Study of the influence of laser energy density on the surface roughness of Scalmalloy® samples manufactured by DMLS technology

C Márquez1, J D López1*, L Cabrera1, L González1 and J Botana1

1 Department of Materials Science and Metallurgical Engineering and Inorganic Chemistry, School of Engineering, University of Cadiz, Av. Universidad de Cádiz, 10, E-11519 Puerto Real, Cadiz, Spain

*Corresponding author: juan.lopezcastro@uca.es

Abstract: Direct Metal Laser Sintering (DMLS) is an additive metal manufacturing technology that allows complex parts to be built without the design constraints of conventional technologies. In addition, the possibility of reusing powder reduces raw material consumption and the amount of waste generated. However, one of the disadvantages of this technology is that, in most cases, it requires post-processing tasks that increase manufacturing costs and delivery times. Some of these additional tasks are aimed at reducing the surface roughness of the parts obtained, using technologies such as grinding, mechanical polishing, shot blasting or electropolishing. This work proposes to improve the surface quality of parts manufactured by DMLS by controlling the processing parameters. In this way, the costs associated with these post-processing tasks could be reduced. Specifically, it is proposed to study the effect of the laser energy density applied to the surface of the parts during the manufacturing process on their surface quality. To carry out this study, powders of the Al-Mg-Sc alloy known as Scalmalloy®, developed to manufacture parts by means of DMLS with application in the aeronautical sector, have been used. In this sector, surface quality is one of the factors limiting the implementation of DMLS technology for the manufacture of parts considered critical.

Keywords: Additive manufacturing; Scalmalloy®; Surface quality; DMLS, Aluminium.

1. Introduction

Additive manufacturing allows objects to be built from a 3D model by depositing layers of material and using printheads, nozzles or other printing technology [1-5]. In its early days, this technology was used for rapid prototyping. Nowadays, the development of additive manufacturing has made it possible to produce fully functional final parts [1, 4-6].

Some of the advantages of additive manufacturing are the customisation of objects, the possibility of manufacturing complex shapes, the construction of assemblies in one single piece and the efficient use of material. On the other hand, disadvantages include the difficulty of reducing porosity to obtain a fully dense part, the need to use supports that require post-processing, the heterogeneity of mechanical properties and the low surface quality, which reduces the resistance to fatigue and impoverishes the visual appearance [1-5, 7-11].

In the field of metal additive manufacturing, the technologies that have achieved the maximum success are those based on powder bed sintering, using different energy sources such as lasers and
electron beams. One of the technologies that has experienced the highest development and implementation is Direct Metal Laser Sintering, which has been successfully used in various industrial sectors, such as the bio-health, automotive and aerospace industries.

An example of the interest in this technology in the aeronautical sector is the fact that Airbus has developed, through its spin-off Apworks, the alloy called Scalmalloy®, specially designed to manufacture aircraft parts by means of DMLS. The most significant advantage of this alloy is that it has better mechanical properties than the Al-Si-Mg alloys used so far [12]. However, the use of Scalmalloy parts made by DMLS is limited by their low surface quality, which limits their fatigue behaviour [15]. To overcome this drawback, different surface quality improvement procedures such as shot blasting, mechanical polishing, electropolishing or even varying the manufacturing conditions are applied [13].

According to the literature, the manufacturing parameters that most influence the surface finish of a part manufactured by DMLS are the power of the applied laser radiation (P), the scanning speed (v) and the hatching distance (h) [14]. These three parameters can be related to each other by equation (1) used to calculate the surface energy density (E).

\[
E = \frac{P}{h \cdot v} \left( \frac{J}{\text{mm}^2} \right)
\] (1)

According to figure 1, depending on their relative orientation with respect to the building platform, three types of surfaces can be distinguished on a part: standard, upskin and downskin. As indicated in figure 1, the difference between the three surfaces is the direction of their normal vector. Thus, the normal vector of the standard surface is parallel to the building platform, while the normal vector of the upskin and the downskin surfaces point upwards and downwards, respectively.

![Figure 1. Upskin, standard and downskin surfaces of a part manufactured by DMLS.](image)

In this work, the effect of the surface energy density used during manufacturing on the roughness of Scalmalloy® parts with simple geometries has been studied. A particular energy density can produce different effects on roughness depending on the orientation of each surface of the part with respect to the manufacturing plane. For this reason, it has been considered convenient to study the effect of the energy density on each of these surfaces independently. The work was aimed at determining the manufacturing parameters that allow the surface quality of the manufactured parts to be improved and, at the same time, to study the influence of these parameters on their mechanical properties.

2. Methodology
Scalmalloy® simple geometry parts with one, two or three different surfaces were designed and manufactured using an EOS M290 DMLS printer. Figure 2 shows the drawings of the specimens
designed to study the effect of surface energy density on the roughness of: (a) standard surface, (b) upskin and downskin surfaces and (c) all three surfaces.

