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FINITE ELEMENT MODEL FOR ANALYZING TEMPERATURE GRADIENT DURING TURNING PROCESS

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Abstract. In turning process, tool life is closely related to the thermal load generated during cutting, as it contributes to different wear mechanisms. Regarding to this and considering the difficulties associated with the measurement of temperature at the tool tip, several researchers have been working in different methods for its prediction. In this context, a finite element model was developed and adjusted with experimental data in order to predict temperature gradient during turning of a stainless steel. The obtained results demonstrated that different convection coefficients should be set for different cutting conditions and that a fixed percentage of electric motor power measured during the process can be used as an input parameter in the numerical model to predict the thermal gradient in the cutting insert.

Keywords: Finite element model, Cutting temperature, Turning

1. INTRODUCTION

Stainless steels are mainly employed in applications, which require materials with high mechanical and corrosion resistance. The addition of chromium to the steel structure contributed to its chemical inertness, but brought disadvantages to the manufacturing process, as the reduction of the tool life, which is due to the occurrence of hardening and the low thermal conductivity of this kind of material (Silva *et al.*, 2007). In this context, Camacho (2014) affirms that the cutting tool corresponds to 5% of the operation cost, but optimizations of the production process can lead to reductions of approximately 25% of the total product cost. In order to improve tool life, an important factor to be considered is the heat dissipation to the cutting insert and the highest temperatures occurring in the tool-chip interface region (Kaminise, 2012). High temperatures decrease the mechanical resistance of the insert and increase its wear. Further, a worn tool generates form errors and damages the part surface quality (Sanchez *et al.*, 2016).

Due to the cutting dynamics and the difficulty in accessing the cutting region, temperature monitoring is a difficult task. Some experimental methods consist of using thermocouples, infrared sensors, thermosensitive films, etc. (Machado *et al.*, 2009). Otherwise, temperature estimation can be obtained by analytical and numerical models. Regarding to this, finite element models (FEM) have been extensively used.

The comparison of experimental and theoretical data is relevant to assess the applicability of the model and to define if some parameter has to be adjusted. Sanchez *et al.* (2016) evaluated the temperature gradient in turning by means of a finite element model and applied different boundary conditions for each element of the cutting region. Moreover, some input parameters came from experimental data, what allowed obtaining physically consistent results.

Due to difficulties related to the determination of boundary conditions, the application of analytical models to define the heat flow to the cutting insert have been used in simple FEM models, which do not consider the chip formation process, but only a simulation of temperature distribution. Based on experimental results, different authors presented percentages of the cutting power transformed into heat and transferred to the cutting tool, workpiece and chip (Boothroyd, 1975; Ferraresi, 1982; Ghani and Abukhshim, 2008). Depending on the material specification and cutting conditions, values between 2% and 20% were reported for the cutting tool.

2. METHODOLOGY

Experimental tests (one test and one replicate) for measuring temperature and power were carried out in a CNC lathe Nardini Fast Trace (maximum power of 12 kW and maximum rotating speed of 3000 rpm). A longitudinal bar of a 304 stainless steel with diameter of 49 mm and length of 190 mm was machined with a cemented tungsten carbide cutting insert ISO grade S20 and geometry DNMG 150608, mounted in a tool holder PDJNR 2020K 15. In order to get knowledge about the influence of the cutting speed on the temperature distribution, cutting speed v_c was varied in two levels: 115 m/min and 230 m/min. Otherwise, feed $f = 0.094$ mm/rev and depth of cut $a_p = 0.5$ mm were kept constant.

The temperature was measured by type K thermocouples connected to an acquisition system National Instruments, set with an acquisition rate of 1 kHz. The thermocouples were fixed on the insert rake face and secondary flank face (Fig. 1). These specific positions were defined by preliminary tests, as thermocouples mounted in other places (main flank face and tool holder face near the insert) were removed due to chip impact during cutting.

