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Selection of Parameters and Strategies to Reduce Energy Consumption and Improve Surface Quality in EN-AW 7075 Molds Machining

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Abstract: The machining of cavities for blow molding is a long and costly process, with the objective of obtaining an excellent surface finish with the minimal possible electrical energy consumption (EEC). This work has studied which combination of cutting parameters and cutting strategies to use to achieve an optimum surface finish on the mold using the minimal associated EEC: in roughing operation, tool path strategy and axial depth of cut were studied; in finishing operation, tool path strategy, spindle-speed, feed-rate, and step-over were evaluated. Thirty-two molds were machined in blocks of aluminium alloy EN-AW 7075 T6 in a machining center of a three-axis, following an orthogonal design of experiments. The analysis of results demonstrates that: a roughing strategy has influence on the surface roughness on the bottom of the mold; a finishing strategy is an influential factor on the surface roughness on the walls of the mold; certain parameters have no relevance on the surface roughness but have an influence on the EEC; an adequate selection of cutting strategies and cutting parameters permit an improvement of surface roughness of up to 70%, and a reduction of 40% in EEC, compared to the less favorable tests.

Keywords: mold; machining; surface roughness; electrical energy consumption

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1. Introduction

Metal molds are some of the tools most used in the industry today. They are used to shape thermoplastic materials through different techniques [1]: injection (parts for the car industry), thermoforming (packaging), rotational molding (kayaks), and compression molding and blow molding (food containers).

The molds are produced by milling, in a machining center with a three- or five-axis [2]. The machining of the molds is undertaken in two stages. The first stage, known as roughing, is for the elimination of the main mold cavity without being concerned with the surface roughness obtained. This operation is usually carried out with a robust flat-end tool. The second stage, known as finishing, permits a fine surface roughness, eliminating the remaining material. This is usually carried out with tools of a smaller diameter and hemispherical end.

The tool-path that the tool has to follow during both phases of milling is undertaken by a pocketing strategy. There are multiple types of strategies, although the most used and studied are the raster (zig-zag, ZZ) and 3-D offset (contour-parallel, CP) [3].

In the manufacturing of a mold, the most important parameter is the surface roughness obtained [4]. In the literature, there is an abundance of references on the study of technical parameters with greater influence on surface finishing [5–8]. Normally, geometrically simple molds are chosen,

and the roughness is measured at the bottom of the pocket [9]. Nevertheless, little attention is paid to the roughness of the walls of the mold [10].

Some authors have studied the impact of the finishing strategies on the quality of the surface roughness obtained. For 2.5-D milling, Gologlu and Sakarya [11] studied, via the Taguchi method, three types of strategies (one-direction, ZZ, and CP) and four cutter parameters (cutting velocity, feed rate, depth of cut, and stepover). Also, Romero et al. [12] compared the ZZ and CP strategy for three different pocket geometries (concave, and convex with and without islands). For complex geometries, Ramos, Relvas, and Simões [13] compared different strategies for finishing (ZZ, CP, and radial) using the same strategies for roughing in every case, while Fagili de Souza et al. [14] studied four different finishing strategies (3-D offset, spiral, radial path, and ZZ) for mold applications. Schützer, Helleno, and Castellari [15] compared a ZZ strategy (45°) in finishing with a mix formed by four strategies adapted to the different regions of the geometry. Normally, the studies found in the literature are focused on finishing strategies and do not analyze the influence of roughing strategies on the surface roughness obtained on the complex surface [13–16].

In recent years, a large number of authors have focused their work on reducing the electrical energy used in the manufacturing processes [17,18]. Yoon et al. [19] have compared which method (bulk forming, substractive process, or additive process) consumes less electrical energy to manufacture the same part. Priarone [20] has evaluated the electrical consumption of a shaping grinding process for different process parameters via a full factorial experimental plan. Eden and Mativenga [21] have quantified the electrical consumption of a milling machine for different linear paths (G1) and circular paths (G2 and G3) in order to predict the electric demand of the machine during the execution of a NC program. Guerra-Zubiaga et al. [22] have studied different cutting trajectories and cutting parameters (feed rate, spindle speed, and depth of cut) in a slot milling process to analyze its influence on electrical consumption of the machining center. Kant and Sangwan [23] have developed a predictive model for the minimization of EEC and surface roughness during the machining of AISI 1045 steel. Based on simulations, Xu and Tang [24] have proposed two energy-saving strategies for rough milling tool path planning. Pavanasar et al. [25] have proposed a toolpath strategy that consumes at least 20% less energy than any conventional toolpath.

