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Cost Estimation of Laser Additive Manufacturing of Stainless Steel

Heidi Piili*[a], Ari Happonen[b], Tapio Väistö[c], Vijaikrishnan Venkataramanan[a], Jouni Partanen[d], Antti Salminen[a,e]

[a]Lappeenranta University of Technology, School of Energy Systems, Laser Processing Laboratory, P.O.Box 20, 53851 Lappeenranta, Finland
[b]Lappeenranta University of Technology, School of Business and Management, Skinnarilankatu 34, 53850 Lappeenranta, Finland
[c]University of Manchester, School of Mechanical, Aerospace and Civil Engineering, Laser Processing Research Centre, Manchester, UK
[d]Aalto University, Department of Engineering Design and Production, Espoo, Finland

Abstract

Laser additive manufacturing (LAM) is a layer wise fabrication method in which a laser beam melts metallic powder to form solid objects. Although 3D printing has been invented 30 years ago, the industrial use is quite limited whereas the introduction of cheap consumer 3D printers, in recent years, has familiarized the 3D printing. Interest is focused more and more in manufacturing of functional parts. Aim of this study is to define and discuss the current economic opportunities and restrictions of LAM process. Manufacturing costs were studied with different build scenarios each with estimated cost structure by calculated build time and calculating the costs of the machine, material and energy with optimized machine utilization. All manufacturing and time simulations in this study were carried out with a research machine equal to commercial EOS M series equipment. The study shows that the main expense in LAM is the investment cost of the LAM machine, compared to which the relative proportions of the energy and material costs are very low. The manufacturing time per part is the key factor to optimize costs of LAM.

Peer-review under responsibility of the Lappeenranta University of Technology (LUT)

Keywords: Laser additive manufacturing;costs evaluation;stainless steel; analysisIntroduction

1. Introduction

Additive Manufacturing (AM) is defined by ASTM standard as "*the process of joining materials to produce*

* Corresponding author. Tel.: +358 40 551 0170
E-mail address: heidi.piili@lut.fi

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objects from 3D model data, usually layer upon layer, as opposed to subtractive traditional machining and manufacturing methodologies". Due to its short production chain, nowadays even very small organizations have been successful in applying this technology for production of finished goods and for development of totally new products. As this practice is expected to take a larger growth in future, it can have significant impact on manufacturing practices and production chains compared to conventional manufacturing methods (Wohlers2014).

Nomenclature

$\bar{A}_p$	Average cross section area of part [mm^2]	l_d	laser beam spot diameter [mm]
A_{psr}	Area rate scanning the interior of the part [mm^2/s]	l_t	Layer thickness [mm]
A_{phr}	Area rate hatching the interior of the part [mm^2/s]	$m_{material}$	Mass of material [kg]
$\bar{A}_s$	Average cross section area of support [mm^2]	N	Number of layers
A_{sr}	Area rate scanning the support [mm^2/s]	$Price_{energy}$	Price of the energy [€/ J]
C_{build}	Cost of build [€]	$Price_{material}$	Price of material [€/ kg]
$C_{indirect}$	Machine costs [€/ h]	S_A	Surface area of part [m^2]
$C_{material}$	Cost of material [€/ kg]	T_{Build}	Total build time [h]
d_p	Density of part [kg/m^3]	T_p	Idle time between layers[s]
d_s	Density of support structure [kg/m^3]	V_P	Process velocity [mm^3/s]
E_{build}	Energy consumed during build [J]	w	Mass of the piece [kg]

Laser additive manufacturing (LAM) is becoming a valid consideration for industrial purposes as a result of development in all its related fields such as materials, part quality, manufacturability, production and economics. In spite of benefits, there are some challenges for LAM, relating to its economic viability, which makes industries to restrict LAM technology implementations. Because of this, the focus on cost estimation and reduction for LAM has been emphasised by researchers for last two decades, (Antzeni & Salmi 2012, Ruffo et al. 2006, Väistö et al. 2013). This study deals with cost estimation of a test case component with two different size scales in two extreme build scenarios to realize the effect of build space utilization using test pieces of two different size scales.

