Preliminary study of abrasive water jet texturing on low thickness UNS A92024 alloy sheets

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Abstract: Texturing and surface modification operations are a line of research of great interest nowadays. The requirement to establish a process that can generate a constant and homogeneous roughness as a previous step to joining operations, application of paint or mechanical tests is a current challenge. Technologies such as shot blasting or laser texturing have achieved great results in terms of roughness and surface activation. Nevertheless, there is an alternative technology that is achieving great interest. Abrasive water jet texturing takes advantage of the combination of the impact of abrasive particles and water at high speed with the controlled displacement of the jet to generate a surface with a controlled roughness. Thus, in comparison with other technologies, abrasive waterjet texturing can achieve higher roughness values and a constant texturing area as a function of the overlap established between the passes. In this work, a preliminary study is proposed in order to establish a direct relationship between the parameters governing the technology and the roughness generated in a low thickness UNS A92024 alloy. Defectology associated to the process, as well as the combination of texturing parameters have been determined.

Keywords: Geometric surface modification, AWJM, Surface quality, Texturing.

1. Introduction

Surface modification of metallic alloys is a line of research of great interest nowadays [1–3]. Surface modification techniques can generate hydrophilic or hydrophobic surfaces and increase the functional performance of their application [4]. The need to establish a process capable of generating a constant and homogeneous roughness as a preliminary step to joining operations, paint application or mechanical tests is a current challenge [2,5]. In recent years, several research studies have focused on the combination of metallic alloys with other dissimilar materials in the form of a hybrid structure by means of adhesive or thermal bonding [6–8]. Surface modification techniques allow to obtain a surface activation in which the adhesive expands completely increasing the bonding between the two elements [1]. Within the surface modification technologies, shot blasting and laser texturing are the most studied and used in the current industry. On the one hand, shot blasting allows the surface modification of large areas in a short time, while laser texturing provides a very well-defined and precise surface [9–11]. Nevertheless, the first technology does not guarantee a homogeneous surface in terms of roughness and the second technology is not suitable for the surface modification of large areas [12].

An alternative surface modification technology is currently being explored that may have a better final performance. Abrasive water jet texturing takes advantage of the combination of high velocity
water and abrasive particle impact with controlled head travel to generate a surface with controlled surface roughness [13]. Surfaces with high values in terms of roughness have been achieved using this technology by setting different levels of traverse feed rate, standoff distance and texturing patterns [14]. This has led to a wide range of applications from increasing surface activation prior to joining operations to surface modification of metal parts obtained by additive manufacturing [15].

However, surface modification by abrasive water jetting has challenges that need to be studied. Due to shear-type stresses and overexposure of the material to the impact of the water jet, stress concentrations are generated on the material [16]. This generates a curvature in the geometry of the material, especially when the thickness is reduced. In addition, it has been corroborated that abrasive particles may be adhered to the modified surface after the operation, which may alter its final function [17]. For these reasons, a preliminary study of the surface modification of a low thickness UNS A92024 aluminium alloy by abrasive water jet machining has been developed.

The surface obtained after each combination has been evaluated in order to determine the degree of surface modification generated. A relationship has been established between the surface quality obtained in terms of Ra and Rt with the parameters that govern the process. This has made it possible to establish the influence of the surface modification parameters and to indicate the significant influence of each parameter that governs the process.

Thus, the erosive capacity of the abrasive particles has been compared with non-abrasive texturing. On the other hand, the divergence of the water jet by increasing the SOD parameter generates a surface modification footprint of greater area but may reduce its texturing capacity. This research aims to establish a starting point for the application of waterjet cutting technology as an optimal surface modification technology for thin metal alloys. This technology can generate interesting results for secondary operations.

For these reasons, different levels of standoff distance (SOD) and abrasive flow rate have been modified to determine the combination of optimum surface modification parameters and defects generated in the metal alloy.

2. Experimental Methodology

An experimental methodology was designed in order to fulfil with the objectives outlined in the introduction.

2.1. Material and machining process

The alloy used was UNS A92024, table 1 [18]. In order to collate the alloy composition, X-ray photoelectron spectroscopy tests (XPS) were carried out. In this case the equipment Spectrolab M12 (Ametek, Kleve, Germany) was used.

| Parameter | Levels |
|-----------|--------|
| AMFR (g/min) | 0, 110 |
| Step (mm-%) | 0.18-25, 0.36-50 |
| SOD (mm) | 10, 50 |
| TFR (mm/min) | 4000, 6000 |

Table 1. Composition of UNS A92024 alloy.

| Al | Cu | Mg | Mn | Si | Fe | Zn | Ti | Cr | Others |
|----|----|----|----|----|----|----|----|----|--------|
| Rest | 3.80 - 4.90 | 1.20 - 1.80 | 0.30 - 0.90 | ≤0.50 | ≤0.50 | ≤0.25 | ≤0.15 | ≤0.10 | ≤0.15 |

Table 2. Variable texturing parameters\(^a\).