The present study has the following main objective: to study different cutting strategies and cutting parameters during the machining of a mold to determine which combination allows one to reach a better surface roughness on the bottom and walls of the cavity with the least possible EEC. For this purpose, an orthogonal design of experiments (DOE) was developed, made up of 32 tests. The variables included in the DOE were: strategy on roughing, axial depth of cut on roughing, strategy on finishing, spindle-speed in finishing, feed-rate in finishing, and step-over in finishing. All the tests were undertaken on EN AW 7075 T6 prismatic parts, using a machining center of a three-axis and coolant.

The work layout is in the following manner: Section 2 describes the materials and the methodology used throughout the tests. Section 3 will show the results obtained; those results will then be discussed in Section 4. Finally, the conclusions will be presented in Section 5.

2. Materials and Methods

The molds designed for the experiments have a particular geometry in order to oblige the tool to work with different parts of its edge (Figure 1): the bottom shows a step and is assembled with planes of different gradients, and the walls have a certain slope (they are not vertical). The 3-D pocket is open on one side to facilitate the readings of the roughness meter.

The cavities were machined with a machining center of a three-axis, a Chevalier, QP2026-L model, whose spindle worked at a maximum of 8000 rpm. The machine was equipped with a numerical control unit, a Fanuc, 0i-MC model, which worked with the look-ahead function activated. All the tests were carried out with refrigerant, based on an oil emulsion Besal 5 (Brugarolas, Rubí, Barcelona, Spain), diluted in water in a proportion of 5% [26].
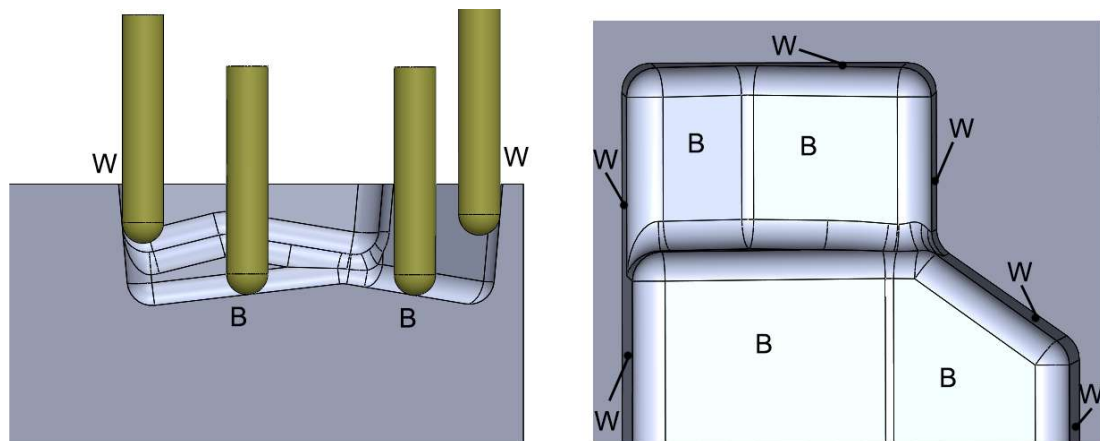
Figure 1. Diagram of the mold used in the tests: section where the gradient of the bottom (B) and the wall (W) are evident (**left**), and top view of the cavity (**right**).

The material used to machine the molds was an EN AW 7075 T6. It is an Al-Zn-Mg-(Cu) alloy, hardened by precipitation and with a high resistance to tensile strength (500–530 MPa). It is used to manufacture molds used in the plastic industry [27].

