{-2}$ | $St_{-1}$ | $St_0$ | $St_1$ | $St_2$ | $St_3$ |
|---|---|---|---|---|---|---|---|
| Laser power [W] | 325 | 325 | 325 | 325 | 325 | 325 | 325 |
| Scan speed [mm/s] | 2600 | 2275 | 1950 | 1625 | 1300 | 975 | 650 |
| Layer thickness [mm] | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| Laser spot size [mm] | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |
| Energy density [$J/mm^3$] | 63 | 71 | 83 | 100 | 125 | 167 | 250 |
| Laser interaction time [s] | $3.9*10^{-5}$ | $4.4*10^{-5}$ | $5.1*10^{-5}$ | $6.2*10^{-5}$ | $7.7*10^{-5}$ | $1*10^{-4}$ | $1.5*10^{-4}$ |

### 5.2. Equations used in analysis

The energy density input in this study was determined according to equation 2. In case of single tracks, the hatch distance is set equal as laser spot size. It was decided in this study to create value to define the rough area of penetrated bead to be able to evaluate properties of single tracks when they were evaluated against each other. Width-depth-area (*WDA*) defines area of the penetration. *WDA* is calculated as equation 3 illustrates.

$$WDA = BW \cdot PD \tag{3}$$

where *WDA* area of penetrated bead,
*BW* bead width,
*PD* penetration depth.

The important feature of the single track tests was to define the penetration depth and single track bead width. This is why a value of width-depth ratio (*WDR*) was created in this study to describe the ratio between bead width and penetration depth. With *WDR* it is easy to conclude when width if the bead is large and penetration is low and vice versa. *WDR* is calculated as equation 4 presents.

$$WDR = \frac{BW}{PD} \tag{4}$$

where *WDR* width-depth ratio of penetrated bead.

Fig. 3 presents diagram of area of penetration, *WDA* and width-depth ratio *WDR*.

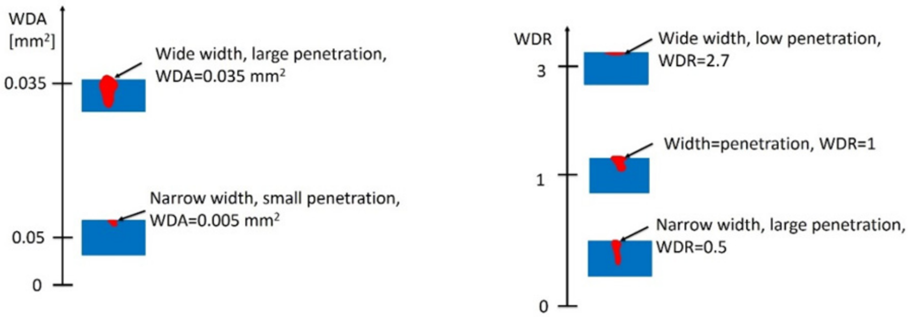


Fig. 3. Diagram of small and large *WDA* and *WDR* values.

## 6. Results and discussion

### 6.1. Energy density vs. penetration depth

The single track specimen made with laser power of 200 W and 325 W were compared against each other, since these test pieces have same energy density inputs (see table 3 and 4). Fig. 4 illustrates energy density input vs. penetration depth when laser power of 200 W and 325 W were used.

As it can be seen from Fig. 4, the penetration depths of the test piece of 200 W single tracks were almost in all cases larger than in test piece of 325 W. This is due to fact that test piece of 200 W single tracks were exposed longer time to laser radiation (see table 3). So penetration depth increases, when laser energy density increases. In test piece of 200 W, test of single track made with highest energy density input has penetration depth almost three times larger than test of single track made with the nominal energy density input of 100 J/mm$^3$ (shown as green dashed line in Fig. 4). Penetration depth (325 W) is linearly dependent on energy density. The penetration depths between test piece 200 W and 325 W have differences between 10-20 μm, when the energy density input is less than 200 J/mm$^3$. When the energy density input increases from 200 J/mm$^3$ (shown as black dashed line in Fig. 4), the penetration depth increases dramatically in test piece of 200 W.

