INFLUENCE OF CUTTING PARAMETERS AND MATERIAL PROPERTIES ON CUTTING TEMPERATURE WHEN TURNING STAINLESS STEEL

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ABSTRACT

Cutting temperature is one of the most relevant aspects of machining operations, since it influences tool life. The feed, the cutting speed, the depth of cut and the workpiece material are some of the most important factors that affect the cutting temperature. In this study an empirical relationship between cutting parameters such as: cutting speed, feed, depth of cut as well as maximum strength and thermal conductivity of different stainless steels, on the cutting temperature is presented. Experiments were conducted on AISI 304, AISI 316L and AISI 420 steels during a turning process. For the measurement of the cutting temperature the “Tool- Piece-Thermopair” method was used and the design of experiments was based on the factorial design method. Results showed that the cutting temperature increases when the values of cutting speed, feed, depth of cut, and material maximum strength are increased and that the cutting temperature decreases with the increase of material’s thermal conductivity, being this last variable the one that showed most influence on the cutting temperature.

Keywords: Turning, Cutting temperature, Stainless steel, Tool-piece-thermopair, Mathematical relationship.

INFLUENCIA DEL TORNEADO Y PROPIEDADES DEL MATERIAL EN LA TEMPERATURA DE CORTE DE ACEROS INOXIDABLES

RESUMEN

La temperatura de corte es uno de los aspectos más relevantes de las operaciones de mecanizado, ya que influye en la vida de la herramienta. El avance, la velocidad de corte, la profundidad de corte y el material de trabajo son algunos de los factores más importantes que afectan a la temperatura de corte. En este estudio es presentada una relación empírica entre los parámetros de corte, tales como: velocidad de corte, avance, profundidad de corte, así como la resistencia máxima y la conductividad térmica de diferentes aceros inoxidables, sobre la temperatura de corte. Los experimentos se llevaron a cabo con aceros AISI 304, AISI 316L y AISI 420 durante un proceso de torneado externo. Para la medición de la temperatura de corte se usó el método termopar herramienta-pieza y el diseño experimental se basó en un diseño factorial de niveles. Los resultados mostraron que la temperatura de corte aumenta cuando los valores de la velocidad de corte, avance, profundidad de corte y resistencia máxima del material se incrementan y que la temperatura de corte disminuye con el aumento de la conductividad térmica del material, siendo esta última variable la que mostró la mayor influencia sobre la temperatura de corte.

Palabras clave: Torneado, Temperatura de corte, Acero inoxidable, Termopar herramienta-pieza, Relación matemática.

INTRODUCTION

During the machining process, which is related to metal cutting, all the mechanical energy generated by the cutting forces is transformed into heat. As a consequence, high temperatures are generated in the area of the tool’s edge, affecting its performance and the quality of the workpiece. Hence, an excessive cutting temperature is the first cause that decreases tool life.

The aim of a machining process is to achieve very good quality of the piece been machined, these include surface finish and geometrical dimensions between tolerances specified by designers. The workpiece quality can be changed due to the thermal effects that affect the cutting tool during the machining process (Field, 1970).

Currently, the most widely used method to measure cutting temperature is the “Tool-Piece-Thermopair”, which consists of measuring the difference of potential generated in the tool-piece interface during a machining process (ASM International Handbook, 1999).

Previous studies have proved that with the Tool-Piece- Thermopair method, the amount of electromotive force (fem) is an indicative of the average temperature in the tool-piece interface. In some occasions, this fem does not correspond to the average cutting temperature of the interface, it only corresponds in the cases when temperature is uniform, or if the thermoelectric "fem" obtained from the tool-workpiece combination varies lineally along with the cutting temperature (Sandvik, 1994).

In 1993, Stephenson studied the Tool-Piece-Thermopair method by using tungsten carbide tools in his experiments. He was able to optimize the cutting temperature since the difference between the cutting temperature and the tool's temperature interface reached a minimum value.

Regarding cutting temperature measuring techniques, in 2005 Longbottom analyzed the benefits and disadvantage of the calorific method, tool-work thermocouples, embedded thermocouples, single wire thermocouple, fibre bragg gratings, PVD film method, infrared thermometers, infrared cameras, remote measuring/inverse methods and thermographic phosphor.