![Figure 2. Drawings of: (a) specimen with standard surface; (b) specimen with upskin and downskin surfaces and (c) specimen with all three types of surface. Distances in millimetres.](image)

To study the effect of surface energy density, a total of 60 specimens, as described in figure 2, were manufactured and processed using 20 different surface energy density values ranging from 1.15 to 23.08 J·mm⁻². Once fabricated, the specimens were heat treated at 325 °C for 4 hours to relieve stresses following the recommendations included in [16]. The separation of the parts from the building platform was carried out with a band saw. Finally, before characterisation, the parts were cleaned for five minutes by immersion in water in an ultrasonic bath.

The samples thus obtained were characterised by evaluating their roughness, porosity and mechanical properties. The surface roughness was evaluated by recording the Ra and Rz values of each piece, using a Mahr MarSurf PS 10 roughness tester. The cut-off value used for the measurements was 0.8 mm and the total length sampled was 4.8 mm.

The porosity study was carried out by image analysis of the cross-section of the samples, using a Leica DM IRM inverted microscope. For this purpose, images were recorded by scanning the entire cross-section of each samples. Afterwards, the images of the whole cross-sections were reconstructed using Microsoft Image Composite Editor software. In this way, images covering 10 mm of the width of the piece and 1.4 mm of thickness were obtained. Subsequently, the pore size of the samples was measured using ImageJ software.

| Supplier        | Our parameters |
|-----------------|----------------|
| Vertical        | 3.55 J·mm⁻²    | 7.68 J·mm⁻²   |
| Oriented at 45º relative to building platform | 3.55 J·mm⁻² | 23.08 J·mm⁻² |

![Figure 3. Surface energy density applied to the tensile test specimens oriented in the directions indicated.](image)
The surface energy density values used to manufacture the samples, in addition to modifying the roughness, can affect their mechanical properties. For this reason, mechanical tests were carried out to study the influence of surface energy density on the mechanical behaviour of the samples. The mechanical properties of the parts were evaluated by means of tensile tests, using a Shimadzu Autograph AG-ES 100 kN universal machine according to the UNE-EN ISO 6892-1 standard [17]. To carry out this study, specimens were manufactured using the processing parameters used in the certification of the machine, in which a surface energy density of 3.55 J·mm⁻² was applied to the three surfaces. On the other hand, specimens were manufactured using those parameters providing a better surface finish, corresponding to 23.08 J·mm⁻² on the downskin surface and 7.68 J·mm⁻² on the standard and the upskin surfaces. In this study, specimens were manufactured vertically, which have standard surfaces, and oriented at 45º with respect to the building platform, which have upskin and downskin surfaces, figure 3. Finally, figure 4 shows a drawing of the flat bone-type specimens used for the tensile tests, manufactured according to ASTM E8/E8M [18].

![Figure 4. Drawing of tensile specimens according to ASTM E8/E8M. Units in millimetres.](image)

3. Results

Figure 5 shows the Ra and Rz values for the three types of surfaces processed under 20 different conditions using surface energy density values between 1.15 and 23.08 J·mm⁻².

![Figure 5. Ra and Rz values obtained for the different surfaces as a function of surface energy density.](image)

Below, figure 6 includes different photographs in which it is possible to observe the visual appearance of the downskin surface of samples processed at four different surface energy densities. Samples with standard and upskin surfaces processed at low energy density presented a visual appearance similar to the image included in figure 6(b), while those processed at high energy density presented a similar appearance to the image included in figure 6(d).
Figure 6. Photographs of the downskin surface of the specimens fabricated using energy density values of: (a) 1.15, (b) 7.68, (c) 11.54 and (d) 23.08 J·mm⁻².

Figure 7 shows a Microsoft Image Composite Editor image of the cross-section of a sample with a downskin surface and manufactured with an energy density of 23.08 J·mm⁻². In order to determine the porosity, similar images were reconstructed for samples with the three types of surface processed at surface energy density values of 1.15, 7.68, 11.54 and 23.08 J·mm⁻². Thus, the porosity values shown in figure 8 were determined as a function of surface energy density by using ImageJ software to analyse the images.

Figure 7. Reconstructed cross-section image of a sample with a downskin surface and manufactured with an energy density of 23.08 J·mm⁻².

Figure 8. Porosity of the different surfaces shown as a function of the applied surface energy density.

Finally, figure 9 shows, in the form of bar diagrams, the results obtained from the tensile tests corresponding to specimens manufactured vertically and inclined at 45° with respect to the
manufacturing plane. In this figure, for comparative purposes, the values of elastic modulus, yield strength and maximum stress of specimens manufactured using the parameters proposed in this work and using the parameters established in the certification conditions have been included.

Figure 9. Modulus of elasticity, yield strength and maximum stress of bone-type specimens manufactured by DMLS under the conditions indicated and subjected to tensile tests.

