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A QUALITATIVE ANALYSIS OF CUTTING PARAMETERS INFLUENCE IN TEMPERATURE OF STAINLESS STEEL AISI 420C TURNING

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Abstract. *The turning process of hardened material, above 45 HRC (455 HB), has been studied frequently in order to replace the cylindrical grinding process, a slower and inflexible process. Due to the increased production necessity associated with costs reduction, the study of input parameters influence in machining is indispensable. Moreover the right parameters combination can bring benefits for both the final product and the machine, making this the motivation for the present work. A study of turning process on martensitic stainless steel AISI 420C was made considering three different cutting speeds and two different feed-rates with a fixed depth of cut. The temperature was measured as a dependent variable by embedded thermocouple into tool-holder. With the results was made an influence analysis of cutting speed and feed-rate on temperature variation during the turning process. It was possible notice that for a fixed workpiece length, as higher is the cutting speed and the feed-rate as lower is the temperature variation. It occurs because the total cutting time in turning is lower. Also was found for this experiment a better combination of parameters that contains lower temperature variation with higher material removal rate.*

Keywords: *temperature, cutting speed, feed-rate and turning process.*

1. INTRODUCTION

The turning of hardened material, above 45 HRC (approximately 455 HB), has been studied frequently in order to replace the cylindrical grinding process (slower and less flexible). The “hard turning” offers benefits when compared with grinding process like manufacture more complex products in a single step, higher material removal rate, lower machining time and lower energy waste (Dogra *et al*., 2010).

Due to the necessity of increasing production associated with the cost reduction, the study of turning parameters influence is essential. The right parameters combination can bring benefits for the final product and the machine, especially because the cutting process is a result of a physical interaction between the cut edge and the work piece (Denkena *et al*., 2012). Machado *et al*., 2011, explained the work, and consequently the heat generated, depends of workpiece material proprieties, tool material, tool geometry and cutting conditions. The heat generates at the cut region increases directly with the material removal rate Q [cm^3/min], as in “Eq. (1)”, either due to the increase of the cutting speed (v_c) [m/min], feed-rate (f) [mm/rev.] or depth of cut (a_p) [mm].

$$Q = a_p \cdot f \cdot v_c \tag{1}$$

Many authors cite that the cutting speed (v_c) is the most influential parameter in the heat generation at cut regions, followed by the feed-rate (f) (Abukhshim *et al*., 2006; Korkut *et al*., 2007).

In the machining of hardened steels, the rising temperature caused from the contact between the tool and the work piece is responsible for wear by abrasion, also others types of wear between the tool and the workpiece as diffusion and oxidation are increased. Furthermore, the temperature is the main factor that influences and is influenced by the tool wear (Diniz *et al*., 2010).

The present paper analyses qualitatively the influence of input parameters in the temperature variation of the stainless steel AISI 420C longitudinal turning process. The stainless steel is one of main materials that have been used in manufacture of critical parts and equipment due to combine favorable mechanical properties and good corrosion resistance (Jang, 1995). Besides, the martensitic stainless steel presents excellent hardenability and high hardness after quenched and tempered (Porto, 2012).

1.1 Stailess Steel AISI 420C

This material is a martensitic stainless steel with high hardenability (when hardened is can gets 55 HRC (560 HB)). It presents high concentration of alloy elements and moderated corrosion resistance, but satisfactory when exposed in moderated environment. They are magnetic materials, present high mechanical resistance and high abrasive and erosion resistance (Porto, 2012).

The AISI 420C does not present good cold conforming capacities being necessary pre-heat the material between 200 and 400 °C. It must be avoid tempering the material between 425 and 525 °C because the material becomes frailer. This stainless steel is generally used in plastic injection mold, surgical and dental instruments, steam and water valves, gas turbine, gears, shafts, among others (Favorit, 2014). "Table 1" shows the chemical composition, in percentage of mass, of stainless steel AISI 420C used in the workpieces.

Table 1. Chemical composition stainless steel AISI 420 C.

Element	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	N
Bulk [%]	0,37	0,34	0,36	0,04	0,01	12,3	0,48	0,07	0,09	0,03

1.2 Machinning Temperature

Temperature is defined as the level of molecular excitation; heat is energy in transit or a way of transfer energy through a border when subjected in temperature difference (IOPE, 2014).

The turning process involves a huge plastic deformation. Around 10% of work created in the process is stored as elastic energy and around 90% is converted in heat between the chip, tool and the workpiece. The work converted in heat in the chip/tool interface is transferred to the tool increasing the temperature near the cutting edge. Because it the hardness and the shear resistance of the material decreases (Machado *et al*., 2011), consequently decreasing the tool lifetime; also, the excessive heat created in the process has negative influences in residual stress, creating tensile residual stress on the workpiece surface (Brinksmeier *et al*., 1982).

