Cutting parameters influence analysis on fatigue behaviour of dry turned UNS A97075 alloy after corrosion

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Abstract. Aluminum alloys, particularly series 2000 (Al-Cu) and 7000 (Al-Zn), are widely used for structural elements in aircraft. Machining processes are frequently applied in manufacturing these parts. The actual trend in the machining of these components is to reduce or eliminate the use of lubricants, due to environmental reasons. Among the different techniques, dry machining is commonly used for aluminum alloys. However, dry machining generates higher severe cutting conditions, which may negatively affect the surface integrity and the mechanical properties of the machined parts. In this regard, fatigue life is one of the most important mechanical properties to take into account. Micro-cracks generation and nucleation strongly depend on the surface conditions of the machined parts. Additionally, the addition of Zn to pure aluminum (7000 series) reduces the corrosion resistance. Despite its importance, there is a lack of research devoted to analyze the cutting parameters influence on fatigue behaviour, before and after corrosion, in dry machining of these alloys. Therefore, in this work, the cutting speed and feed rate influence on fatigue behaviour of the UNS A97075 (Al-Zn) alloy has been analyzed. Several rotating bar bending fatigue tests have been carried out, studying and comparing the fatigue life curves obtained as a function of the cutting parameters, before and after an immersion corrosion process. The experimental results have revealed that an increment in the cutting speed and feed rate gives rise to fatigue life reduction.

1. Introduction

Actually, the aeronautical industry takes special interest due to the extensive use of aircrafts. Aluminium alloys (2000 and 7000 series) are widely employed for the manufacture of the airplanes due to their excellent mechanical properties and density relationship. Particularly, UNS A97075 (Al-Zn) alloy is used in the manufacturing of the wings, spar caps and the upper skins [1].

Machining operations are commonly employed in the structural aircraft manufacturing (milling and drilling), where turning operations are used to obtain revolution pieces designated to fit. Furthermore, the actual trend is to employ environmental friendly techniques in machining operations, reducing or eliminating lubricants (dry machining, cryogenic, minimum quantity of lubricant, etc.). Nevertheless, these cutting conditions affect negatively to the process performance (functional, economic and energetically) due to the action of high temperature and pressures [2].

Manufacturing processes (machining operations among others) generate variations in the surface conditions of the manufactured parts. In this sense, the surface integrity evaluates those variations, being an appreciate quality requirement in aeronautical industry. Three levels can be considered for the surface integrity evaluation: macro-geometrical (size, shape, geometrical deviations, etc.), micro-geometrical (roughness profile, micro-cracks, etc.) and physicochemical properties (fatigue behaviour, corrosion, etc.) [3].
Fatigue behaviour is one of the most important mechanical properties to take into account in the evaluation of aircrafts structural parts in service due to security reasons. Fatigue fracture occurs in three phases: microcracks generation and nucleation (usual in aluminium alloys surface), crack growth and ductile fracture due to the reduction of the section that support the stress [4]. Different researches relate fatigue behaviour with other surface integrity properties such as microhardness, residual stress and surface roughness [5,6]. Therefore, the surface integrity of manufactured parts affects the initial phase of the fatigue fracture.

On the other hand, cutting parameters (cutting speed, feed rate and cutting depth) has been related with microhardness, residual stress and surface roughness of machined parts. Hence, it can be established that the cutting parameters affect the fatigue behaviour [7].

In general terms, aluminium alloys show a good corrosion resistance due to the alumina layer that is generated on the free surface under corrosion conditions. In spite of this, in the series 7000, the zinc addition to aluminium reduces this corrosion resistance compared with pure aluminium (series 1000). In aluminium-zinc alloys, corrosion is usually localized under the appearance of pitting corrosion, as well as intergranular corrosion, which can be considered as the generation and nucleation points of microcracks [8,9]. Thus, the corrosion process affect negatively to the surface integrity of manufacturing parts and, therefore, fatigue behaviour is negatively affected too, due to the reduction of the generation and nucleation of microcrack phase.

In previous research of aluminium alloys machined parts, the immersion corrosion process has been affect negatively the surface conditions of machined parts. In this sense, in [10] the machining of the fatigue test notch provoke an increase of the fatigue crack length in corroded parts compared with other process.

Additionally, the influence of initial surface conditions in the corrosion activity has been considered in [11]. In this case, higher surface roughness previously the corrosion process, affect negatively to the surface conditions of corrode parts. Hence, the previous surface conditions in machined parts take especial relevance in the surface of corroded parts. Furthermore, the surface conditions affect fatigue behaviour as previously commented.

Therefore, in this work, a preliminary study of the cutting parameters influence in the fatigue behaviour of corroded parts in dry turning UNS A97075-T6 (Al-Zn) alloy has been performed. From the experimental results, the influence of the cutting parameters in the surface roughness and the fatigue behaviour previous and post immersion corrosion has been analysed.

