Deep hole finishing of Inconel 718 SLMed features by endmilling and reaming

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Abstract: Additive manufacturing by selective laser melting (SLM) allows significant flexibility in obtaining components with complex morphologies, which usually require finishing to correct the geometric distortions and roughness inherent in the process. This paper investigated surface quality by milling and reaming deep holes into ducts obtained by SLM technology. For this purpose, tools with different characteristics were tested, with a reaming stage necessary to obtain roughness levels of less than one μm. Dimensional distortions in SLMed ducts led to substantial variability in axial cutting forces. The helix angle of the endmill had a significant influence on the axial cutting force and roughness.

Keywords: Additive manufacturing, Selective laser melting, Deep hole finishing, Reaming, Milling, Roughness, Axial cutting force.

1. Introduction

Additive manufacturing processes have developed significantly over the last few years, and the number of industrial applications of metal printing has exploded, including parts such as turbine blades, special ducts, and complex-shaped parts with internal ducts, among others [1,2]. Selective laser melting (SLM) is one of the most developed metal additive manufacturing techniques based on the powder bed principle. It is a very versatile and flexible process that makes it possible to obtain parts that, in some cases, cannot be obtained by subtractive manufacturing. The SLM process depends on four fundamental parameters – laser power (P), hatching space (h), layer thickness (t), and laser speed (Vb)[3,4] (see figure 1 left) – which, configured in different ways, allow different mechanical properties to be obtained depending on its desired use in the final function of the part [5,6]. The high solidification rate in the SLM process enables the development of a microstructure dominated by columnar grains, which grow in a direction as close as possible to the thermal gradient [7,8]. This results in columnar grains that share a crystalline orientation to form macro-grains. The sub-granular structure of the macro-grains is dendritic-cellular, and this has a significant effect on the anisotropy of such materials [9,10] (see figure 1 right). The inherent surface roughness of SLM components and the geometrical distortions generated during the primary manufacturing stage [11] or heat treatment [12] make post-processing by machining necessary [13,14]. Different studies were carried out on tool wear by milling Inconel 718 SLM components. Kim et al. [15] analyzed the wear on milling cutters during the post-processing of Inconel 718, finding differences in wear according to the cutting direction and relating these differences to
different degrees of hardness. The effects of micromachining [16] on the surface integrity of Inconel 718 [17] have also been studied, but there is not much research into deep-hole reaming of Inconel 718 SLMed components, which is one of the reasons for this research.

This study presents the results obtained from milling and reaming tests carried out on Inconel 718 SLMed ducts using two types of milling cutters and one type of reamer. It aims to measure the quality of the surface-finishing process applied to holes obtained from printed ducts and subsequent post-processing by milling and reaming as an alternative to the traditional processes of drilling, milling, and reaming. Another objective is to establish the degree of finish provided for this type of material by the milling process as compared with the reaming process and thereby find out which type of endmill geometry favors a better finish by reaming.

Figure 1. SLM parameters and sub-granular structures of a SLMed macro-grain.

2. Methodology and experimental set-up

A batch of four hundred Inconel 718 SLMed ducts (Φ_{EXT} = 8 mm, Φ_{INT} = 4 mm and height h = 40 mm) was manufactured on a Renishaw AM400 machine – see figure 2(a). The ducts were then subjected to age-hardening heat treatment according to the ASTM B637 standard, which consisted of an initial solution treatment for half an hour at 950°C after an eight-hour precipitation hardening treatment at 720°C and eighteen hours at 625°C with a final air cooling. The AS-SLM duct had an initial hardness of 33 HRC, which after heat treatment reached 49 HRC. An analysis of the microstructure of the printed parts by SEM (scanning electron microscope) showed dendritic structures in the YZ plane, figure 2(b), and cellular structures in the XY plane, figure 2(c), which is evidence of predominantly epitaxial grain growth in Inconel 718 SLMed components.

Figure 2. (a) Batch of printed ducts; (b) Optical micrography of Inconel 718 SLM sample on the YZ plane; (c) SEM image of Inconel 718 SLM sample on the XZ plane.

Subsequent milling and reaming tests were carried out on a Kondia A6 machining center. The machining strategy followed during the reaming tests was that defined by default on the Fagor 8070
CNC. During the tests, torque and axial cutting force measurements were taken using the Artis® data acquisition system. In addition, breaks were taken between passes to analyze the evolution of wear on the tools, which was measured using a PCE-200® microscope. The coolant used contained a 9-percent concentration of Horocut® 940 synthetic oil and was injected externally through hoses.

The experimental set-up is shown in figure 3. Four endmills of two types (A and B) and two identical reamers (1 and 2) were used for these tests. Table 1 summarises the typology of tools and cutting parameters. Each endmill machined fifty holes and each reamer one hundred holes, as shown in figure 3 right.