The influence of the cutting parameters on the tool temperature was studied among other researches by Chu and Wallbank in 1998, where a relationship between the cutting parameters and the cutting temperature for a specific range of cutting speed and feed was established.

Furthermore, it has been demonstrated that an increase in the cutting parameters such as cutting speed, feed and depth of cut, as well as the maximum strength, causes an increase in the cutting temperature, and that the cutting temperature decreases when increasing the thermal conductivity of the workpiece (Boothroyd, 1978; Stephenson, 1993; Chu, 1998; Astakhov, 1999). Mean while experiments made by O'Suvillan in 2001, showed that by knowing the influence of the cutting parameters on the cutting temperature an estimation of tools life during a machining process can be obtained.

In 2005, Liu and co-workers developed a non linear mathematical model to represent the effect of the cutting parameters on the cutting temperature during a turning process. The experiments were conducted on $38CrNi_3Mo$ using a P05 alloy steel as cutting tool. They concluded that the Particle Swarm Optimization (PSO) is an excellent method to model the cutting temperature.

Also researchers Saglam, Unsacar and Yaldiz in 2006 studied the influence of cutting parameters and tool's geometry on the cutting temperature and the cutting forces during the turning of carbon steels. The results of this study suggest that tools approaching and rake angle have a considerable effect on the cutting forces and on the tool-chip interface temperature.

Majumdar, P. *et al*. (2005) conducted a finite element analysis of temperature distribution in the metal cutting process considering cutting conditions, tool geometry and tool material being incorporated into this analysis the models for heat generations within primary and secondary zones, and in the rake face due to friction at the tool-chip interface.

The temperature dependency of material properties was included in a numerical model to determine temperature distribution in orthogonal metal cutting elaborated in 2006 by Dogu, Aslan and Camuscu.

In 2007, Chang C studied by finite element analysis the heat partition factors between the tip and chip using the inverse heat transfer analysis, which utilizes temperature on the carbide tip´s surface measured by infrared as the input.

More lately regarding the influence of lubricant/coolant on surface roughness, cutting conditions, etc, due to the impact of these fluids on the environment there is a tendency to work without them during the machining process. Due to this fact, more researches have been focused on dry or MQL (Minimum Quantity of Lubrication) machining process, such as the study conducted by Steven and Liang in 2003, where it was concluded that by using a MQL during a turning process allows not only to reduce the effect of lubricant on the environment but it seems that a better surface roughness can be achieve due to a decrease in cutting temperature. Also experiments made by Richard et al. in 2005, showed that a decrease in the cutting temperature can be obtained by using a heat dissipater on the cutting tool during the machining process. The device was designed by them in order to reduce not only the cutting temperature but also health problems (skin contact and inhalation of the product).

Once analyzing all the literature, the aim of this research is to predict the cutting temperature as well as the optimal set of cutting parameters in order to obtain low values of cutting temperature that will help to increase tool life during a dry turning process of AISI 304, AISI 316L and AISI 420.

EXPERIMENTAL PROCEDURE

AISI 304, AISI 316L and AISI 420 stainless steel round bars with 76.2 mm diameter and 500 mm length were used for the experiments. These steels were selected since they are often used in the food industry due to their low chemical interaction with food products. Also they are used as implants prosthesis due to their high compatibility with the human body tissue and their relative low cost compared to titanium alloy.

Table 1 show the chemical composition of the stainless steels used in this research and Table 2 the mechanical properties.

Table 1. Chemical composition of AISI 304, AISI 316L and AISI 420 stainless steels

AISI	304	316L	420
%C	0.0667	0.0180	1.3450
%Cr	18.1200	16.9280	13.1000
%Ni	9.5800	9.5800	5.3000
%Mn	0.6020	0.6020	0.7860
%Si	0.3644	0.3644	0.4049
%Mo	0.2898	0.2898	0.1338
%P	0.0015	0.0015	0.0014

Table 2. Mechanical properties of of AISI 304, AISI 316L and AISI 420 stainless steels

AISI	*HBW**	S_u[MPa]	*K*[W/mºC]
304	130	615	16.2
316L	148	597	16.2
420	449	839	24.9

*Brinell Hardness: ϕ 10mm and load of 3000 kg.