The power measurement was performed by a Hall effect sensor Grove-Electricity, connected to an Arduino Mega 2560 acquisition board, set with an acquisition rate of 66.7 Hz.
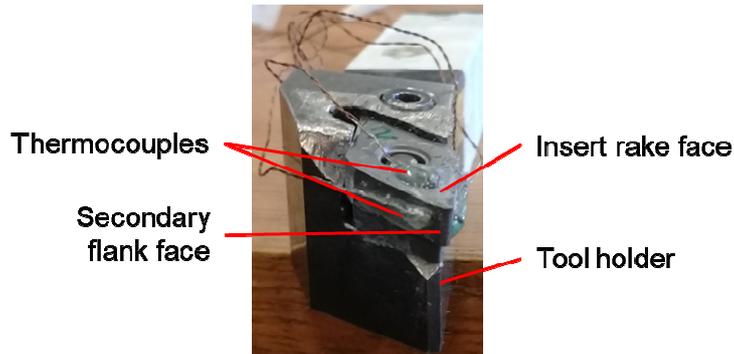

Figure 1. Type K thermocouples used in the experiments

The CAD data for the finite element simulation was taken from the manufacturer website and the meshes were created with tetrahedral elements. For the cutting insert, a mesh with 7983 elements and 13674 nodes was applied, while for the tool holder, 5613 elements and 9569 nodes were used. Cutting insert and tool holder physical properties can be seen in Tab. 1.

Table 1. Physical properties used in the finite element simulation

Object	Material	Density [kg/m³]	Specific heat [J/kg.K]	Thermal conductivity [W/m.K]
Cutting insert	Cemented tungsten carbide	4370	750	44
Tool holder	Hardened steel	7844	470	50

Material removal process is considered in the model as a thermal load, which acts on the tool during 20 s for the test with a lower cutting speed and 11 s for the test with a higher cutting speed. It was assumed that such load starts acting at the beginning of the cutting process and increases linearly up to one revolution of the workpiece, when it becomes constant. For the first case (v_c = 115 m/min), the increase of the thermal load takes 0.08 s and for the second case (v_c = 230 m/min), 0.04 s.

3. RESULTS AND DISCUSSION

The finite element model was adjusted according to the temperature curves measured at the rake face and the secondary flank face during turning with different conditions. In order to fit the curves, values of the heat transferred to the tool (thermal load), convection coefficient and thermal coupling were iterative tested. Experimental and simulated temperature curves during cutting with different conditions are observed in Fig. 2, while Tab. 2 shows the final values used in the simulations.
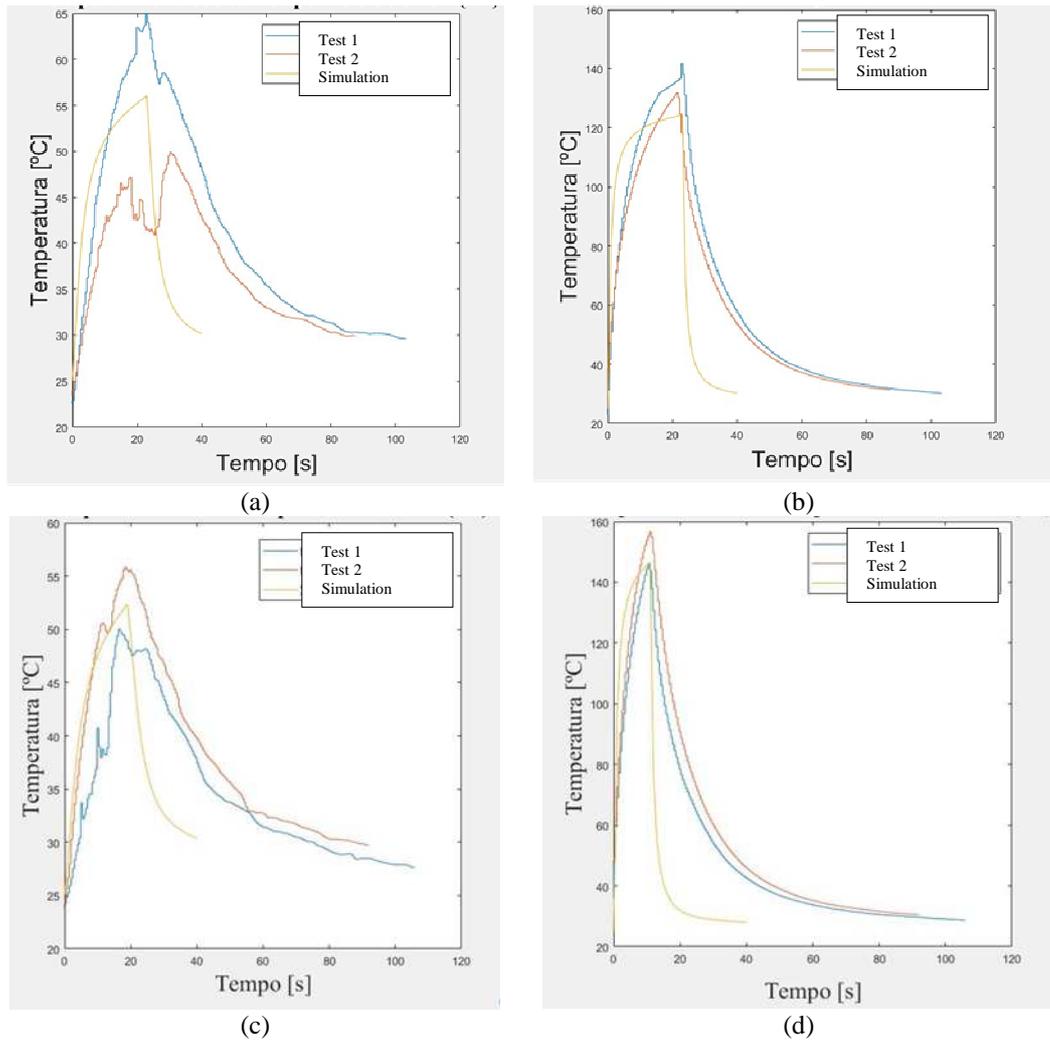
(a)

