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ORIGINAL ARTICLE

Sustainable machining as a mean of reducing the environmental impacts related to the energy consumption of the machine tool: a case study of AISI 1045 steel machining

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Abstract

Due to the rising concerns related to the depletion of fossil fuel sources, and the climate change associated to the usage of such sources for electricity generation, there is a high pressure for diminishing the energy consumption of all the industrial sectors in order to mitigate the negative impacts associated to the energy required to manufacture a product. Computer numerical control (CNC) machining accounts for a larger portion of the total energy drawn from the grid by the manufacturing sector. Therefore, the energy efficiency of the manufacturing operations should be enhanced to optimize their energy consumption and to reduce their environmental burden as well. As a mean for achieving sustainable manufacturing operations, the present paper outlines an experimental study to optimize cutting parameters in turning of AISI 1045 steel. One of the main objectives was to minimize the total specific energy consumed by the CNC machine tool during material removal, considering dry cutting to decrease the environmental impacts linked to the coolant usage. As a measure of the surface quality, the second objective was to reduce the average surface roughness of the workpiece. The same material removal volume was considered for all the experimental trials. The response surface method was used to obtain the regression models for all the variables studied, and the desirability method was selected for defining the values of these variables, named the cutting parameters, that minimized the quantity of electrical energy consumed, and surface roughness. The results achieved showed that it is possible to obtain a more sustainable machining process without sacrificing the productivity of the process and the final quality of the product.

Keywords Energy consumption reduction · Turning · Sustainable manufacturing · Response surface method

Nomenclature

CNC	Computer numerical control
AISI	American Iron and Steel Institute
RSM	Response surface method
CCD	Central composite design
ANOVA	Analysis of variance
n_f	Factorial runs of the central composite design
n_c	Center runs of the central composite design
α'	Distance of the axial runs to the center of the central composite design
Z_i	Real value of the factor to be studied
x_i	Coded value of the factor to be studied
Z_H	Real value equivalent to 1 in coded variables
Z_L	Real value equivalent to − 1 in coded variables
RPM	Revolution per minute
NI	National instruments
NC	Numerical control
Ra	Average value of surface roughness
MRV	Material removed volume
E	Total energy consumed by the CNC machine tool
MRR	Material removal rate
SE	Total specific energy consumed by the CNC machine tool
SR	Surface roughness
α	Confidence level of the ANOVA analysis performed
ISO	International Organization for Standardization

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1 Introduction

An increasing environmental awareness, along with the rising prices of electricity, is one of the main factors that have urged for a better understanding of the energy consumption during computer numerical control (CNC) machining processes. Balogun and Mativenga [1] reported that the carbon footprint of a product is associated with the energy required to produce it. Therefore, the science of manufacturing should find strategies that can be employed to reduce the environmental impact of the products by optimizing the manufacturing parameters or by selecting different technologies and materials for such products [2].

Machine tools consume large amounts of electrical power. As stated by Li et al. [3], more than 99% of the environmental impacts related to the machine tools used for milling and turning operations are due to their energy consumption. Also, the amount of carbon dioxide emitted in producing the electrical energy required for the machine tool contributes to global warming and it represents a large environmental burden [4, 5]. The reduction of the energy consumed by the industrial sector is a measure that must be considered along with the traditional measures named cost, processing time, and quality. The manufacturing sector accounts for over 30% of global CO_2 emissions and energy consumption. Moreover, this trend is rising in several countries considered as emerging economies, mainly China, India, and Brazil [6].

Table 2 Chemical composition of AISI 1045 steel

Element	Alloying %
Carbon (C)	0.312
Silicon (Si)	0.189
Manganese (Mn)	0.852
Chromium (Cr)	0.025
Molybdenum (Mo)	0.033
Titanium (Ti)	0.005
Vanadium (V)	0.004
Tungsten (W)	0.033
Phosphorous (P)	0.039
Sulfur (S)	0.011
Copper (Cu)	0.031
Aluminum (Al)	0.037
Iron	Remainder

Energy consumption modeling and optimization has been gaining more attention in all industries, especially the ones with energy-intensive processes [7]. It is very important to investigate the material removal energy, due to the fact that it is related to the generation of a new surface, and it is also responsible for the quality of the machined part [8]. Although several studies [9, 10] indicated that the energy spent during machining is a small part of the total energy needed by the CNC machine tool, Apostolos et al. [11] pointed out that the study of the process is interesting because it provides a deeper

Table 1 Central composite design test plan

Run	Coded values			Real values		
	a_p (mm)	f (mm/rev)	v_c (m/min)	a_p (mm)	f (mm/rev)	v_c (m/min)
1	− 1	− 1	− 1	1.00	0.20	375
2	1	− 1	− 1	2.00	0.20	375
3	− 1	1	− 1	1.00	0.25	375
4	1	1	− 1	2.00	0.25	375
5	− 1	− 1	1	1.00	0.20	400
6	1	− 1	1	2.00	0.20	400
7	− 1	1	1	1.00	0.25	400
8	1	1	1	2.00	0.25	400
9	− 1.68	0	0	0.66	0.23	388
10	1.68	0	0	2.34	0.23	388
11	0	1.68	0	1.50	0.18	388
12	0	1.68	0	1.50	0.27	388
13	0	0	− 1.68	1.50	0.23	366
14	0	0	1.68	1.50	0.23	409
15	0	0	0	1.50	0.23	388
16	0	0	0	1.50	0.23	388
17	0	0	0	1.50	0.23	388
18	0	0	0	1.50	0.23	388
19	0	0	0	1.50	0.23	388
20	0	0	0	1.50	0.23	388

Table 3 Cutting tool specifications

Tool manufacturer	Sandvik Coromant
Tool ID	DCMT11T308-PM 4235
Depth of cut (ap)	0.6–3.2 mm
Feed rate (*f*)	0.1–0.3 mm/rev
Cutting speed (vc)	355–470 m/min
Indexable insert form	D
Tool clearance	7°
Corner radius	0.794 mm
Cutting material	Tungsten carbide with CVD coating (MT-Ti(C,N) + Al_2O_3 + TiN)

understanding of the energy transformations that occur during the machining process.

The electrical energy demanded by the CNC machine varies with respect to the process to be executed and to its operational state. As a consequence, it is fundamental to explore options to optimize this consumption and provide insights to CNC machining practitioners to raise the efficiency of this process [12]. An appropriate selection of process parameters leads to a reduction of the energy spent by the machine peripherals that are greater consumers of energy, like the coolant pump needed to deliver the cutting fluid to the cutting zone during machining [11].

Recently, several researchers have been investigating the effect of cutting parameters on the cutting power consumed by the machine tool and the surface roughness of the workpiece during turning, using different methods as tools for optimization. Bhattacharya et al. [13] investigated the effects that the cutting parameters have on surface roughness and power consumption in turning of American Iron and Steel Institute (AISI) 1045 steel. Taguchi method was used to obtain the levels of each control factor that optimized the machining process. The aim of the work reported by Fratila and Caizar [14] was to minimize the cutting power and the surface roughness during milling of $AlMg_3$. Mativenga and Rajemi [15] aimed to determine the minimum footprint and maximum tool life during turning of AISI 1040 steel. For both works, optimization of the cutting parameters was performed using Taguchi methodology.