Each cavity was machined in two stages (Figure 2). The roughness stage was carried out with a tungsten-carbide cylindrical flat-end milling tool with an 8 mm diameter, and two cutting edges with a helical angle of 45° (DIN 6527). The finishing stage was carried out with a tungsten-carbide hemispherical tool, titanium nitride coated (TiN), with a 5 mm diameter. The path and working numerical control (NC) code was generated by means of a Mastercam software program (Version v10.2 MR2, CNC Software Inc., Tolland, CT, USA) [28].
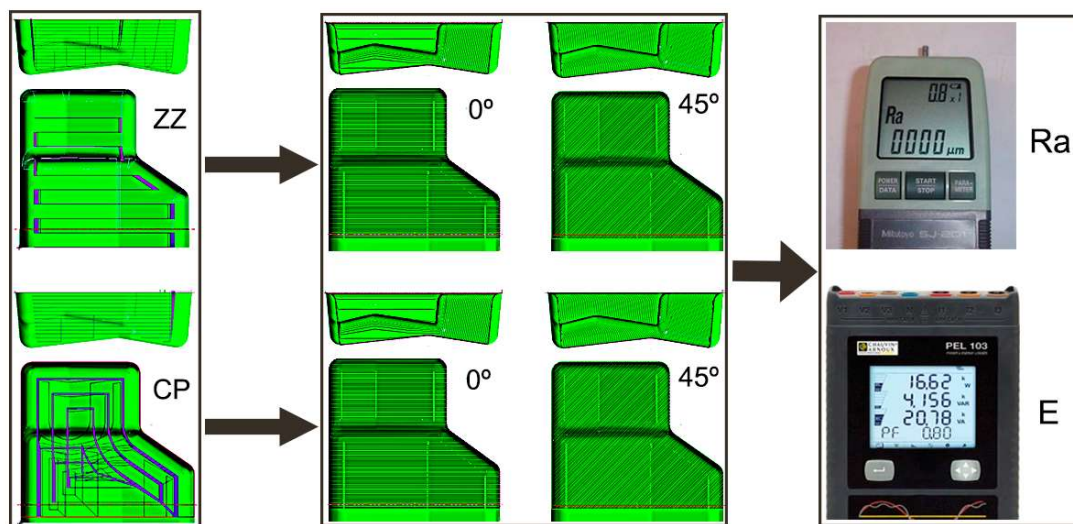

Figure 2. Scheme of the experiments: the strategies used in the roughing stage are zig-zag (ZZ) and contour-parallel (CP) (**left**), the strategies used in finishing stage are ZZ 0° and ZZ 45° (**centre**), and Mitutoyo roughness meter and energy data logger employed in the measurements (**right**).

During the roughing stage, the tool worked according to the manufacturer recommendations: spindle-speed equal to 6366 rpm, feed-rate in radial direction equal to 764 mm/min, feed-rate in axial direction equal to 382 mm/min, and step-over equal to 4 mm. The values used for the rest of the parameters for roughing and finishing are shown in Table 1. To study the influence of these parameters on the output variables, an orthogonal design of experiments was developed, as seen in Table 2 [29].

Table 1. Process parameters and levels.

	Roughing			Finishing		
Level	Strategy (A)	Axial Depth of Cut, mm (B)	Strategy (C)	Spindle Speed, rpm (D)	Feed Rate, mm/min (E)	Step-over, mm (F)
−1	Zig-Zag	1	Zig-Zag (0°)	6366	764	0.1
+1	Contour-Parallel	3	Zig-Zag (45°)	8000	1146	0.3

Table 2. Taguchi orthogonal array.