A standard insert holder, with WIDIA DNMG 150612 TN200 coated tungsten carbide inserts was used for the experiments, whose quality according to ISO 513 is HC-M20. This type of insert is recommended for stainless steel cutting operations and Figure 1 shows the scheme of the tip's geometry.

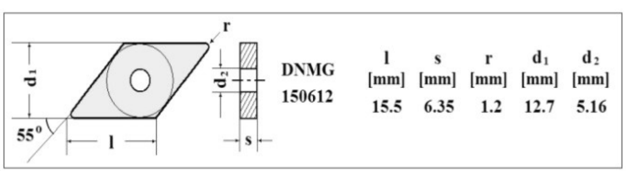

Figure 1. Scheme of the tip geometry used in the experiment

Cutting speed, feed and depth of cut were the variables chosen for the study since in previous researches it was observed that these cutting variables had the most influence on the cutting temperature and tool´s life (Boothroyd, 1978).

Selected cutting parameters are shown in Table 3.

Table 3. Selected cutting parameters

Level	V_C[m/min]	*f* [mm/rev]	*d*[mm]
Low (1)	59	0.1	0.5
Medium (2)	95	0.2	1.0
High (3)	190	0.3	1.5

A low, medium and high level was selected for each of the cutting variables. These values are recommended from the tools manufacturer as well as within the lathe limitation.

An Amutio-Cazeneuve, model HB 575 lathe, with a maximum spindle speed of 2000 rpm was used for the turning experiments. The tests were conducted under a dry cutting condition using the cutting parameters shown in Table 3.

A three-level full factorial design was used for the study. Table 3 shows the factors selected for the experiments, with their respectives levels. An amount of 27 experiments were conducted for each of the stainless steels used in this study. In order to assure the reliability of the results, experiments were repeated, yielding a total amount of 54 experiences for each stainless steel and a general total of 162 experiences. The experiments were performed in a random order to avoid any possible experimental errors which could affect any group of experiences. Also new tips were used for each trial.

Figure 2 shows a scheme of the experimental arrangement used to measure the cutting temperature during the turning process. In such arrangement four coils were distributed at 0, 90, 180 and 270 degrees around the lathe's rotary axis that it's connected to the workpiece through the feeding hole.

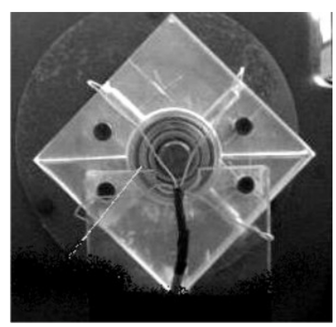

Figure 2. Scheme of the four coils distributed around the lathe rotary axis

The rotary axis, the workpiece and the cutting tool are all electrical isolated as shown in Figure 3. The coils and the cutting tool are connected to the modules (voltmeters) to measure the electromotive force (fem) generated from the tool-piece thermopair.

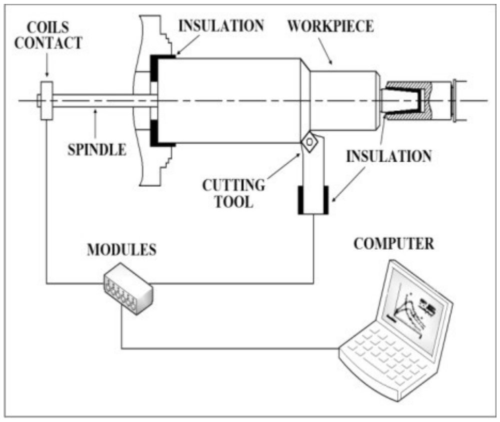

Figure 3. Scheme of the experimental tool-work thermocouple arrangement for cutting temperature measurement

RESULTS AND DISCUSSIONS

Once experiments were concluded, the following results were obtained. figure 4 shows the influence of the depth of cut on the cutting temperature when turning AISI 304 steel. As it is observed the cutting temperature increases as the depth of cut is also increased.

