INFLUENCE OF TURNING PARAMETERS ON CUTTING TEMPERATURE BY APPLYING THE DESIGN OF EXPERIMENTS WITH THE DEFINITION OF THE WORKPIECE MATERIAL BEHAVIOR

by

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This paper evaluates the behavior of cutting temperature under the influence of specific cutting parameters by applying both Factorial Design and the Surface Response Methodology. Cutting speed, the feed rate and type of material were selected as input parameters to perform this study. As type of material is a non quantitative factor, it is necessary to establish a particular index to define it. Although different properties were analyzed, the average stress between the yield and strength stresses was demonstrated as the most representative property to describe material. The experimental values of temperatures during the turning process were obtained with an infrared thermography camera and experiments were designed to run the statistical analysis with commercial software. Both the Factorial Design and Surface Response methodologies showed the influence that specific values of the input parameters had on cutting temperatures. Factorial Design allowed more accurate results, but more experiments had to be carried out, while the Surface Response Methodology provided suitable information with fewer tests. A comparison was made between the experimental and some analytical results, for example those obtained by Cook, and showed a good agreement.

Key words: *turning parameters, cutting temperature, thermography, DOE*

Introduction

All machining processes generate energy, which is converted into heat. Thus, the temperature in the cutting zone dramatically rises. Rise in temperature can have some negative effects during turning processes. These effects are related to the characteristics and shape of the tool, which can be altered, to dimensional variations in the workpiece, and also to properties changes in the machined surface [1].

Different experimental techniques have been developed to measure temperatures generated during machining processes [2-4] as knowing the heat produced, and the consequences that can result from it, are important. Experimental approaches based on pyrometry fundamentals within the visible spectral range have been developed to measure temperature during

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turning processes. Nevertheless, this methodology entails problems as to the uncertainty in the emissivity of the material surface [5, 6].

Other authors have used thermographic cameras as these devices have been able to review temperature distribution in parts without having to be in contact with them [7-9]. The function of these devices is based on the infrared radiation emitted by objects [10]. Thus, parameters like room temperature, relative humidity, the object distance to the camera and the emissivity of the material [11] have to be taken into account. This methodology is most interesting as temperatures can be measured without long set-up times and allows us to register the temperature changes very quickly.

Cutting speed, feed rate and depth of cut are the most commonly analyzed variables. Ay and Yang [12] employed infrared thermovision to evaluate global temperature distribution over the workpiece, the tool and the chip under different cutting conditions. Korkut *et al.* [13] examined the influence of cutting parameters on chip-back surface temperatures by applying embedded thermocouples. But these authors did not obtain any multivariable modeling. Das *et al.* [14] investigated the effect that cutting parameters had during a machining process by applying Taguchi's design method, but they only used a specific high alloy steel.

Several authors have successfully researched the influence of these cutting variables by the infrared technique. Sun *et al.* [15] used an infrared thermal imager to analyze the effect of feed rate and cutting speed on cutting temperatures and workpiece surfaces. O'Sullivan and Cotterell [16] checked to see how cutting speed affected surface temperatures during a turning process with an infrared imaging camera. These authors focused their research on qualitative effects and they did not establish any modeling.

It is also possible to predict cutting temperature during a turning process using the appropriate methodology and taking into account the parameters that affect cutting processes. Thus, the temperature values reached during a machining operation can be estimated by applying an analytical method. Yet there are not many theoretical methodologies related to this subject. Some authors explain their results with analytical methods [2-4, 17]. Nevertheless, the analytical equations developed by those research works are greatly conditioned to the experimental range of variables they work with.

Cook's method [4, 18] is one of the most extensively analytical method used to predict machining temperature values. Its main drawback is that the calculated temperature corresponds to the tool-chip interface and it is not possible to know the temperature value that will be reached by the chip during the process.

To select cutting variables correctly, some mathematical methods have been developed based on statistical techniques, which have been employed for modeling machining process behavior [19, 20]. The main applied methodologies are the Taguchi method [21], Factorial Design [22], and the Response Surface Methodology [23]. However, the effectiveness of these statistical techniques has not been sufficiently compared. On the other hand, the parameters selected for modeling the process do not best represent the phenomena to be studied.