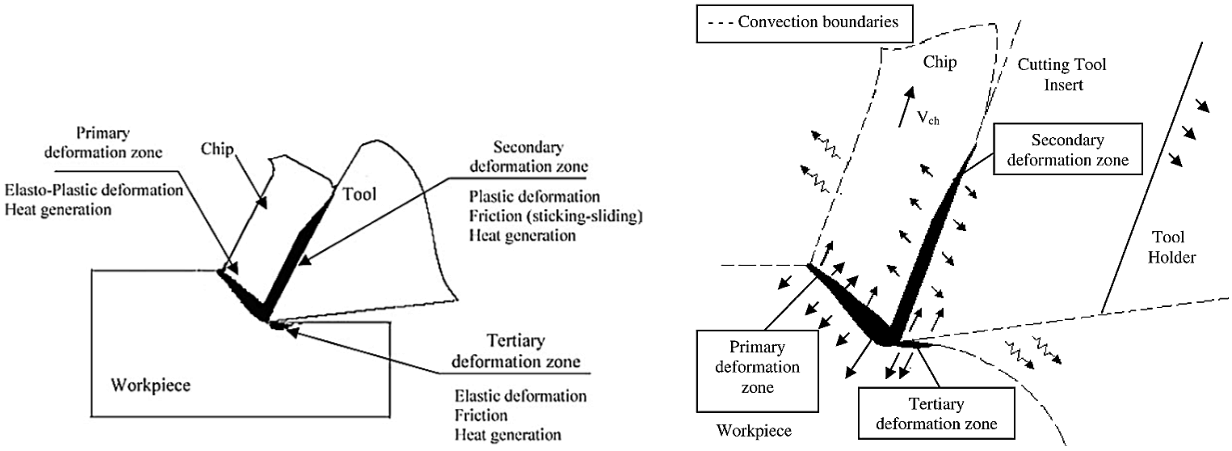
The thermal energy from the chip formation is observed in three different regions: at the shear zone or primary deformation zone; at the interface between the chip and the tool or secondary deformation zone and at the contact surface between the workpiece and the tool also called tertiary deformation zone. The heat at primary deformation zone is generated due to the plastic work at the shear plane. In the same time, the heat on both others zone (secondary zone and tertiary zone) is generated due to friction and shear between the contact surfaces (Machado *et al*. 2011). Furthermore, the heat generated on the primary deformation zone can be beneficial for the turning process because the rising temperature decreases the material mechanical resistance during the cutting time (Abukhshim *et al*., 2006). The heat generates at the secondary zone represents about 20-30% of the primary zone heat (Trent and Wright, 2000) and it has high influences about the tool performance limiting the material removal rate. The heat generated at the tertiary zone can be noticed even when the tool is not worn.

The heat generated during the turning process depends of the material and tool properties, tool geometry and cutting parameters. The study of the parameter influences in the turning process is essential for increase the process efficiency and the process cost reduction. Likewise, the cutting speed (v_c) is the parameter that most influences the heat generation at the region of cut (Abukhshim *et al*., 2006; Korkut *et al*., 2007). As the v_c increases, the cutting process becomes more adiabatic and the heat generated at the primary zone due to plastic deformation is not conducted to the tool and to the workpiece due to the short contact time between tool and chip (milliseconds) and the thermal energy is dissipated by the chip; however, the thermal energy generated at the secondary and tertiary zone causes a heat flow through the parts due to the higher contact time and it is responsible for increases the tool and workpiece temperature (Machado *et al*., 2011).

To measure the temperature and to predict the heat distribution during the machining process are very difficult due to narrow shear area, the chip obstruction and because the relative movement between tool and workpiece is continuous (Liang *et al*., 2013).

According to Machado *et al*., 2011, the measurement methods of machining temperature are divided in: embedded thermocouple, tool/workpiece thermocouple, thermal radiation, heat sensitive varnishes, metallography properties, chemical powders and PVD films. However, according to Abukhshim *et al*., 2006, the embedded thermocouples, tool/workpiece thermocouple, thermal radiation and metallography properties methods are the most utilized.

"Figure 1a" shows the three regions where the heat is generated and "Fig. 1b" shows schematically the heat transference between chip, tool and workpiece.



(a) (b)

Figure 1. Heat sources during machining process (Abukhshim *et al*., 2006)

1.3 Thermocouple

Thermocouples are devices used to measure temperature derived from potential difference (electrical voltage or electromotive forces) generated because the difference of temperature between the cold junction and the hot junction (Beckwith *et al*., 2007). The thermocouple principle is based in Seebeck effect. This effect is produced because the difference of electrons density between both conduction metals that compound the thermocouple; in other words, when two different conductors are connected each other to create the junctions and the junctions are kept in different temperatures, the electrons diffusion at the junctions is also different creating a moving of electrons in a non-electrostatic field. The curve line integral from this field through the thermoelectric pair is called Seebeck F.E.M. (Machado *et al*., 2011). The relation between F.E.M. and temperature at the junctions is converted in temperature. The tables to do the conversion follow the ITS-90 (International Temperature Scale 1990).