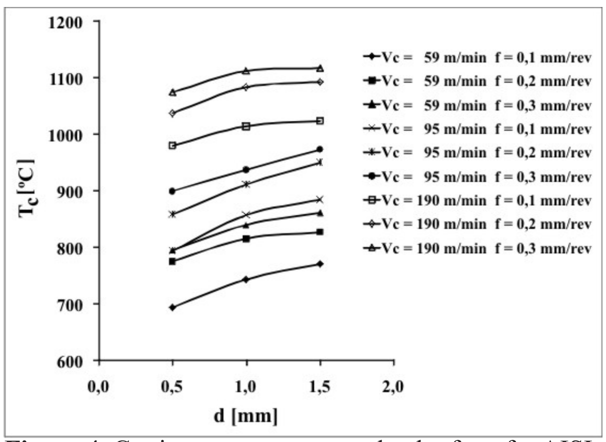

Figure 4. Cutting temperature vs. depth of cut for AISI 304 stainless steel

When a material is plastically deformed, most of the energy is turned into heat since the material is subject to extremely severe deformations; being the elastic deformation the ones that represents a small part of the total deformation. Hence, the increase of depth of cut represents a bigger compression in the tool-workpiece interface this will increase the energy supplied to the system during the cut of the material. This behaviour kept constant for AISI 316L and AISI 420 stainless steels and is in agreed with previous research (Stephenson, 1993; Chu, 1998; Astakhov, 1999).

In Figure 5, the influence of the feed on the cutting temperature for AISI 304 can be observed. As it is observed an increase of the feed produces an increase of the cutting temperature. This result is probably due to the fact that an increase of the feed generates a higher friction between the material been removed and the cutting tool, this will also increase the energy in the system, generating at the same time an increase of the cutting temperature. Once again this behaviour kept constant for AISI 316L and AISI 420 stainless steels. This result agrees with previous researches (Stephenson, 1993; Chu, 1998; Astakhov, 1999).

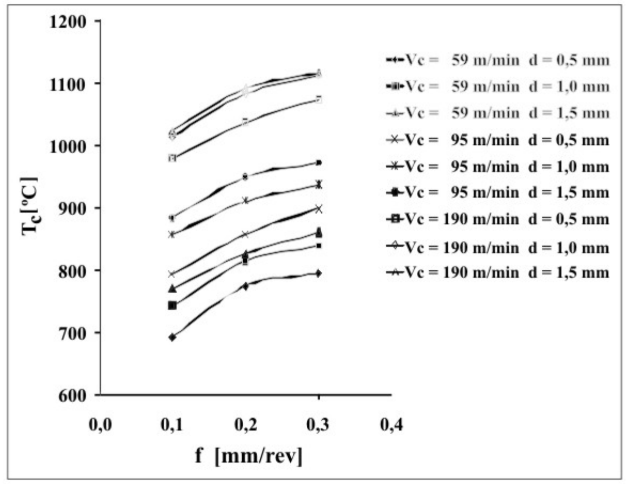

Figure 5. Cutting temperature vs. feed for AISI 304 steel

Analyzing Figure 6 where the influence of the cutting speed on the cutting temperature it's shown, it can be observed that an increase of the cutting speed produces an increase of the cutting temperature. This result is due to the fact that an increase of the cutting speed produces an increase of the cutting forces. More energy is needed to remove the material away increasing the cutting temperature. This behaviour kept constant for AISI 316L and AISI 420 stainless steels.

Comparing figures 4, 5 and 6, it can be observed that the cutting speed has the most influence on the cutting temperature, since it has a greater slope in the curves generated in these graphs. This result is in agreed with previous researches. (Chu, 1998; Astakhov, 1999).