(b)

(c)

(d)

Figure 2. Experimental and simulated temperature curves for (a) rake face, v_c = 115 m/min; (b) secondary flank face, v_c = 115 m/min; (c) rake face, v_c = 230 m/min; and (d) secondary flank face, v_c = 230 m/min

Table 2. Finite element model adjusted values

Test condition	Thermal load [W]	Convection coefficient [W/m².°C]	Thermal coupling [W/°C]
v_c = 115 m/min	11 W	30	base: 200 / side: 50
v_c = 230 m/min	15 W	150	base: 200 / side: 50

Figures 2a and 2b present the curves of the turning tests performed with a cutting speed v_c = 115 m/min. As Test 2 is a replicate of Test 1, an average curve can be considered for analysis purposes. Up to the maximum temperature, an adequate fit of the simulated curve is observed. Otherwise, the temperature decrease after this point is much faster than those obtained in the experiments. Such result is explained by the use of a unique convection coefficient in the model, which contributed to the fit of the simulated curve during cutting. However, at the end of the process, the regular air flow generated by the rotating workpiece ceases, reducing the thermal exchange between tool and environment. Similar results were found for the simulations performed for the turning tests with a higher value of cutting speed (Figs. 2c and 2d).

Comparing both cases (lower and higher cutting speed), a higher maximum temperature value is noted in the secondary flank face during turning with the cutting speed v_c = 230 m/min (Fig. 2d). On the opposite, small differences between the maximum temperature values at the rake face (Figs. 2a and 2c) are observed, even considering that an increase of the cutting speed should lead to an increase of the temperature in the cutting region, as material deformation rate rises significantly. Regarding to this, two hypotheses can be raised: a strong gradient does not allow obtaining different temperatures at the measuring point for the distinct conditions; higher values of cutting speed increases

workpiece rotation, which can generate an air flow around the tool, leading to higher convection coefficients. This contributes to temperature reduction even when high cutting speeds are applied.

