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Mass customization of sunglass frame utilizing metallic laser additive manufacturing

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Abstract

Additive manufacturing (AM) of metallic materials has widened the horizon for customized part production by completely eliminating tools and fixtures of manufacturing. Its subsequent importance lies in economic aspects of the use of metal AM for mass customization (MC). This study analyses the manufacturing time and cost per part for MC of metallic sunglass frames by using powder bed fusion (PBF). A method of parametric cost analysis for MC through PBF process is developed. Effect of build orientation on build time is studied. Sensitivity of manufacturing cost to geometric parameters is analysed. The manufacturing cost is found to be 51% sensitive to part height in building direction, 30% sensitive to part volume and 14% sensitive to area connected to supports. The build time per sunglass frame for a given build area is found to be the least for horizontal build orientation. The post-processing cost per sunglass frame is maintained to be less than 25% of its total manufacturing cost.

Keywords: Laser additive manufacturing; mass customization; sunglass frames; machine utilization cost

1. Introduction

Metallic sunglass frames are fashionable components that require more varieties in design to fulfil diversified interests of customers. They are also functional parts meeting dimensional requirements during manufacturing. Most commonly, the metallic sunglass frames are mass produced using manufacturing processes like metal forming, cutting, welding and casting. The mass production has limitations for design variations since it would lead to high tooling expenditure followed with higher unit cost. In cases of more varieties in design, customized production of metallic sunglass frames using powder bed fusion (PBF) process provides solution for manufacturing. The aim of this study is to estimate manufacturing cost per customized metallic sun glass frame built with PBF process and followed with post-processing. A parametric cost analysis is carried for set of ten customized sunglass frames made of stainless steel considering the effect of individual part volume and part height in building direction on cost. The post processing costs are determined based on total surface area of part and connecting surface area in part-support interface and support-base plate interface. Effect of three different build orientations on build time per part for a given build area is analysed.

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Nomenclature

A_{con}	Area connecting part-support-baseplate (mm^2)	T_{he1}	Handling time for wire erosion setup 1 (s)
A_s	Surface area of part (mm^2)	T_{he2}	Handling time for wire erosion setup 2 (s)
C_{PBF}	PBF process cost per part (€)	T_{hf}	Handling time for finishing work phases (s)
C_{post}	Post-processing cost (€)	t_l	Constant time for recoating a layer (s)
$d_{i,i+1}$	Distance between part i and part i+1(mm)	$t_{p.exp}$	Experimental time for building part (s)
h_d	Depth of end holes (mm)	T_{p_Build}	Part build time (s)
h_i	Height of part 'i' (mm)	T_{P_Idle}	Idle time per part (s)
HR_{edm}	Hourly cost for wire erosion machine (€/hr)	$T_{P\_Melting}$	Melting time per part (s)
HR_{tool}	Hourly cost for finishing tools (€/hr)	T_{P_Recoat}	Recoating time per part (s)
h_s	Initial support height (mm)	T_{setup}	Time for setting up of machine (s)
LHR	Labour hourly cost (€/hr)	$t_{s.exp}$	Experimental time for building support (s)
L_t	Layer thickness for part (mm)	v_d	Drilling feed speed (mm/s)
L_{ts}	Layer thickness for support (mm)	v_{edm}	Wire erosion speed (mm^2/s)
MHR	Machine hourly cost (€/hr)	V_i	Volume of part (mm^3)
N	Total number of parts	V_{i_exp}	Volume of experimental part (mm^3)
N_p	Number of layers of part	V_{si}	Volume of support structures (mm^3)
N_s	Number of layers of support	V_{si_exp}	Volume of experimental support (mm^3)
S_p	Scanner positioning speed (mm/s)	υ_p	Material melting speed for part (mm^3/s)
$T_{clearup}$	Time for clearing part from machine (s)	υ_s	Material melting speed for support (mm^3/s)

2. Experimental case

A basic model of sunglass frame as shown in Fig. 1a is created using CAD software, Solidworks and manufactured by using PBF process. Time consumption of sub-processes such as machine setup, initial support building, part building, layer recoating and machine clear-up are measured through experiment. The material melting speed with laser for building typical sunglass frame and support structure is calculated using the experimental results.