	Roughing			Finishing		
No.	(A)	(B)	(C)	(D)	(E)	(F)
1	−1	−1	−1	−1	−1	−1
2	−1	−1	−1	+1	−1	+1
3	−1	−1	−1	−1	+1	+1
4	−1	−1	−1	+1	+1	−1
5	−1	−1	+1	−1	−1	+1
6	−1	−1	+1	+1	−1	−1
7	−1	−1	+1	−1	+1	−1
8	−1	−1	+1	+1	+1	+1
9	−1	+1	−1	−1	−1	+1
10	−1	+1	−1	+1	−1	−1
11	−1	+1	−1	−1	+1	−1
12	−1	+1	−1	+1	+1	+1
13	−1	+1	+1	−1	−1	−1
14	−1	+1	+1	+1	−1	+1
15	−1	+1	+1	−1	+1	+1
16	−1	+1	+1	+1	+1	−1
17	+1	−1	−1	−1	−1	+1
18	+1	−1	−1	+1	−1	−1
19	+1	−1	−1	−1	+1	−1
20	+1	−1	−1	+1	+1	+1
21	+1	−1	+1	−1	−1	−1
22	+1	−1	+1	+1	−1	+1
23	+1	−1	+1	−1	+1	+1
24	+1	−1	+1	+1	+1	−1
25	+1	+1	−1	−1	−1	−1
26	+1	+1	−1	+1	−1	+1
27	+1	+1	−1	−1	+1	+1
28	+1	+1	−1	+1	+1	−1
29	+1	+1	+1	−1	−1	+1
30	+1	+1	+1	+1	−1	−1
31	+1	+1	+1	−1	+1	−1
32	+1	+1	+1	+1	+1	+1

The EEC of the machining center was measured on each test by Chauvin Arnoux PEL 103 equipment (Chauvin Arnoux, Paris, France) [20]. The EEC during a milling process depended on the electrical power of the machining center and the machining time:

- According Yoon et al. [19], the energy consumed by a machining center has the following distribution: basic consumption (52%), coolant pump (19%), stage movement (1%), spindle rotation (21%), cutting (7%). During the tests, the terms basic consumption, coolant pump, and stage movement did not change, so the data logger measures allowed us to know the differences in the terms spindle rotation and cutting.
- In the other hand, every strategy (ZZ, CP, ZZ 0°, and ZZ 45°) generated a particular machining time. This fact produced different EEC for the same feed-rate of spindle speed.

The surface roughness was measured by a Mitutoyo roughness meter, SJ-201P model (Mitutoyo Corporation, Sakado, Japan) (Figure 2). Five measurements were taken in each plane of the bottom of the 3-D pocket. The cut-off value was selected as recommended by ISO 4288 [30].

To analyze the influence of each parameter or strategy, the Taguchi method was used [31]. This method allows one to find optimal process values for improving the quality characteristics in a manufacturing process [9]. Through the use of orthogonal arrays, the Taguchi method allows one to completely study the space within a parameter with a reduced amount of experiments. Taguchi recommends using the signal-to-noise ratio (S/N ratio) in order to determine the quality characteristics implemented in problems that arise in design engineering (in this instance, "the smaller the better" was used).

In addition to the S/N ratio, a statistical analysis of variance (ANOVA) was used to certify the influence of studied parameters and strategies on surface roughness and EEC. In this way, the optimal levels of process parameters and strategies could be estimated.

3. Results

The measurements for surface roughness, *Ra* (μm), at the base (B) and walls (W) of the molds and the EEC (kJ) [21,24] corresponding to each of the 32 tests undertaken are shown in Table 3. This table also shows the active electrical energy consumed by the machining center during each cycle of milling. From this data, and by means of statistical software, the mean of the means and the signal to noise relation (S/N ratio) was calculated for each parameter and level (Tables 4–9). The results of ANOVA are presented in Tables 10–12.

Table 3. Parameters and strategies studied in the work using an orthogonal design of experiments.

Exp. No.	Bottom Ra (μm)	Wall Ra (μm)	Electrical Energy Consumpt. (kJ)	Exp. No.	Bottom Ra (μm)	Wall Ra (μm)	Electrical Energy Consumpt. (kJ)
1	0.375	0.340	1892.295	17	1.096	1.180	726.544
2	1.096	0.906	952.221	18	0.378	0.302	1959.509
3	1.115	1.112	746.164	19	0.321	0.280	1246.159
4	0.367	0.342	1745.124	20	1.067	1.130	665.313
5	0.893	1.916	852.554	21	0.411	0.410	1730.213
6	0.349	0.496	2108.123	22	1.071	1.792	857.676
7	0.378	0.386	1407.184	23	1.127	1.836	599.942
8	0.925	1.734	736.073	24	0.453	0.420	1500.760
9	1.160	0.918	914.459	25	0.391	0.464	1466.522
10	0.356	0.378	1850.367	26	1.097	1.010	651.152
11	0.387	0.588	1143.106	27	1.159	1.528	443.197
12	1.167	1.934	558.109	28	0.426	0.568	1317.950
13	0.387	0.392	1877.920	29	1.109	2.012	698.821
14	0.996	2.010	846.666	30	0.356	0.492	2051.546
15	0.984	2.020	590.787	31	0.381	0.402	1296.372
16	0.363	0.618	1787.599	32	1.165	2.016	618.689

Table 4. *Ra* response table for surface roughness at the bottom (μm).