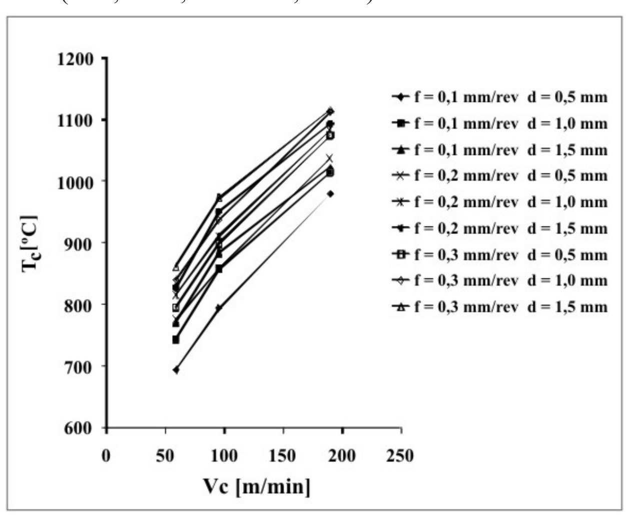

Figure 6. Cutting temperature vs. cutting speed for AISI 304 steel

The data presented in Table 4 shows the analysis of variance (ANOVA) for the main factors and are analyzed with the Minitab 14 software. Its purpose is to determine which factors are statistically significant in affecting the cutting temperature. Based on a 95% confidence interval, cutting speed, feed and depth have a statistically significant impact on cutting temperature, since their p-values are smaller than 5%. Among the main effects, the cutting speed has the greatest impact on the cutting temperature, in addition to other factors, followed by feed and depth respectively.

In addition, when analyzing the influence of all the cutting variables it seems that the cutting speed has most influence over all since by increasing the cutting speed almost 225% (from 59 m/min to 190 m/min) the cutting temperature increases 34%, while an increase of 200% on the feed and on the axial depth of cut it only produces an increase of 11.14% and 7.81% on the cutting temperature respectively. Once again this result is in agreement with previous researches. (Stephenson, 1993; Chu, 1998; Astakhov, 1999).

In Figure 7 it can be observed the influence of thermal conductivity over cutting temperature for each of the studied materials while Figure 8 shows the influence of maximum strength on cutting temperature.

Table 4. Analysis of Variance with the main factors for AISI 304 stainless steel

Source	Degree of Freedom	Sum of Squares	Mean Square	*F*	*p*
Vc [m/min]	2	328658	164329	2064,63	< 0,0001
f [mm/rev]	2	41861	20930	262,97	< 0,0001
d [mm]	2	20482	10241	128,67	< 0,0001
Error	20	1592	80		
Total	26	392593			

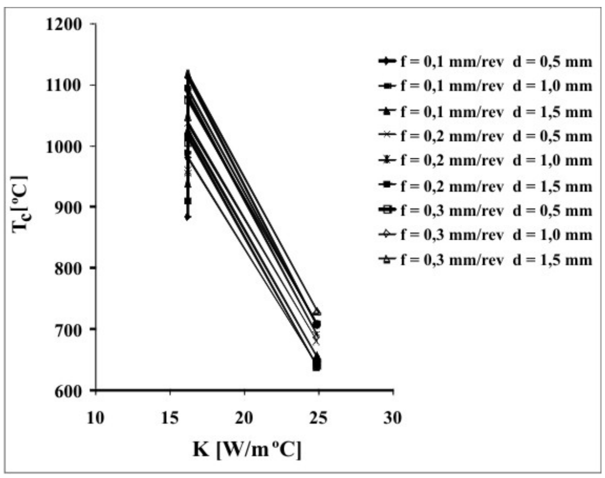

Figure 7. Cutting temperature vs. thermal conductivity when using a cutting speed of 190 m/min

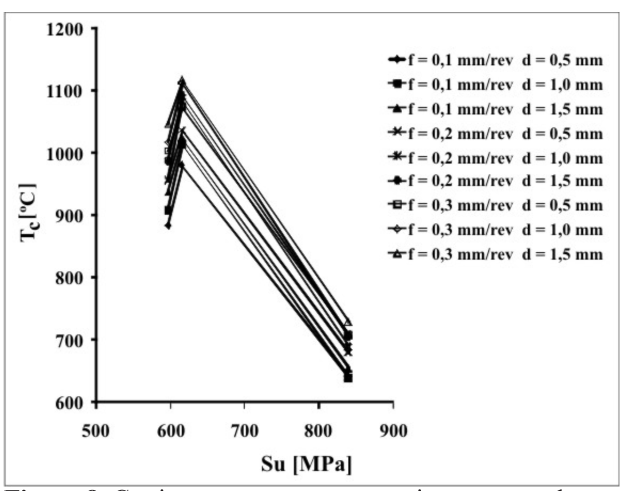

Figure 8. Cutting temperature vs. maximum strength when using a cutting speed of 190 m/min

When analyzing Figure 7 where the relationship between cutting temperature and thermal conductivity is shown, it is observed how the cutting temperature decreases with an increase of thermal conductivity. This is due to the fact that material with a high thermal conductivity value, are able to release the heat by conduction through the chips that are been removed from the workpiece (Boothroyd, 1978). Likewise the same behaviour could be observed for 59 m/min and 95 m/min cutting speeds.