2. Methodology
Several dry-turning tests were carried out in order to evaluate the cutting parameter influence on the fatigue behaviour of UNS A97075-T6 aluminium alloy corroded parts. The test alloy composition (% mass), obtained with arc atomic emission spectroscopy (AES), is shown in Table 1.

| Zn    | Mg | Cu  | Cr  | Si  | Mn  | Al     | Rest |
|-------|----|-----|-----|-----|-----|--------|------|
| 6.01  | 2.61 | 1.88 | 0.19 | 0.08 | 0.07 | Rest   |

Different standards can be used to evaluate the material fatigue behaviour. Among them, ISO 1143:2010 standard [12] has been selected due to aeronautical parts are usually subjected to bending stress. The selected specimen geometry and dimensions are shown in Figure 1.

Different specimens were turned under dry conditions. A finishing step was carried out for each sample using different cutting speed \((v_c)\) and feed-rate \((f)\) values, remaining constant the cutting depth for every test. The selected values are shown in Table 2. Although this alloy is not usually machined with low cutting speed values, it requires low \(v_c\) values when it is hybridized with other materials.

Four specimens were machined for each cutting parameter combination to ensure a confidence level of 95% and a 50% failure probability, according to the ISO 12107:2017 standard [13]. Therefore, 96 specimens were manufactured for each tested surface state (corrode and non-corrode).
After the turning tests, a micro-geometrical control was carried out. The average roughness (Ra) and the maximum height of the profile (Rz) were used as parameters to evaluate the surface quality. For this purpose, a portable roughness tester (Mitutoyo SURFTEST SJ-210) was used.

Once the surface roughness was measured, 4 samples of each cutting parameter combinations were corroded. The corrosion process was carried out in a solution of deionized water and NaCl (3.5% concentration), keeping the specimens in that corrosive environment for 72 h. Hence, to ensure the corrosion process homogeneity on the surface of all samples, a pump was used inside the solution.

The rotating bar bending tests were carried out in a rotating bar bending bench, manufactured in the University of Malaga. Before the test start, once the specimen is placed in the fatigue test bench, the concentricity between the extreme of the specimen and the chuck was controlled, according to the ISO 1143:2010 standard [12]. A single load was applied in the extreme of the specimen, assuming 244.40 MPa stress in the expecting fatigue fracture section.

Finally, a fractography image of the fracture sections was performed. A stereoscopic microscope, NIKON SMZ 2T, with a Kappa Image Bases CF11 DSP camera and PSI SC module capture card was used for this purpose.

3. Results
Figure 2 shows the Ra results as a function of vc and f, before and after the corrosion process. A general trend to increase Ra with f is observed, regardless vc. The Ra highest values have been obtained for 0.20 mm/r, regardless vc.

For samples before corrosion, from $f = 0.05$ mm/r to 0.10 mm/r, a slightly Ra increase can be observed. Notwithstanding, from $f = 0.10$ mm/r to 0.20 mm/r, Ra increase with f is more noticeable. The cutting speed influence in Ra is less noticeable. Only for $f = 0.15$ mm/r, a difference in the Ra values obtained can be appreciated for different vc. In this case, for vc = 40 m/min, the Ra mean value is higher than for vc = 60 and 80 m/min. This effect can be explained due to the appearance of some vibrations during the turning process. These results are in good agreement with previous research [14,15].

It can be appreciated how the corrosion process has affected negatively the surface roughness, increasing the Ra values. For samples after corrosion, Ra increase can be observed clearly along all f values rang, regardless vc. In this case, vc influence is less noticeable too. The corrosion process has increased the Ra results dispersions, being more relevant at higher f values (0.15-0.20 mm/r).
Figure 2.1 Average Roughness ($Ra$) as a function of feed ($f$) and cutting speed ($v_c$): (a) previous corrosion process, (b) post corrosion process.

Figure 3 shows the $R_z$ results as a function of $v_c$ and $f$. The influence of the cutting parameters ($v_c, f$) in $R_z$ is similar to $Ra$. Nevertheless, the corrosion process has provoked a higher $R_z$ increase than observed for $Ra$. This effect can be explained taking into account the corrosion process in aluminium alloy. The appearance of pitting corrosion may have affected the values of the microgeometrical deviations at one point (localized corrosion). This effect was softened in the calculation of the average values to obtain $Ra$.

It is important to highlight that the $Ra$ and $R_z$ measurements, represented previously, were carried out in the specimens that were corroded, being the specimen $Ra$ and $R_z$ values in good agreement with the fatigue test that were performed without the corrosion process.

Figure 4 shows several SOM images from the fatigue fracture section of a non-corroded test (Figure 2a) and of a corroded test (Figure 2b). The initial cracks can be observed in the surface. This effect occurs in corroded and non-corroded specimens. In spite of this, in the corroded fracture section (Figure 4b) two initiation crack point can be observed. This is due to the pitting corrosion, that facilitates microcracks generation and nucleation.