In addition to the limits in the cutting temperature researching indicated above, it is significant that material is not included as a variable in the Design of experiments (DOE), methodologies due to its influence on that phenomenon cannot be directly linked to an intrinsic property or index, as different aspects take part in the chip removal process. In machining processes the main sources of heat are friction and plastic deformation. Friction, heat conduction, elastic and plastic deformation energy are different phenomena that depend on the different machined material properties and it is not easy to establish only one indicator for defining the material behavior in a DOE methodology.

Nevertheless, the main part of the heat generated in a machining operation is evacuated through the chip, taking into account that higher speeds encourage this phenomenon. Thus, the process is close to adiabatic conditions and heat transferred by radiation can be neglected. If the process is carried out without coolant, the effect of thermal convection can also be neglected [24]. Thus, parameters associated with the thermal properties of the material are not decisive. On the other hand, friction is a phenomenon that is affected by some different factors as the tool material and shape, the workpiece material and properly by cutting conditions and, thus, it is not directly linked to the material workpiece.

The aim of this paper was to analyze the influence of the cutting parameters on the temperatures generated while turning three different materials. Two statistical techniques were applied to the same experiments and the obtained results were compared to establish the most accurate procedure. Another finding was that an adequate material behavior parameter must be considered to obtain good results. According to the indicated above the definition of that parameter must represent the material plastic behavior in the process with reliability. The Minitab 16® software was applied in order to design the experiments according to the fundamentals of these methods which permits the parameters involved in the process to be combined.

Experimental details

Turning tests were carried out on three different materials: L-3130 aluminum alloy, F-1110 carbon steel, and AISI 316 stainless steel, tab. 1.

Table 1. Properties of tested materials

Property/Material	L-3130 Aluminum alloy	F-1110 Carbon steel	AISI 316 Stainless steel
Density, [kgm^{-3}]	2800	7800	7950
Yield strength, [MPa]	400	250	358
Tensile strength, [MPa]	460	400	720
Elongation at break, [%]	6	25	65
Thermal conductivity, [WK^{-1}m^{-1}]	154	51.9	16.3
Specific energy, [Nmmm^3]	0.8	1.6	2.8
Thermal diffusivity, [m^{2}s^{-1}]	$6.68\cdot10^{-5}$	$1.49\cdot10^{-5}$	$3.48\cdot10^{-6}$

The parts to be turned were 300 mm long with a 50 mm diameter. Only one 150 mm length was machined in each test. Machining was done with a Microcut H-2160 lathe. A general turning tool composed of an insert TNMG 16 04 08-MM (grade GC2025) was used and was held onto a MTJNR 2525 M16 tool holder. This type of tool can machine without using a coolant, so all the tests were run dry. The selected tool geometry is valid for all experimented materials according to the manufacturer supplier (Sandvik-Coromant) and corresponds to a tungsten carbide, insert coated with titanium nitride. Although this quality is not necessary to machine aluminum alloy parts, that can be turned with a bare tungsten carbide tool insert, this kind of coating does not represent any incompatibility with the alloy. This situation has been probed with the tests done in this research. According to the experiment planning design, the experimental cutting parameters are shown in tab. 2. It is well known that the experimented materials are not usually

Table 2. Cutting parameters according to experiment designs

	Unit	Cutting parameters		
Rotational speed	[rpm]	650	950	1400
Feed rate	[mm·revolution^{-1}]	0.05	0.1	0.2
Depth of cut	[mm]	0.5		

turning in the same range of machining conditions. The turning parameters selected are right to machine stainless steels according to the tool employed and those conditions were established for the rest of materials. According to the tool manufacturer, the experimented parameters are included in the lowest range recommended for the machining of carbon steels parts. Although cutting velocity and feed rate are too low for the machining of aluminum alloys, they are fixing for considering a reference point for the comparison executed.

