Advances in efficiency in the groove milling of aluminium EN AW 2024-T3 with zig-zag and trochoidal strategies

O Rodríguez¹, P E Romero¹, E Molero¹ and G Guerrero¹

¹ Department of Mechanics, University of Córdoba, Córdoba. Spain.

*Corresponding author: guillermo.guerrero@uco.es

Abstract: Manufacturing process engineers must continually take decisions to make the processes efficient. Manufacturing time, surface finish and energy consumption are aspects to be optimized in machining. This study analyzes the efficiency of groove milling in milling aluminum alloys EN AW 2024-T3 with zig-zag and trochoidal strategies. Dynamic milling is designed to maximize the removal rate and optimize the tool performance. This generates a discontinuous cutting with minimum of heat reducing build-up with an optimal chip removal minimizing cutting edge wear. The influence of lateral pitch, feed per tooth, cutting speed and coolant pressure has been analyzed. The depth of cut has been adapted for each strategy and tool type. The study was proposed through a factorial design of experiments by the Taguchi method. The machining time (T) and energy consumption (EC) show a strong influence of the lateral step (ae) in conventional milling. A similar level of influence appears with the feed per tooth (fz) on the trochoidal. The roughness (Ra) is more influenced by cutting speed (Vc) for conventional milling and by feed per tooth (fz) and lateral pitch (ae) for the trochoidal.

Keywords: Trochoidal milling, Zig-zag milling, Trochoidal toolpath, Dynamic milling toolpath, Energy saving, Groove milling.

1. Introduction

The aluminum alloy ENAW 2024-T3 has an excellent mechanical behavior. In addition, with the T3 state, the elongation, tensile strength, and fatigue resistance are substantially improved compared to any aluminum of the 2000 series. To achieve this hardening, the metal is thermally treated in solution, hardened by deformation and then naturally aged. It is commonly used in structures, transport and aviation industry components [1]. Many of the elements manufactured with this alloy require machining to obtain the final geometry, lighten weight and improve accuracy. It is an aspect of interest to study the factors that make machining more efficient [2].

Grooving and pocketing operations are among the most common of the milling processes. In this case the cycle time is an aspect that directly affects the efficiency of the process in technological, energy and economic terms. Among the strategies for tackling machining in this type of operation, it is common to use zig-zag strategies. These strategies are efficient, but they have certain disadvantages, among them the continuous change of direction of the machining, the high generation of vibrations and the relatively low quality of the finished surfaces [3]. Dynamic trochoidal milling has advantages, among which are that the mechanical stress is low, the contact times between the cutting edge and the material are reduced [4,5]. In principle these strategies allow higher cutting parameters and a high rate of machining (MRR) with low tool wear.
Several studies, including those for aluminum alloys EN AW7075 [6] and EN AW 6061-76 [7] have addressed the factors influencing surface finish and energy consumption in grooves obtained by milling. Also, in other experimental works, the procedures to minimize the milling cycle time by optimizing the cutting forces and the tool vibrations have been addressed [8-12]. Similarly, there are proposals to minimize the carbon footprint that is related to cycle time and removal rate [13,14].

The work has made it possible to determine the influencing factors for improving surface quality and energy consumption in slot milling of EN AW 2024-T3 aluminum alloy. The Taguchi method combined with analysis of variance (ANOVA) has been used to address these objectives [15]. The input variables have been: (i) radial cutting depth ($a_e$), (ii) cutting speed ($V_c$), (iii) feed per tooth ($f_z$) and (iv) coolant pressure. The process responses to evaluate have been: (i) machining time ($T$), (ii) surface roughness level ($R_a$) and (iii) energy consumption ($EC$).

2. Materials and methods

The specimens used are 75×75×30 mm³ of EN AW 2024-T3 aluminum alloy. The milling work was carried out on a 3-axis machining center model Chevalier QP2026L (Chevalier Machinery Inc., California, USA) equipped with a Fanuc Oi-MC CNC unit (Fanuc Corporation, Oshino-mura, Yamanashi, Japan). The milling tools used are made of integral, uncoated tungsten carbide (WC). A high-performance trochoidal cutting tool (TPC) and a multi-tasking cutting tool (MTC) milling tool from the manufacturer Hoffmann (Hoffmann Iberia, Madrid, Spain) have been used. Figure 1 includes a picture of the tools used.