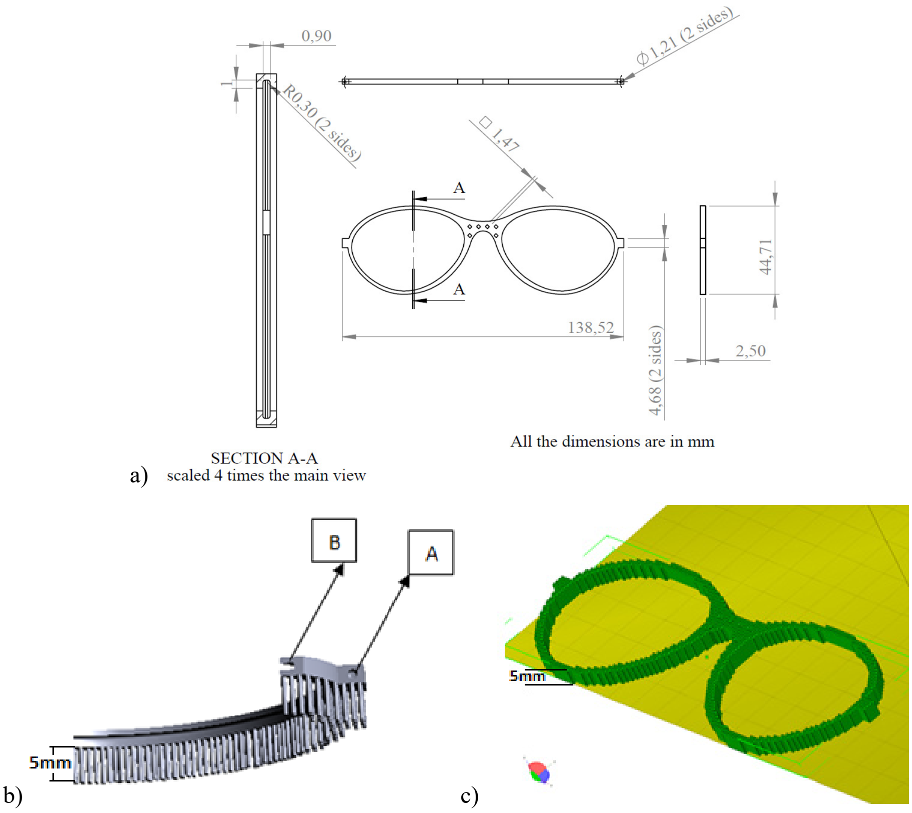


Fig. 1. (a) 2D drawing representing experimental sunglass frame (b) support type 1 (c) support type 2.

Two types of support structures are considered as shown in Fig. 1b and Fig.1c. The cylindrical support shown in Fig. 1b has a risk of getting easily dislocated during recoating action. This may happen when molten metal get stuck and pulled with re-coater. A design of closely packed supports of square cross section as shown in Fig. 1c is used to obtain a thicker structure. The overhang (B) shown in Fig. 1b acts as a self-supportive structure due to its shorter length which is equal to a millimetre. In such cases the side wall provides sufficient support and conducts heat from the overhang. The hole (A) is left blind at both the ends to just locate drilling spots in the finishing work phase. The PBF research machine, similar to EOSINT 270 M-series equipment, which is located in Lappeenranta University of Technology (LUT) is used for experiment. A 200 W IPG fibre laser producing continuous beam of wavelength of 1070 nm is used. The laser beam is transferred from laser device to Scanlab galvanometric scanner via optical fibre. The focal length of the system is 400 mm and the focal point diameter of the laser beam is 70-100 µm. The platform is maintained at a temperature of 80°C. The chamber is filled with 99.8 % of nitrogen gas. The raw material is gas atomized AISI graded austenitic stainless steel 316L spherical shaped powder. The machine parameters for part building are recommended by the machine manufacturer to achieve 100% relative density. The recommended minimum layer thickness is 20 µm and minimum wall thickness is 0.3 mm to 0.4 mm. The attainable part dimensional accuracy is ± (40 - 60 µm), EOS GmbH, material datasheet (2014). Table 1 shows the machine parameters and geometrical parameters used for the experimental case of sunglass frame.