The latter hypothesis can be demonstrated by the convection coefficients chosen for both simulations, as it can be seen in Tab. 2. Aiming at fitting the curve, a higher coefficient value was used when a higher cutting speed was applied. The first hypothesis can be proved by the temperature gradient at the cutting insert when the maximum values of temperature at the measuring point are achieved (~23 s). Figures 3a and 3b show that temperature variation can just be noted in a distance of approximately 2 mm in any direction.
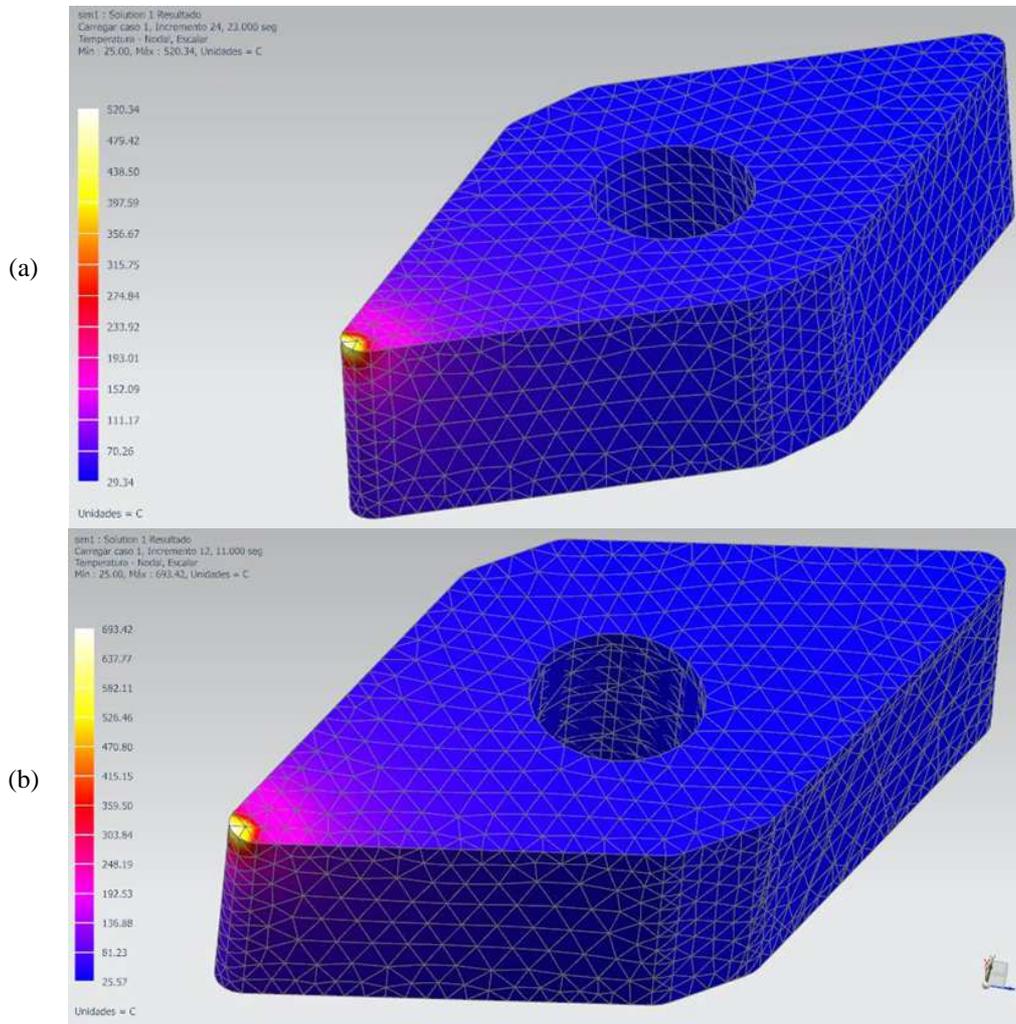

(a)

(b)

Figure 3. Simulated temperature gradient [°C] at the cutting insert during turning with (a) v_c = 115 m/min and (b) v_c = 230 m/min

With the goal of determining the percentage of energy transformed into heat and transferred to the cutting tool, turning tests were carried out and power was acquired. For the experiment with lower cutting speed, a power of 276 W was obtained, while the experiment with higher cutting speed delivered a power of 432 W. Considering the thermal loads given in Tab. 2, between 3.5% and 3.9% of the total energy consumed by the electric motor contributes to the temperature increase in the cutting insert. These similar percentage values obtained for the different situations give evidence of the robustness of the model, which is able to simulate the temperature increase considering a thermal load based on the experimental obtained electric power.