![High-performance cylindrical cutter (TPC)](image1)

![Multi-task cylindrical cutter (MTC)](image2)

Figure 1. (a) High-performance cylindrical cutter (TPC) with $z = 3$ and Ø 10 mm for trochoidal milling (b) Multi-task cylindrical cutter (MTC) with $z = 3$ and Ø 10 mm for zig-zag milling.

An oil-water emulsion with 5% of oil was used in all the tests (Besal 5, Brugarolas Lubricantes Industriales S.A., Barcelona, Spain). Two different flow pressures were applied: (i) high pressure fluid to provoke the evacuation of the chips and (ii) low pressure, by gravity [16].

The characteristics of the tools and the cutting recommendations are shown in table 1.

| Table 1. The geometrical and cutting features recommended by Hoffmann Group. |
|------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Ø (mm)     | Cutting edges / tooth, $z$ | Helix angle (°) | Total length, $L$ (mm) | Max. cutting length, $(mm)$ | Max. cutting depth grooving, $a_p$ (mm) | Max. radial cutting depth, $a_e$ (mm) | Cutting speed, $V_c$ (m/min) | Feed per teeth, $f_z$ (mm/teeth) |
| MTC        | 10 | 3 | 45 | 72 | 22 | 15 | 5 | 250 | 0.070 |
| TPC        | 10 | 3 | 30 | 104 | 51 | 41 | 1.5 | 270 | 0.134 |
Table 2. The factors and levels established in the experiments for the two-case study (30%, 50% and 70% of the recommended).

| CASE STUDY | FACTORS AND LEVELS |
|------------|---------------------|
| Tool       | Cutting depth $a_p$ (mm) | Lubricant pressure | Radial depth, $a_e$ (mm) | Cutting speed $V_c$ (m/min) | Feed per teeth $f_z$ (mm/teeth) |
| MTC        | 10                   | high, low          | 1.5, 2.5, 3.5             | 75, 125, 175                | 0.021, 0.035, 0.049            |
| TPC        | 30                   | high, low          | 0.45, 0.75, 1.05          | 69, 115, 161                | 0.047, 0.078, 0.109            |

The values established in the experiments for the cutting parameters have been 30%, 50% and 70% of those recommended by the tool supplier and are shown in table 2.

The groove that has been designed for the experiments is 30 mm deep, 20 mm wide and 75 mm long. The TPC tool can perform it in a single $Z$-pass while the MTC tool must use at least two $Z$-passes. The final geometry of the groove is shown in figure 2. It has been machined in a single operation and without finishing passes in all tests included in the experimental plan.

The machining operations were programmed with the CAD-CAM Mastercam X software (CNC Software Inc., Tolland, CT, USA). The machining with MTC in zig-zag was carried out in three passes in $Z$ ($a_p = 10$ mm per pass) with the depth of radial passage ($a_e$) in the direction of the $Y$ axis. When cutting with TPC, the entire depth of the groove was worked in a single pass ($a_p = 30$ mm).

The DOE was constituted by the Taguchi method as a combination of 4 parameters (factors) in each strategy: lubrication (2 levels), axial depth of cut (3 levels), feed per tooth (3 levels) and cutting speed (3 levels). The DOE gave a total of 54 runs (2*27) which the Taguchi method allowed us to set at 18 representative runs per case study.

The energy consumption ($EC$) was measured in real time by the electric energy recorder, model Chauvin Arnoux PEL 103 (Chauvin Arnoux, Paris, France) [17]. The roughness $Ra$ and $R_z$ on the bottom and, in the case of trochoidal milling [18], [19], on the side walls of the grooves, were measured with a Mitutoyo Surftest SJ201-P roughness meter (Mitutoyo Corporation, Sakado, Japan). Five measurements were made on each of the surfaces to be checked (bottom and side walls).

