Assessing additive and subtractive manufacturing technologies for the production of tools in the automotive industry

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Abstract: Tooling is an integral component to the traditional manufacturing cycle, despite the fact that it's both costly and time-consuming to produce. Additive manufacturing (AM) is currently considered viable in certain instances, often competing against subtractive manufacturing in the delivery of tools, on time, with the required quality. This paper considers the use of AM and computer numerical control (CNC) machining to manufacture an insert for the tooling of a vehicle headlight adjuster clip. The proposed methodology for manufacturing the insert is composed of two manufacturing techniques: AM using selective laser melting (SLM) technology and CNC milling. The tool material used to manufacture the inserts in both cases is Stainless Steel 316L, whilst the injected parts are manufactured in polypropylene. Performance tests were applied to each of the two inserts in the context of material chemical composition, microstructure, hardness, surface roughness, and dimensional accuracy. Furthermore, the injected parts produced were tested to determine dimensional accuracy, quality and functionality. Finally, it was concluded that both the SLM insert and CNC machined insert successfully produced functional parts. Moreover, the products from the SLM tool insert were more accurate dimensionally, but in terms of surface finish, the CNC product was perceived to be better quality.

Keywords: Additive Manufacturing, Selective Laser Melting CNC Machining, Injection Mould Tools, Tool Manufacturing, Automotive Industry.

1 Introduction

Regardless of the dynamic technological advancement in product development and manufacturing techniques, tooling is still considered to be essential and irreplaceable. Some applications for high production volumes require tooling despite the fact that in most instances, it is time consuming and costly (Altan *et al.* 2001). As reported by Ilyas *et al.* (2010), Karunakaran *et al.* (2010), Lupeanu *et al.* *(*2012), Mellor *et al.* (2014), it is well established that additive manufacturing (AM) advantages precede those of subtractive manufacturing in reducing time for the development of new products with the added benefit of customisation. Potentially, AM cuts down manufacturing lead-times resulting in reduced processing costs (Kerbrat *et al.* 2011).

AM processes are now capable of creating functional parts from metallic alloy powder *(e.g. Vayre et al.* 2012) such as with selective laser melting (SLM). It is noted that cost does not fluctuate with the complexity of the design (Cooper *et al.* 2012; Nagahanumaiah *et al.* 2008), although, poor surface finish and dimensional accuracy are two major predicaments when it comes to successful employment of AM (Karunakaran *et al.* 2000; Newman *et al.* 2015). Tay and Haider (2002) were able to improve surface roughness of AM components from 17–19 μm to 2–3 μm through a process of electroless nickel plating without impacting adversely on the final dimensional accuracy.

Previous studies compared traditional tool fabrication methods with Direct Metal Laser Sintering (DMLS) for an automotive company. The results were satisfying, showing a reduction in lead-time and cost when using AM for tooling. Traditional machining and Electric Discharge Machining (EDM) took twice as long as DMLS, while tolerances and overall quality were considered equivalent (Wohlers 2010). Moreover, (Newman *et al.* (2015) and Swamidass and Winch (2002) state that 70% of manufacturing businesses in the UK and the US adopting CNC machining, produce significant material waste. (Townsend *et al.* 2012) related AM and machining to assess time, money, knowledge limitations, and opportunities while ensuring that the end product accomplishes the goals of the industrial sectors.

This paper considers the techniques employed for tool manufacturing, discussing the different experimentation executed on the tool inserts produced by both SLM and CNC machining, and how these were employed successfully in the injection moulding process.

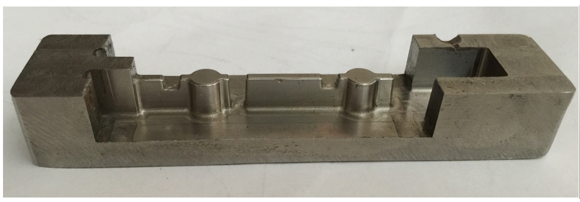
2 Tool Manufacturing

The fabrication of the tool inserts is initiated. Therefore, the CAD design is directed for execution on a CNC milling machine and a SLM machine.