The generation of heat during the metal cutting process arises the primary deformation zone at the tool workpiece interface, the secondary deformation zone at the tool-chip interface. It is reported that around 85% of the heat generated is transferred to the chip while 15% of the heat goes to the cutter and workpiece material (Chang, 2007). The high temperature occurs in the tool-chip interface. This is due to the fact that most of the energy of deformation is transformed into heat in the chips. This heat energy is subsequently dissipated in the chips, as well as in the workpiece and the tool by conduction (Majumdar, 2005).

Figure 8 shows the influence of the maximum strength over the cutting temperature. As it is observed, between 597 MPa and 615 MPa the cutting temperature increases but when having a maximum strength higher than 615 MPa the cutting temperature decreases. The expected behaviour of such graphics should be a proportional increase of the cutting temperature when increasing the maximum strength, due to the need of supplying more energy to the system to carry out the cutting process.

In our case, this result is probably due to the difference of 57.70% among the thermal conductivity values between the AISI 420 steel and the AISI 304 and AISI 316L steels. With this result it seems that apparently material's thermal conductivity has more influence over the material's maximum strength, as it will be discussed later. Likewise the same behaviour could be observed for 59 m/min and 95 m/min.

The relationship between two of the cutting parameters over the cutting temperature can be observed by using Response Surface Methodology (RSM). The results are shown in Figures 9, 10 and 11. In such graphs, it can be appreciated that the cutting temperature increases with the simultaneous increase of cutting speed and feed while the depth of the cut was kept constant when turning AISI 304, AISI 316L and AISI 420 steels.

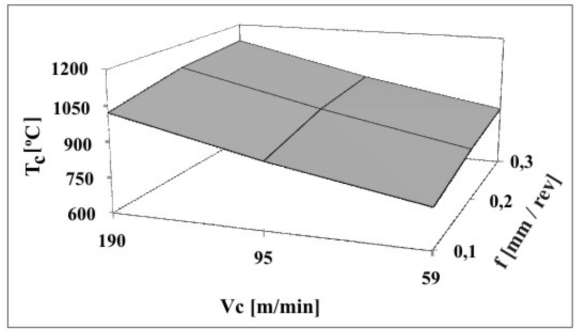

Figure 9. Cutting temperature vs. cutting speed and feed, when turning AISI 304 steel with a depth of cut of 1,5mm

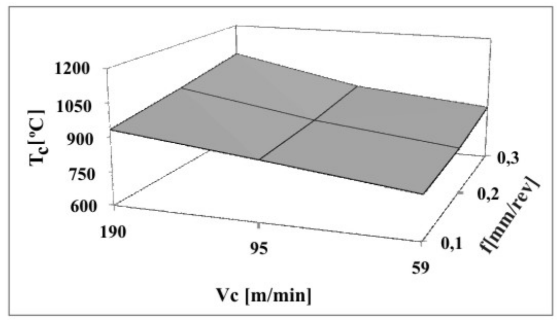

Figure 10. Cutting temperature vs. cutting speed and feed, when turning AISI 316L steel with a depth of cut of 1,5mm

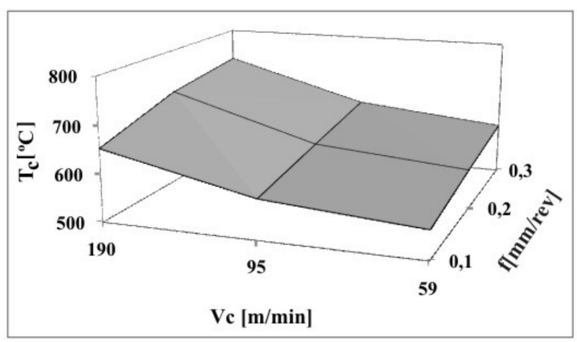

Figure 11. Cutting temperature vs. cutting speed and feed, when turning AISI 420 steel with a depth of cut of 1,5mm

Figures 12, 13 and 14, show the increase of cutting temperature with the simultaneous increase of cutting speed and depth, when turning AISI 304, AISI 316L and AISI 420 steels, while the feed was kept constant (0.3 mm/rev).