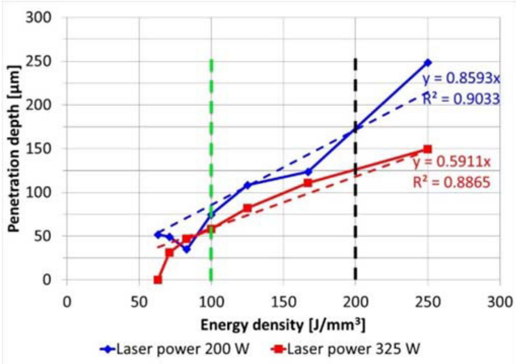


Fig. 4. Energy density vs. penetration depth.

### 6.2. Energy density vs. WDA

The area of the penetrated tracks were also roughly calculated and compared between specimens made with laser power of 200 W and 325 W. The energy density vs. *WDA*, when laser power of 200 W and 325 W were used, is presented in Fig. 5. As it can be observed from the Fig. 5, *WDA* is very close to each other with both of the test pieces when energy density input is less than 100 J/mm$^3$ (shown as black dashed line in Fig. 5). *WDA* of 200W increases when energy density input increases. This is because of the large penetration depth of the single-tracks in this test piece. Fig. 5 shows also similar behavior when laser power of 325 W was used. Fig. 5 shows that when energy density is increased, the *WDA* is also increasing.

### 6.3. Energy density vs. WDR

Fig. 6 presents energy density vs. *WDR*. It can be observed from Fig. 6 that WDR decreases when energy density input increases. It can be seen, that WDR values, when laser power of 200 W was used, decreases as energy density input increases. It is also noticeable that WDR values when laser power of 325 W was used are larger than WDR values with laser power of 200 W. This can be because the 200 W single-tracks were made with slower scan speeds and it might cause deeper penetration rather than wider bead width. However, this issue needs further study. Single tracks manufactured with 200 W has overall deeper penetration than single tracks fabricated with laser power of 325 W.

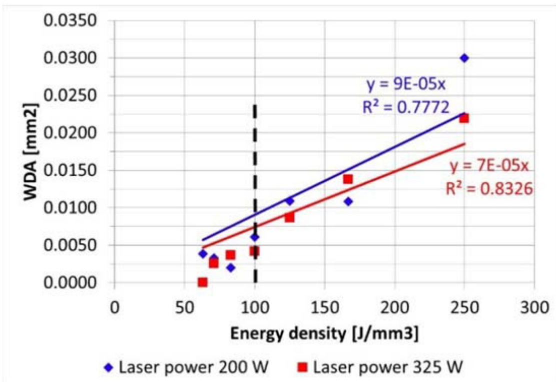


Fig. 5. Energy density vs. *WDA*.

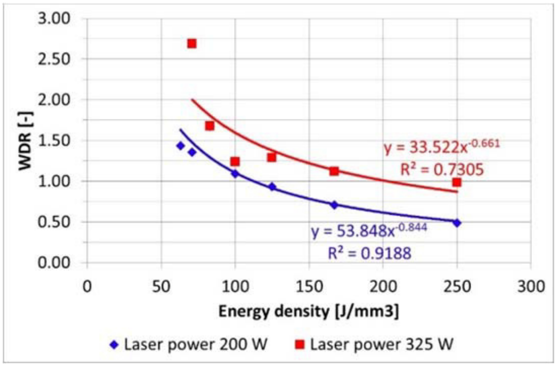


Fig. 6. Energy density vs. *WDR*.

### *6.4. Input parameters vs. output parameters of interaction model*

The overall goal of this study was to create preliminary model for interaction between laser beam and powder material in laser additive manufacturing of metallic materials. This is how fundamental analysis of process efficiency during the LAM process can be improved and understanding gathered during study leads to deeper understanding of whole interaction model, especially relations concerning input parameters and output parameters. Aim in future is to publish further studies which goes more detailed into interaction of laser beam and powder material.

When understanding the relations of input and output parameters of this model (see Fig. 1), such as energy density input, laser interaction time, penetration depth and *WDA*, it is possible to evaluate and analyze the process efficiency. As literature review presented, process build rate can be evaluated as equation 1 shows. However, in order to adjust the process to be more efficient, the effect of input parameters into output parameters should be understood.