2. Factors influencing manufacturing cost in LAM

From previous studies (Antzeni & Salmi 2012, Ruffo et al. 2006, Väistö et al. 2013), the major fraction of cost is found to be due to investment on machine. The energy cost only contributes to minor level. Also simultaneous building of parts in LAM, rather than building a single part at a time in a chamber resulted massive cost reduction (Rickendacher et al. 2012, Väistö et al. 2013). So it has become evident that in order to minimize cost of the part, more importance should be given for minimizing building time. It also reveals the importance of building optimum number of parts simultaneously to reduce time consumption of building per part. Several studies were carried in this regard to estimate and optimize generic part build time (Angelo & Stefano 2011, Byun & Lee 2005, Munguia et al 2009, Pham & Wang 2000, Zhang & Benard 2013). A basic build time model is developed by Pham and Wang and it includes powder addition time, machine idle time and scan time. In order to minimize the build time it is recommended to orient the part in such a direction it has lesser height, (Pham & Wang 2000). During building number of parts in a single chamber, the total volume covered by arrangement should be planned as less as possible so that it reduces the total travelling distance of laser head (Pham & Wang 2000). Byun and Lee developed mathematical models for finding optimum part orientation with respect to build time and surface roughness, (Byun & Lee 2005). This is useful in calculating the minimum build time by substituting geometric parameters like height and area of cross section that suits for best orientation to build a part. Equation 1 shows the relationship between build time and parameters considered (Byun & Lee 2005).

$$T_{build} = N\left(T_p + d_p\left(\frac{\bar{A}_p}{A_{phr}} + \frac{\bar{A}_p}{A_{psr}}\right)\right) + d_s\frac{\bar{A}_s}{A_{sr}} \quad (1)$$

$$\overline{A}_s = S_A . l_d/(N. l_t) \quad (2)$$

$$\overline{A}_p = V_p/(N. l_t) \quad (3)$$

From Equation 1, it is noted that the build time is proportional to summation of idle time between layers, time for fusing the powder layer and time for support structure generation, (Byun & Lee 2005). Basic cost calculation for laser additive manufacturing was discussed by Baumers et al. The approach was to study the costs of LAM process only. The costs of post processing were not taken into account as they vary according to the user. The total cost can be calculated using Equation 4 (Baumers et al. 2012).

$$C_{build} = m_{material} \cdot C_{material} + T_{build} \cdot C_{indirect} \quad (4)$$

The direct costs are product of the part mass and raw material cost. The indirect costs are product of whole platform build time and machine cost rate. Cost per part, is obtained dividing C_{build} with number of parts built simultaneously (Baumers et al. 2012). With interest in environmental considerations, it was decided to calculate the electricity consumption separately. For this Baumers et al., proposed a more detailed model for the expenses, as Equation 5 illustrates (Baumers et al. 2012).

$$C_{build} = C_{indirect} \cdot T_{build} + w \cdot Price_{material} + E_{build} \cdot Price_{energy} \quad (5)$$

Equation 5 takes into account the energy expenses separated from the machine upkeep and overheads. These overheads are found to be less than 10% (Baumers et al. 2012). This equation also applies to production of multiple instances of same part. The shielding gas cost is included in machine cost itself as a nitrogen gas generator is included with same machine. Other variables such as cost of the material and energy consumption of the LAM machine were based on findings from literature (Baumers et al. 2011, Baumers et al. 2012, EOS GmbH 2012, Officer et al. 2013, Ruffo & Hague 2007).

3. Cost effectiveness of LAM parts

The cost efficiency realization of LAM is easiest via case examples. In studies of Antzeni and Salmi the main landing gear of an airplane was the case. Fig. 1 shows a landing gear of an airplane. Part was redesigned according to AM design rules, for LAM case shown right side in Fig. 1 (Antzeni & Salmi 2012). Detailed cost models were developed to compare the production costs of the aluminium landing gear structure both for high-pressure die-casting (HPDC) and for LAM process. LAM structure was lighter and differed from the die casted model, but both served same functionalities.