A previous turning operation was performed before each test in order to remove any oxide layer or imperfection on the round surface. Tests were done in triplicate. To this end, every workpiece was divided into three parts and each part was mechanized under similar conditions; that is, depth and cutting speed were fixed every three experiments and the feed rate was the parameter to be modified. Hence the different parts in the workpiece were designed by taking into account that the total time for each experiment was the equivalent. This process was repeated for the different experimented materials until all the combinations between cutting speed and the feed rate were performed.

Furthermore, the maximum and average temperature in the chip during the machining tests was recorded by a SATIR thermographic camera, model HotFind-LXT. It is very important to define some properties, such as room conditions, temperature range and material emissivity, in such cameras. For the measuring process, the camera was implemented into a special support that held it in an appropriate location for this purpose. The specific area in which the temperature was to be known was selected thanks to the SatIrReport USB® software.

For determining the emissivity values of different materials herein experimented a specific procedure was carried out. This procedure compares the existing temperature in a black-painted area to another zone of the same part, which was not painted. As usual a value of 0.95 was considered to be the emissivity of the painted area in all cases [9, 25]. Thus temperature was determined in the black area and the emissivity of the bare area was modified to a similar value for the temperature to be obtained. The emissivity of the materials was obtained for 200 °C according to the expected chip temperature results. Therefore emissivity results were established as 0.08 for aluminum alloy, 0.39 for carbon steel, and 0.38 for stainless steel.

Statistical and analytical methods

Factorial design

The turning parameters selected for Factorial Design as input variables are shown in tab. 3. Each parameter was defined at three levels and 27 test experiments were needed to constitute a factorial design according to the levels, see tab. 4. Two replicas were done for each experiment.

Type of material is not a quantifiable parameter itself and it is necessary to define it by using intrinsic properties that can be linked to its role in heat generation or heat concentration. Conductivity coefficient was selected as a possible variable that allowed to explain the influence of the material in the process. Break elongation was other parameter taken into account. Finally, the energy generated in the machined process is strongly influenced by the mechanical properties of the material. Some authors state that other causes as friction have a minor effect, less than 20% [26]. During turning, the chip is obtained by a deformation process and stress values between the yield strength and break strength, UTS, can be considered as representative of the heat generation during chip removal. However, it is very difficult to know the real stress value at all times. Intermediate stress was determined as the mean value between yield strength and tensile strength, as shown in eq. (1).

Table 3. Levels of the input variables used in the experiments in the factorial design

Input variables		Levels		
		1	2	3
Cutting speed [m min^{-1}]		92.06	126.09	175.45
Feed rate [mm revolution^{-1}]		0.05	0.1	0.2
Type of material	Thermal conductivity [Wm^{-1}K^{-1}]	16.3	51.9	154
	σ_i [MPa]	325	430	539
	Elongation at break [%]	6	25	65

Table 4. Combination of input variables in the RSM and factorial design. V_c: cutting speed; f: feed; σ_i: intermediate stress

Test	V_c [m·min^{-1}]	f [mm·rev^{-1}]	σ_i [MPa]	Test	V_c [m·min^{-1}]	f [mm·rev^{-1}]	σ_i [MPa]
1	92.06	0.05	325	15	126.09	0.20	430
2	92.06	0.10	325	16	175.45	0.05	430
3	92.06	0.20	325	17	175.45	0.10	430
4	126.09	0.05	325	18	175.45	0.20	430
5	126.09	0.10	325	19	92.06	0.05	539
6	126.09	0.20	325	20	92.06	0.10	539
7	175.45	0.05	325	21	92.06	0.20	539
8	175.45	0.10	325	22	126.09	0.05	539
9	175.45	0.20	325	23	126.09	0.10	539
10	92.06	0.05	430	24	126.09	0.20	539
11	92.06	0.10	430	25	175.45	0.05	539
12	92.06	0.20	430	26	175.45	0.10	539
13	126.09	0.05	430	27	175.45	0.20	539
14	126.09	0.10	430				

$$\sigma_i = \frac{\sigma_R + \sigma_E}{2} \tag{1}$$

The reason why this value was selected was because some materials could have the same yield strength, although this parameter would not be adequate to represent the material behavior during turning processes since the plastic phenomenon takes place in them. Otherwise there are materials with a similar hardening Hollomon exponent that present very different tensile strength values. In this way, σ_i was an indicator that contains both the afore-mentioned aspects. Linear plastic behavior was assumed.