3. Results

The 36 Taguchi DOE tests and the values are shown in tables 3 and 4, corresponding to the roughness ($Ra$) and ($R_z$) on the walls and at the bottom of the grooves, the total cycle time ($T$) and the energy consumption ($EC$) (Table 3). From these results it has been possible to evaluate the influence of the different variables analyzed on the efficiency of the process.

The evaluation of the experimental responses was based on the analysis of variance (ANOVA) and a standard analysis.
Table 3. Roughness, cycle time and energy consumed obtained in the tests for conventional zig-zag and trochoidal milling.

| Test Nr | Ra [µm] bottom | Rz [µm] bottom | Cycle time, T [s] | Energy, EC [kJ] | Test Nr | Ra [µm] bottom | Rz [µm] bottom | Ra [µm] wall | Cycle time, T [s] | Energy, EC [kJ] |
|---------|----------------|----------------|------------------|-----------------|---------|----------------|----------------|--------------|-----------------|-----------------|
| 1       | 0.424          | 2.768          | 896              | 1270.8          | 19      | 1.250          | 7.584          | 0.704        | 773             | 1137.6          |
| 2       | 0.702          | 4.572          | 240              | 378             | 20      | 1.354          | 7.660          | 0.87         | 256             | 500.4           |
| 3       | 1.076          | 6.506          | 114              | 255.6           | 21      | 1.826          | 11.168         | 1.146        | 252             | 457.2           |
| 4       | 0.620          | 5.164          | 180              | 313.2           | 23      | 2.036          | 12.032         | 0.928        | 156             | 356.4           |
| 5       | 0.928          | 4.872          | 110              | 248.4           | 24      | 1.628          | 9.974          | 1.292        | 699             | 950.4           |
| 6       | 0.468          | 2.600          | 880              | 1116            | 25      | 0.758          | 4.370          | 0.684        | 324             | 626.4           |
| 7       | 0.888          | 4.632          | 112              | 241.2           | 27      | 1.230          | 8.556          | 1.342        | 340             | 572.4           |
| 8       | 0.730          | 4.108          | 407              | 601.2           | 28      | 0.828          | 4.708          | 0.600        | 378             | 680.4           |
| 9       | 0.488          | 2.776          | 371              | 615.6           | 29      | 1.812          | 9.686          | 0.934        | 344             | 408             |
| 10      | 0.900          | 4.780          | 168              | 349.2           | 30      | 1.312          | 8.406          | 1.474        | 345             | 579.6           |
| 11      | 0.656          | 3.488          | 254              | 446.4           | 31      | 1.270          | 6.066          | 0.624        | 246             | 482.4           |
| 12      | 0.722          | 4.474          | 289              | 554.4           | 32      | 1.148          | 7.888          | 0.958        | 780             | 1036.8          |
| 13      | 0.742          | 3.766          | 295              | 453.6           | 33      | 1.370          | 7.904          | 1.326        | 295             | 489.6           |
| 14      | 0.874          | 4.572          | 271              | 702             | 34      | 0.890          | 4.670          | 0.864        | 580             | 1004.4          |
| 15      | 0.778          | 3.866          | 275              | 536.4           | 35      | 1.220          | 7.140          | 1.320        | 528             | 748.8           |
| 16      | 0.508          | 2.786          | 284              | 468             | 36      | 1.794          | 10.438         | 1.304        | 159             | 316.8           |

3.1. Time

Table 4 shows the cycle time (T) statistics analyzed in consideration of the different strategies (MTC and TPC). It is known that with high values of p < 0.05 and % Contribution the associated variable is an influential factor in the response.

Table 4. ANOVA values for the cycle time, T.

| Factor    | DOF | F-ratio | % Contribution | p    |
|-----------|-----|---------|----------------|------|
| CONVENTIONAL |
| Coolant   | 1   | 50.95   | 3.03           | 0.000|
| a_e       | 2   | 37.10   | 47.67          | 0.000|
| V_c       | 2   | 22.06   | 27.46          | 0.000|
| f_z       | 2   | 77.44   | 20.52          | 0.000|
| Error     | 10  | 1.32    |                |      |
| Total     | 17  | 100     |                |      |
| TROCHOIDAL |
| Coolant   | 1   | 0.00    | 0.00           | 0.000|
| a_e       | 2   | 13.02   | 6.62           | 0.000|
| V_c       | 2   | 15.92   | 37.08          | 0.000|
| f_z       | 2   | 29.78   | 48.20          | 0.000|
| Error     | 10  | 8.09    |                |      |
| Total     | 17  | 100     |                |      |

3.2. Roughness

In conventional milling, the roughness of the walls is so coarse that measuring roughness has been ruled out. The imprint on the bottom and on the walls of the groove is shown in figure 3.