Table 1. Machine parameters and geometry parameters used in experimental case.

Parameters	Values	Feature	Dimension
Laser power	200 W	Height of part	2.5 mm
Layer thickness (part)	20 µm	Height of support structure	5 mm
Layer thickness (support)	40 µm	Volume of part	1571.73 mm^3
Laser scan speed (part)	1000 mm/s	Volume of support	3500 mm^3
Laser scan speed (support)	1200 mm/s		

3. Research methodology

Parametric cost estimation is carried for predicting machine utilization cost per sunglass frame produced in simultaneous building condition. The PBF process cost per part, C_{PBF} is obtained from the product of total hourly cost and total time the machine is allocated per part as given by equation 1. Equations 1-7 are formulated on the basis of algebraic expression of PBF process in terms of its process parameters affecting machine utilization time and cost per part.

$$C_{PBF} = (MHR + LHR).\left(T_{P\_Build} + \left(T_{setup} + T_{clearup}\right)/N\right) \quad (1)$$

The machine hourly cost for EOS M 270 equipment is considered as 35 €/hr, Atzeni et al. (2013) and labour hourly cost is considered as 8.04 €/hr (6.14 £/hr), Baumers et al. (2016). The building time per part including supports is derived from summation of three components of time such as recoating time per part, melting time per part and idle time per part as shown in equation 2.

$$T_{P\_Build} = T_{P\_Recoat} + T_{P\_Melting} + T_{P\_idle} \quad (2)$$

Recoating time per part is calculated from lowest part to highest part as given by equation 3. The time taken for recoating each layer of lowest part is shared by all the parts in the platform. In case of second lowest part, the time taken for recoating the layers for portion taller than first lowest part is shared to all the parts except the first lowest part. So the total recoating time for second lowest part is obtained by adding time consumed for recoating the first part and the portion of second part taller than first lowest part.

$$T_{P\_Recoat} = \frac{h_s.t_l}{N.L_{ts}} + \sum_{1}^{i} \frac{\left(h_i - h_{i-1}\right).t_l}{\left(N - i + 1\right).L_t} \quad (3)$$

The time taken for scanner to melt a single part and the support structure associated with it is estimated using equation 4.

$$T_{P\_Melting} = \left(V_i / \upsilon_p\right) + \left(V_{si} / \upsilon_s\right) \quad (4)$$

The melting speeds, given in equation 5 and equation 6 are the parameters that define the volume of material fused by laser per second. These are obtained by dividing respective part and support volumes by time required for melting them.

$$\upsilon_p = V_{i\_exp} / \left(t_{p.exp} - N_p . t_l \right) \tag{5}$$

$$\upsilon_s = V_{si\_exp} / \left(t_{s.exp} - N_s . t_l \right) \tag{6}$$

The exposure of laser beam stops during positioning of scanner in the interval between one part to other. The time of positioning of scanner from one part to other is accounted as idle time which is given by equation 7.

$$T_{P\_idle} = d_{i,i+1} \cdot \left(\frac{h_i}{L_t . S_p} + \frac{h_s}{L_{ts} . S_p} \right) \tag{7}$$