The response surface methodology (RSM), Box-Behnken

Box-Behnken is the type of design used herein and has the particularity of that each variable levels correspond to its highest level selected, the lowest and an intermediate value between them. In this case, the intermediate level, coded as level 0, was calculated by the software Minitab 16® as the mean of the extreme values. Sometimes it is not possible to consider the real experimental conditions that correspond to the mean level values since they cannot be experimentally selected. For this reason, the experimental values of the variables related to level 0 were fixed as closely as possible to the DOE. The turning parameters selected as input variables are shown in tab. 5.

Table 5. Levels of the input variables used in the tests in RSM

Input variables		Levels		
		–1	0	1
Cutting speed [m min^{-1}]		92.060	133.755	175.450
Feed rate [mm revolution^{-1}]		0.05	0.125	0.2
Type of material	Thermal conductivity [Wm^{-1}K^{-1}]	16.30	85.15	154.00
	σ_i [MPa]	325	430	539
	Elongation at break [%]	6	35.5	65

For RSM, a quadratic model was planned to be applied in accordance with eq. (2), where β numbers refer to regression coefficients and X_i, X_j refer to the input variables of the function:

$$Y = \beta_0 + \sum_{i=1}^{K} \beta_i X_i + \sum_{i=1}^{K} \beta_{ii} X_i^2 + \sum_{\substack{i=1 \\ i<j}}^{K} \beta_{ij} X_i X_j \tag{2}$$

Analytical method

Cutting temperatures can be estimated by different analytical methods. Cook's method applies eq. (3) to calculate an approach of the temperature at the tool-chip interface during a machining process. In this equation ΔT represents the mean temperature, U is the specific energy in the operation, ρ and C are the density and heat coefficient of the material, respectively, V_c is the cutting speed, t_0 – the chip thickness before being cut, and K –the thermal diffusivity of the work material [4]:

$$\Delta T = \frac{0.4U}{\rho C} \left(\frac{V_c t_0}{K} \right)^{0.333} \tag{3}$$

Results and discussion

After performing all the analyses, intermediate stress proved to be the input variable that best define the type of material. Therefore, all the statistical methodologies were applied using cutting speed, the feed rate and intermediate stress as input parameters.

RSM model

The p-value associated with each analyzed option was determined by applying an ANOVA analysis of temperatures, tab. 6.

The analysis results showed that the elongation at break and thermal conductivity were not decisive for the temperature values since the p-value obtained for both cases was above the level of significance α of 0.05.

Table 6. The p-value and R^2 (adjusted) for each material property

Feature to describe the material	R^2 (adjusted) for $T_{\max}$	p-value for $T_{\max}$	R^2 (adjusted) for T_{av}	p-value for T_{av}
Thermal conductivity	63.28%	0.173	71.37%	0.124
Intermediate stress	99.48%	0.000	93.17%	0.016
Elongation at break	63.28%	0.173	71.37%	0.124

However, when the material was defined using intermediate stress, the p-value obtained for the maximum temperature and average temperature was 0.000 and 0.016, respectively; both were below the level of significance α of 0.05. Thus both variables were experimentally significant and correlated well with temperatures according to the R^2 (adjusted) index observed.

