High- performance manufacturing with trochoidal milling strategies

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***Abstract*— Along with technological progress, manufacturing processes have been constantly innovated, hoping to reduce manufacturing time, extend the useful life of tools and offer high quality finishes of the product, however, information on the product is scarce. Machined in 7075 - T6 aluminum, which, due to its mechanical properties, is more used for the manufacture of molds and dies than other materials. In this project, a high-performance machining is studied, improving cycle times by comparing trochoidal and conventional milling roughing strategies, without the use of coolants that can contaminate the chip allowing the recycling of material, these strategies are found in a large part of CAM software. The experimentation was carried out in a Hision CFV 1100 vertical machining center with Fanuc Oi MF control, supported by the Taguchi L18 methodology for the milling parameters and roughing strategy. 9 tests were carried out for each strategy with a 25 mm flat cutting tool with 4 high speed steel (HSS) lips based on the 3 levels of the milling parameters, in the range of 800 m / min to 1000 m / min, with a feed per tooth of 0.25 to 0.35 mm / tooth. The results obtained for both time and temperature have a behavior described by Mr. Salomón for high-speed machining (HSM), an ANOVA statistical analysis was carried out that determined that the trochoidal machining strategy presents a reduction in the 93.27% compared to the conventional machining strategy and a stable temperature of 25°C in the cutting tool.**

***Index Terms*— trochoidal machining, conventional machining, high speed machining, prodax aluminum**

I. Introduction

Aluminum (Al) is the most abundant metal in the earth's crust, above iron, it is a metal that can be machined without great difficulty, it has a high thermal conductivity and as regards the electrical conductivity, it is a good conductor (like all metals except for titanium), it also has a face-centered cubic crystalline structure, thus it has a non-ferromagnetic behavior and resistance to oxidation and corrosion.[1]

The alloying element in Prodax aluminum is zinc, which acts by giving it greater hardness and resistance. The T6 heat treatment that the material has, in effect is solubilized and later aged in order to increase its resistance. Thus, they are delivered in round bars and plates, heat treated, which are subjected to a special cold stretching operation for maximum stress relief, obtaining high strength and good stability. [2]

In 2019, at the University of the Armed Forces -ESPE, a rough milling comparison was carried out with both conventional and trochoidal strategies in a range of 400 to 700 m/min [3], for which it seeks to complete the range of 800 to 1000 m/min in which a stabilization of the temperature of the cutting tool is achieved and the machining time with trochoidal strategy is significantly reduced.

II. Experimental Methods

The test machine was a HISION CVF Series vertical machining center with a Fanuc model Oi MF control unit, the main specifications are 4 axes, maximum spindle speed of 15000 rpm. The experimentation processes were carried out with a combination of high-speed machining parameters in order to reach high-performance machining, that is, to carry out the tests without coolant that contaminates the chips The cutting parameters were the following: cutting speeds: 800, 900 and 1000 m / min; feed speeds: 0.25, 0.30 and 0.35 mm / tooth. In the conventional strategy, the depth constant of 2,185 mm was used with a cutting width of 64% of the tool diameter. In the adaptive strategy, a constant depth of cut of 15 mm was used with a width of cut at 10% of the diameter of the tool. the configuration of the machining tests is shown in Figure. 1

Figure 1. Machining configuration

A. Material specification

A 7075- T6 aluminum with a density of 2,810 g/cm3 with a length of 70 mm, width of 70 mm and height of 20 mm was used as work piece. The chemical composition is shown in table I.

TABLE I
AL 7075- T6 CHEMICAL COMPOSITION

Chemical Composition (%)							
Al	Zn	Cu	Cr	Si	Mg	Fe	Ti
87-91.4	5.1-6.1	1.2-2	0.18-0.28	0.4	2.1-2.9	0.5	0.2

B. Cutting Tool

The tool used in the test is a 25 mm diameter milling with four flutes. the specifications for this tool are the following:

- Manufacturer: Somta
- Material: High speed steel (HSS)
- Cutting depth: 1.25 mm
- Cutting feed rate: 4800 mm/min

C. Taguchi methodology

The Taguchi method develops the procedures applying orthogonal matrices between parameters and levels in the experiment to obtain the best model with a reduction in the number of tests and minimizing the time and cost of experimentation [4].

Identifying the factors that affect the machining process is important, so the factors must vary within the design of the experiment to assess which factors have the most impact on the process. For this experiment, the parameters and levels are shown in Table II.

