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Comparative study of Sustainability Metrics for Face Milling AISI 1045 in different Machining Centers

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Abstract

The objective of this study is to compare a set of sustainability metrics between different manufacturing resources applied to high performances machining centers. The research compares distributed scenarios in order to find the optimal conditions that allow the minimum consumed power and the minimum roughness when performing face milling operations of AISI 1045 steel. The set of experiments for the surface machining was carried out considering different path strategies in three main directions for two dimensional movements of the tool. The selected experiments considered the main axis movement, the perpendicular axis movement and a 45 degrees movement. Besides, it was considered the feed rate speed and the cutting depth. The design of experiments was developed with the Taguchi method considering an orthogonal matrix of L27 design type, and three levels of experimental design, and the analysis of variance and noise signal were performed. The methodology to determine the lowest power consumed and the best surface quality allowed to establish the working condition in the most sustainable machining. The results show how the cutting parameters influence in each manufacturing resource.

Keywords: Taguchi method; AISI 1045; Sustainability Metrics; Milling Operatios; Green Manufacturing.

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1. Introduction

The industrial need to evaluate the manufacturing operations, and processes, from the sustainability point of view requires determining the appropriate metrics for operations that can complement standard ones in order to characterize the influence of operation parameters. This will help us not only to correct strategies and to select the most suitable parameters for the part manufacturing but also to analyze the influence of different machines. In this work, a contribution is made comparing the results between two different sets of experiments at shop floor level considering sustainability perspectives such as economic, social and environmental dimensions

In the shop floor, decisions to allocate a production batch considering the three pillars of sustainability (economic, environmental and social) should be based on a comparison of indicators, which can help to make the best decision. Moreover, some indicators can vary from one machine to another and could drive us in the wrong decision unless the differences between stations are clearly defined. This characterization can be only achieved through a model with indicators and methodological experiments that supports the expected results. This paper shows a comparative study of sustainability indicators applied to milling operations including not only minimum quantity lubrication but also different machining strategies.

The evaluation models of machining processes have allowed the important results for the selection and optimization of the best cutting conditions, the performance of energy and materials, in the different stages of the life cycle (previous manufacture, manufacturing, use and subsequent use) energy consumption, machining costs, waste management, environmental impact and health and personal safety [1]. It is important to define the measurement method for each indicator and the factors of importance in the production process.

In the shop floor decisions to allocate a production batch, considering the three pillars of sustainability (economic, environmental and social) should be based on a comparison of indicators, which can help to make the best decision. Moreover, some indicators can vary from one machine to another and could drive us in the wrong decision unless the differences between stations are clearly defined [2]. In recent years, different frameworks and indicator systems have been proposed to evaluate sustainable manufacturing at the product, process and system levels [3].

Bhanot et al [4], propose a tentative list of parameters for the indicators for sustainability. In the economic dimension, it is suggested the following aggregate metrics: *Production Cost*, *Cutting Quality*, *Production Rate* and *Process Management*. In the same way, the tentative list of parameters for the environmental dimension are: *Water Intensity, Energy Intensity*, *Materials* and *Waste Management*. Finally, for the Environmental Regulations it is proposed: *Worker Health*, *Worker Safety*, *Labor Relations* and *Training and Education*.

In the literature, many works propose indicators that explain how to analyze the machining processes sustainability ([5], [6]). For the present study, two of these metrics are selected, power consumption and surface roughness, since at the workshop level they can be evaluated online and offline, respectively, for each machining condition.

For the input power, Zhang et al, show that the power consumed during machining operations is a non-constant value according to the strategy [7]. Besides, the measurement of the resulting surface roughness is an indicator of the cutting operation quality among many others factory level [8].

2. Experimental equipment and procedure

2.1. Experimental Resources.

For the present study, two different machining centers were used in order to analyze how different industrial setups affect the sustainability metrics of power consumption and surface roughness. The Gentiger GT16 machining center at Universitat Politècnica de València, (UPV) and the Deckel Maho 70V machining center at Universitat Jaume I (UJI) served as industrial workshop platforms.

- Machine #1: Machine center Gentiger GT 16B, travel (X/Y/Z, 1000 mm x 550 mm x 500 mm; total power 45 kVA; the spindle motor is 26 kW, 380 V/3PH ; rapid federate 30 m/min; spindle speed range 1 – 16000 rpm, spindle taper is BT-40. Control Siemens 840D.
- Machine #2: Machine center Deckel Maho DMC 70V; travel (X/Y/Z) 700 mm x 550 mm x 500 mm, total power 40 kVA; the spindle motor is 10/15 kW; rapid feedrate 50 m/min; spindle speed 15000 rpm; spindle taper is CAT 40; Control TNC 426 Heidenhain.