Levels	A	B (mm)	C	D (rpm)	E (mm/min)	F (mm)
−1	0.7505	0.7139	0.7475	0.7297	0.7201	0.3801
+1	0.7063	0.7429	0.7093	0.7270	0.7366	1.0767
$\Delta_{max-min}$	0.0442	0.0290	0.0383	0.0027	0.0165	0.6966
Classification	2	4	3	6	5	1

Table 5. S/N response table for surface roughness at the bottom.

Levels	A	B (mm)	C	D (rpm)	E (mm/min)	F (mm)
1	3.6584	4.0406	3.7795	3.9017	3.9996	8.4293
2	4.1559	3.7736	4.0348	3.9125	3.8147	−0.6150
$\Delta_{max-min}$	0.4974	0.2670	0.2553	0.0108	0.1849	9.0443
Classification	2	3	4	6	5	1

Table 6. *Ra* response table for surface roughness at the wall (μm).

Levels	A	B (mm)	C	D (rpm)	E (mm/min)	F (mm)
−1	0.9901	0.9114	0.8113	0.9865	0.9386	0.4299
+1	1.0056	1.0844	1.1845	1.0092	1.0571	1.5659
$\Delta_{max-min}$	0.0155	0.1730	0.3733	0.0227	0.1185	1.1360
Classification	6	3	2	5	4	1

Table 7. S/N response table for surface roughness at the wall.

Levels	A	B (mm)	C	D (rpm)	E (mm/min)	F (mm)
1	2.1013	2.9030	3.3421	2.2105	2.5153	7.5513
2	1.9234	1.1217	0.6826	1.8142	1.5094	−3.5266
$\Delta_{max-min}$	0.1778	1.7812	2.6594	0.3963	1.0059	11.0779
Classification	6	3	2	5	4	1

Table 8. Response table for EEC (kJ).

Levels	A	B (mm)	C	D (rpm)	E (mm/min)	F (mm)
−1	1114.4	1232.9	1142.4	1102.0	1339.8	1648.8
+1	1250.5	1132.1	1222.6	1262.9	1025.2	716.1
$\Delta_{max-min}$	136.1	100.8	80.2	160.9	314.6	932.6
Classification	4	5	6	3	2	1

Table 9. S/N response table for EEC.

Levels	A	B (mm)	C	D (rpm)	E (mm/min)	F (mm)
1	−60.01	−61.05	−60.28	−60.05	−61.75	−64.19
2	−61.12	−60.08	−60.85	−61.08	−59.38	−56.94
$\Delta_{max-min}$	1.12	0.97	0.57	1.04	2.37	7.26
Classification	3	5	6	4	2	1

Table 10. ANOVA results for surface roughness at the bottom of the mold.

Source of Variation	Degree of Freedom	Sum of Squares	F Ratio	*p* Value
A	1	0.01561	4.54	0.043
B	1	0.00673	1.96	0.174
C	1	0.01170	3.41	0.077
D	1	0.00006	0.02	0.899
E	1	0.00218	0.63	0.434
F	1	3.88183	1129.33	0.000
Error	25	0.08593	-	-
Total	31	4.00403	-	-

Table 11. ANOVA results for surface roughness at walls.

Source of Variation	Degree of Freedom	Sum of Squares	F Ratio	*p* Value
A	1	0.0019	0.03	0.864
B	1	0.2394	3.73	0.065
C	1	1.1145	17.37	0.000
D	1	0.0041	0.06	0.802
E	1	0.1123	1.75	0.198
F	1	10.3240	160.86	0.000
Error	25	1.6045	-	-
Total	31	13.4009	-	-

Table 12. ANOVA results for EEC.