\(^a\) Meaning of the acronyms: AMFR, abrasive mass flow rate; SOD, stand-off distance; TFR, traverse feed rate.
To accomplish this experimental, one sheet of UNS A92024 T3 alloy with 2 mm of thickness were used. From this material, 36 specimens with dimensions of 20x50 mm were obtained. On the other hand, the parameters to perform surface texturing of these specimens are as follows. As can be seen, in the experimental design some parameters are variable (table 2) while others remain constant (table 3).

Both, texturing and contour machining, were carried out using a TCI Cutting (TCI cutting, Valencia, Spain) abrasives water jet machining (AWJM). The texturing strategy used was a back and forth process. In order to avoid inaccuracies in the texturing process, the methodology used by A. Alberdi et al. in [19] was followed. The CAD/CAM software performed to program the trajectories was LANTEK.

Table 3. Constant texturing parameters

| WP (MPa) | Orifice Diameter (mm) | Nozzle Diameter (mm) | Nozzle Length (mm) | Abrasive Size (µm) | Abrasive Type |
|---------|-----------------------|----------------------|-------------------|-------------------|--------------|
| 800     | 0.30                  | 250                  | 380               | 120               | Garnet       |

b Meaning of the acronyms: WP, water pressure.

2.2. Test Evaluation
Surface integrity was evaluated in terms of microgeometrical properties, in this case, roughness average (Ra) was measured. To carry out the measurements, the roughness tester Mahr Pertometer Concept PGK 120 (Mahr, Göttingen, Germany) was employed. For measuring roughness profiles the following methodology was taken into account. Thus, the standard used as a reference for roughness measurement was ISO 4287 [20]. In this sense, the cut-off used during the whole measurement process was 2.5 mm. Finally, all the measurements were carried out in the center of each specimen and always in the transversal direction of the trajectory followed by the water-abrasive jet. In addition, in the evaluation of the microgeometrical properties, an optical inspection was also carried out. In this sense, an analysis by stereoscopic optical microscopy (SOM) techniques was performed using a SMZ-800 Nikon microscopy, (Nikon, Tokyo, Japan) which had a 5 Mpx optical camera Optikam B5 (Optika, Ponteranica, Italy). Moreover, to complete the inspection an Inverted Metallographic Microscopy Eclipse MA200 was used.

2.3. Data treatment
The analysis of results was carried out following three main steps. The first one consisted in identify the trends between cutting parameters and variables studied. The second step was based on quantifying the weight of each of the cutting parameters. To do this, a study of analysis of variance (ANOVA) was carried out with a 95% confidence interval. Finally, the graphic representation of the contour graphs was made taking into account the results obtained.

![Figure 1](image)

(a) Texturing with pure water. (b) Texturing with abrasive.
3. Results and discussion

Figure 1 shows macrographs of the textured surface obtained by metallographic microscopy under conditions of TFR 4000 mm/min and SOD 50 mm. These macrographs show how the tests performed with abrasive show a more homogeneous finish than those textured with pure water jet, which demonstrates the abrasive effect that the material undergoes when textured with abrasive particles. However, it should be taken into account that tests performed with abrasive can be contaminated by abrasive particles embedded in the surface of the material. This effect is reflected in other scientific investigations such as those carried out by A. Alberdi et al. [19] and F. Bañon et al. [13].

In general, for the four macrographs shown in figure 1, the homogeneity of the surfaces obtained was apparent. It should be taken into account that a low traverse speed can generate a surface with a lower roughness and greater depth in the material due to the fact that it is subjected to a longer exposure time, although this effect can lead to an irregular surface morphology [21–24]. On the other hand, the textured surface shows significant changes in step variation. As shown in figure 2 a step of 25% has a larger overlap of the passes than for step of 50%. This makes the texturing pattern more distinguishable for any given traverse speed when selecting higher steps.

![Macrographs taken at 10x on the surface of the material for texturing: (a) with pure water. (b) with abrasive.](image)

Figure 2. Figure 3 shows the results obtained for the arithmetic mean roughness (Ra) according to the test carried out. The bars correspond to the tests with pure water and with abrasive. Firstly, it can be seen how the tests performed with abrasive (110 g/min) reach higher roughness values than the tests with pure water (0 g/min), with 11.53 μm being the highest value with abrasive, and 8.84 μm the highest value with pure water jet. The inclusion of abrasive particles in the waterjet results in different jetting behavior when texturing. Abrasive particles increase erosion upon impact on the surface of the material, resulting in steeper craters and valleys, that is to say, less homogeneous and rougher surfaces.