Table 4 Experimental equipment employed

Variable to be measured	Measurement equipment used
Current	Current transformer CR8350–2000 from CR Magnetics
Voltage	Voltage probes from Fluke
Power	Data acquisition card NI USB-6211 from National Instruments
Surface roughness	Roughness tester SJ-201 from Mitutoyo

Table 5 Cutting parameters and their levels, according to the CCD

Levels (coded variables)	Factors		
	a_p (mm)	f (mm/rev)	v_c (m/min)
− 1.68	0.66	0.18	366
− 1	1.00	0.20	375
0	1.50	0.23	388
1	2.00	0.25	400
1.68	2.34	0.27	409

Asiltürk and Neseli [16] employed the response surface method (RSM) in order to model the surface roughness related to the turning of AISI 304 austenitic stainless steel under dry conditions. The impact of the cutting parameters on surface quality was estimated. Hanafi et al. [17] reduced the power consumption and surface roughness in steel machining by applying the Taguchi method.

Brushan [18] used the response surface method to determine the influence of cutting parameters on the power consumed and tool life during turning of 7075 Al alloy SiC composite. The aim of the work of Yan and Li [19] was to identify the optimal milling parameters during milling of steel. The authors employed a multi-objective optimization in order to reduce the surface roughness and the energy consumption. Campatelli et al. [20] optimized the cutting parameters in the milling of AISI 1050 steel applying the response surface methodology. The objective was to minimize the energy consumed during the material removal process. Priarone et al. [21] worked on a model for the system-level energy analysis of the machining process in turning of a titanium alloy under various lubrication strategies.

The authors [22] optimized the cutting parameters regarding turning of AISI 1018 steel at a constant material removal rate, in order to minimize the energy consumed by the machine tool. Robust design was used to determine the effects of the cutting parameters on the response variable, considering two sources of noise. In the work of Bilga et al. [23], cutting parameters were studied using an orthogonal array in order to define their relationship with the energy consumption of the machine. Wang et al. [24] focused on the specific cutting energy required during high speed cutting of 7050-T7451 aluminum alloy.

Jia et al. [25] worked on a novel Therblig-embedded value stream mapping method to improve the energy transparency and reduce the energy waste in turning operations. Lv et al. [26] investigated the prediction accuracy of the material removal power in turning processes for turning of carbon steel, aluminum, and ductile iron.

Turning is a manufacturing process widely employed. The works mentioned above presented the optimization of cutting parameters with regard to the cutting energy consumed and the surface roughness in turning and milling of steel, aluminum, and titanium. Nevertheless, the optimization of cutting parameters should be conducted taking into account the surface quality and the total energy consumed by the machine, not only the portion required to remove the material but the necessary energy for running the auxiliary systems required to perform the cutting operation.

In the present work, cutting parameters (cutting speed, depth of cut, and feed rate) were optimized in order to minimize energy consumption and surface roughness during turning of AISI 1045 steel. Optimum values of cutting parameters have been found out by a central composite design (CCD), ANOVA and desirability analysis. The results have been modeled employing the response surface method.

The research objectives can be divided into the following specific objectives: the first one is to study the effect that the cutting parameters have on the electrical energy consumed by the CNC machine tool and on the surface roughness obtained. The second objective is to reduce this energy consumption of the machine tool without worsening the quality of the surface.

As previously mentioned, according to the operational state of the machine tool, its components spend different amounts of electrical energy. The energy needed for roughing is higher than the energy required for finishing. An example is the main spindle drive, which spends a greater amount of energy in roughing due to the greater quantity of material to be removed from the workpiece [27].

Moreover, the absence of cutting fluids during machining helps to diminish the environmental burden associated with their usage. According to Weinert et al. [28], the cost related to the usage of cutting fluids is about of 7 to 17% of the total cost of the manufactured product, depending on the type of piece

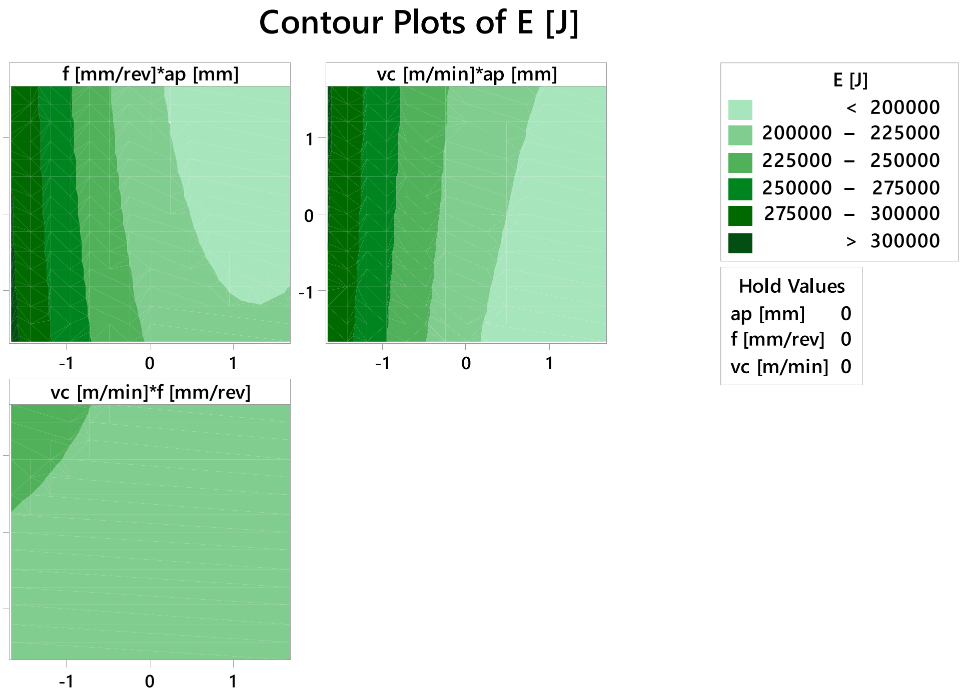
Table 7 Coded coefficients of the regression model for the response variables

Term	Coefficients			
	E	MRR	SE	SR
Constant	213,120	2232.11	6.089	2.377
a_p	− 55,177	1232.5	− 1.576	0.049
f	− 8611	419.1	− 0.246	0.624
v_c	6237	120.4	0.178	0.005
$a_p \times a_p$	33,984	− 19.8	0.971	− 0.307
$f \times \mathrm{f}$	1197	− 68.3	0.034	− 0.177
$v_c \times v_c$	− 1398	− 22.7	− 0.040	− 0.162
$a_p \times f$	− 4880	227.8	− 0.139	0.268
$a_p \times v_c$	3131	66.2	0.089	− 0.353
$\mathrm{f} \times v_c$	− 7791	22.1	− 0.223	0.282

Table 6 Results of the tests carried out

Experiment	Cycle time (s)	Energy (J)	MRR (mm^3/s)	SE (J/mm^3)	SR (μm)
1	29.46	251,263.88	1250.00	7.18	1.77
2	14.98	192,345.82	2500.00	5.50	1.84
3	29.36	255,558.67	1562.50	7.30	1.96
4	12.79	184,042.54	3125.00	5.26	2.76
5	27.95	263,793.11	1333.33	7.54	1.71
6	14.47	203,630.03	2666.67	5.82	1.63
7	23.55	251,363.87	1666.67	7.18	2.65
8	12.29	189,966.44	3333.33	5.43	2.60
9	38.12	307,030.81	981.64	8.77	2.22
10	12.07	190,278.11	3480.36	5.44	2.02
11	21.08	227,724.55	1746.00	6.51	1.64
12	15.51	204,010.50	2619.00	5.83	2.86
13	18.15	205,796.95	2104.50	5.88	2.33
14	16.77	220,747.19	2351.75	6.31	2.20
15	17.37	211,363.63	2231.00	6.04	2.37
16	17.39	212,322.34	2231.00	6.07	2.38
17	17.47	209,174.17	2231.00	5.98	2.41
18	17.37	213,031.96	2231.00	6.09	2.36
19	17.47	218,568.76	2231.00	6.24	2.37
20	17.36	213,707.81	2231.00	6.11	2.36

Fig. 1 Contour plots of total energy consumed



to be produced, the structure, and the location of the facility that manufactures it.