Source of Variation	Degree of Freedom	Sum of Squares	F Ratio	*p* Value
A	1	148,292	8.43	0.008
B	1	81,264	4.62	0.041
C	1	51,419	2.92	0.100
D	1	207,149	11.78	0.002
E	1	791,929	45.02	0.000
F	1	6,958,669	395.62	0.000
Error	25	439,727	-	-
Total	31	-	-	-

The R_a response results at the bottom are given in Table 4. As can be seen, the parameter step-over in finishing (F) were the most influential on those analyzed. Following this, in order of importance, was the strategy on roughness (A). Both parameters, (F) and (A), were those that had the most effect on the S/N ratio (Table 5) and presented a *p*-value under 0.05 (Table 10).

The R_a response results at the wall are given in Table 6. In this case, the parameter for the step-over (F) was also the parameter with the greatest influence. Following this, in order of importance, was the strategy on finishing (C). Both parameters, (F) and (C) were those with the greatest effect on the S/N ratio (Table 7) and presented a *p*-value under 0.05 (Table 11).

The response results for EEC are presented in Table 8. The step-over (F) was again the most influential parameter. It was followed by, in order of importance, the feed-rate programmed in the finishing operation (E). Both parameters, (F) and (E) were those that had the greatest effect on the S/N ratio (Table 9). In this occasion, the parameters (F), (E), (D), (A), and (B) presented a *p*-value under 0.05 (Table 12). However, (F) and (E) had the highest importance, as they had the highest F-ratio.

In Figure 3, the roughness of the base of the cavity obtained, in each of the tests, was related to the electrical energy invested in machining the aforementioned 3-D pocket (each point on the graph represents one test). Figure 4 shows the existing relation between the surface roughness obtained on the walls on each cavity with the active power used in its machining.
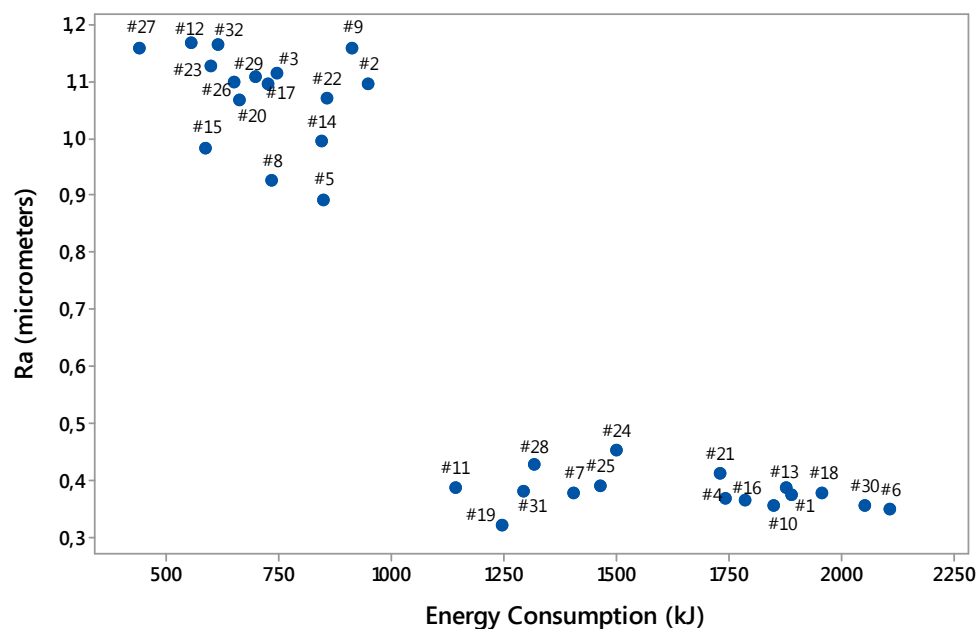