4. Discussion

As mentioned in the introduction of this work, one of the problems of metal additive manufacturing by DMLS is the high roughness of the manufactured samples. In the certification conditions of the Scalmalloy® alloy, the samples are processed with an energy density of 3.55 J·mm⁻², regardless of the type of fabricated surface. According to the Ra and Rz data included in figure 5, under these conditions Ra takes values of 15.3 µm, 14.5 µm and 21.6 µm for standard, upskin and downskin surfaces, respectively. These values will be used as a reference to determine the influence of the surface energy density on the roughness of the different surfaces studied.

According to the values of Ra and Rz represented in figure 5, there is a gradual decrease in roughness for upskin and standard surfaces as the applied surface energy density increases. For these two types of surfaces, using a surface energy density of approximately 7.68 J·mm⁻², a minimum roughness is reached at which the Ra value is 3.2 µm. The roughness on these surfaces does not decrease when applying higher values of surface energy density. Comparing these values with the reference value, it is observed that it is possible to decrease the roughness of the samples on the standard and upskin surfaces by 78 % by increasing the energy density from 3.55 J·mm⁻² to 7.68 J·mm⁻².

In the case of downskin surfaces, it is noticed that the roughness does not change when working with surface energy density values lower than 5.77 J·mm⁻². From this value onwards, it is observed that the roughness decreases with the surface energy density applied, so that a minimum Ra value of 4.5 µm is reached when employing an energy density of 23.08 J·mm⁻². It can therefore be concluded that in the case of the downskin type surfaces it is necessary to apply energy densities of the order of 23.08 J·mm⁻² to reach the levels of roughness reduction that are achieved when processing the other two surfaces with an energy density of 7.68 J·mm⁻².

As can be seen in figure 6, the aforementioned reduction in Ra and Rz values when increasing surface energy density give rise to an improvement in the visual appearance and an increase in the brightness of the samples.

Regarding the porosity, figure 7 shows that in the case of the standard and upskin surfaces, the porosity does not undergo significant changes as the surface energy density is increased. Thus, this figure shows that the porosity of these surfaces processed at the certification conditions is of the order of 0.1% for the upskin surface and 0.5% for the standard surface. When processing these samples at 7.68 J·mm⁻², it is observed that the porosity presents a value of 0.3% on the upskin surface and 0.5% on the standard surface, similar to that obtained in the certification conditions.

On the contrary, in the case of downskin surfaces, the porosity presents a value of 0.2 % when working with energy densities equal to or lower than 7.68 J·mm⁻². At this energy density, Ra becomes
13.7 µm, 35% lower than that obtained in the certification conditions. On the other hand, from this energy density onwards, a progressive decrease in roughness is observed, which is associated with an increase in the porosity of the samples, which reaches a value of 1.4% when working at 23.08 J mm⁻², a condition in which the minimum roughness of downskin-type surfaces is achieved.

A final aspect studied has been the influence of surface energy density on the mechanical properties of specimens showing different types of surfaces. As can be seen in figure 9, the increase in surface energy density does not cause significant variations in the values of Young's modulus, yield strength and maximum stress of the specimens. It should be remembered that each surface in these specimens was processed using the energy density value necessary to obtain the minimum roughness values, i.e. 23.08 J mm⁻² for downskin surfaces and 7.68 J mm⁻² for upskin and standard surfaces.

These results show, therefore, that it is possible to improve the surface roughness of the samples by controlling the surface energy density without affecting the mechanical properties of the manufactured material.

5. Conclusions
The results obtained in this work show that it is possible to control the roughness of Scalmalloy® parts manufactured by DMLS by modifying the surface energy density used during processing. The effect of energy density on roughness depends on the type of surface manufactured. It has been observed that for standard and upskin surfaces, the values of Ra and Rz decrease progressively when the energy density increases, reaching a minimum value when working with an energy density in the order of 7.68 J mm⁻². Under these conditions, the porosity and mechanical properties of the parts are similar to those obtained when manufactured under the certification conditions. This implies that standard and upskin type surfaces can be obtained with Ra values close to 4 µm, a value considerably lower than the 15 µm obtained for these surfaces under certification conditions.

In the case of downskin type surfaces, it is observed that the initial roughness is maintained up to densities of the order of 5.77 J mm⁻². For higher values of energy density, the roughness decreases progressively. When using an energy density of 7.68 J mm⁻², the Ra value of the downskin surface becomes 13.7 µm, compared to 21.6 µm for the certification conditions. Furthermore, using this energy density, the porosity of the surface does not change significantly. If the energy density is increased to 23.08 J mm⁻², a value of Ra close to 4 µm is achieved, similar to the upskin and standard surfaces. However, under these conditions, although the mechanical properties are maintained compared to the certification, there is an increase in the porosity of the samples from 0.2 to 1.4%.

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