Due to the good accessibility of the cutting zone, the turning operations are excellent candidates for applying the dry machining strategy [29]. In turning and milling of steel or cast iron, the use of cutting fluids can be omitted owing to the great capacity of the cutting tools with regard to their thermal resistance provided by the coatings applied to them. Nayak et al. [30], Bhattacharya et al. [13], Carou et al. [31], Sharma et al. [32], Patil et al. [33], and Qehaja et al. [34] showed the feasibility of dry machining during cutting of different types of material, such as austenitic stainless steel, AISI 1045 steel, magnesium alloy, AISI D2 steel, Inconel 718, and cold rolled steel C62D.

Fig. 2 Contour plots of material removal rate

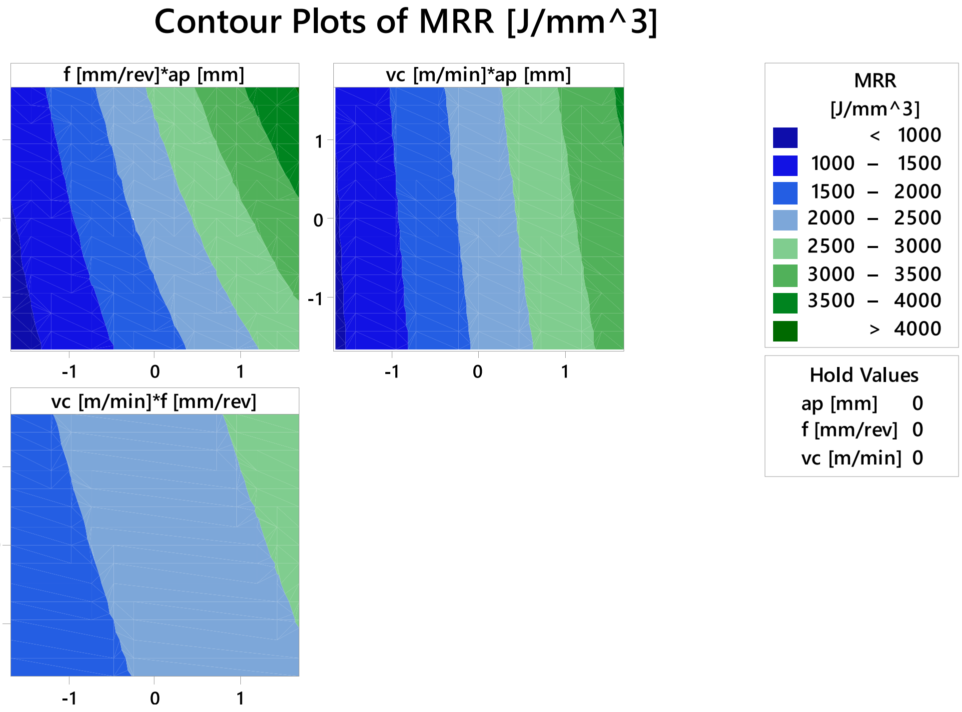
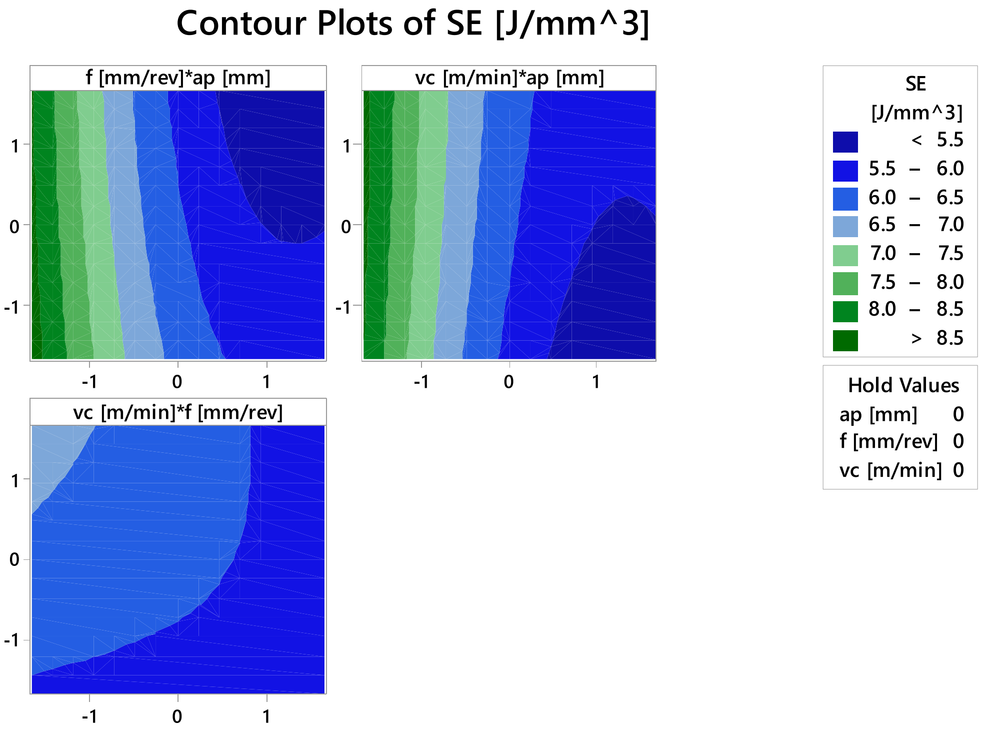


Fig. 3 Contour plots of total specific energy



Therefore, in order to enhance the energy efficiency of the manufacturing process, all the experimental trials were carried out without any cutting fluid (dry machining). A constant volume of material removed from the workpiece was considered in roughing machining. The results showed that it is feasible to obtain a balance between sustainability and good surface quality.

2 Response surface method

Several works presented in the previous section employed the response surface method for optimizing the cutting parameters and finding out the values that minimized the response variables, mainly cutting energy and surface roughness.