The experimental setup for measuring the consumed power used the device HT 9022 multimeter and the surface roughness was measurement using Mitutoyo SJ201 for the Machine #1and SJ210 for the Machine #2 (Fig. 1).

a) Machine #1 Gentiger GT 16B: HT9022 / SJ201 b) Machine #2 Deckel Maho DMC 70D: HT9022 /SJ 210

Fig. 1. Equipment for measuring power and roughness in each machining center.

2.2. Cutting tool and work piece material.

The machining operation cutting conditions for the specific raw material and cutting tool followed the recommendations of Mitsubishi Materials tool manufacturer. The Mitsubishi tool selected was the VPX300R 4004SA32SA with the insert LOGU1207080PNER-M (MP6120) of 40 mm diameter and number of inserts (z_c) 4 and the main cutting angle (K) of 90 ° (Fig 2).

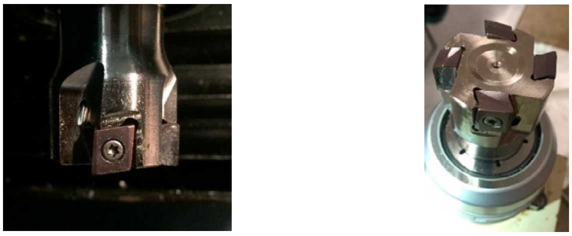

Fig. 2. Mitsubishi tool VPX300R 4004SA32SA with insert LOGU1207080PNER-M (MP6120)

The selected material was AISI 1045 with a raw prismatic stock of 205 mm length, 140 mm width and 36 mm height. The chemical composition of AISI 1045 is: Carbon 0.45 % max, Silicon 0.25 % max, Manganese 0.75 % max, Phosphorus 0.050 % max, Sulphur 0.050 % max. For the face milling, the machining directions used in the experimentation were: (a) 0° (X X), (b) 45° (X to Y) and (c) 90° (Y-Y) (Fig 3).

(a) (b) (c)

Fig. 3. Machining Directions (a) 0 ° (X-X); (b) 45° (X-Y) and (c) 90° (Y-Y).

As it can be seen from the figure, the measurements were carried out for each pass and direction and repeated in order to validate the experiments.

2.3. Experimental Parameters.

The strategy for generating the surface to be machined was performed using Inventor HSM CAD/CAM application and it was post-processed for the Siemens 840D controller of the Machine #1 and for the Heidenhain 426PB post-processor of the Machine #2. The levels of the cutting parameters were the cutting movement direction (main axis inclination in degrees p_d, °), the cutting depth (a_p, mm), the cutting speed (v_c, m/min) and the feed per tooth (f_z, mm/tooth). Considering the recommendations of the manufacturer of the Mitsubishi tool, it was programmed 27 cutting conditions (L27) according to Taguchi design of experiments methodology.

3. Taguchi Method - Experimental procedure

For the experimental process, the Taguchi method was applied in 5 stages: (1) Problem Formulation, (2) Design of experiments in the machining centers, (3) Data Analysis, (4) Determining the optimal levels of the factors and (5) Sustainable analysis.

3.1. Problem Formulation.

The analysis of sustainability in the machining process requires a thorough analysis of the process, for which the development of the material removal diagram from the life cycle perspective, will allow to identify the inputs, outputs, resources and indicators, which can be monitored. In the present study, consumed process energy and surface roughness are analyzed.

3.2. Design of Experiments in the machining centers.

An orthogonal array L27 is selected for the Taguchi method to be applied. Table 1 show the factors and their levels. Table 2 shows the orthogonal array with the factors and interactions assigned to columns. The experimental design consists of 27 trials, and the columns are assigned to the factors and their interactions.

Table 1. Factors and Levels.

	Factors	Units	Levels		
			1	2	3
A	Pass Direction p_d	°	0	45	90
B	Cutting depth a_p	mm	0.8	1.0	1.2
C	Cutting Speed v_c	m/min	140	180	210
D	Feed per tooth f_z	mm/tooth	0.08	0.10	0.12

3.3. Data Analysis

The following tables show the experimental results of the tests carried out, according to the experimental plan. The statistical analysis was performed using the Mathlab R15b software.