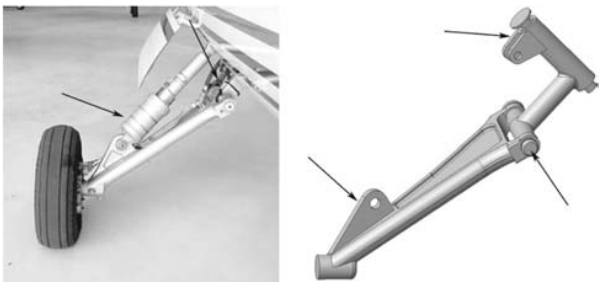


Fig.1. Main landing gear of the Italian aircraft P180 Avant II by Piaggio Aero Industries S.p.A. (Antzeni & Salmi, 2012).

Cost evaluation for the main landing gear produced by HPDC is based on quote from mould maker. The estimate takes into account the part geometry and the fact that production volume can be low. The possibility of combination die enables the process using single mould, (Antzeni & Salmi, 2012). The structure possible to manufacture by HPDC required an assembly operation to mount the hinge costing 0.04 €/piece. In AM, the elimination of this assembly and possibility of producing 4 parts at a time owed to cost savings (Antzeni & Salmi, 2012).When comparing manufacturing costs of HPDC and AM, up to production volume of 42 parts, the competitiveness of AM is high and then it starts to decrease. Fig.2 shows the change of manufacturing cost with HPDC and AM as a function of production volume. The break-even point is 42 pieces, (Antzeni & Salmi, 2012). So the competitiveness of LAM is evident for aerospace industries where the volume of production is typically low.

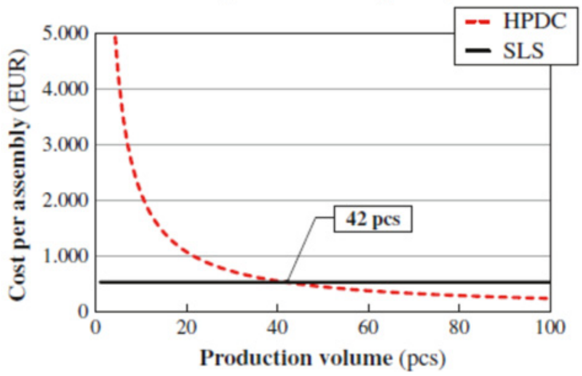


Fig. 2. Breakeven analysis comparing conventional HPDC process with SLS technique (Anzeni & Salmi, 2012).

4. Aim and purpose of this study

The processing time along with the mass of material consumed, are the main variables in several cost models, (Baumers et al. 2011, Baumers et al. 2012, Ruffo & Hague 2007). So the aim of this economical analysis concentrates on the LAM process induced expenses excluding other cost factors giving understanding of the process related costs. In order to show how drastically the utilization rate affects, the building costs were calculated considering two extreme building platform filling scenarios. First the costs were calculated for building one single piece and these costs were compared to a case in which the building platform was utilized to the maximum. This is valid for all additive manufacturing process. In order to show the effect of the size of the part, the part was linearly scaled 50 % smaller compared to the base size. Both platform filling scenarios were calculated for this reduced size piece also. The key difference was that in the case of the smaller piece, it was possible to build 170 pieces simultaneously.

5. Experimental procedure

5.1. LAM device

The LAM machine used is a prototype machine similar to commercial EOSINT M-series shown in Fig.3. Commercial line consists of a laser unit, a process chamber, a nitrogen shield gas generator and a control computer. The fiber laser in the study was 200 W IPG YLS-200-SM-CW. The laser beam is transferred via optical fiber from the source to Scanlab hurrySCAN 20 galvanometric scanners. The produced maximum continuous power was 200 W at a wavelength of 1070 nm. Focal length of the system is 400 mm and the focal point diameter for beam is 70-100 μm. Building chamber is divided in to builder, powder dispenser and collector platforms. A re-coater spreads the powder evenly on the building platform. The build temperature is constant 80 °C in 99.8 % nitrogen gas atmosphere which avoids oxidation of metal during fabrication. The mean real power for an EOSINT M 270 machine was measured to be 2.55 kW, (Baumers et al. 2011).When this was calculated as energy consumption per kilogram deposited, it varied between 339 – 241 MJ / kg. Variation of is due to different capacity utilizations, e.g. building one piece or full platform at a time (Baumers et al. 2011).