Table II
PARAMETERS AND LEVELS OF THE EXPERIMENT

Item	Parameter	Units	Level		
			1	2	3
A	Strategy	-	Conventional Machining Strategy (CMS)	Trochoidal Machining Strategy TMS	
B	Cutting Speed	m/min	800	900	1000
C	Feed per tooth	mm/tooth	0.25	0.30	0.35

In the methodology, the minimum number of experiments must be greater than or equal to DOF [5]

$$TotalDegreesOfFreedom(DOF) = (ni - 1) * nf \qquad (1)$$

Where:
ni: number of parameters nf:
number of levels

According to the Table II, in this experiment ni=3 and nf=3, then:

$$DOF = (3 - 1) * 3 = 6 \qquad (2)$$

Then, the minimum number of experiments is calculated as follow:

$$MinimumNumberOfExperiments = DOF + 1 \qquad (3)$$

$$MinimumNumberOfExperiments = 6 + 1 = 7 \qquad (4)$$

For this project, total combination between parameter and levels are 18. Therefore, all test was done.

D. Machining strategies and tool path

The tool path in conventional machining strategy (CMS) was follow periphery, since it is the path with the shortest execution time [3], and the tool path in the trochoidal machining strategy was trochoidal through the adaptive strategy, the machining tool paths that were obtain using CAD CAM software are show in the Figure 2.

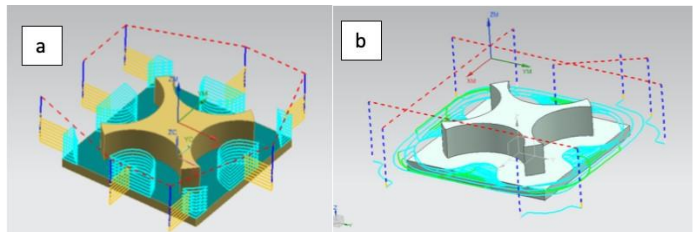

Figure 2. a) Conventional tool path, b) Trochoidal tool path

III. RESULTS

Machining time data were obtained through the HISION VMC Series. Simulation times were obtained by CAD CAM software and real times were measured on the experimental test. similarly, temperatures were measured in tool flutes immediately after the machining process, data are shown in Table III.

Table III
EXPERIMENTAL DATA

Test	A 1 CMS- 2 TMS	B Vc [m/min]	C fz [mm/tooth]	Machining time [s]		Tool Temperature [ºC]
				Simulation	Real	
A1B1C1	1	800	0.25	215	217	32.7
A1B1C2	1	800	0.30	211	213	30.5
A1B1C3	1	800	0.35	209	212	30.2
A1B2C1	1	900	0.25	212	213	31.6
A1B2C2	1	900	0.30	209	210	30.4
A1B2C3	1	900	0.35	206	208	30.1
A1B3C1	1	1000	0.25	210	212	29.4
A1B3C2	1	1000	0.30	207	209	29.2
A1B3C3	1	1000	0.35	205	208	28.9
A2B1C1	2	800	0.25	19	25	28.0
A2B1C2	2	800	0.30	16	22	27.8
A2B1C3	2	800	0.35	13	19	27.7
A2B2C1	2	900	0.25	17	23	27.5
A2B2C2	2	900	0.30	14	18	27.2
A2B2C3	2	900	0.35	12	17	26.4
A2B3C1	2	1000	0.25	15	17	25.7
A2B3C2	2	1000	0.30	12	15	25.7
A2B3C3	2	1000	0.35	11	14	25.3

IV. ANALYSIS OF RESULTS

A. Time analysis

When comparing the data of the conventional machining strategy and the trochoidal machining strategy with similar cutting parameters indicated in table IV, the real machining time of the trochoidal strategy is less than that of the conventional strategy.

In conventional machining strategy, test A1B1C1 presents a maximum machining time of 217 [s] and test A1B3C3 shows a minimum machining time of 208 [s]. Similarly, in the trochoidal machining strategy, test A2B1C1 presents a maximum time of 25 [s] and test A2B3C3 shows a minimum time of 14 s.

At the same cutting speed (B1=800 m/min), the percentage of machining time reduction increases while the cutting feed rate increases, it increases from 88.48% to 91.04%. In the same way (B2=900 m/min), the percentage increases from 89.20% up to 91.83 %, and soon.

Therefore, tests with the lowest cutting parameters show the lowest time reduction percentage of 88.48%. On the opposite side, tests with the highest cutting parameters show the highest time reduction percentage of 93.27%.

The trend of the graphs is decreasing for both strategies as can be seen in Figure 3.