Fig. 4 Contour plots of surface roughness

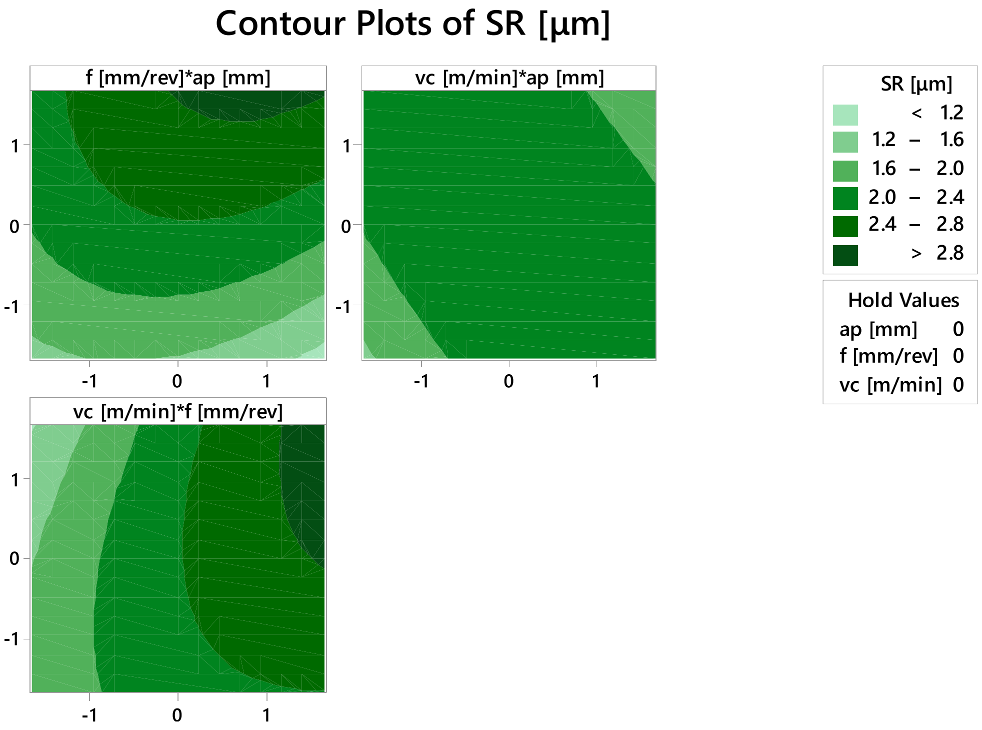


Table 8 ANOVA—total energy consumed

Factor	DoF	SS	MS	F	P value
Regression model	9	17,488,721,232	1,943,191,248	117.37	0.000
Error	10	165,557,160	16,555,716		
Total	19	17,654,278,392			
$S = 4068.87$		$R^2 = 99.06\%$		R^2 (adj) = 98.22%	

The response surface method comprises mathematical and statistical techniques that are used for solving problems when different variables have an impact on one response of interest and the goal is to optimize it [35].

Gaitonde et al. [36] evaluated the effects of depth of cut and machining time employing the RSM. Asiltürk and Neseli [16] used the RSM to obtain a model that described the surface roughness behavior. Yan and Li [19] optimized the milling parameters in machining of steel, and Brushan [18] minimized the power consumption by considering the response surface method. Sahu and Andhare [37] employed the RSM for improving the machinability of Ti–6Al–4V, Saravanakumar et al. [38] found optimum parameters (feed rate, cutting speed, and depth of cut) during machining of aluminum alloy 6063. Nataraj et al. [39] used the RSM for showing the influence of cutting parameters while machining aluminum alloy LM6 reinforced with Al_2O_3.

The RSM reduces the overall number of experimental trials needed. Therefore, it saves cost and time regarding testing. Moreover, this method enables the estimation of the optimum levels of each factor in a more accurate fashion. It is recommended to select a second-order model when it is necessary to obtain the optimum value of a response. These type of models incorporate curvature to approximate the response.

Regarding the response surface method, there are several second-order RSM designs. The central composite design (CCD) is one of the most widely used. Generally, it consists of a 2^k factorial with n_f factorial runs, 2^k axial runs, and n_c center runs. For a CCD, it is important to define two key parameters: α', which is the distance of the axial runs to the center of the design, and the number of center runs to be considered, named n_c. The value of α' is selected to provide rotatability of the design and it is calculated considering the number of points in the factorial portion of the design (n_f), as shown in Eq. 1.

$$\alpha' = \left(n_f\right)^{1/4} \tag{1}$$

Rotatability means that the second-order model should be able to provide good predictions across the region of interest, and the variance of the response at some point is the same for all the points that have the same distance to the center of the design [40]. In addition to this, the CCD design should include center runs to allow a stable variance of the response. It is recommended to add from three to six center runs and normalize the data using coded variables to conserve the quality of the model. Generally, the values of the coded values are in the range − 1 to 1. Equation (2) is used to transform the coded values into the real ones, where Z_i is the real value, x_i is the value in coded variables, Z_H corresponds to the real value equivalent to 1 in coded variables, and Z_L is the real value equivalent to − 1 in coded variables.

$$Z_i = \frac{x_i(Z_H - Z_L) + (Z_H + Z_L)}{2} \tag{2}$$

3 Experimental procedure

The control of the cutting parameters and the knowledge of the cutting process help to improve the quality of machined parts and to reduce costs [41]. The tool geometry, tool material, and cutting parameters affect the quality and characteristics of turned parts. These parameters are related to the workpiece material and to the machine tool to be used.

The experimental trials presented in Table 1 were performed using 150-mm length AISI 1045 steel cylindrical billets ($L/D = 4$), with the chemical composition described in Table 2. The cutting length was equal to 50 mm, and the bars were machined using a 10 hp. HAAS SL10 lathe with a

Table 9 ANOVA—material removal rate

Factor	DoF	SS	MS	F	P value
Regression model	9	8,329,475	925,497	1658.96	0.000
Error	10	5579	558		
Total	19	8,335,053			
$S = 23.6195$		$R^2 = 99.93\%$		R^2 (adj) = 99.87%	

Table 10 ANOVA—total specific energy

Factor	DoF	SS	MS	F	P value
Regression model	9	14.2765	1.5863	117.37	0.000
Error	10	0.1351	0.0135		
Total	19	14.4117			
$S = 0.116253$		$R^2 = 99.06\%$		R^2 (adj) = 98.22%	

Table 11 ANOVA–surface roughness

Factor	DoF	SS	MS	F	P value
Regression model	9	2.4072	0.26747	14.80	0.000
Error	10	0.18072	0.01807		
Total	19	2.58792			
$S = 0.134432$		$R^2 = 93.02\%$		R^2 (adj) = 86.73%	

maximum spindle speed of 6000 RPM. The cutting tool selected to machine the workpiece was a carbide insert manufactured by Sandvik [42] (Table 3). The cutting condition for all the trials was dry machining. The current and voltage drawn from the grid during machining were measured using current transformers and a circuit that reduces 1000 times the voltage from the grid. These signals were acquired by a data acquisition card (NI USB-6211) [43]. The values of voltage and current were computed through a LabVIEW [44] interface each 0.1 s from the main switch of the lathe, three times for each experimental trial of the CCD design matrix (Table 1). Finally, the average energy consumed was obtained by multiplying the average power consumed times the cycle time.

For each experimental trial, the data acquisition initiated with the machine in the idle state. Then, the numerical control (NC) program was executed, and when the spindle returned to the idle condition once the program was over, data acquisition was stopped. The surface quality obtained after each trial was quantified measuring the Ra roughness of the surface, that is the average value of surface roughness. This measurement was performed using an SJ-201 Mitutoyo roughness tester, and the Ra roughness values were recorded three times per each machined surface. Table 4 shows the experimental equipment described above.

As mentioned in the Introduction section, for all the experimental trials carried out, the material removed volume (MRV) was set to a specific value. In this work, that value was equal to 35,000 mm^3. The cutting parameters chosen were depth of cut (a_p, mm); feed rate (f, mm/rev); and cutting speed (v_c, m/min), and their levels are presented in Table 5. The decoded values of the cutting parameters were obtained using Eq. (2). The CCD (Table 1) consisted of a 2^3 factorial design with eight factorial points, six axial points, and six central points. Therefore, the value of α' according to Eq. (1) is 1.68 in coded variables.