The first set of core and cavity inserts was manufactured at *Al Fouad for Automotive Spare Parts Co*. (Alexandria, Egypt) on two 3-axis First V 700 machines with maximum spindle motor power of 5.5-7.5 KW and 10,000-15,000 RPM. Two End mill carbide tools and one ball nose cutter were used. The diameters for the tool cutter were 4, 16, and 4 mm respectively. The material supplied for manufacturing was Stainless Steel 316L. The approximate time for manufacturing the core and cavity were 12 and 6.5 hours respectively. Cost elements contemplated included labour, conventional and CNC machines depreciation, tooling, energy consumption, and maintenance. The final cost for manufacturing the core and cavity inserts using the conventional subtractive manufacture route was £150.

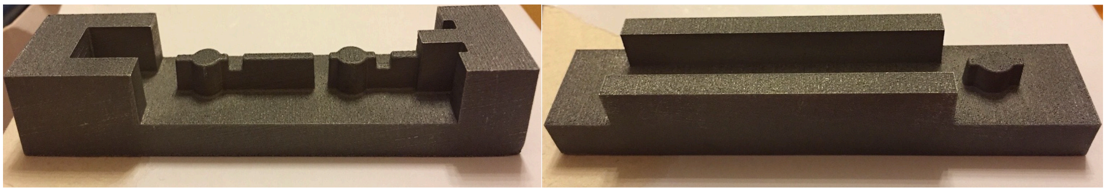
The second set of parts was built at *Croft Additive Manufacturing Ltd* (Warrington, UK) on a ReaLizer SLM 250 with a laser power of 200 W. The material provided for fabricating the inserts was Stainless Steel 316L powder supplied by LPW Technology Ltd (Runcorn, UK), with particle size nominally in the range 45-150 μm and a layer thickness of 50 μm. The approximate cost of fabricating the parts is 129 Build time for these parts is difficult to define, as the parts are not built individually. Other components were built in the same chamber to maximize the available build area/volume and economies of scale. Furthermore, the cost for fabricating the insert using the SLM process is marginally less than the cost of CNC machining. This might indicate that SLM is more cost effective compared to machining.

Fig. 1 shows the manufactured tool inserts. The first set was CNC machined, while the second set was built using SLM.



CNC machined core

CNC machined cavity



SLM core **SLM cavity**

Fig. 1 Manufactured tool inserts

3 Experimental Evaluations of the Tool Inserts

Several experiments were executed on the two sets of Stainless Steel 316L inserts. The following experiments were implemented in the sequence below:

- Spectral Analysis Test
- Microscopic Testing
- Hardness Test
- Surface Roughness and Dimensional Accuracy Tests

Spectral Analysis Test

A Spectral Analyzer was used to determine the chemical composition of the material used to manufacture the two sets of inserts. Table 1 shows the standard chemical composition values of Stainless Steel 316L and how this compares with the SLM and CNC machined versions. These were found to be within an acceptable range as compared to the standard composition of Stainless Steel 316L. However, the slightly increased difference between the CNC and SLM inserts is expected to have a direct influence on the performance and hardness of the inserts.

Table 1 Chemical composition (Wt%)

	Wt %								
Sample	C	Si	Mn	P	S	Cr	Mo	Ni	Fe
Standard (AK Steel 2007)	0.035	0.75	2	0.045	0.03	16-18	2-3	10-14	Balance
CNC	0.079	0.411	1.43	0.026	0.017	16.645	2.09	9.9	68.283
SLM	0.071	0.52	1.33	0.045	0.045	16.352	2.02	11.19	67.893