3.3.1. Anova

The purpose of ANOVA (Analysis of variance) in his study is to determine he significant process parameters and to measure their effects on the power consumption and the surface roughness. The pooled ANOVA results are given in Table 2 that shows the signal noise radio S/N analysis for the surface roughness in the Machine #1 and the Machine #2.

In the ANOVA, the ratio between the variance of the process parameter and the test error called as F test determines whether the parameter has a significant effect on the quality characteristic ([9], [10]). This process was carried out by comparing the F test value of the parameter with the standard F table value ($F_{0.05}$) at the 5% significance level, determining the optimal levels of the factors. If the F test value is greater than 0.05 the process parameter is considered significant, otherwise it is considered not relevant.

Table 2. Experimental results from distributed Machining centers. Mean Consumed Power and corresponding signal noise ratios (partial view).

					Machine #1				Machine #2			
					Power		Roughness		Power		Roughness	
Trial	A	B	C	D	P_{mean} kWh	S/N	S_{mean} μ_m	S/N	P_{mean} kWh	S/N	S_{mean} μ_m	S/N
1	0	0.8	140	0.08	3.3933	-10.613	0.71	2.880	4.8822	-13.77	2.81	-9.016
2	0	0.8	180	0.10	2.8289	-9.032	0.98	-0.172	5.0611	-14.08	1.97	-6.033
3	0	0.8	210	0.12	3.1744	-10.034	0.55	5.102	5.2556	-14.41	2.06	-6.356
4	0	1.0	140	0.10	2.8322	-9.043	1.48	-3.498	5.2022	-14.32	2.06	-6.273
5	0	1.0	180	0.12	3.2244	-10.169	1.02	-0.191	5.4100	-14.66	1.94	-5.827
6	0	1.0	210	0.08	3.1433	-9.948	0.60	3.806	5.1800	-14.29	1.54	-3.818
7	0	1.2	140	0.12	3.2189	-10.154	1.56	-3.983	5.5589	-14.90	1.96	-5.860
8	0	1.2	180	0.08	2.9989	-9.553	0.77	1.702	5.2367	-14.38	1.72	-4.735
9	0	1.2	210	0.10	3.5033	-10.890	0.72	2.719	5.4811	-14.78	1.42	-3.237
10	45	0.8	140	0.10	3.7244	-11.421	2.22	-6.938	5.0700	-14.10	2.91	-9.337
15	45	1.0	210	0.10	3.2467	-10.229	1.63	-4.272	5.3511	-14.57	1.47	-3.417
20	90	0.8	180	0.08	2.8656	-9.144	1.04	-0.419	7.5067	-17.51	1.64	-4.308
25	90	1.2	140	0.10	2.8033	-8.954	1.57	-3.980	7.6600	-17.68	2.86	-9.113
27	90	1.2	210	0.08	3.5933	-11.110	1.19	-1.567	7.6333	-17.66	1.20	-2.030

3.3.2. Signal Noise Ratio

Table 2 shows the Signal Noise ratio (S/N) analysis for the consumed power and roughness of the Gentiger machining center and for the Deckel Maho machining center respectively. For the power consumed, measurements were made in each pass. For surface roughness, a mapping was made on the machined surface and the average value was calculated. Equation 1 was used to calculate the S / N ratio

$$\frac{S}{N} = -10\,log\left[\frac{1}{n}\sum_{i=1}^{n} y_i^2\right] \tag{1}$$

3.3.3. Machine Analysis

Table 3 shows the results of the ANOVA for power consumption and surface roughness in both machines.

Table 3. ANOVA results for Power Consumption and Surface Roughness for both machines.

		Machine #1				Machine #2			
		Power		Roughness		Power		Roughness	
Source	D.F.	F	Prob>F	F	Prob>F	F	Prob>F	F	Prob>F
A	2	0.4760	0.6429	39.7342	0.0003	39.7342	0.0003	0.1487	0.8649
B	2	3.8298	0.0848	0.8924	0.4578	0.8924	0.4578	0.0481	0.9534
C	2	5.1518	0.0498	12.0893	0.0079	12.0893	0.0079	38.2880	0.0004
D	2	3.8687	0.0833	0.6125	0.5727	0.6125	0.5727	1.2388	0.3545
AxB	(4)	Pooled	-	Pooled	-	Pooled	-	Pooled	-
AxC	(4)	Pooled	-	Pooled	-	Pooled	-	Pooled	-
BxC	(4)	Pooled	-	Pooled	-	Pooled	-	Pooled	-
Error	6								
Total	26								

D.F. degree of freedom, F Prob> P. F, $F_{0.05,2.6} = 5.1433$, $F_{0.05,2.6} = 4.5337$

3.4. Determining the optimal levels of the factors

Figure 4 shows the optimal levels of the factors determined considering the ANOVA and the main effects for the power consumption in the Machine #1. Table 4 shows the response table where the values of the average Power Consumption for each level of the factors are given.