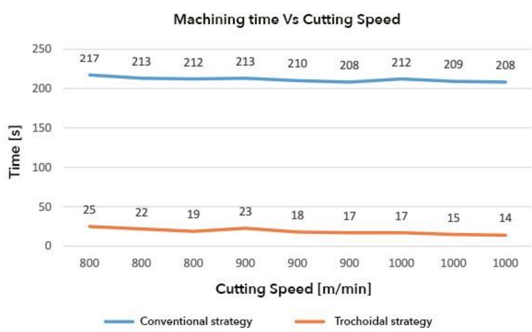

Figure 3. Machining time comparison between CMS and TMS

B. Temperature analysis

When comparing the temperature between machining strategies, in the trochoidal strategy it presents lower temperature values as can be seen in figure 4, which indicates a better heat distribution in the cutting tool, thus prolonging its useful life.

According to the proposed theory and the curves of Dr. Salomon, the value of the temperature decreases when increasing´ the cutting speed until it becomes constant, it is observed that for the value of the cutting speed 1000 [m / min] it is achieved that the temperature stabilizes at 25ºC, its decimal values being those that vary, in turn the wear on the tool is less and the cooling medium of the cutting tool is air in a heat transfer by convection, which does not Contaminates the aluminum chip making it suitable for recycling.

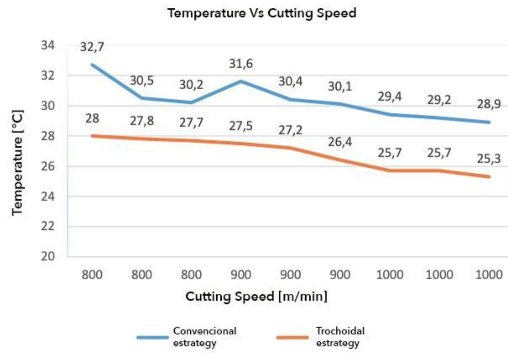

Figure 4. Machining temperature comparison between CMS and TMS

C. Taguchi analysis

The operating time and temperature of the cutting tool were analyzed using the Taguchi experimental method to determine the influence of each parameter (A=strategy, B=Vc, C=fz) in the machining process as indicated Table V

Respect to machining time, the least values are reached with the following conditions:

- Strategy trochoidal (A2) with 18.89
- Cutting speed 1000 m/min (B3) with 112.5
- Cutting feed per tooth 0.35 mm/tooth (C3) with 113

Respect to temperature, the least values are reached with the following conditions:

- Strategy trochoidal (A2) with 26.81
- Cutting speed speed 1000 m/min (B3) with 27.36
- Cutting feed per tooth 0.35 mm/tooth (C3) with 28.1

Table V
RESPONSE FOR THE MEANS OF OPERATION TIME

Level	Control Factors					
	Machining time [s]			Temperature [ºC]		
	A	B	C	A	B	C
1	211.33	118	117.83	30.33	29.48	29.15
2	18.89	114.83	114.5	26.81	28.86	28.46
3		112.5	113		27.36	28.1
Delta	192.44	5.5	4.83	3.52	2.12	1.05
Classification	1	2	3	1	2	3

D. ANOVA Method

The ANOVA statistical analysis, known as the analysis of variance, is used to determine the variability of the data, obtaining the level of confidence of the experimental data. Analysis of variance establishes whether the population means are the same or different and determines the interrelationships between all the factors using in the test design, in addition to calculating the degrees of freedom, the sum of squares, F test, variance [6].

Analysis of the results of ANOVA concerning machining time is shown in Table VI. It was performed, with a significance level of 5% and a confidence level of 95%, the control of the ANOVA methodology was done by comparing the values of F and P. According to table VI was defined whether there is a statistical difference in the results.

Table VI
TIME AND TEMPERATURE VARIANCE ANALYSIS

		Time				Temperature			
Source	DOF	S	V	F	P	S	V	F	P
A	1	1666657	1666657	14905.96	0.00	54.43	54.43	45.40	0.00
B	2	477203.33	119346.55	4.00	0.00	14723.14	7361.56	4.00	0.00
C	2	238657.11	119328.56	4.00	0.00	14701.51	7350.75	3.99	0.00
Error	16	179	-	-	-	19.18	-	-	-
Total	17	166836	-	-	-	73.61	-	-	-

Table VI defines the results of the analysis of variance of time with a statistical F 95% confidence, the main parameter that defines this experimentation, that is, FA (0.05: 1: 16) = 14905.96, for the cutting speed that we have FA (0.05: 2: 24) = **-** 4 and for the advance per tooth FA (0.05: 2: 24) = **-** 4, having a higher value in the strategy rejects the hypothesis that mentions that the means of the data are equal and accepts the alternative hypothesis that indicates that the mean of the data are different, obtaining an error less than the allowed F <0.05.