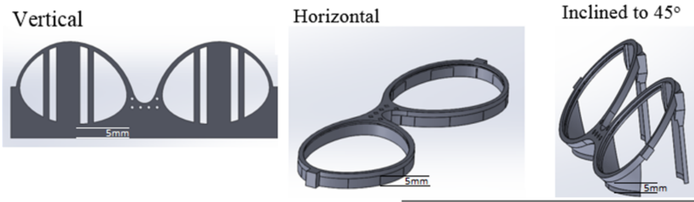
The post processing cost is calculated using equation 8, as a sum of support removal cost by EDM wire erosion and cost of finishing with a flexible shaft tool, K.TX 300 jeweller kit, Foredom rotary tools (2016). The finishing operation includes drilling two through holes in the ends and polishing the work piece to mirror finish. The support removal cost depends on erosion speed and connecting surface area in part-support and base plate-support interfaces. Polishing time depends on total surface area of part and polishing speed by labour. Drilling time depends on hole depth and drill feed speed by labour. Handling time during part setups for EDM and finishing work phases are also accounted in equation 8.

$$C_{post} = (LHR + HR_{edm}).(T_{he1} / N + T_{he2} + A_{con} / v_{edm}) + (LHR + HR_{Tool}).(2T_{hf} + A_s / v_f + 2.h_d / v_d) \tag{8}$$

Hourly cost for EDM wire erosion machine is considered as 6.86 €/hr, Ćurčić et al. (2011). The base plate is separated from all the parts in first setup of wire erosion EDM. Then the supports are removed from individual sunglass frames with one EDM setup each. Erosion speed of 50 mm^2/min, Zhang et al. (2011) and a handling time of 10 min per EDM setup are considered. The first phase of finishing involves drilling two holes at the ends as shown in Fig. 1a with help of table vise clamp and flexible shaft drill tool. The second phase of finishing involves polishing the surface area of sunglass frame with use of flexible shaft abrasive tools. Drill feed speed of 0.1 mm/s and polishing speed of 1.5 mm^2/s are assumed for a skilled labour. A handling time of 5 min for each finishing phase is considered. The cost of flexible shaft K.TX 300 jewellers kit including shipping cost and taxes is accounted as 508 € for useful life of 5000 hours and the cost for abrasives and consumables are roughly accounted as 50 € for useful life of 10 hours. Thus the hourly cost of finishing equipment is estimated to be 5.1 €/hr, Foredom rotary tools (2016), Foredom accessories (2016), Pitney Bowes Inc, duty calculator (2016).

4. Results and discussion

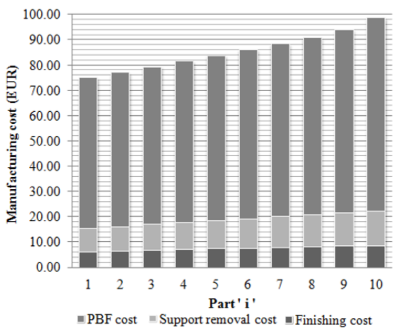
In the experimental case example, the time used to build the part is 3600 s and that for building initial support is 4560 s. Constant time for recoating single layer is 16s. Time for preparing the machine ready to start building process is 45 minutes. The time for separating the build plate from the machine and collecting the un-exposed powder is 45 minutes. Material melting speed with laser is calculated to be 0.98 mm^3/s for part and 1.37 mm^3/s for support. The build time per sunglass frame in three types of orientation is compared by building maximum number of copies in a fixed build area of 45 mm x 140 mm as demonstrated in Fig.2.