Table 5 shows the statistics of the Ra ANOVA analysis at the bottom and wall.
Figure 3. The tool footprint at the bottom and walls of the groove: (a) zig-zag; (b) trochoidal.

Table 5. ANOVA values for the average surface roughness, \( Ra \) (bottom) and \( Ra \) (wall).

| Factor | DOF | \( F \)-ratio | \% Contribution | \( p \) | \( F \)-ratio | \% Contribution | \( p \) |
|--------|-----|---------------|-----------------|------|---------------|-----------------|------|
| Coolant | 1  | 0.33          | 0.01            | 0.579 | 1  | 1.67          | 1.99            | 0.226 | 0.061 |
| \( a_e \) | 2  | 0.10          | 25.15           | 0.905 | 2  | 8.70          | 50.68           | 0.006 | 0.000 |
| \( V_c \) | 2  | 4.88          | 35.89           | 0.033 | 2  | 0.11          | 0.97            | 0.901 | 0.40  | 1.58  | 0.682 | 0.000 |
| \( f_z \) | 2  | 5.82          | 20.25           | 0.025 | 2  | 14.39         | 34.41           | 0.001 | 0.70  | 1.71  | 0.518 |
| Error  | 10 |               |                 |       |               |                 |       |       | 11.96 | 12.19 |
| Total  | 17 |               |                 |       |               |                 |       |       | 100   |       |

3.3. Energy

Table 6 shows the statistics on energy consumption (\( EC \)) in response to the factors involved in the two strategies (TPC and MTC) used in this work and the influence of each of the factors involved on this response variable is shown in figure 4.

Table 6. ANOVA values for the energy consumption (EC).

| Factor | DOF | \( F \)-ratio | \% Contribution | \( p \) |
|--------|-----|---------------|-----------------|------|
| Coolant | 1  | 4.46          | 0.22            | 0.061 | 1  | 0.05          | 0.03            | 0.831 |
| \( a_e \) | 2  | 16.07         | 53.38           | 0.001 | 2  | 17.45         | 17.13           | 0.001 |
| \( V_c \) | 2  | 3.27          | 17.10           | 0.081 | 2  | 10.35         | 23.04           | 0.004 |
| \( f_z \) | 2  | 16.82         | 24.69           | 0.000 | 2  | 36.59         | 52.61           | 0.000 |
| Error  | 10 |               |                 |       |               |                 |       | 7.19  |       |
| Total  | 17 |               |                 |       |               |                 |       | 100   |       |

4. Discussion

4.1. Time

The radial depth of cut (\( a_e \)) and the cutting speed (\( V_c \)) are the factors that most influence the cycle time (T) in the case of the conventional zig-zag groove milling strategy and show 47.67% and 27.46% of
contribution in the cycle time response, respectively. In trochoidal milling, the feed per tooth \((f_z)\) and the cutting speed \((V_c)\) are the factors that have a greater influence on the response of the cycle time \((T)\) with 48.20% and 37.08% of contribution, respectively. From the above observations it can be deduced that with an increase in the feed per tooth \((f_z)\), for the trochoidal case, its efficiency can be significantly improved while waiting for a good response in terms of tool wear. The conventional zig-zag requires increasing the radial depth of cut \((a_e)\) to obtain an improvement in efficiency, a solution that is not normally advisable in terms of tool wear.

![Figure 4. Response results for the energy consumption, EC (conventional strategy vs. trochoidal strategy).]