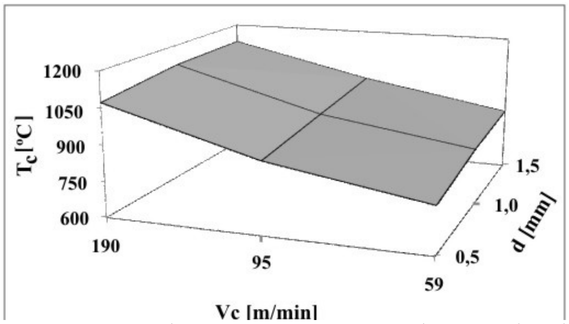

Figure 12. Cutting temperature vs. cutting speed and depth of cut, when turning AISI 304 steel with 0.3 mm/rev

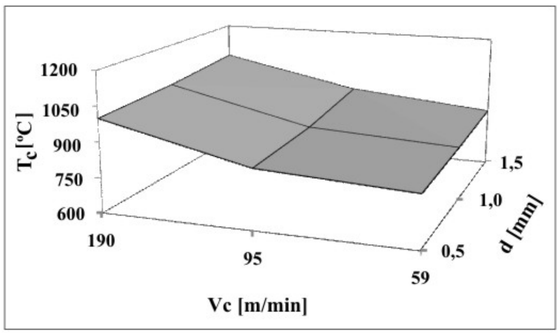

Figure 13. Cutting temperature vs. cutting speed and depth of cut, when turning AISI 316L steel with 0.3 mm/rev

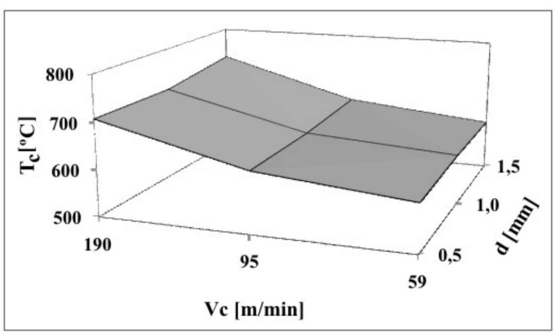

Figure 14. Cutting temperature vs. cutting speed and depth of cut, when turning AISI 420 steel with 0.3 mm/rev

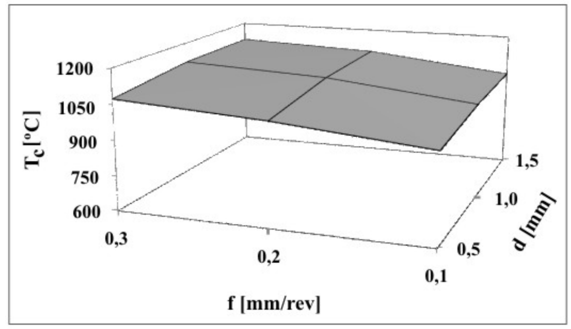

Figure 15. Cutting temperature vs. feed and depth of cut, when turning AISI 304 steel at a cutting speed of 190 m/min

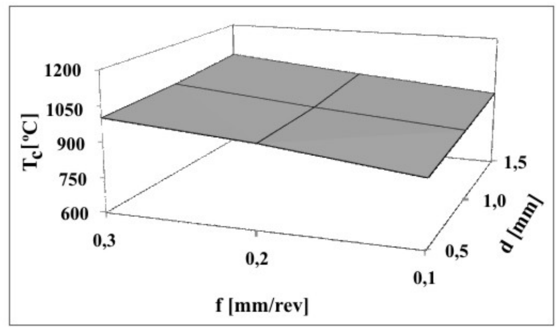

Figure 16. Cutting temperature vs. feed and depth of cut, when turning AISI 316L steel at a cutting speed of 190 m/min

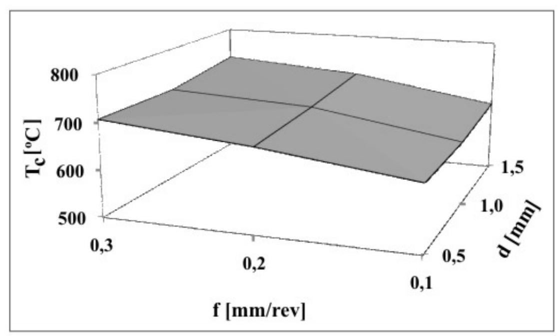

Figure 17. Cutting temperature vs. feed and depth of cut, when turning AISI 420 steel at a cutting speed of 190 m/min

Additionally, in Figures 15, 16 and 17, there is also a similar behavior of the cutting temperature by varying simultaneously the feed and depth with a constant cutting speed when turning AISI 304, AISI 316L and AISI 420 steels.