4 Results and data analysis

The results obtained from all the experimental runs performed are presented in Table 6. Cycle time for each trial and four response variables are shown. The first response variable is the total energy consumed by the machine tool during turning (denoted by letter E). The second variable is the material removal rate (MRR) that indicates the quantity of material removed in the cutting operation per second. The total specific energy (SE) is the third response variable, and it is linked to the energy needed to remove 1 mm^3 of material. Finally, the surface roughness (SR) is the variable that quantifies the quality of the piece, and it is expressed as the arithmetic average of the absolute values of the roughness profile.

The regression models for the response variables (E, MRR, SE, and SR) were obtained using the software Minitab v18. Table 7 shows the coefficients corresponding to the model for each one of the response variables being studied. These coefficients are related to the coded values of the cutting parameters; Figs. 1, 2, 3, and 4 present a graphical representation of the models.

According to the graphs shown in Fig. 1, the values of feed rate and depth of cut must be at their highest levels in order to decrease the value of the energy consumed by the machine tool, and the cutting speed must be at its lowest level. The time required to remove the material from the workpiece is lower when the value of the feed rate is high. Therefore, if the cycle time is reduced, the quantity of energy needed to produce the piece is reduced as well. These findings are consistent with the ones stated by Li et al. [12], Brushan et al. [18], Bilga et al. [23], and Camposeco-Negrete [45].

For the material removal rate, it is increased when the values of the cutting parameters are also increased (Fig. 2). The MRR is linked to the specific energy; as a consequence, the levels of the cutting parameters that increment the volume of material evacuated from the workpiece match to the ones required to reduce the energy consumption during turning as

Table 12 Constraints employed for the multi-objective optimization

Parameter	Constraint	Lower limit	Upper limit	Weight	Importance
a_p [mm]	In range	0.66	2.34	1	1
f [mm/rev]	In range	0.18	0.27	1	1
v_c [m/min]	In range	366	409	1	1
SE [J/mm3]	Minimize	4.45	8.48	1	1
SR [μm]	Minimize	1.54	3.05	1	1

Table 13 Desirability solutions

Solution	a_p (mm)	f (mm/rev)	v_c (m/min)	SE (J/mm^3)	SR (μm)	Desirability
1	2.22	0.18	366	5.32	1.62	0.99
2	2.13	0.19	382	5.62	1.65	0.93
3	1.41	0.18	366	6.08	1.67	0.85
4	1.30	0.18	366	6.33	1.64	0.82
5	1.50	0.20	366	5.89	1.99	0.75

presented in Fig. 3. This conclusion was also stated by Yan and Li [19] and Chabbi et al. [46].

In order to increase the surface quality, it is necessary to achieve a lower value of surface roughness. The minimum level of feed rate reduced the value of Ra, according to the graphs shown in Fig. 4. These findings are consistent to the results of the works published by Bhattacharya et al. [13], Asiltürk and Neseli [16], Hanafi et al. [17], Saravanakumar et al. [38], and Nataraj et al. [39].

The significance of the regression models was verified using the analysis of variance (ANOVA) and F test. They were carried out for a significance level of $\alpha = 0.05$ (confidence level of 95%). A summary of ANOVA results for each of the regression models is presented in Tables 8, 9, 10, and 11. According to the results shown in these tables, the values of R^2 and R^2 adj are higher than 90%, or very close to this value. Therefore, the models obtained for each one of the response variables can be used for predicting the value of these responses.

4.1 Desirability analysis for enhancing sustainability and economic performance of CNC turning

As previously discussed, it is fundamental to find out a balance between sustainability and economic metrics related to CNC machining. As stated in the results obtained, the levels of the cutting parameters that minimize the quantity of energy required to machine the workpiece are not the same as the ones needed for improving the surface quality.

Consequently, the desirability approach was employed for determining the values of the cutting parameters that optimize the energy consumption and the surface roughness. This optimization was carried out using Minitab software. This approach has been employed when optimizing machining process, as shown in Brushan [18], Chabbi et al. [46], Sengottuvel et al. [47], Sharma and Balwinde [32], Elbah et al. [48], and Tank et al. [49].

The specific energy and the surface roughness were the two response variables optimized by means of the desirability analysis. The former was selected due to the fact that the specific energy is related to the total energy drawn from the grid to machine the workpiece; the higher the energy consumption, the greater the environmental burden. The latter is used to quantify the quality of the final product and it is one of the economic metrics of the CNC machining. The constraints employed in the multi-response optimization are shown in Table 12. In Table 13, the results obtained from this optimization analysis are presented. Solutions with desirability values close to 1 are the best options. Owing to that, the levels of the cutting parameters provided by the solution 1 were chosen. Furthermore, this solution predicted the smallest values of specific energy and surface roughness among all the solutions obtained.

With regard to the machining processes, when one response is enhanced, another one could get worse. Solution 1 in Table 13 showed the lowest value of surface roughness. Nevertheless, the value of specific energy corresponding to this solution is not the lowest one. Both variables are equally relevant and should be taken into account when optimizing machining operations. This is the purpose of the desirability

Table 14 Standardized procedure for measuring the electrical energy consumption of the CNC machine tool

#	Component	Operation	Time (min)
1	Power meter	Start recording	00:00
2	Main switch	On	00:30
3	Panel	On	01:30
4	Door	Open/close	03:00
5	Standby (idle) power		03:30
6	Coolant pump	On	06:30
7	Coolant pump	Off	09:30
8	Panel	Off	10:00
9	Main switch	Off	10:30
10	Power meter	Stop recording	11:00

Table 15 Energy saving due to the usage of the dry machining strategy in turning

Case	Cycle time (s)	Energy (J)	SE (J/mm^3)
Case 1—no cutting fluids	15.01	189,383.25	5.32
Case 2—cutting fluids used	15.01	193,885.76	5.53
% Energy savings	4.13		

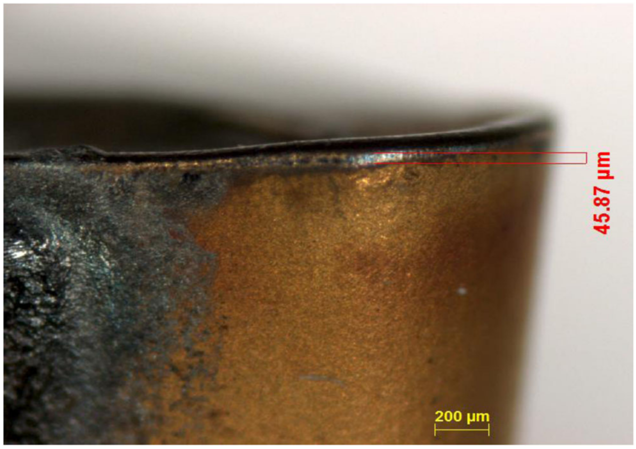


Fig. 5 Width of the flank wear after 1 min of continuous machining

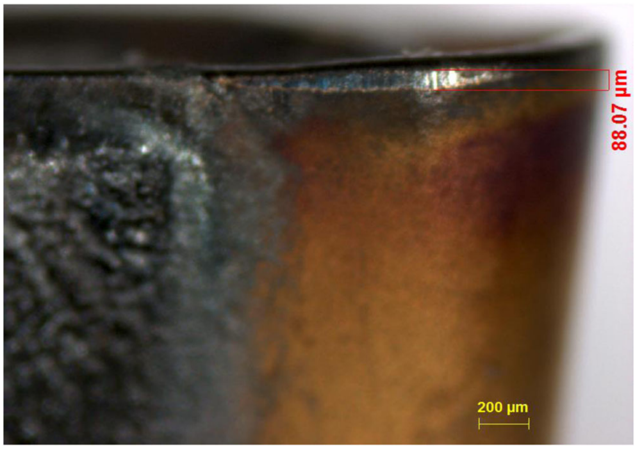


Fig. 7 Width of the flank wear after 3 min of continuous machining

analysis, to determine the tradeoff between sustainability and economics of the process.