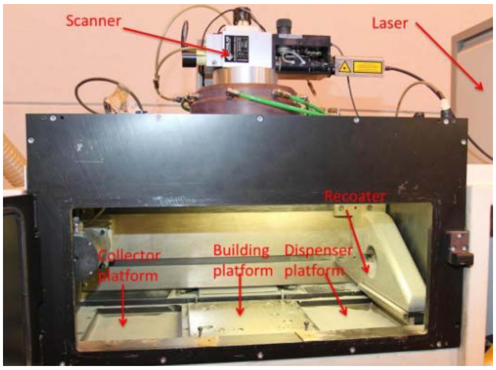


Fig. 3. Process chamber of the LAM machine.

5.2. Material and test piece

Material used in this study was EOS Stainless Steel PH1 powder which is fine martensitic, providing good corrosion resistance and mechanical properties, costing 80 €/kg (the price for small and medium sized companies, purchasing the material in relatively small quantities). This material finds wide use in medical and aerospace applications fulfilling requirements of high hardness, strength and corrosion resistance. (EOS GmbH 2012). In typical manufacturing analysis, benchmark test pieces, as presented in Fig. 4., are considered to analyze the process accuracy and limitations (Castillo 2005, Cooke & Soons 2010, Kruth et al. 2005).

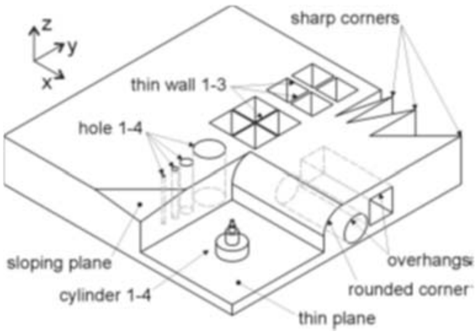


Fig. 4. An example of typical test piece for LAM research (Kruth et al. 2005).

This type of test pieces is suitable for examining the manufacturing possibility of different features and benchmarking the parameters. Disadvantage is that these kinds of parts are not very illustrative or practical in the economical point of view. This brings additional challenges in building fragile thin walls and cylinders, small gaps or holes and so on (Castillo 2005, Cooke & Soons 2010, Kruth et al. 2005, Matilainen 2012). It was decided that in this study the piece would exploits the benefits of the process and presents a plausible object as well as possible. For this purpose, the piece chosen was a pipe fitting in which three different cross-sections join together as shown in Fig. 5

The structure shows the benefits of additive manufacturing such as the possibility to use whatever shapes needed and as being a thin walled structure, the volume of the material deposited is small and the laser melting time is relatively short making it effective. To study the effect of the size of the piece two different sizes of the piece were calculated. Dimensions of the test piece A were 40 x 20 x 39 mm (height x width x depth), with a wall thickness of 1 mm. Mass of the piece was 30.54 g. Fig. 5 presents the test piece A after sandblasting. The cost of the post processing was calculated in overheads. Test piece B was linearly scaled into 50% size, except the wall thickness. Size was 20 x 10 x 19.5 mm.

Fig. 5. Full size test piece used in this study. Second piece is similar, but scaled down by factor of two.

6. Build cost analysis

The build costs were studied by calculating the cost structure of test pieces in two scenarios. So this is why, personnel working hours were left out of this study. The pieces would be built one at a time in first scenario. Secondly, the building platform was filled with maximum amount of pieces, yielding a simultaneous build of 40 pieces of test piece A and 170 pieces of test piece B. Fig. 6 shows platform for test piece A, when fabrication of one piece (see Fig. 6a) or fabrication of 40 pieces (see Fig. 6b) is executed. The total manufacturing cost was divided into machine cost, material cost and energy cost. The cost calculations were based on estimated build times. The times were calculated with the PSW software of the LAM machine. Two platform filling scenarios were compared, 1) building a piece at a time, 2) building platform with full fill-up. Scenarios were repeated for smaller test pieces. Cost per part in full fill-up build case is calculated by dividing the whole build cost with the number of pieces built