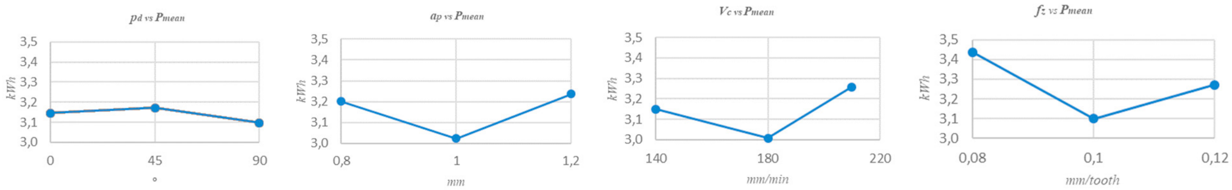

Fig 4. Main effect plot for Power Consumption. Machine #1.

Table 4. ANOVA Power Consumption Response for Machine #1.

Level	Pass Direction p_d °	Cutting depth a_p mm	Cutting Speed v_c m/min	Feed per tooth f_z mm/tooth
	A	B	C	D
1	3.1464	3.2016	3.1498	3.4374
2	3.1722	3.0221	3.0077	3.0984
3	3.0970	3.2364	3.2583	3.2710
Delta	0.0752	0.2143	0.2506	0.3390
Rank	4	2	3	1
P_{mean}	3.1386			

Figure 5 shows the levels of optimal factors are determined considering the ANOVA and the main effects, for the surface roughness in the Machine #1. Table 5 shows the response table where the values of the average surface roughness of the levels of the factors are given.

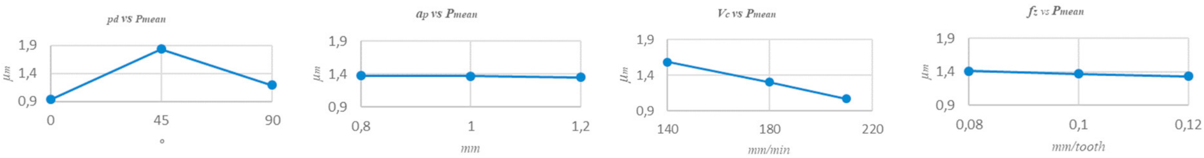

Fig 5. Main effect plot for Surface Roughness. Machine #1.

Table 5. ANOVA Surface Roughness Response for Machine #1.

Level	Pass Direction p_d °	Cutting depth a_p mm	Cutting Speed v_c m/min	Feed per tooth f_z mm/tooth
	A	B	C	D
1	0.9313	1.3750	1.5841	1.4158
2	1.8352	1.3670	1.3011	1.3737
3	1.1902	1.3507	1.0715	1.3379
Delta	0.9039	0.0243	0.5126	0.0779
Rank	1	4	2	3
R mean	1.3189			

Figure 6 shows the levels of optimal factors that are determined considering the ANOVA and the main effects for the surface roughness in the machine #2. This analysis comes from a response table where the values of the average power consumption for each level of each factor is given.

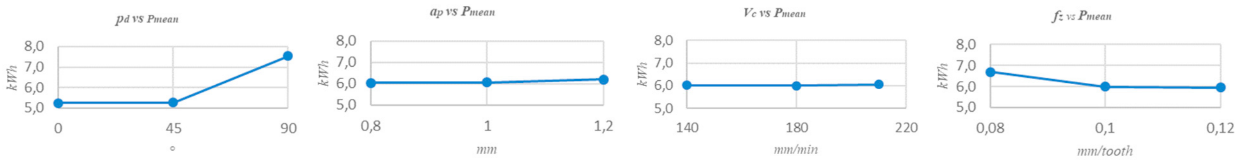

Fig 6. Main effect plot for Power Consumption. Machine #2.

From the response analysis in Figure 7 it is shown levels of optimal factors are determined considering the ANOVA and the main effects for the surface roughness in the machine #2.