As mentioned in Section 1, dry machining was selected for all the experimental trials in order to minimize the environmental impacts related to the usage of cutting fluids and the energy consumption associated to the coolant pump. To determine the energy savings related to the dry machining strategy, the methodology proposed by Behrendt et al. [50] was implemented to quantify the power consumed by the coolant pump when it is activated. This methodology established that the data acquisition should start before the CNC machine tool was turned on. Once the machine tool was powered, and it was in a stable (idle) state, the coolant pump was turned on for 3 min. Then, it was turned off, and 30 s later, the machine tool was also turned off. This process was repeated five times, and the average power consumption of the coolant pump was equal to 300 W. Table 14 summarizes the steps previously described.

Considering the cutting parameters proposed by solution 1 of the desirability analysis and the cycle time needed for machining the workpiece using this set of parameters, the energy consumed by the coolant pump was equal to 4502.50 J. Adding this value to the total energy consumed by the CNC machine tool during cutting and obtaining the specific energy required for removing the volume of material selected (35,000 mm^3), there was an energy saving of 4.13% when the coolant pump is not activated. Table 15 shows the data used for this analysis.

Referring to the tool life obtained during machining of AISI 1045 under dry machining conditions, a study was executed according to the International Organization for Standardization (ISO) 3685:1993 standard to test the cutting tool under the cutting parameters dictated by the desirability analysis. The characteristics of the steel bars, the cutting tool, and the CNC machine tool employed for this study were the same as the ones described in Section 3.

The tool life criterion was set to a maximum width of the flank wear land of 0.3 mm located at the tip of the cutting tool. A Zeiss stereomicroscope, model Stemi 200-C, and the AxioVision software were used for measuring the cutting tool wear when 1 min of continuous material removal had elapsed since the beginning of the test. This wear was measured every

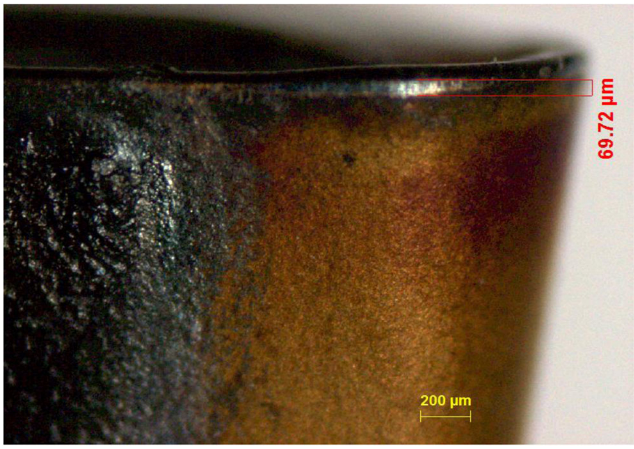


Fig. 6 Width of the flank wear after 2 min of continuous machining

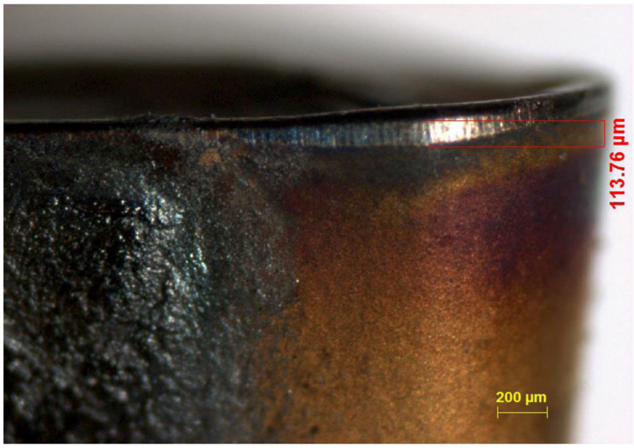


Fig. 8 Width of the flank wear after 4 min of continuous machining

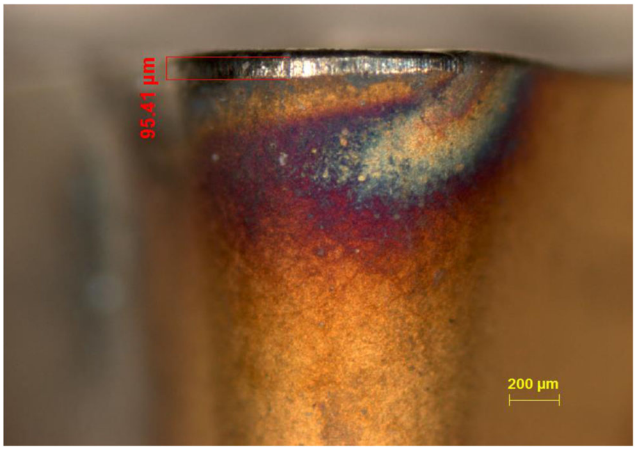


Fig. 9 Width of the flank wear after 5 min of continuous machining

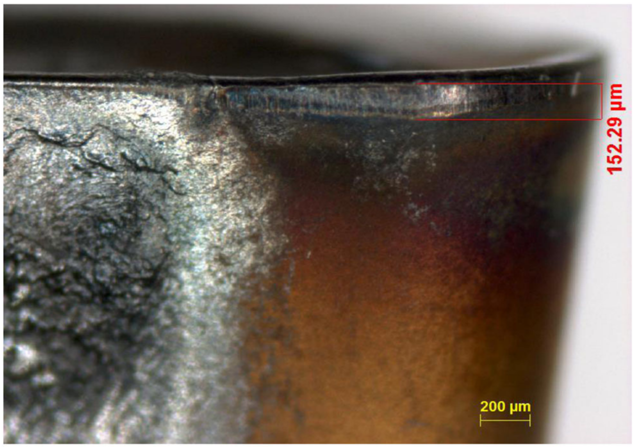


Fig. 11 Width of the flank wear after 7 min of continuous machining

minute until the tool life criterion was reached. Figures 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, and 19 present the images of the tool wear using the ×5 zoom, and Fig. 20 shows a graph about the cutting time and flank wear. In minute 15, the flank wear was 396.32 µm. Therefore, the cutting tool had a proper life, equal to the one that could be obtained when the cutting parameters recommended by the cutting tool's manufacturer were used in turning [51].

4.2 Comparative analysis

Generally, the cutting parameters are selected based on the experience of the operator of the machine tool or they can be obtained from specialized handbooks. However, the parameters proposed by these sources could not be the optimal ones. Values stated for experiment 14 (Table 1) could be an option for the machine operator since they can be found in such specialized handbooks.

Traditionally, cutting parameters were optimized considering only the material removal rate and the surface quality. The sustainability of the process was not a part of the optimization process, and the energy consumption was not added to these objectives. This type of optimization is named traditional objective optimization.