Energy density input was decided to include in these equations since it includes important process input parameters, such as laser power, scan speed, layer thickness and hatch distance. The *WDA* value was decided to include because of the similar reasons. It includes important output parameters, the penetration depth and bead width. Fig. 7 presents energy density vs. penetration depth.

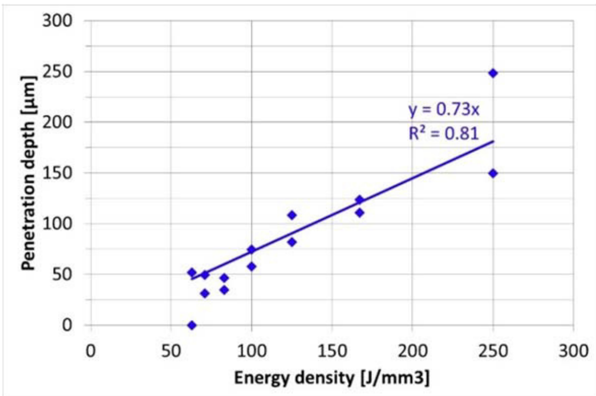


Fig. 7. Energy density vs. penetration depth.

As the Fig. 7 shows, the dependency between energy density input and penetration depth is linear. Figure 7 also illustrates that $R^2$ is 0.81 which can be considered reliable in case of this kind of preliminary study. Fig. 7 shows that that the penetration depth as function of energy density input can be described with equation 5.

$$PD = 0.73 \cdot ED \tag{5}$$

where, *ED* energy density.

Fig. 8 represents energy density input vs. *WDA*.

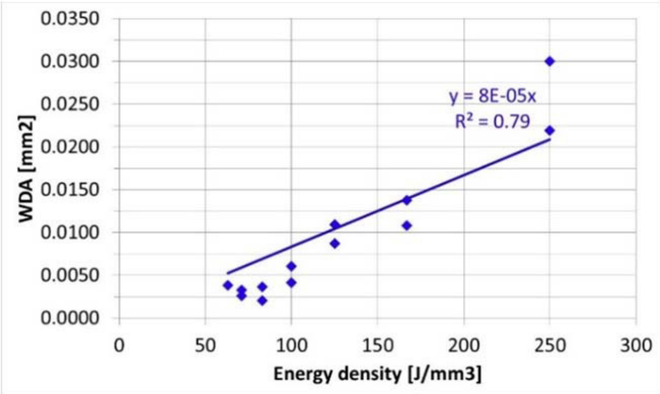


Fig. 8. Energy density vs. *WDA*.

As the Fig. 8 presents, the *WDA* increases while energy density increases. Dependency between energy density and WDA is exponential. It can be also observed that $R^2$ is 0.79 and this can be considered relatively good. Of course, in further studies as more test points are included, more reliable results are gathered, but this $R^2$ value for preliminary study can be considered reliable. According to Fig. 8, *WDA* can be calculated as function of energy density as equation 6 represents.

$$WDA = 8 \cdot 10^{-5} \cdot ED \tag{6}$$

As these equations presents, it is possible to estimate the input-output parameter relations from the experimental results. Equation 6 describes the input-output relation very well, since it includes the important input parameters and also the important output parameters. It is possible to evaluate the bead area of the single track with equation 6, and with help of that information, optimizing the process parameters could be one of the further studies.

## 7. Conclusions

Aim of this study was to investigate the aspects for increasing the process efficiency of laser additive manufacturing (LAM) process. The process efficiency in LAM process found from literature concentrates very often on the build rate of the parts. It was noticed actually that there is only a few studies about process efficiency and LAM build rate in literature and most of these are rather old or made by machine manufacturers R&D departments for their own purposes.

It was decided to study the input-output parameter relations more closely, since the process efficiency adjustment requires basic understanding and knowledge of these parameters. Aim to create interaction model introduced was to preliminary evaluate relation between input parameters to output parameters. If there can be found out dependency between them, preliminary equations describing this interaction between laser beam and powder material could be created. These equations could then act also as tool for rough evaluation of process efficiency.