Table VI shows the summary of the analysis of variance of the temperature with an F with a 95% reliability for the strategy we have F (0.05: 1: 16) = 45.40, for the cutting speed and feed per tooth an F corresponding to 4, as these values are greater than those tabulated in the Fisher tables, which means that The null hypothesis that indicates that the data are equal is rejected and the alternative hypothesis is accepted where the means of the data are different, therefore the allowed error is less F <0.05, being reliable values that comply statistically.

E. Regression analysis time and temperature

Regression analysis is used for modeling and analysis that exists between one or more independent variables concerning the dependent variable. For this study, the independent variables are the machining strategy, the cutting speed (Vc) and the feed per tooth (fz). The prediction equations were obtained from the linear regression analysis as indicated in equations (5) and (6). The regression equation of time and temperature will serve to relate the response parameter, concerning the experimental model parameters [6].

$$Time[s] = 443.03 - 192444A - 0.02750B - 48.33C \quad (5)$$

$$Temperature[C] = 46.53 - 3.522A - 0.01085B - 10.50C \quad (6)$$

These mathematical models have an error below 5% which makes valid models for the design of roughing processes for both strategies.

We also have the confidence interval (CI) for both time and temperature that were obtained from the statistical analysis using software, which can be seen in tables VII and VIII.

Table VII
CONFIDENCE INTERVAL FOR THE TIME

Strategy	No. Test	Media	standard deviation	C.I.
Conventional	9	211.33	2.915	208.971 - 213.696
Trochoidal	9	18.89	3.72	16.53 - 21.25

Table VIII
CONFIDENCE INTERVAL FOR THE TEMPERATURE

Strategy	No. Test	Media	standard deviation	C.I.
Conventional	9	30.333	1.200	29.560 - 31.107
Trochoidal	9	26.856	0.979	26.082 - 27.629

V. CONCLUSIONS

It was determined that the trajectory with the shortest time is follow the periphery, being a parameter that influences the machining time, in which an operating time of the trochoidal machining strategy of 14 seconds is established with the A2B3C3 parameters, it presents an optimization of the time versus machining time of the conventional strategy that presents 208 seconds with A1B3C3 parameters, for a cutting speed of 1000 [m / min] and a time feed of 0.35 [mm / tooth], a reduction of 93.27% of the time, for a cutting speed of 700 [m / min] and a feed per tooth of 0.25 [mm / tooth] a reduction of 88.48% in time.

With the design of parameters using the Taguchi methodology, it is observed that for temperature the parameter with the greatest influence on cutting speed, determining a minimum temperature for conventional machining of 28.9ºC and a minimum temperature for trochoidal machining of 25.3ºC, this being a reduction of 12.46% between strategies.

In the process of the tests using the trochoidal and conventional machining strategy without the use of coolants that contaminate the chip, they present a good finish, without blunting the cutting tool in both cases, without leaving burrs in any of the test tubes of the experiment, there was a correct chip evacuation, stabilizing the temperature of the cutting tool at 25ºC

Optimization of the machining parameters of the Somta brand four lips 25 mm HSS cutting tool obtained in the Ecuadorian market was obtained, the manufacturer recommends a radial depth of 1.25 mm and an advance of 4800 mm / min. , using in this study a radial depth of 2.5 mm which is an increase of 50%, in addition to using a feed rate of 17825.4 [mm / min] which gives us an increase of 13025 [mm / min] being an increase of the 271.36%, there were no pitting or burns in the cutting tool during the tests, which prolongs the useful life of the tool.

With the statistical analysis of the data obtained in table 18 of temperature and machining time, with the Anova statistical analysis presented in table VI, values of F <0.05 are established, which shows that it is unlikely that the data is due to randomly, resulting in a reliable study, that is, it is likely to obtain the same or similar values when performing the experiment under the same study parameters.

By means of the regression equation 5 corresponding to the combination of parameters A2B2C2 for time, an error was obtained 4.94 % and with the corresponding regression equation 6 for the temperature a 3.38 %, being the two equations are a good mathematical approximation of machining design for both time and temperature.

Through experimentation with the Taguchi methodology, the optimal machining parameters were obtained, reducing the machining time and reaching a temperature stability of 25ºC in the cutting tool with the combination of the A2B3C3 parameters: trochoidal machining strategy with cutting speed of 1000 m / min, with an advance by tooth of 0.35 mm / tooth. With this machining configuration, the behavior of time and temperature is decreasing as shown in figures 3, as the curves of Dr. Salomón describes, that at a higher cutting speed the temperature drops until it stabilizes.

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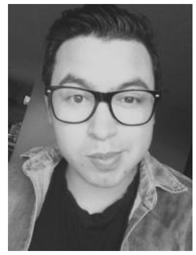

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