This work presented the multi-objective optimization that considers the energy needed to remove the material and the surface roughness of the final piece. In order to compare the initial turning parameters, the ones corresponding to the traditional objective optimization, and the values of the multi-objective optimization, it was necessary to obtain the values of the traditional objective optimization by means of applying the desirability approach only for optimizing the MRR and the SR. The comparison is given in Table 16.

According to the results presented in Table 16, the initial turning parameters provided the highest value of surface roughness. The multi-optimization registered the smallest value of specific energy, and the maximum material removal rate was obtained when the traditional objective optimization was employed.

When comparing the results given by the initial machining parameters and the multi-objective optimization method, the

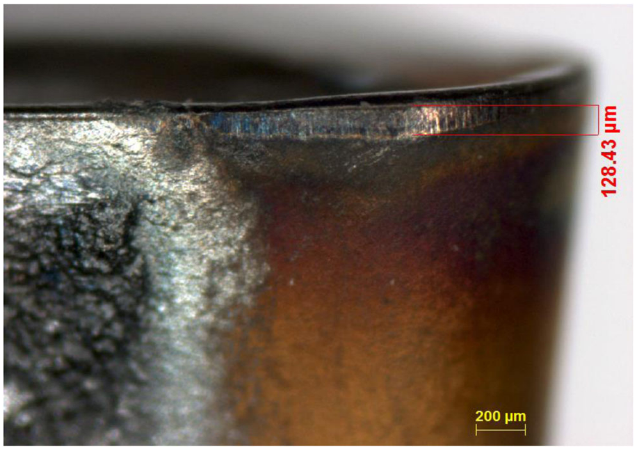


Fig. 10 Width of the flank wear after 6 min of continuous machining

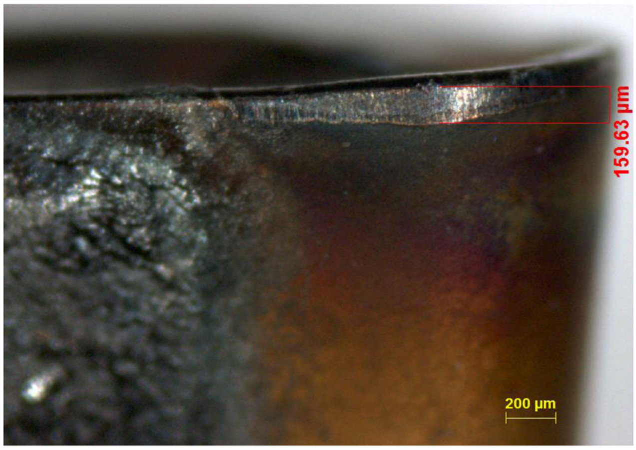


Fig. 12 Width of the flank wear after 8 min of continuous machining

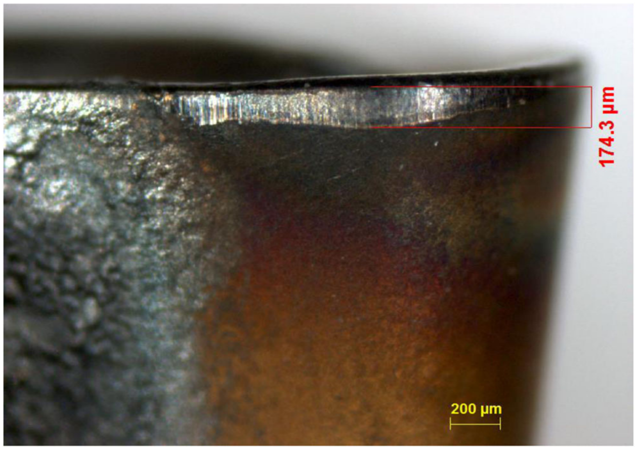


Fig. 13 Width of the flank wear after 9 min of continuous machining

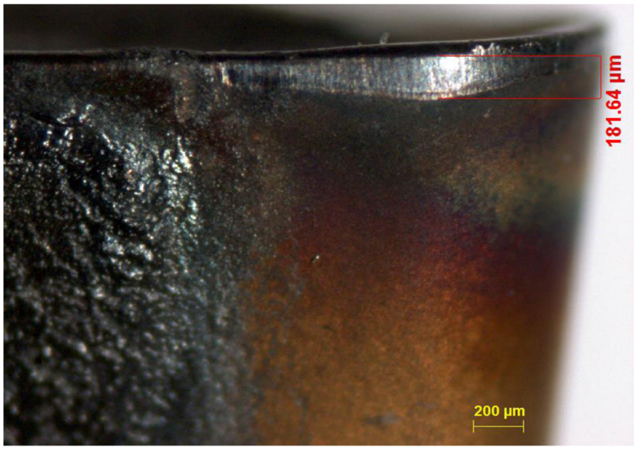


Fig. 14 Width of the flank wear after 10 min of continuous machining

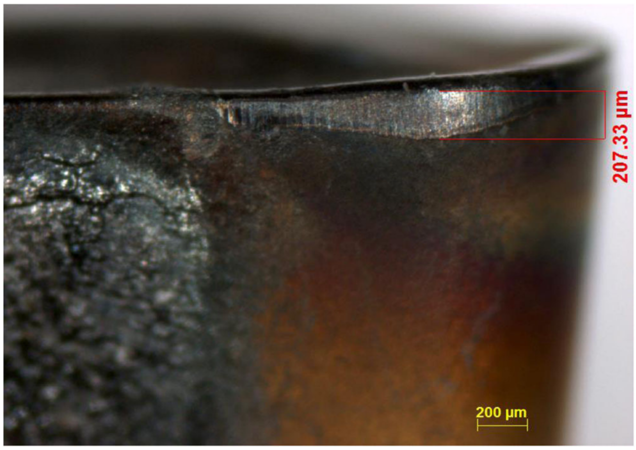


Fig. 15 Width of the flank wear after 11 min of continuous machining

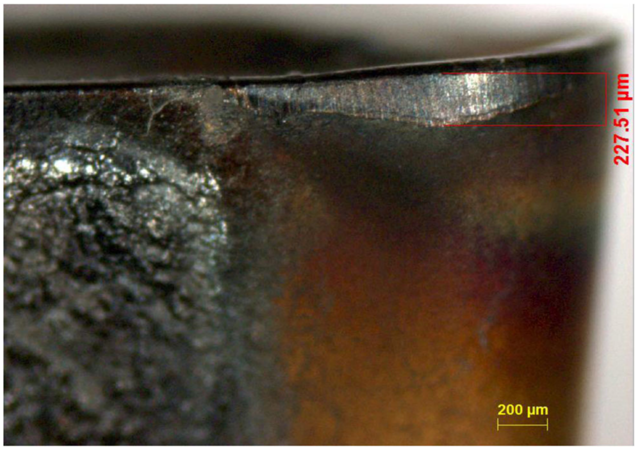


Fig. 16 Width of the flank wear after 12 min of continuous machining

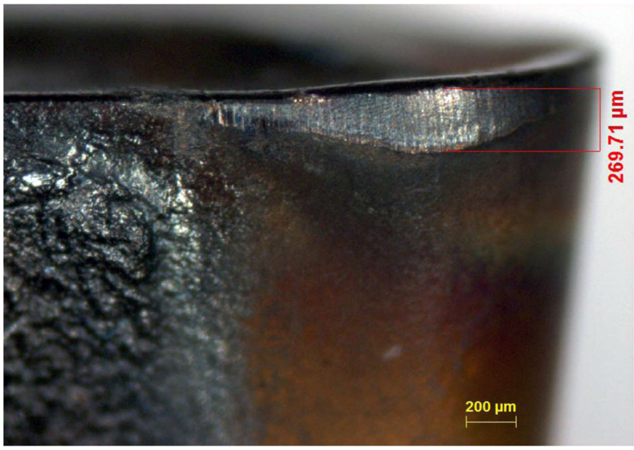


Fig. 17 Width of the flank wear after 13 min of continuous machining

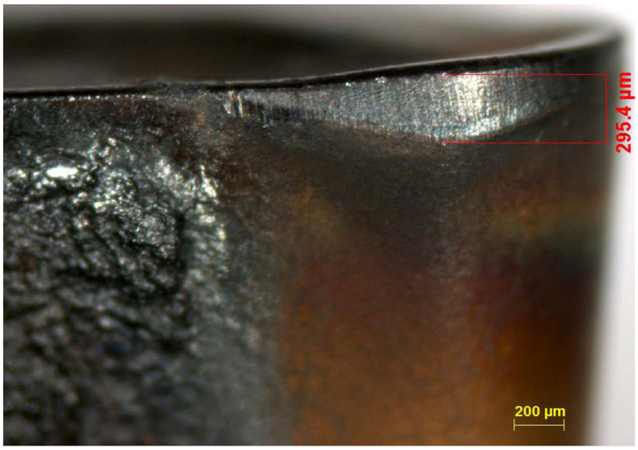


Fig. 18 Width of the flank wear after 14 min of continuous machining

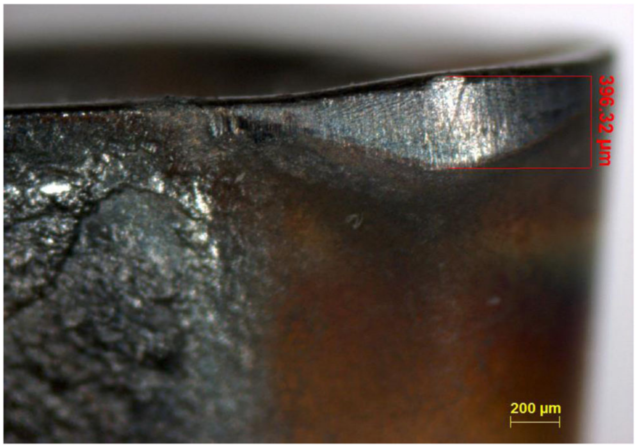


Fig. 19 Width of the flank wear after 15 min of continuous machining

material removal rate was increased in 3.6%, the specific energy was reduced in 15.69%, and the surface roughness decreased in 26.36% when the multi-objective optimization was employed. If the cutting parameters dictated by the multi-optimization are used, the material removal rate decreased in 27.23%, the specific energy was reduced in 22.45%, and the surface roughness increased in 15.7% when compared to the results achieved with the traditional optimization.

The optimization of the specific energy consumed during the machining process and the surface roughness of the workpiece were shown in the present work. This optimization was achieved by employing the response surface method and the desirability approach. The energy required by the machine tool to remove the material from the workpiece is related to the CO_2 emissions generated during the production of electricity. A lower carbon footprint for the finished product was achieved when the energy consumption was minimized.

It is certainly presented that the multi-optimization method granted the improvement of the responses related to the turning process. Furthermore, this optimization method considered the energy needed by the CNC machine tool, so there is a benefit for the environment, without reducing either the final quality of the machined piece or the quantity of material removed per second from the workpiece.

5 Conclusions