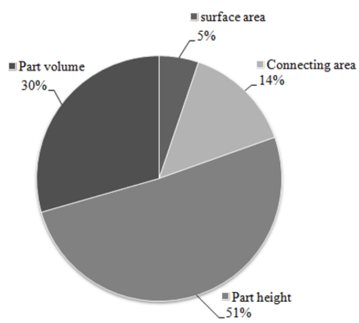


Orientation	Vertical	Horizontal	45° Inclined
Part volume (mm^3)	1571.73	1571.73	1571.73
Support volume (mm^3)	6911.37	3905.37	3820.56
Part build height (mm)	44.71	2.5	31.62
Initial support height (mm)	5	5	5
Number of pieces in area (45mmx140mm)	9	1	3
Exposure time per part (s)	1600	1600	1600
Recoat time per part (s)	3974.22	2000	8432
Exposure time for support per part (s)	5055.17	2856.5	2794
Initial support recoat time per part (s)	222.3	2000	667
Total time per part (s)	10851.69	8456.5	13493

Fig. 2. Effect of vertical, horizontal and inclined build orientation on build time and build space.

It can be noted from Fig. 2, that the vertical orientation requires more support due to larger overhangs to ensure sufficient heat flow between the part and base plate. Although by building maximum number of parts the cost of per part is still higher compared to cost of building single part in horizontal orientation. Number of sunglass frames which can be put in 45 mm x 140 mm space by using a 45^o inclined orientation is limited to three. As the build height is higher, the recoating time per part is high thus its build time is increased. As the parts are of distinct geometric dimensions in customized production, the maximum number of parts produced in a given area would decrease in cases of vertical and inclined orientations which will lead to much higher recoating cost per part. On the other hand, the post processing of horizontally built sunglass frame requires a minimum number of EDM setups making the support removal simpler. So the horizontal orientation is found to be more economic for simultaneous building of sunglass frames of same or different geometries. Manufacturing cost per sunglass frame in a simultaneous production of ten pieces with different geometric profiles is analysed for horizontal build orientation. A 5 mm initial support height is considered for all the pieces. The part height in build direction is increased from 2 mm to 4.5 mm and the part volume is increased from 1600 mm^3 to 2050 mm^3. Fig. 3 shows the cost of manufacturing phases per part and sensitivity of manufacturing cost to geometric parameters.

a) 

b) 

c)

Part i	V_i (mm^3)	h_i (mm)	A_s (mm^2)
1	1600	2	1600
2	1650	2.3	1700
3	1700	2.6	1800
4	1750	2.9	1900
5	1800	3.2	2000
6	1850	3.5	2100
7	1900	3.7	2200
8	1950	3.9	2300
9	2000	4.2	2400
10	2050	4.5	2500

Fig. 3. (a) Cost of manufacturing phases; (b) sensitivity of manufacturing cost to geometric parameters; (c) Part dimensions.

Fig. 3 shows that the major proportion of manufacturing cost is the cost for PBF per part. The post processing cost is maintained to be less than 25% of total manufacturing cost. The sensitivity of manufacturing cost to the height in building direction is the maximum. This effect is realized for profiles with higher curvature that resulted in increased part height and larger volume of support below the part. As a result, both the recoating time of part and melting time of support increase leading to higher build cost per part. There is also an increase in connecting area between part-support interfaces due to effect of increase in curvature which leads to increase in support removal cost. The increase in part volume increases the part melting time thus part volume is the second largest sensitivity factor for manufacturing cost. Increase in part surface area has effect in finishing time thus giving a least impact on manufacturing cost per part.

5. Conclusion

A method of parametric cost analysis is developed for calculating cost per part for mass customization through PBF process. The manufacturing cost per part for simultaneous production of customized metallic sunglass frames using PBF process is analysed. Melting speed of material, stainless steel 316L is obtained to be 0.98 mm^3/s for part and 1.37 mm^3/s for support through PBF experiment of a typical sunglass frame geometry. The build time per sunglass frame for a given build area is found to be the least for horizontal build orientation. The manufacturing cost is found to be 51% sensitive to part height in building direction, 30% sensitive to part volume, 14% sensitive to area connected to supports and 5% sensitive to surface area of part. The major proportion of manufacturing cost is the cost for PBF per part. The post-processing cost per sunglass frame is maintained to be less than 25% of its total manufacturing cost.

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