If the material was defined by intermediate stress, the results for the maximum and average temperatures, T_{max} and T_{av}, would be expressed according to the RSM model by means of eqs. (5) and (6), respectively.

$$T_{max} = -1238.240 + 16.881V_c + 4710.910f + 0.921\sigma_i - 5.402 \cdot 10^{-2} V_c^2 - \\ -15455.100f^2 - 1.469 \cdot V_c f - 4.364 \cdot 10^{-3} V_c \sigma_i - 1.001 f \sigma_i \tag{5}$$

$$T_{av} = -1729.340 + 19.076V_c + 6794.970f + 1.593\sigma_i - 5.655 \cdot 10^{-2} V_c^2 - \\ -21158.200f^2 - 1.357V_c f - 7.652 \cdot 10^{-3} V_c \sigma_i - 2.178 f \sigma_i \tag{6}$$

Figures 1 and 2 show the response surface graph of the analyzed variables in terms of the parameters selected from the turning process. These types of graphics allow us to know the way in which a temperature is simultaneously influenced by two parameters.

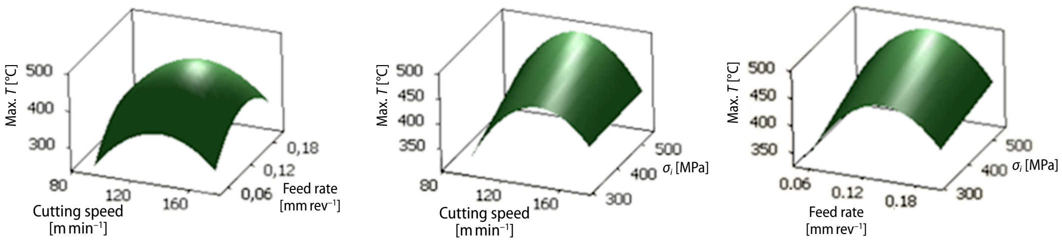

Figure 1. Response surface graph for maximum temperatures (max. *T*)

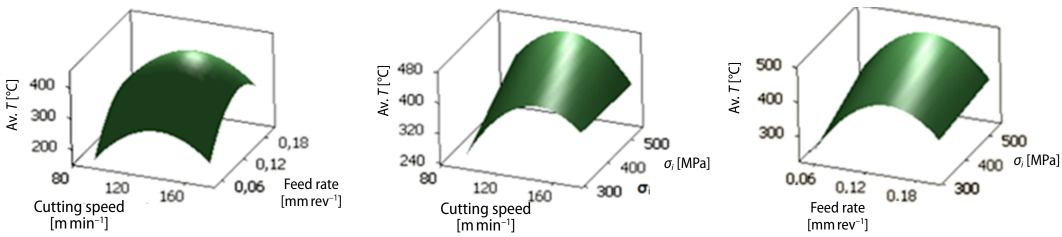

Figure 2. Response surface graph for average temperatures (av. *T*)

Looking at the graphs, we can see that the highest temperature values were obtained for the medium cutting speed and feed rate values. Similarly, we can observe that the highest temperature values were achieved in the material that presented a higher intermediate stress value.

Another type of graph that allows us to know the behavior of the different turning parameters is the main effects plot. This plot depicts the way in which one of the input variables affects the temperature results. The influence of each input variable on the temperature values is shown in fig. 3.