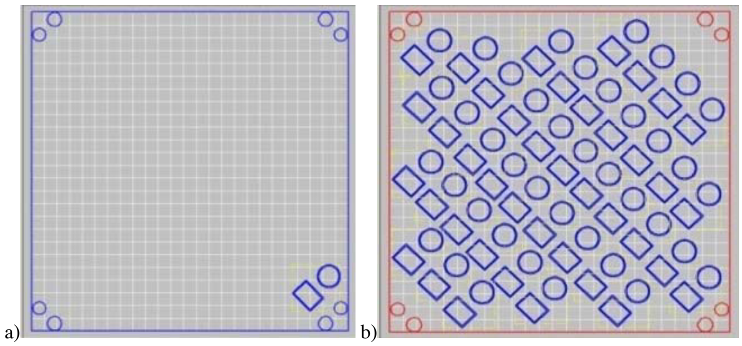


Fig. 6. Picture to illustrate the layout of samples on the platform when fabrication of test piece A (a) one sample at a time and (b) full platform (40 pieces).

Electricity consumption is based on manufacturing time and average power consumed by machine. The machine cost was from literature (Baumers et al. 2012). Energy price is based on Energy Market Authority of Finland statistics, (statistics, 2013) as it is the official source for the price of electricity in Finland.

7. Results and discussion

An economical analysis was made to calculate the costs of laser additive manufacturing in two different build scenarios as explained in previous section. Total cost calculated for building parts A and B in two scenarios and cost savings due to full platform utilization are shown in Table 1. Personnel working hours were not included to this model.

Table 1.Cost of building a part compared to utilizing the build platform fully.

Test piece	Single piece	Full platform	Savings by utilization of full platform	Savings by utilization full platform
A	158.00€	32.30 €	126.00 €	79.6 %
B	72.2 €	6.38 €	65.8 €	91.6 %

The analysis of test piece A for building one piece at a time shows a total cost of 158.00 €. The cost of the test piece B is 45.6 % smaller. As the volume is 50% reduced, also the height does the same, and this lead to reduced number of recoats needed. In the case of test piece A, in full platform condition, the total cost per piece is 32.30 €. This corresponds to savings of nearly 80 %. The same practice in test piece B, lead cost savings to 92 %. The effect of efficient filling of building platform on different cost components in case of part A can be seen in Table 2. The cost falls as the building time per piece decreases. Building one piece A at a time takes 8 h 49 min, but when building a full platform of pieces the time per piece reduces to 1 h 42 min. This yields a time saving of 81 %.

Table 2. Costs and cost structures of test builds of piece A and piece B.

Piece A				Piece B			
Cost components	Single piece	Full platform build (40 pieces)	Full platform build savings %	Cost components	Single piece	Full platform build (170 pieces)	Full platform build savings, %
Machine cost, €	158.00	29.50	81.30	Machine cost, €	72.20	6.38	91.20
Material cost, €	2.44	2.44	-	Material cost, €	0.31	0.31	-
Energy cost, €	1.94	0.37	80.90	Energy cost, €	0.89	0.08	91.00
Total cost, €	162.38	32.30	79.60	Total cost, €	73.60	6.38	91.20
Work time, min	529	102	80.70	Work time, min	244	20.6	91.60

Table 2 shows cost structure for sample B. For test piece B case, the times per part are 4 h 4 min for fabrication of one piece at a time and 21 min for whole building platform, yielding a time saving of 93 %. Time saving also results similar cost reduction of a piece, since the material and energy costs are very low. Fig. 7 and Fig. 8 show that the machine cost as the major factor in total cost structure.

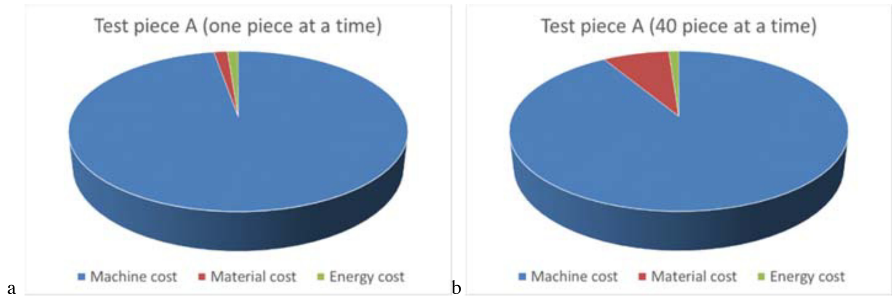
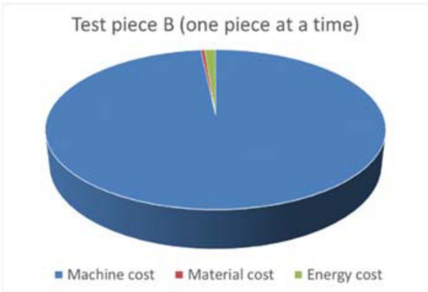