The corrosion affects a maximum depth of 0.40 mm [6]. Therefore, cracks growth and ductile fracture surface show a similar performance, in corroded and non-corroded specimens, taking into account that they are under the same stress in the fracture section ($S = 244.40$ MPa).
Figure 4. Fracture section SOM capture (x30): (a) previous corrosion process, (b) post corrosion process for \( v_c = 40 \) m/min and \( f = 0.10 \) mm/r.

The number of cycles \((N)\) obtained for the rotating bar bending non-corrode tests are represented in Figure 5a, and results of the corrode specimen are shown in Figure 5b, as a function of \( v_c \) and \( f \). Figure 5a shows that, in general, an increase of \( f \) tends to reduce \( N \). This trend can be observed for \( v_c = 40 \) and 80 m/min. For \( v_c = 60 \) m/min, an increase of \( N \) can be observed in the range of 0.05 to 0.10 mm/r. The lower \( N \) values were obtained for higher \( f \) values (0.15-0.20 mm/r) and \( v_c \) (80 m/min). Taking into account these results, the fatigue behaviour \((N)\) of non-corrode specimens is influenced by \( f \), associated with a \( Ra \) and \( Rz \) increase and \( v_c \) related with the appearance of residual stresses and microstructural changes [7].

Figure 5. Number of cycles \((N)\) as a function of feed \((f)\) and cutting speed \((v_c)\): (a) previous corrosion process, (b) post corrosion process.

It can be observed that the corrosion process affects negatively the fatigue behaviour \((N)\) due to the changes in the specimen surface, being influenced by \( v_c \) and \( f \). In Figure 5b, a general trend to reduce \( N \) with \( f \) can be observed, regardless \( v_c \). The increase of surface irregularities, associated with a \( f \) increase, provokes that the microcrack initiation and nucleation phase requires less number of cycles. In addition, the corrosion process affects the surface residual stresses and microstructure, that encourage the acceleration of the initial fatigue fracture step.

4. Conclusions
In this work, an analysis of the influence of the cutting speed and feed-rate on fatigue behaviour of UNS A97075 dry turning corrode specimens has been carried out. The surface roughness (\( Ra \) and \( Rz \)) has been evaluated on the fatigue test samples, before and after the corrosion process.
Regarding the surface roughness, the feed-rate has been shown as the most influential variable in both parameters studied (Ra and Rz). However, the cutting speed influence has been less noticeable. The corrosion process has affected negatively Ra and Rz, increasing their values in all the f values rang. Rz has experimented a higher increase than Ra, due to the pitting corrosion, that is originated in the corroded specimens surface. These observations are in good agreement with previous works performed under similar cutting conditions.

Fracture section fractography has shown that the microcracks initiation and nucleation occur in the surface for both corroded and non-corroded specimens. Furthermore, in the corroded samples fractography several initial microcrack points can be observed. Crack grown and ductile fracture surface are independent of the surface conditions, depending on the load applied.

The fatigue behaviour experimental data showed that increments in v, and f results in a fatigue life (N) reduction, according with a surface roughness increase. The cutting parameters influence in fatigue life (N) of corroded parts is less noticeable. This effect may be explained taking into account the surface alterations, reducing the number of cycles during microcrack initiation and nucleation phase.

5. References
[1] Goncharenko A V 2018 Int. J. Aerosp. Eng. 2018 pp 75-92
[2] Batista Ponce M Del Sol Illana I. Fernandez-Vidal S and Salguero Gomez J 2018 Materials (Basel) 9 1598.
[3] Davim J P 2010 Surface integrity in machining 53-69
[4] Schijve J 2008 Fatigue of Structures and Materials 13–58
[5] Novovic D Dewes R C Aspinwall D K Voice W and Bowen P 2004 Int. J. Mach. Tools Manuf. 44 125–134
[6] Rotella G 2019 J. Manuf. Process. 41 83–91
[7] Surya Sundara Rao K and Viswanath Allamraju K 2017 Materials Today: Proceedings. 4 975–981
[8] Zupanc U and Grum J 2010 J. Mater. Process. Technol. vol 210 n 9 pp 1197–1202
[9] Shen Y 2019 Bioelectrochemistry 107408.
[10] Arunachalam S R Galyon Dorman S E Buckley R T Conrad N A and Fawaz S A 2018 Int. J. Fatigue 111 44–53
[11] Bienvenido R Díaz Vázquez J E Botana F J Cano M J and Marcos Bárzcaena M 2010 Adv. Mater. Res. 107 117–121
[12] International Standaring Organization ISO 1143:2010. Metallic materials-Rotating bar bending fatigue testing 2010.
[13] International Standaring Organization ISO 12107:2017 Metallic materials - Fatigue testing-Statistical planning and analysis of data 2017.
[14] Bermudo C Trujillo F J Herrera M and Sevilla L 2017 Procedia Manuf. 13 81–88
[15] Martín S Trujillo F J Bermudo C and Sevilla L 2019 Metals (Basel) 9 11.

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