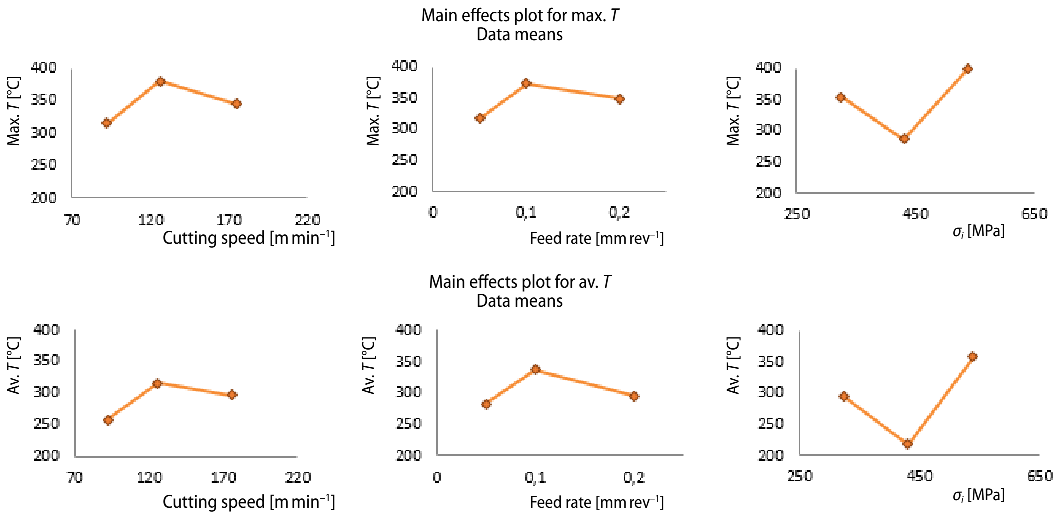

Figure 3. Main effect plots for maximum and average temperatures in RSM

Table 7. ANOVA analysis results in factorial design

	Degrees of freedom	Sum of squares	Mean square	Coefficient F	p-value
Maximum temperatures					
V_c [m·min^{-1}]	2	2030.6	1015.3	1.8	0.183
f [mm·rev^{-1}]	2	21569.0	10784.5	19.3	0.000
σ_i [MPa]	2	128712.8	64356.4	114.9	0.000
Error	26	14567.3	560.3	–	–
Total	53	189819.8	–	–	–
Average temperatures					
V_c [m·min^{-1}]	2	4184.4	2092.2	4.4	0.023
f [mm·rev^{-1}]	2	46646.7	23323.3	48.5	0.000
σ_i [MPa]	2	151723.0	75861.5	157.8	0.000
Error	26	12496.4	480.6	–	–
Total	53	246878.6	–	–	–

Factorial design results

To obtain the ANOVA results with Minitab 16®, it was necessary to carry out replicas. All the tests were repeated under the same conditions as the original one. Thus 54 tests were run in the laboratory.

Comparing the original temperature values and the replicas allowed us to prove that all the temperature results were similar when the same conditions were taken into account. This fact proved the repeatability of the experiments. The ANOVA analysis results are summarized in tab. 7.

Figure 4 depicts the effect of the different variables. As seen, the response of the studied variables on the maximum and average temperatures was similar. For the maximum temperatures, if the main effects plot was observed, fig. 4, then cutting speed was the only variable that had no significant effect on the response. However, the other variables have a similar effect on these temperature values. With the average temperatures, all the input variables had a similar effect on the response, as seen in fig. 4.

Therefore, as expected, the higher the cutting parameters values, the higher the temperatures obtained. Nevertheless, and logically, thermal conductivity led to the opposite effect; that is, low thermal conductivity values involve higher temperatures being reached during machining operations.

The main effects plots represent the data means of each input variable level. Consequently, the values represented in the plot are more accurate if some experiments are run at each