Figure 3. Electrical energy used in milling in each mold against the surface roughness obtained at the bottom of each one (each point corresponds to one of the tests undertaken in this study).
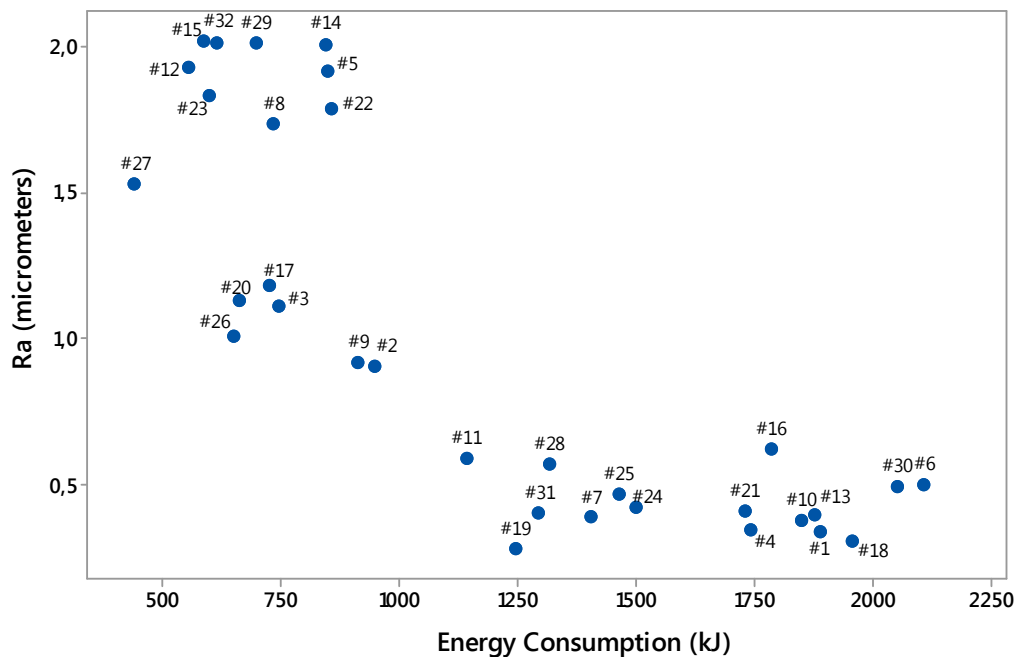
Figure 4. Electrical energy used in milling in each mold against the surface roughness obtained on the walls of each one (each point corresponds to one of the tests undertaken in this study).

4. Discussion

The present work has studied the influence of cutting parameters and cutting strategies, as much in roughing as in finishing, relative to surface roughness and EEC used during the machining of molds. To this end, 32 molds were machined, following an orthogonal design of experiments. In addition, the combinations that showed the best results from the point of view of the EEC during the mold manufacturing cycle have been determined.

In the literature, this problem has been studied beforehand [9]. Nevertheless, no works have been found that take into account the parameters and strategies on the roughing phase [13] and approach of the reduction of EEC.

The results of the tests allow one to come to the following conclusions:

- The step-over in the finishing (F) was the most influential in the surface roughness of the bottom (Tables 4 and 5) and of the walls of the 3-D pockets (Tables 6 and 7). This was confirmed in the analysis ANOVA (Tables 9 and 10). Lower values of this parameter produced a better surface roughness; however, this choice meant a higher EEC (Tables 8 and 12). These results coincided with those obtained by Baptista and Antune [32].
- The strategy used in the roughing (A) had some influence on the surface roughness on the bottom of the 3-D pocket (Table 10). The use of ZZ gave a better surface quality (Tables 4 and 5), although it resulted in greater EEC (Table 8). No previous works have been found that have studied the influence of the roughing strategy on the final surface roughness. This finding can be considered the main contribution of the work.
- The strategy used in finishing (C) was an influential factor on the surface roughness on the walls (Table 11). The ZZ (0°) produces a better surface roughness than the ZZ (45°) (Tables 6 and 7); this was due to the contact tool-surface [14]. In the present study, strategy in finishing (C) had no relation to the EEC (Tables 8 and 12). However, diverse authors have compared other finishing strategies, concluding that a 3-D offset is the most efficient [13,14].
- Certain parameters that do not seem to have much relevance on the surface roughness do however have an influence on the effective EEC during the manufacturing of the molds (Table 12). This is

the case with: axial depth of path in the roughing (B), spindle-speed used in finishing (D), and feed-rate in finishing (E). Oda et al. [33] also concluded that large feed rate values led to reduced power consumption.