Microscopic Testing

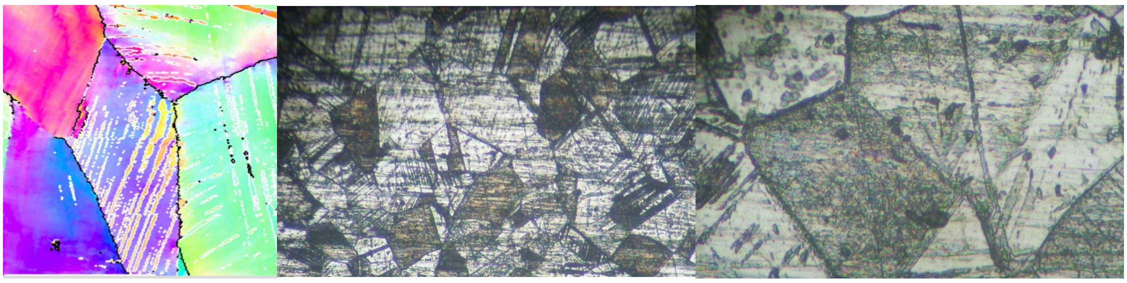
The two sets of Stainless Steel 316L specimens were prepared for microscopic viewing. The first step was to polish all the surfaces to get them as scratch free as possible. The parts were wet smoothed by a linish belt grinder using 180 grit abrasive sand paper (approx. 5 mins for each part). The samples were further polished successively with 220 and 1000 grit abrasive sand paper to acquire the necessary surface smoothness. Fig. 2 illustrates the preliminary polishing methods used.

Belt linish grinding **Surface polishing 1000 grit abrasive sand paper**

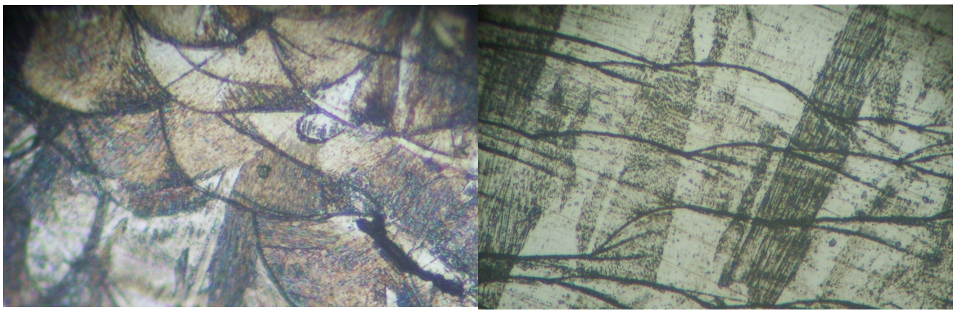
Fig. 2 Sample pictures of surface polishing

Maintaining a glossy look to the surfaces, a polishing paste (Microid Diamond Compound, LECO Corp. Michigan, USA) was applied to the surfaces and rubbed with a smooth cloth. Polishing was a preliminary stage to prepare the specimens for etching, hence an acidic solution was prepared containing pure white Alcohol 96%, Nitric Acid 2% (with a concentration of 69%) and Hydrochloric Acid 2%. Each designated surface on the specimens was submerged for approximately 20 mins.

The etched surfaces were subsequently inspected using a Carl Zeiss Axiovert 200 microscope for grain microstructure viewing. Fig. 3 shows 200x and 500x magnified images for the microstructure of the CNC machined core, machined cavity, SLM core, and SLM cavity respectively. When comparing the microstructure of Stainless Steel 316L of both the CNC machined core and cavity with the standard microstructure, there are no apparent differences (Odnobokova et al. 2014). Nevertheless, for the SLM inserts it is hard to distinguish the grain size and boundaries due to distortion caused by melting. The lack of uniform distribution of temperature during the build causes unpredictable formations and influences the uniformity of grain sizes.



Standard Stainless Steel 316L (Odnobokova et al. 2014) **CNC machined core** **CNC machined cavity**



SLM core SLM cavity

Fig. 3 Comparison between microstructure (200x and 500x magnification)

Hardness Test

A Vickers hardness test was conducted I to measure hardness for both sets of inserts. For the CNC machined specimen, the HV value is 270, while the SLM is 199. Therefore, increased lifetime, durability and wear resistance is expected of the CNC machined specimen as compared to the SLM.