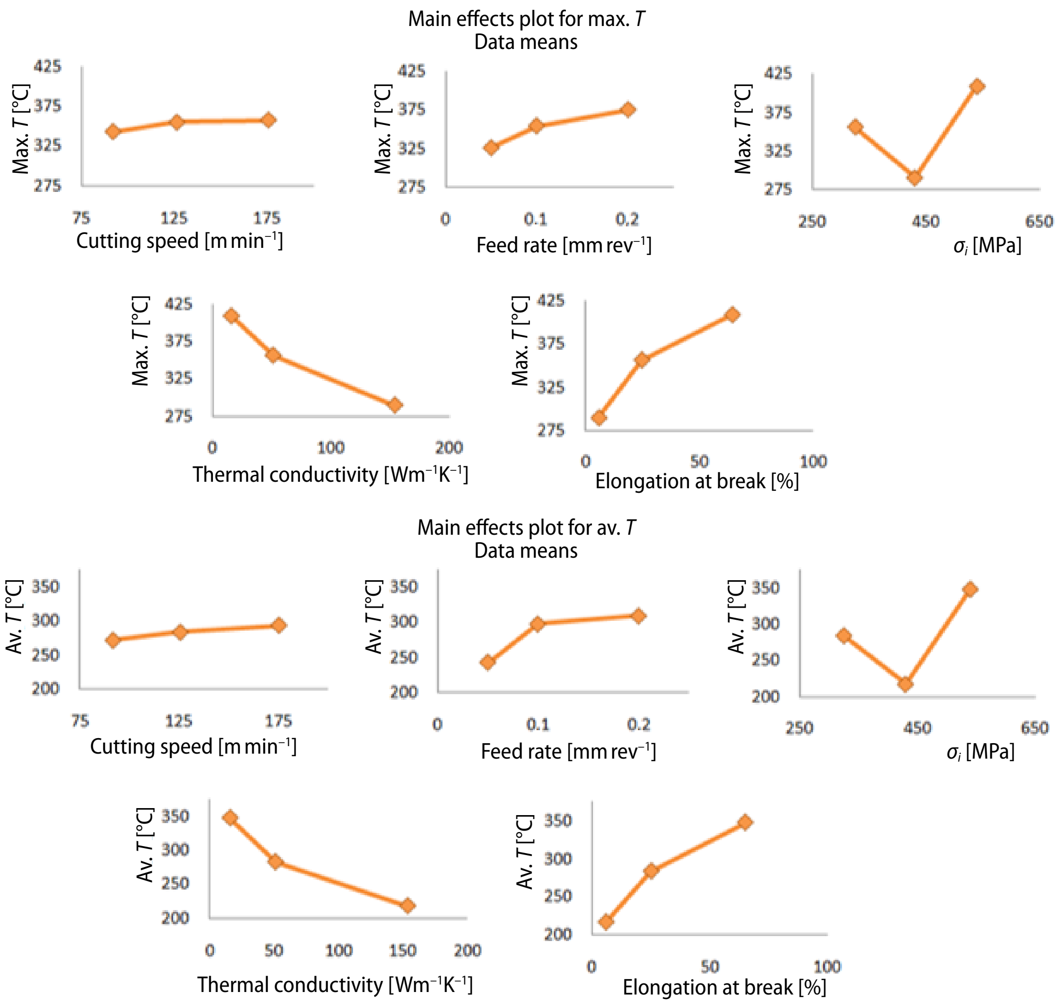

Figure 4. Main effect plot for maximum and average temperatures in Factorial Design

level. Thus the main effects plots in Factorial Design present a slight variation compared with those obtained by RSM. Nevertheless, the difference found between the represented temperature values was no higher than 20 °C.

Analytical analysis

After considering the influence of cutting parameters on the experimental temperature values, it is possible to analyze whether the application of analytical methods can be effective for obtaining an approximate cutting temperature value in this machining process type. Cook's analytical method was applied to calculate the theoretical temperature values by considering identical conditions to those used during the experimental machining operations. Theoretical and experimental results are represented in fig. 5 according to Cook's equation. Each point in the graph, fig. 5, represents one of the 27 experiments that resulted from the combination of the different turning parameters studied.

By comparing the experimental values and the theoretical temperature results, we found that they behaved differently depending on the machining material type. The turning of aluminum alloy L-3130 was the only process that allowed similar cutting temperature values to be obtained as the theoretical results calculated according to Cook's equation. Nevertheless, the temperatures measured when machining other materials, such as F-1110 steel or AISI 316 stainless steel, differed vastly from the temperatures obtained by applying the appropriate calculations, eq. (3).

Cook's equation, eq. (3), was adjusted by performing experiments under specific cutting conditions. The values that had been fixed for each parameter were cutting speed of about 210 m/min, a feed rate of 0.15 mm/rev and depth of cut of 1.30 mm [18]. These values are quite different to the parameters used to do all the experiments of the present work. The equation predicted the temperature which occurred at the tool-chip interface and it was not possible to know the temperature at another cutting zone point. Nevertheless, the position of the thermographic camera only allowed us to record the temperature of the outside chip surface.