This work aimed to optimize a turning process using the response surface methodology and the desirability analysis. The material to be machined was AISI 1045 steel bars, considering a constant material volume removed for all the experimental trials. The objective was to minimize the specific energy drawn from the grid during machining to enhance the sustainability of the process by the reduction of the electrical energy consumed, as well as to minimize the surface roughness Ra to ensure the quality of the final product. The dry machining strategy was executed for all the trials, and according to the results presented in Section 4.1, an energy saving of 4.13% was

Fig. 20 Flank wear vs machining time

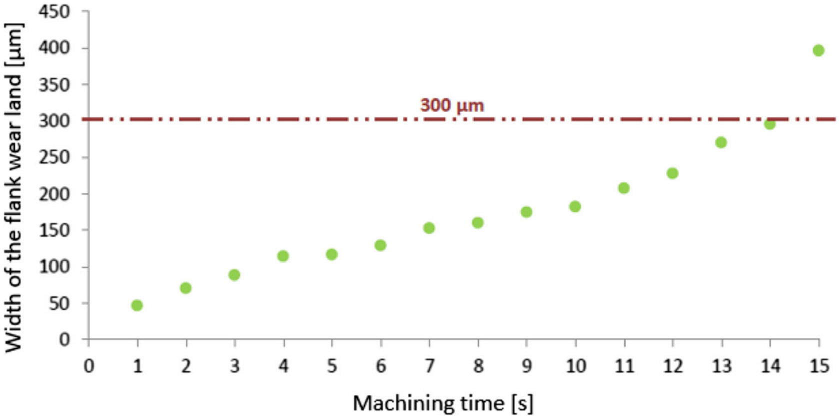


Table 16 Results achieved with different types of optimizations

Item	MRV (mm^3)	a_p (mm)	f (mm/rev)	v_c (m/min)	MRR (mm^3/s)	SE (J/mm^3)	SR (µm)
Initial turning parameters	35,000	1.50	0.23	409	2351.75	6.31	2.20
Traditional objective optimization	35,000	2.34	0.21	409	3349.71	6.86	1.40
Multi objective optimization	35,000	2.22	0.18	366	2437.56	5.32	1.62

achieved when the coolant pump was not turned on. Moreover, the tool life test results showed that it was feasible to obtain a proper tool life, equivalent to the one that is achieved when the values of the cutting parameters recommended by the tool's manufacturer are employed.

The most significant factors in order to optimize the specific energy consumed were the feed rate and the depth of cut. The feed rate was also the most significant factor for reducing the surface roughness. The optimal results were obtained using a value of feed rate of 0.18 mm/rev, depth of cut of 2.22 mm, and cutting speed of 366 m/min. Using the desirability approach, the proposed values of the cutting parameters allowed to achieve a reduction of the specific energy of 15.69%, the surface roughness was decreased in 26.36%, and the material removal rate was increased in 3.6% when compared to the initial turning parameters commonly used.

According to these results, it was possible to find out the balance between the sustainability of the process and the final quality of the product. The energy needed for the removal of material was reduced without affecting the surface quality and the tool life, factors that are very important for the economics of the turning operation. For the industrial practitioners, it was illustrated the significance of considering the sustainable metrics besides the economic ones in turning. The method employed in this work can be applicable to any other machining process to minimize its environmental burden.

With regard to the limitations of the methodology presented, it should be considered that the cutting tool selected for the test has a specific geometry and purpose (medium machining to finishing operations) for the material being cut. According to previous works discussed in Section 4, similar conclusions were obtained for different materials and cutting tools, but for mass production, an analysis should be conducted to ensure a proper set of cutting parameters are selected, and the economic and environmental targets are met. However, the recommendations given could be used as a starting point for the optimization of such cutting parameters.

As future work, the authors will explore the application of the methodology presented to milling processes, mainly slot and pocketing milling, to find out the relationship between the selection of the cutting parameters and the energy consumed during the material removal.

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