Surface and Dimensional Measurements

In order to assess and quantify the roughness of the SLM specimens, a Talysurf instrument was used to measure the surface roughness. Fig. 4 illustrates a 2D drawing of the core and cavity inserts with the surfaces that have been selected and measured: surfaces A, B1, B2, and C. Table 2 gives the average roughness (Ra) values of the SLM specimens depicting rather high values for surface roughness in comparison to the surface roughness of the CNC machined specimen.

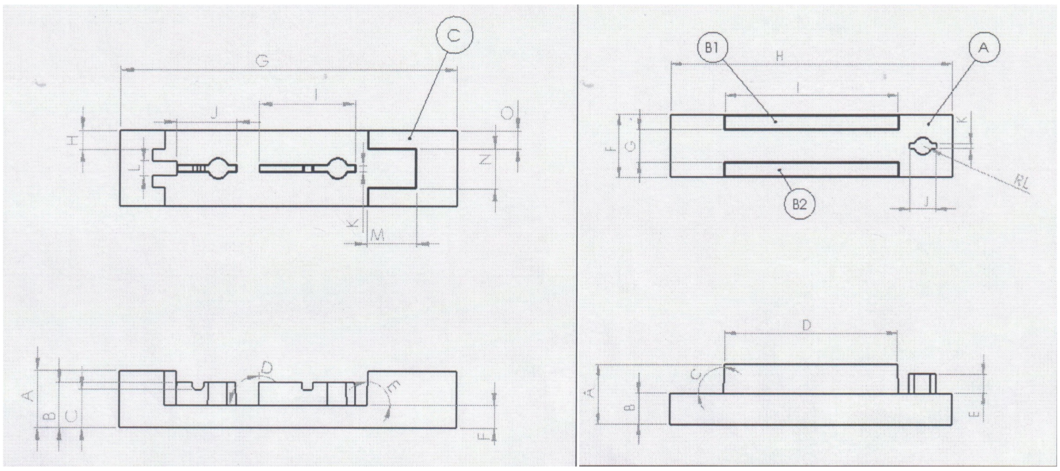


Fig. 4 2D drawing of core and cavity tool inserts

Table 2 Average roughness (Ra) measurements

Surface	Ra (um)
A	10
B1	14
B2	14
C	15

Further analysis determined the dimensional tolerances of the SLM and the CNC machined tool insert measurements in relation to the CAD geometry. The CNC machined tool insert shows no noticeable deviation in dimensional values, whereas the SLM tool inserts show slight dimensional errors. Specific dimensional measurements were accounted for as highlighted in Fig. 4. Furthermore, Tables 3 and 4 illustrate the specified measured values of both the core and cavity in relation to the geometric CAD measurements. A 0.005 mm shrinkage allowance is deliberately considered for polypropylene injection.

Table 3 Dimensional measurements for core tool inserts

Dimensions	Nominal Value (mm)	SLM Measured Values (mm)	Error (mm)	Dimensions	Nominal Value (mm)	SLM Measured Values (mm)	Error (mm)
A	15	14.9	-0.1	**I**	26	26	0
B	12	12.05	0.05	**J**	16	15.8	-0.2
C	10	10.05	0.05	**K**	2	2.03	0.03
D (Deg)	92°	91° 47’	-13’	**L**	4	4.01	-0.01
E (Deg)	88°	88° 13’	13’	**M**	12.7	12.71	0.01
F	6	6	0	**N**	9.5	9.4	-0.1
G	90	90.1	0.1	**O**	5	4.9	-0.10
H	5	5.15	0.15				

Table 4 Dimensional measurements for cavity tool insert

Dimensions	Nominal Values (mm)	SLM Measured Values (mm)	Error (mm)	Dimensions	Nominal Values (mm)	SLM Measured Values (mm)	Error (mm)
A	19.05	19	-0.05	**G**	10	10	0
B	10	10.05	0.05	**H**	90	90	0
C (Deg)	92°	92° 18’	18	**I**	56	55.96	-0.04
D	55.4	55.45	0.05	**J**	8.7	8.8	0.1
E	6	6.06	0.06	**K**	2	2.06	0.06
F	20	19.95	-0.05				

4 Injection Moulding

The SLM and CNC machined tool inserts were both assembled to the same tool plates. Therefore both sets of inserts would undergo the same impressions at the same working conditions, ensuring direct comparability of the results.