It was concluded in this study that energy density input is suitable value when studying the effect of input parameters to output parameters. Energy density input includes all the important input parameters such as laser power, scanning speed, layer thickness and hatch distance. It was also concluded in single track tests that the energy density input has effect on penetration depth and bead width of the single tracks. When energy density input is increased, the penetration depth also increases. The area of penetration, *WDA*, was also calculated. It was concluded that the *WDA* is increasing when energy density input is increasing. Width-depth ratio, *WDR,* was calculated and it showed that the *WDR* is decreasing when energy density input increasing. The test results showed that there is correlation between input and output parameters when energy density vs. penetration depth and energy density vs. *WDA* are concerned. Equations were created from the measurement data and it showed that it is possible to have rough estimations on the single track formation with these equations.

This study is first published study of a series of studies concentrating in understanding of interaction between laser beam and powder material. Also implementation of monitoring equipment in the process will be studied. When the phenomena between laser beam and powder material is clarified and understood, the process can be adjusted and optimized to be more efficient.

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**References**

Buchbinder, D., Schleifenbaum, H., Heidrich, S., Bültmann, J., 2011. High Power Selective Laser Melting (HP SLM) of Aluminum Parts, Physics Procedia Volume 12, Part A, 2011, Proceedings of the 6th International WLT Conference on Lasers In Manufacturing, p.271-278, Elsevier Ltd. [Web document] From: http://www.sciencedirect.com/science/article/pii/S1875389211001143 [referred: 25.3.2014]

Ciurana, J., Hernandez, L., Delgado, J., 2013, Energy density analysis on single tracks formed by selective laser melting with CoCrMo powder material, The International Journal of Advanced Manufacturing Technology, Volume 68, Issue 5-8, p. 1103-1110, Springer-Verlag London, Online ISSN: 1433-3015

Kelbassa, I., Gasser, A., Meiners, W., Backes, G., Müller, B., 2012, High speed LAM, Conference proceedings of the 37th International MATADOR Conference, University of Manchester, July 2012, Edited by Srichand Hinduja and Lin Li

Piili, H., 2013, Characterization of Laser Beam and Material Interaction, Doctoral Thesis, Acta Universiatis Lappeenranta 512, ISBN: 978-952-265-381-9

Schleifenbaum, H., Meiners, W., Wissenbach, K., Hinke, C., 2009, High Power Selective Laser Melting: A New Approach for Individualized Series Production, Conference Proceedings of the 28th International Congress on Applications of Lasers & Electro-Optics (ICALEO), LIA Publication # 612, Volume 102, ISBN: 978-0-912035-59-8

Schleifenbaum, H., Meiners, W., Wissenbach, K., Hinke, C., 2010, Individualized production by means of high power Selective Laser Melting, CIRP Journal of Manufacturing Science and Technology, Volume 2, Issue 3, Elsevier Ltd. ISSN: 1755-5817

Schleifenbaum, H., Diatlov, A., Hinke, C., Bültmann, J., Voswinckel, H., 2011, Direct photonic production: towards high speed additive manufacturing of individualized goods, Production Engineering, Volume 5, Issue 4, p. 359-371, Springer-Verlag, Online ISSN: 1863-7353

Steen, W.M., Mazumder, J., 2010, Laser Material Processing, 4th Edition, Spinger-Verlag London Limited, ISBN: 978-1-84996-061-8

Yadroitsev, I., Smurov, I., 2010, Selective laser melting technology: from the single laser melted track stability to 3D parts of complex shape, Physics Procedia 5, p. 551-560, Conference proceedings of 6th International Conference of Laser Assisted Net Shape Engineering, Elsevier, ISSN: 1875-3892

Yadroitsev, I., Krakhmalev, P., Yadroitsava, I., Johansson, S., Smurov, I., 2013, Energy input effect on morphology and microstructure of selective laser melting single track from metallic powder, Journal of Materials Processing Technology, Volume 213, Issue 4, p. 606-613, Elsevier, ISSN: 0924-0136