![Experimental set-up for milling and reaming in deep hole finishing.](image)

**Figure 3.** Experimental set-up for milling and reaming in deep hole finishing.

| Tool     | z  | Helix angle(β) (°) | ∅  (mm) | Fz (mm/rev) | N (rev/min) | Vc (m/min) | ap (mm) |
|----------|----|--------------------|--------|-------------|-------------|------------|--------|
| Endmill type A | 4  | 20                 | 4.5    | 0.05        | 2122        | 30         | 25     |
| Endmill type B | 4  | 35                 | 4.5    | 0.05        | 2122        | 30         | 25     |
| Reamers(1 and 2) | 6  |                    | 5      | 0.04        | 764         | 12         | 20     |

The cutting conditions in table 1 correspond to the parameters established by the manufacturers. The end-of-test criterion was established according to the indications of the ISO3685 standard.

In order to measure the roughness caused by milling and reaming, each row of ducts was separated, and the ducts were cut in half for further analysis; see figure 4. Roughness measures and surface topography were obtained with a Leica DCM3D confocal microscope.

![Ducts cut in half for roughness measuring.](image)

**Figure 4.** Ducts cut in half for roughness measuring.
3. Results and discussion

Figures 5(a), 5(c), and 5(e) correspond to the wear, axial force, and torque present in the milling operations, respectively. It is important to note that the type B endmill showed a higher level of wear despite the lower levels of axial cutting force and torque compared to the type A endmill, with the former reaching the wear limit allowed (0.3mm) by the standard before 40 rebored holes, while the type A endmill showed more resistance to wear, reaching 50 holes without exceeding the wear limit allowed. The wear behavior of both endmill types shows a gradual increase, being very similar at 25 mm of machined length but growing significantly further apart between 25 mm and 250 mm machined lengths. The wear slope on both endmills is similar within the 250 mm and 1250 mm milled-length range.

The axial cutting forces and milling torque showed a significant variability from one duct to another, which is related to the geometrical distortions of the ducts inherent to the SLM process and caused by
the residual stresses produced by rapid solidification and columnar grain growth. These distortions in the ducts increase during the heat treatment stage. The difference in the level of force between endmill type A and endmill type B is due to the helix angle ($\beta$), whereby the axial component of the cutting edges that counteracts the axial component due to the feed advance is lower in the type A endmill than in the type B, leading to a higher resulting axial force from the type A endmill.

Figures 5(b), 5(d) and 5(f) correspond to the wear, axial force, and torque present in the reaming operations, respectively. It is important to note that the wear is roughly similar for both reamers, albeit slightly higher for reamer 2. The higher wear value of reamer 2 could be connected to the higher roughness values left by the type B endmill (see figure 6), which in turn relates to the greater wear appearing on this endmill and the added effect of surface topography due to the greater helix angle of this endmill ($35^\circ$). Figure 6 right shows a significant decrease in the roughness of the ducts following the reaming operation compared to the roughness after milling. Additionally, it can be seen that the roughness of the ducts due to the milling operation affects the roughness in the reaming, with roughness being greater in the ducts where the type B endmill was previously used. The axial cutting force of reamer 1 is much greater than that of reamer 2; this effect is linked to the interaction between the primary cutting edge angle of the reamer in the axial direction and the surface topography of the duct after the milling operation with the type A endmill.

![Figure 6. Tool wear.](image)

Figure 7 shows a proportional relationship between tool wear and axial cutting force for the milling and reaming tools, with the slope being greater for endmill type A and reamer 1 owing to the greater cutting forces, as explained above.

![Figure 7. Tool wear vs Axial force.](image)
The milling operation improves the surface quality of the ducts compared to the initial roughness of the printed component. However, the reaming process achieves Rz roughness values of less than one micron. Figure 8 shows a comparison of the surface topographies, roughness profiles and roughness parameters for a duct after milling, figure 8(a), and after reaming, figure 8(b).

4. Conclusions

In this paper, tool wear and surface quality in SLMed deep holes have been studied. The main findings from this research can be summarized as follows:

- Dimensional distortions in deep holes manufactured by SLM are related to the significant variability in axial cutting force. Distortions are caused by residual stress, which is induced by the columnar grain solidification mode of this process. The dendritic and cellular structures observed in SEM micrographs are related to the columnar grain growth mechanism.
- The helix angle ($\beta$) of endmill tools significantly affected the surface quality. The roughness level was reduced when endmill type A was used (with a lower helix angle) despite higher axial cutting forces. The length milled before reaching the wear limit by endmill type A was almost twice that of endmill type B.
- The excellent surface quality observed after reaming indicates that the traditional drilling stage in the creation of deep holes is not necessary when the SLM process manufactures initial holes.

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