Fig. 7. Cost structures of sample A, when (a) costs for single unit build up and (b) costs calculated for fabrication of batch of 40 pieces.

The proportion of machine cost lowers by 6 % when building 40 pieces simultaneously. The time saving lowers the energy consumption per piece by 81 %, but since its share is low it is not as visible as the reduction of machine time and cost. It should be noted that the machine cost includes all consumables, maintenance, shielding gas generation as well as the purchase costs. When building one piece at a time, the build time per piece was 529 min. When building as many pieces as possible within the machine dimensions, the time was reduced to 102 min per piece. This indicates that the machine time is heavily dependent on the time consumed in recoating procedures. One recoating procedure takes roughly 12 s. This equals to some 10 minutes per mm. As the piece was 40 mm high, it can be calculated that the time spent for recoating only is approximately 400 min. This time does not change if the number of pieces changes.

In the case of building a single piece, time for recoating is 76 % of the total build time, but in the case of simultaneous building of 40 pieces its share is only 10 %. It can easily be seen that the maximum utilization of the building platform is in key position in cutting the costs.

a


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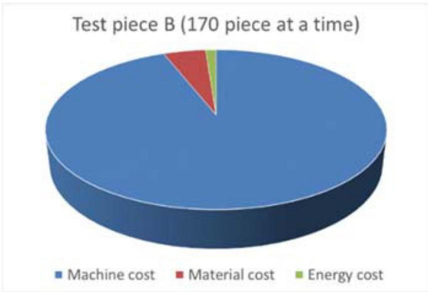

Fig. 8.Cost structures of sample B, when (a) single unit costs are considered (b) when costs are calculated for fabrication of batch of 170.

The finishing was made by sawing the pieces of from the platform, and gently shot peening the pieces to smoothen the irregularities. Sometimes, the pieces are attached heavily on building platform and removal happens with more costly wire eroder. Wire eroder as the detaching method will have a significant effect on the price of the finishing phase compared to the sawing. This was the main reason not to include the price of the finishing in the total cost in this study. The economic analysis in this study has some noteworthy assumptions. By any means it is not possible to predict the yearly working hours for a machine. As the machine investment cost is by far the biggest factor in the cost of a part, the utilization rate should be very accurate. As machine time is the largest price factor, all measures to reduce the time also reduce the cost accordingly (e.g. by reducing the material deposited, for example in multiple ways in the product design phase). The designer must know the manufacturing method thoroughly since its properties and limitations are very different from conventional manufacturing. This approach is known as design for manufacturing and assembly, DFMA.

8. Conclusions

The LAM was found to depend heavily on the costs of the machine time. The machine cost was by far the biggest factor in a LAM manufactured piece leaving the effect of material cost and energy cost to less than 3 % of the total costs in the worst case studied. Building only a single piece at a time was found to be very ineffective. By building as many pieces as possible simultaneously reduced the costs by 81 to 92 % compared to building single objects separately. The optimal utilization of the process chamber can be seen as the main variable the user can affect. Taking the building platform into full use is the most important thing the user should concentrate in.

In this study the finishing work phases were taken into account by calculating the cost of work. It was found that in the simplest case of solely removing and lightly sandblasting the pieces, the cost per piece was only 5 %. Although the machine cost appears dominant, the finishing costs should be considered carefully also. The costs can be calculated using a similar model to this study and this sort of a study would be an excellent future research topic.

In future, the general price development of LAM machinery should be examined, as it has the biggest costs influence. Also the long payback time, calculated in this study, might shorten dramatically, with the fast developing LAM machinery. It was discussed that this change is currently less evident in metallic LAM machines, but as the development cycle for all materials seems to be continuously shortening, this factor should be noted too.

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