![Graphical representation of Ra values for texturing with and without abrasive.](image)

Figure 3. Graphical representation of Ra values for texturing with and without abrasive.
In the abrasive tests, a trend of increasing roughness is observed as the nozzle-to-workpiece distance and the traverse speed increase. This discussion matches with that carried out by R. Pahuja et al. [15] in their research on the surface treatment of Ti-6Al-4V. For the pure water tests, it is worth noting the decreasing trend that the Ra values undergo as the step employed increases. For these test conditions (0 g/min), it may be that the step is the most influential parameter during texturing. This makes sense since a lower step implies a greater number of trajectories, so that the jet passes more times over the same surface generating a greater erosion on the material. On this occasion, the lowest Ra values are obtained for tests without abrasive, being 2.79 and 2.93 μm. These results are obtained for tests with a high traverse feed rate (6000 mm/min) and a high step (50%) regardless of the nozzle-workpiece distance used. The minimum values of Ra match with the minimum values of Rt obtained in figure 4, being 35.97 and 40.25 μm. Again, there is a large difference between the Rt values obtained in tests with and without abrasive.

Figure 4. Graphical representation of Rt values for texturing with and without abrasive.

For a more detailed analysis of the results, this section analyses the degree of influence of each parameter by zone. For this purpose, table 4 and 5 shows the F-value and p-value for Ra and Rt.

**Table 4.** Analysis of variance (ANOVA) of the evaluated variables. Pure water.

| Step   | TFR | SOD  |
|--------|-----|------|
| Variable | F-Value | p-Value | Variable | F-Value | p-Value | Variable | F-Value | p-Value |
| Ra (μm) | 9.070 | 0.039 | Ra (μm) | 0.410 | 0.558 | Ra (μm) | 0.200 | 0.675 |
| Rt (μm) | 1.890 | 0.241 | Rt (μm) | 1.450 | 0.295 | Rt (μm) | 0.040 | 0.856 |

**Table 5.** Analysis of variance (ANOVA) of the evaluated variables. With abrasive.

| Step   | TFR | SOD  |
|--------|-----|------|
| Variable | F-Value | p-Value | Variable | F-Value | p-Value | Variable | F-Value | p-Value |
| Ra (μm) | 0.770 | 0.429 | Ra (μm) | 0.010 | 0.918 | Ra (μm) | 0.010 | 0.942 |
| Rt (μm) | 0.330 | 0.596 | Rt (μm) | 0.530 | 0.508 | Rt (μm) | 0.180 | 0.697 |

The results show that the most influential technological parameter in the process is the step, although the magnitude of the F-factor shows the degree of relevance of each parameter. In addition, for the machining mode without abrasive this value becomes significant for Ra with a p-value of 0.039. As for TFR, the data show that there is a difference depending on the incorporation of abrasive, the parameter being more relevant when cutting in the absence of abrasive. Finally, SOD shows a similar behaviour to TFR, which implies a notable decrease in its influence when abrasive is incorporated.
On the other hand, figure 5 shows the main effects plot of Ra and Rt for both cutting modes. In a first analysis of the results, the difference can be seen when abrasive is incorporated. The average Ra results without abrasive is approximately 6 µm, while with abrasive this value rises up to 9.5 µm. Similarly, with Rt, where the average increases from about 55 µm to almost 80 µm. As mentioned above, the addition of abrasive increases the values of roughness and material removed on the material layer. In addition, it can be seen how the slope of the parameters is reduced when the abrasive flow rate is incorporated, which is in good agreement with the ANOVA and the importance of selecting the right amount of abrasive in processes where the thickness removed is controlled due to its high influence.

![Graphs showing main effects plots for Ra and Rt](a) Ra with pure water. (b) Ra with abrasive. (c) Rt with pure water. (d) Rt with abrasive.

Figure 6 shows the contour plots of the results in order to analyse the roughness range as a function of the most influential parameters: Step and TFR. It is shown that the variability of the results is considerably reduced when abrasive is incorporated. Thus, figures 6 (b) and (d) show that the roughness values Ra and Rt remain practically constant in ranges of 9.5 µm and 80 µm, respectively, while for cutting in the absence of abrasive the results show a greater dispersion. Specifically, Figures 6 (a) and (c) show ranges of decrease in roughness recorded when step and TFR grow, reaching values below 2 µm in Ra and 35 µm in Rt for this combination of parameters.

4. Conclusions
Abrasive water jet machining can be an alternative as a surface modification technology in order to obtain a surface with a high roughness. In the results obtained, it has been corroborated that the effect of the abrasive produces a rougher and more defined surface. The use of abrasive particles enhances the erosive effect of the water jet. These increase the penetration capacity and produce a greater number of craters on the surface increasing the final roughness. In addition, the increase in the step parameter has a direct effect on surface quality. On the other hand, reduced values of SOD and a reduce traverse feed rate increase the exposure of the water jet with the surface and minimize the kinetic energy loss of the
water jet increasing the Ra values. Finally, contour diagrams relating the surface quality to the parameters governing the process and showing similar trends between Ra and Rt parameters in abrasive and non-abrasive conditions have been obtained.

![Contour plots](image)

**Figure 6.** Contour plots for: (a) Ra with pure water. (b) Ra with abrasive. (c) Rt with pure water. (d) Rt with abrasive.

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