Multiple linear regression analysis was applied to obtain the empirical mathematical models. Several adjustments were studied such as linear, exponential and potential. The selection of the model was based on the one that fulfil all the statistical variables, such as the statistical variable R^2 should be close to 100% and the standard deviation (s) should be very low (close to 0).

Equations (1), (2) and (3) represent the empirical relationship between the cutting parameters on the cutting temperature for AISI 304, 316L and 420 stainless steels. The equation (4) shows a general expression for these stainless steels studied, where the maximum strength and thermal conductivity variables are included.

AISI 304:

$$T_{CT} = 338.84 \cdot V_C^{0,251} \cdot f^{0,098} \cdot d^{0,069} \quad (1)$$

$$s = 0.006251 \qquad R^2 = 99.0\%$$

AISI 316L:

$$T_{CT} = 489.78 \cdot V_C^{0,151} \cdot f^{0,065} \cdot d^{0,033} \quad (2)$$

$$s = 0.008160 \qquad R^2 = 95.4\%$$

AISI 420:

$$T_{CT} = 371.54 \cdot V_C^{0,145} \cdot f^{0,093} \cdot d^{0,020} \quad (3)$$

$$s = 0.005927 \qquad R^2 = 97.7\%$$

General expression:

$$T_{CT} = 0,0174 \cdot V_C^{0,182} \cdot f^{0,085} \cdot d^{0,040} \cdot S_u^{2,840} \cdot K^{-2,900} \quad (4)$$

$$s = 0.01339 \quad R^2 = 97.8\%$$

As it is observed the values of the coefficient of multiple determinations (R^2) for each equation are very high and close to 100%, concluding that the expression presents a very reliable adjustment with reality. Also it is observed that the value of the standard deviation is extremely small, reflecting that the predicted values do not present a strong variation with the experimented values.

Additionally, it can be observed that the material's thermal conductivity is the variable that has most influence on the cutting temperature followed by the maximum strength, cutting speed, feed and by last the depth of cut.

Once the general empirical expression was developed, new combination of cutting parameters were established in order to validate this general expression.

Table 5 shows new cutting variables as well as the experimental, theoretical and error of cutting temperature.

Table 5. Theoretical, experimental and % error of cutting temperature when using equation 4

V_C [m/min]	235	118	294
f [mm/rev]	0.40	0.15	0.45
d [mm]	2	0.3	2.5
S_u [MPa]	615	615	615
K [W/mK]	16.2	16.2	16.2
T_C [ºC]	1223	904	1277
T_{CT} [ºC]	1157	869	1228
Error [%]	5.42	3.87	3.83

CONCLUSIONS

For the turning of AISI 304, AISI 316L and AISI 420 and stainless steels under the cutting conditions established, it can be concluded:
The empirical expressions showed in equations (1), (2), and (3) are reliable to predict the cutting temperature for AISI 304, AISI 316L and AISI 420 respectively.

Expression (4) allows to predict cutting temperature when turning AISI 304, 316L and 420 stainless steels.

Cutting temperature increases when increasing cutting speed, feed and axial depth of cut.

Cutting temperature increases when increasing maximum strength between 597 MPa and 615 MPa and decreases when using a maximum strength higher than 615 MPa.

As the thermal conductivity of the material (K) increases the cutting temperature decreases.

The cutting speed is the cutting parameter with most influence on the cutting temperature followed by the feed and the depth of cut.

NOMENCLATURE

d :	Depth of cut (mm)
f :	Feed (mm/rev)
fem :	Electromotive force
HBW :	Brinell hardness
p :	Probability
K :	Thermal conductivity (W/ m ºC)
R^2 :	Multiple determination coefficient
s :	Standard deviation
S_u :	Maximum strength (MPa)
T_C :	Experimental cutting temperature (ºC)
T_{CT} :	Theoretical cutting temperature (ºC)
Vc :	Cutting speed (m/min)

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