- Figure 3 shows a diagram of dispersion with the 32 tests undertaken, where the *x*-axis corresponds to EEC and the *y*–axis corresponds to the surface roughness on the bottom of the 3-D pocket. Here there are two clusters of very polarized points. The first group is made up of the greater values of surface roughness (*Ra* > 0.9 micrometers) but which have required low EEC (EEC < 1000 kJ). The second group is made up of tests with low values of surface roughness (*Ra* < 0.5 micrometers) but are associated with high EEC values (EEC > 1000 kJ). In Figure 4, relative to surface roughness on the walls, one can appreciate an additional group, between the aforementioned groups.

- Test 19 produced a better finish as much on the bottom as on the walls of the mold, requiring lower EEC. This test was undertaken with a roughness strategy CP, an axial depth of cut for roughness of 1 mm, a finishing strategy ZZ (0°), a spindle-speed of 6366 rpm, a feed-rate on the finishing of 1146 mm/min, and a step-over in the finishing of 0.1 mm.

- An adequate selection of parameters and strategies allowed for an improvement of 70% in the surface roughness of the mold, with an electrical energy saving of 40%.

The ZZ roughing strategy produced a remaining material whose morphology presented a clear directionality characteristic (Figure 5). On the other hand, the CP strategy used for roughing produced a remaining material whose morphology presented steps whose height was equivalent to the depth of passage and multiple changes of direction were seen in the way in which these remains were presented in the form of steps. This difference in the morphology of the remaining material has been indirectly affected in the finishing results.
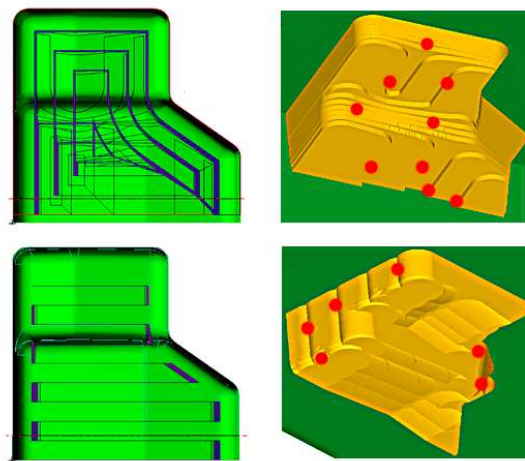

Figure 5. Scheme of the morphology and points of discontinuity presented in the remaining material after roughing strategies, with contour parallel (**up**) and zig-zag (**down**).

The load on the finishing endmill tool suffered many changes of direction and discontinuities when the remaining material presented the morphology obtained in the roughing by the CP strategy, while the directionality of the cutting load was more stable when it presented the morphology obtained in the case of the roughing ZZ.

This phenomenon caused by the changes of direction and discontinuities in the loading of the finishing tool may have caused more vibrations in the finishing tool and in the piece itself during the finishing operation. It has been possible to verify that when the load of the finishing tool was affected to a lesser extent by the changes of direction in the material to be eliminated, the obtained superficial quality was better.

5. Conclusions

In the present work, cutting strategies and cutting parameters in roughing and finishing stages have been studied in order to reach better surface roughness values with a lower EEC during the manufacturing of EN-AW 7075 T6 molds via a machining process.

The results obtained allow us to affirm that lower values in step-over in the finishing stage were absolutely necessary in order to obtain a good surface roughness (both in the bottom and on the walls of the mold), although this resulted in higher EEC.

The strategies for roughing and finishing had an influence on the surface roughness on the bottom and the walls, respectively. The strategy chosen for roughing also had an influence on the EEC of the machining center.

It has also been demonstrated that an adequate choice of values for certain variables (axial depth of cut in roughing, feed-rate in finishing, and spindle-speed in finishing) allowed for the manufacturing of molds with a lower EEC without negative repercussions on the resulting surface roughness. The most satisfactory test showed an improvement in surface quality of 70%, and a reduction in EEC of 40% (compared to the more unfavorable tests).

Future research will concentrate on searching for new parameters and strategies that allow even further reduction in EEC in the processes of manufacturing molds by machine production. A study will also be carried out on the wear of the tools and the influence of the use of coolant in the surface roughness and EEC.

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