The tool was injected using a Nurnak MMRJ 130-225 Injection moulding machine with clamping force of 100 ton. Polypropylene was used with a material feed stock rate of 15 grams/stroke and injection pressure of 70-80 bar at a temperature of 170-190°C. The average cycle time was approximately 30 seconds. The net weight for the SLM-derived product was 4.20 g, whilst the CNC-derived product was 4.24 g. 500 impressions were batched into two packages, one for the SLM product and the other for the CNC machined product. 10 samples from each package were selected for 10 measurements. These measurements with their corresponding nominal values are given in Fig. 5. More importantly, it should be highlighted that the resulting dimensional measurements (as shown in Table 5) of the SLM product have minimal error in comparison with the CNC product. Despite the fact that, the SLM tool insert measurements have shown deviations from the nominal values. Moreover, these results are caused by the shrinkage allowance of the polypropelene injected parts.

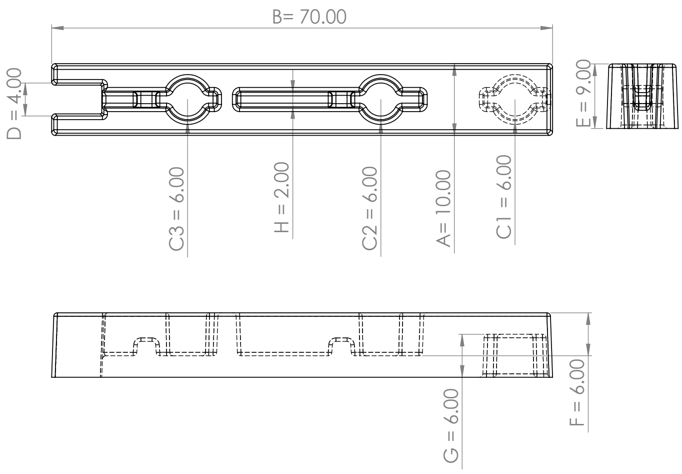


Fig. 5 Product measurements

Table 5 Dimensional measurements for CNC and SLM products

Dimensions	Nominal Values (mm)	Average CNC Product Measurement (mm)	Error (mm)	Average SLM Product Measurement (mm)	Error (mm)
A	10.00	9.75	0.04	9.75	0.00
B	70.00	69.03	0.05	69.64	0.02
C1 (Φ)	6.00	5.78	0.04	5.80	0.00
C2 (Φ)	6.00	5.67	0.05	5.20	0.00
C3 (Φ)	6.00	5.66	0.05	5.50	0.00
D	4.00	4.00	0.00	4.00	0.00
E	9.00	8.77	0.05	8.80	0.00
F	6.00	6.20	0.01	5.90	0.00
G	6.00	6.00	0.02	5.75	0.00
H	2.00	2.02	0.04	1.95	0.00

5 Conclusions

The results from the different experiments that were executed on the tool insert are summarized as follows: the SLM tool insert is productive and achieves significant benefits in terms of cost, product functionality and dimensional accuracy. During the spectral analysis test, chemical composition of both inserts was within acceptable range as compared to the standard composition of Stainless Steel 316L. Nevertheless, when observing the SLM inserts, grain size and boundaries were indefinable due to distortion caused by melting as compared to the CNC machined insert. As for the surface roughness, SLM lags behind CNC machining but with a slight difference. Finally, the resulting dimensional measurements of the SLM product showed no error in comparison with the CNC product proving product reliability.

Acknowledgments

The authors are appreciative of the technical support provided by *Croft Additive Manufacturing Ltd* (UK), *Al Fouad for Automotive Spare Parts Co.* (Egypt) and the Department of Manufacturing Engineering at Alexandria University (Egypt) for the assistance provided during the preparation of this paper.

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