4.2. Roughness

In the case of roughness \(Ra\) at the bottom, the cutting speed \((V_c)\) and the feed per tooth \((f_z)\) are the most influential factors in the conventional milling process (35.89% and 20.25%), respectively. The radial depth of cut \((a_r)\) and the feed per tooth \((f_z)\) are the factors that show the greatest influence in the trochoidal milling of grooves (50.68% and 34.41%, respectively). For the measurement of \(Ra\) on the wall with trochoidal milling, the contribution of \(a_e\) is very high, 82.96%. Observing the results of \(Ra\) at the bottom in the trochoidal milling of grooves, when the cutting speed \((V_c)\) is increased, the value of roughness decreases. On the other hand, it is interesting to note that in the case of conventional milling, when the cutting speed \((V_c)\) is increased, the roughness value increases. This phenomenon indicates that, despite the fact that better (lower) roughness values are obtained in the conventional strategy than in the case of trochoidal milling, in the latter the milling operation has a higher degree of stability against vibrations. It should be taken into account that the lateral load \((a_r)\) is more aggressive in conventional milling, and, in addition, its own dynamics implies more abrupt changes of direction which, consequently, are associated with more pronounced ups and downs in the value of the radial cutting force. This aspect, together with the progressive increase in cutting speed, may be causing the deterioration of the surface quality obtained by the conventional zig-zag strategy. It is observed that the conditions of the trochoidal strategy allow a high stability in the tool during the operation, despite using a depth of cut \((a_e)\) up to 3 times higher (30 mm vs. 10 mm) than in the case of the conventional strategy. However, the \(Ra\) (bottom) roughness values obtained by the trochoidal strategy are slightly higher (worse) than those obtained by the zig-zag strategy, indicating that to improve this response it would be desirable to adapt the cutting.
4.3. Energy

Regarding the consumption of electrical energy \((EC)\), the radial cutting depth \((a_e)\) has a greater influence in the case of conventional groove milling (contribution of 53.38%) than in the case of trochoidal milling (contribution of 17.13%). In the trochoidal case, the most influential factor is the feed per tooth \((f_z)\) with a contribution of 52.61%. At the same time, the experiment performed by the trochoidal strategy showed that \(V_c\) has a low impact in terms of \(EC\). It should be noted that, as shown in the latest works consulted, trochoidal milling strategies are suitable for the use of high-speed machining (HSM) 50 conditions, being able to reach cutting speeds of the order of 300 ÷ 6000 m/min. This point foresees the possibility of improving cycle time, and energy consumption given its applicability to any dynamic milling strategy such as trochoidal groove milling.

5. Conclusions

The aim of this work was to investigate the process efficiency in terms of surface quality and energy consumption by the study of two different experimental variants in the groove milling of EN AW 2024-T3 aluminum alloy. On the one hand, the conventional proposal with a multitask cutting tool (MTC) using a conventional zig-zag groove milling toolpath and, on the other hand, the proposal of a trochoidal performance cutting tool (TPC) using a trochoidal machining path were programmed by the CAD-CAM software application Mastercam X. The factors studied were: (i) \(V_c\), (ii) \(a_e\), (iii) \(f_z\) and (iv) coolant pressure. The following conclusions can be drawn from this work:

- To achieve the best efficiency in terms of machining time in conventional milling, the most influential factor is the radial depth of cut \((a_e)\). In trochoidal milling, the most determining factor is the feed per tooth \((f_z)\) and, in both cases, the contribution is around 48%, respectively.
- In the case of \(Ra\) (bottom) and in the case of conventional milling, the most important factor is the cutting speed \((V_c)\) with a contribution of 36% while in the case of trochoidal milling, the greatest influence is the radial pass \((a_e)\) with a contribution of 51%.
- The \(Ra\) on the walls in the case of trochoidal milling is mainly affected by the value of the radial depth of cut \((a_e)\) that contributes almost 82% to this response value.
- For the energy consumption \((EC)\), the value of the radial depth of cut \((a_e)\) is the first influencing factor in the case of conventional milling, and the feed per tooth \((f_z)\) in the case of trochoidal milling. The contribution is in the range of 52-53 % in both cases.

Ultimately in zig-zag and trochoidal the greatest influence for time and energy are \(a_e\) in one case and \(f_z\) in the other (≈ 50 %). For roughness at the bottom is \(V_c\) in the zig-zag and \(a_e\) in trochoidal.

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