A further analysis can be performed considering the tool holder. Figures 4a and 4b demonstrate the temperature gradient in the tool holder when the maximum temperatures at the experimental measuring points are reached (~23 s). Compared to the cutting insert, the temperature values are significantly lower and a smoother gradient is noted in both cases, as well as the difference between the maximum (~50°C) and minimum (~25°C) temperature values.
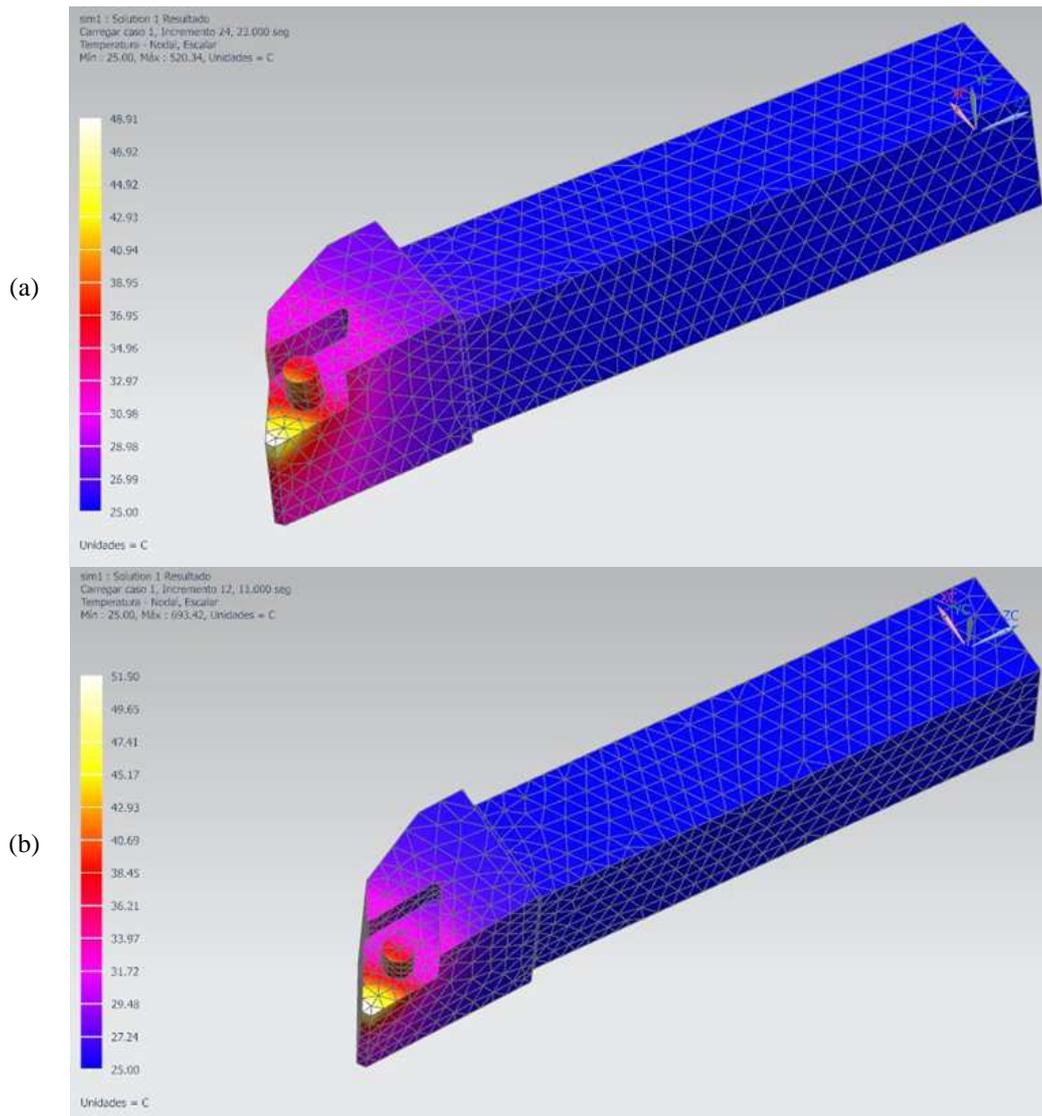
Figure 4. Simulated temperature gradient [°C] at the tool holder during turning with (a) v_c = 115 m/min and (b) v_c = 230 m/min

This means that an efficient temperature control during turning process is not possible by monitoring the tool holder, as it is not sensitive enough to detect temperature variations due to changes in cutting conditions. Otherwise, only a very restricted region of the cutting insert can provide relevant information due to the high thermal gradients found in this area.

4. CONCLUSIONS

Based on the obtained results and considering the applied conditions, it can be concluded that:
-The developed finite element model proved to be useful to predict temperature increase during cutting. In order to better estimate the temperature behavior at the end of the process (decrease of temperature), another convection coefficient should be set, as air flow around the tool changes with the rotating speed of the workpiece.
-Also due to the air flow around the tool, the temperature at the rake face did not change significantly when different cutting speeds were applied.
-The thermal gradient at the tool tip during turning was very high and an effective temperature control could only be performed in a very limited region.
-A fixed percentage (average value of 3.7%) of the measured electric power can be applied in the numerical model as the heat transferred to the tool.
-The tool holder presented approximately the same thermal gradient and temperature amplitude for the different cutting speeds applied. This means that measuring the temperature in the tool holder does not enable to monitor the cutting process.

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6. RESPONSIBILITY NOTICE

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