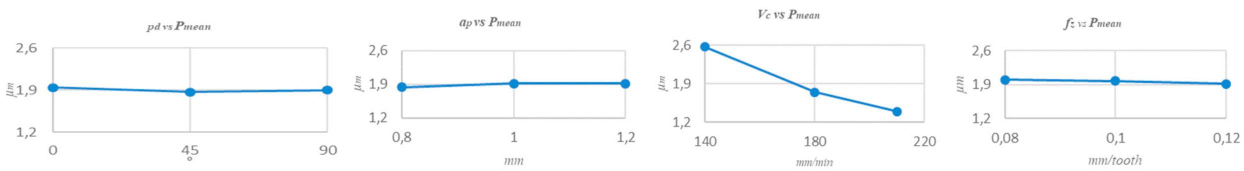

Fig 7. Main effect plot for Surface Roughness. Machine #2.

3.5. Sustainability Analysis.

Once the experimental analysis has been carried out, the results of our interest will define the parameters that will be obtained to obtain the lowest power consumed and the lowest roughness. As indicators of sustainability.

In a first analysis, to obtain the minimum values of consumed power, depending on the machining center where the experiments were carried out, it could be proposed an initial machining parameters values for sustainable operations. For the Machine #1, the minimum value of power consumption is 2.79 kWh and it is obtained with the following conditions: pass direction 90 °, cutting depth 1.0 mm; cutting speed 180 m/min; feed per tooth 0.1 mm/tooth.

On the other hand, for the Machine #2, the required cutting power consumption for minimum consumption in this operation is 4.88 kWh and it is obtained with the following cutting conditions: pass direction 0 °, cutting depth 0.8 mm, cutting speed 140 m/min and feed per tooth of 0.08 mm/tooth.

If we focus on the surface roughness, it can be noticed that, for the machine A, it is obtained a value of R_a=0.55 µm with the cutting conditions: Pass direction 0 °, cutting depth 0.8 mm, cutting speed 210 m/min; feed per tooth 0.12 mm/tooth. For the Machine #2, it is obtained a value of R_a=0.83 µm with the cutting conditions of pass direction 45 °, cutting depth 0.8 mm, cutting speed 210 m/min and feed per tooth of 0.08 mm/tooth.

The response table 6 summarize the conditions in which the minimum values of the parameters A B C D for each machining center are obtained.

Table 6. Proposed Parameters for sustainable machining operation in each machine.

Machine center	Index	Pass Direction p_d °	Cutting depth a_p mm	Cutting Speed v_c m/min	Feed per tooth f_z mm/tooth
		A	B	C	D
Machine #1	Min Power	90	1.0	180	0.10
	Min R_a	90	1.0	180	0.10
Machine #2	Min Power	0	1.2	220	0.12
	Min R_a	0	0.8	180	0.10

It is important to notice that the research monitored the tool wear after the 27 trials, and it was observed that the value was within the parameters by the international standard as expected form the parameters definition for the operation.

4. Conclusions

The present work has helped to validate that, although technical parameters for manufacturing cutting operations can be predefined, it is needed a customization process for each machine tool. For the same material removal operation, the same rough stock part material and the same cutting tool we have obtained different cutting parameters from the sustainability perspective.

For the machining center Machine #1, the ANOVA response to power consumption shows a significance (F) value of the cutting speed (v_c, factor C), while for the Machine #2 the significance depends on the pass direction (p_d, factor A), the cutting depth (a_p, factor B) and the feed per tooth (f_z, factor D)

For the ANOVA response to the surface roughness in Machine #1 shows a significance (F) value of pass direction (p_d) and the cutting speed (v_c) while for the Machine #2 the significance depends only on the cutting speed (v_c)

This means that for each machine, there are different optimization parameters. In almost all machinability studies depth of cut, cutting speed and feed rate are used as process parameters and they are the factors that can be taken as reference but there could be more in complex machining systems.

The validation of this study demonstrates that there could be another important influence in the result as, for example, the cutting trajectory direction or very little machine features differences. We believe that several considerations must be deeper analyzed about the attained results as they may influence in the transportability of them and may alter the expected results. Some of them could be:

- Machine Tool cooling system
- Part mooring device or tool holding system.
- Post processing procedure and CAM tool path generator.
- Machine Tool Total Productive Maintenance

Future work must be done ongoing this study that may vary the sequence of parameters within the design of experiments in order to see what the influence of them is and to determine the relationship among all of them. Besides some of the considerations must be progressively included in order to have a better knowledge the influence of all the parameters for most accurate future simulations.

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