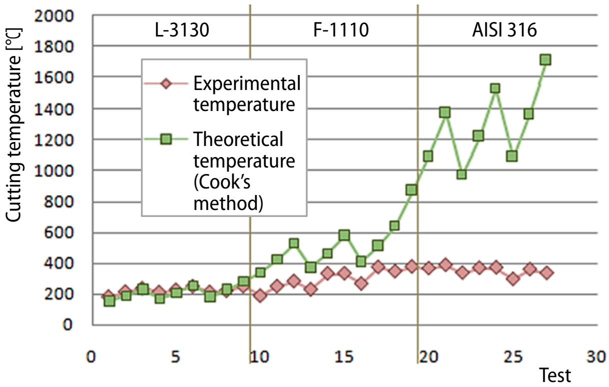

Figure 5. Comparison between the experimental and theoretical average temperature values during a turning process

As seen in fig. 5, the L-3130 aluminum alloy was the only material in which the theoretical results and the experimental ones fitted. Thermal conductivity could explain this fact. High thermal conductivity is characteristic of this aluminum alloy. Therefore, the heat generated during the turning operation was transmitted very quickly through chip thickness. The tool-chip interface temperature was similar to that which corresponded to the chip outer surface.

The F-1110 carbon steel had a lower thermal conductivity than the aluminum alloy, and there were slight differences between the experimental and analytical results obtained with Cook's equation.

Otherwise, AISI 316 stainless steel is the material with the lowest thermal conductivity. The heat generated during the process cannot be rapidly transferred to equalize the temperature on both sides of the chip. Thus the tool-chip interface temperature differs vastly from the experimental values.

Conclusions

This work has been demonstrated that a thermography technique is a useful procedure for establishing an experimental methodology to evaluate cutting temperature during turning operations according to the different cutting parameters that define the process. The parameters we considered were cutting speed, the feed rate and the material to be machined.

Different methodologies based on DOE have been successfully applied to determine the influence of cutting parameters on cutting temperatures. In this context, Factorial Design permits accurate information to be obtained about how turning parameters can affect the maximum and average temperature values during a machining operation. The main rawback of this method is that many tests are necessary according to the replicas that must be considered. RSM significantly cuts the number of tests to be performed and enables suitable results to be obtained if both procedures are compared.

To characterize type of material, it was necessary to define an average stress value, σ_i, according to its yield and break strength since other properties, such as elongation at break and thermal conductivity, gave inaccurate results. It has been proved that σi represents not only the range of stress values in the plastic field, but also the reinforcement by deformation of the material. Low p-values and high correlation rate have been obtained by this parameter as the definition of the material behaviour and thus, this method can be considered valid for the materials belonging to the same category than those experimented herein. That is, thermal behaviour in turning operations of carbon steels, alloyed steels and aluminium alloys can be predicted by applying the equations deducted in this paper. Other properties as elongation at break and thermal conductivity were demonstrated have mismatch with cutting temperature.

As expected, high values of cutting parameters are required to obtain maximum temperature values.

According to the analytical and experimental methods in the literature, the thermographic methodology applied herein is an effective approach to measure temperature during cutting operations by turning materials with high thermal conductivity properties. A uniform temperature through chip thickness was found in these materials.

Nomenclature

C – specific heat, [$\mathrm{Jkg^{-1}K^{-1}}$]
El – elongation at break, [%]
f – feed rate [$\mathrm{mm \cdot revolution^{-1}}$]
K – thermal diffusivity, [$\mathrm{m^2s^{-1}}$]
T_{av} – average temperature, [°C]
T_c – cutting temperature, [°C]
TC – thermal conductivity, [$\mathrm{Wm^{-1}K^{-1}}$]
$T_{\max}$ – maximum temperature, [°C]
T_r – room temperature, [°C]
t_0 – chip thickness before cut, [mm]
U – specific energy in the operation, [$\mathrm{Nmmm^{-3}}$]
V_c – cutting speed, [$\mathrm{mmin^{-1}}$]
ΔT – mean temperature, [°C]

Greek symbols

ρ – density, [$\mathrm{kgm^{-3}}$]
σ_E – yield stress, [MPa]
σ_i – intermediate strength, [MPa]
σ_R – tensile strength, [MPa]

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