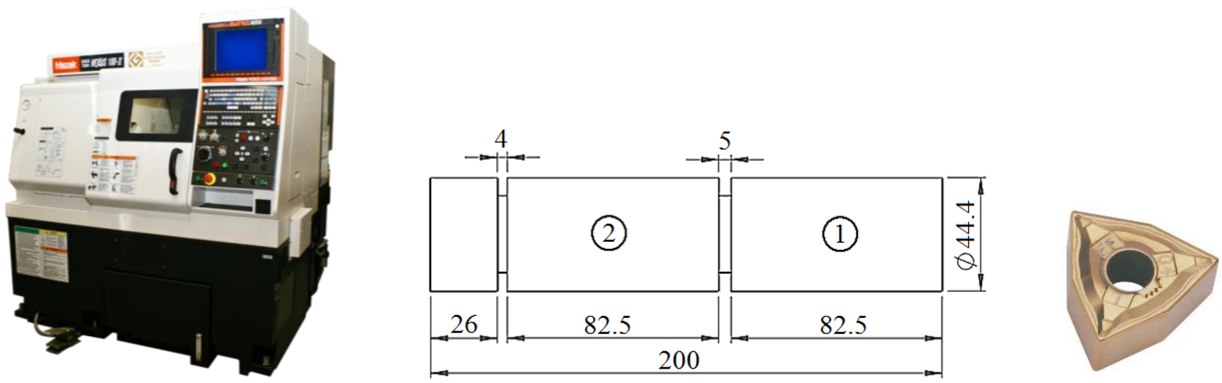
2. METODOLOGY

The experiment is characterized for a cylindrical dry turning of 12 hardened stainless steel AISI 420C workpieces. The turning experiment is composed for six different input parameter combinations and the respective duplicate.

The cutting tool used is a carbide insert and the lathe is a CNC Mazak model Quick Turn Nexus 100-II (Fig. 2a).

The development of this work required six bars of martensitic stainless steel AISI 420C hardened up to 48 HRC (455 HB). “Figure 2b” shows the workpiece dimension. This geometry combines the original test ① and the respective duplicate test ② in the same sample ensuring the same condition for both tests.

It was used two carbide inserts Seco model WNMG 060404 MF1 TS2000 and a tool-holder Sandvik model MWLNR 2020K06 with position angle χ_r = 95°. The insert has chip-former (MF1) recommended for finishing process in stainless steel, super alloys and titanium alloys. Its class (TS2000) presents high hardness micro grain, alloys elements like W, Co, Cr and C and its PVD cover is formed by (Ti, Al)N and TiN layers (Fig. 2c).



(a) (b) (c)

Figure 2. (a) Lathe CNC Mazak QTN 100-II; (b) AISI 420C workpiece; (c) carbide insert Seco WNMG.

The parameters used in the cylindrical turning are presented on the “Tab. 2”

Table 2. Parameters combinations.

a_p [mm] 0,5	**A**	v_{c1} [m/min] 60	f_1 [mm/rev] 0,1	**B**	v_{c1} [m/min] 60	f_2 [mm/rev] 0,2
	C	v_{c2} [m/min] 80	f_1 [mm/rev] 0,1	**D**	v_{c2} [m/min] 80	f_2 [mm/rev] 0,2
	E	v_{c3} [m/min] 100	f_1 [mm/rev] 0,1	**F**	v_{c3} [m/min] 100	f_2 [mm/rev] 0,2

The depth of cut (a_p) was kept constant in 0.5 mm. The parameters presented on the “Tab. 2” were specified based on the manufacturer data and it was used a maximum number of cutting speeds because the bibliography references cites that the cutting speed (v_c) has more influence in the temperature than the others parameters (like f and a_p).

A thermocouple Type J was used to measure the temperature. It has iron as positive thermo-element and constantan as negative thermos-element. The measuring data storage was realized by Field-Logger modulus using a data acquisition rate of 10 pps (points per second). The thermocouple associated errors are defined for the maximum deviation that can be presented in relation an absolute standard. “Table 3” shows the error limit for the thermocouple type J following the standard ANS MC 96.1 (1992).

Table 3. Application range and errors for thermocouple type J.

Type	Temperature Range	Error Limits		Time Constant
		Standard (choose the higher)	Special (choose the higher)	
J	0 to 750°C	±2,2°C or ±0,75%	±1,1°C or ±0,40%	0,5 s

The thermocouple response time is intrinsically associated with the system and it is presented in section 3.1. The thermocouple was inserted in the tool-holder through a small hole that enabled the contact between sensor and bottom surface of the insert. “Figure 3” shows the thermocouple position.

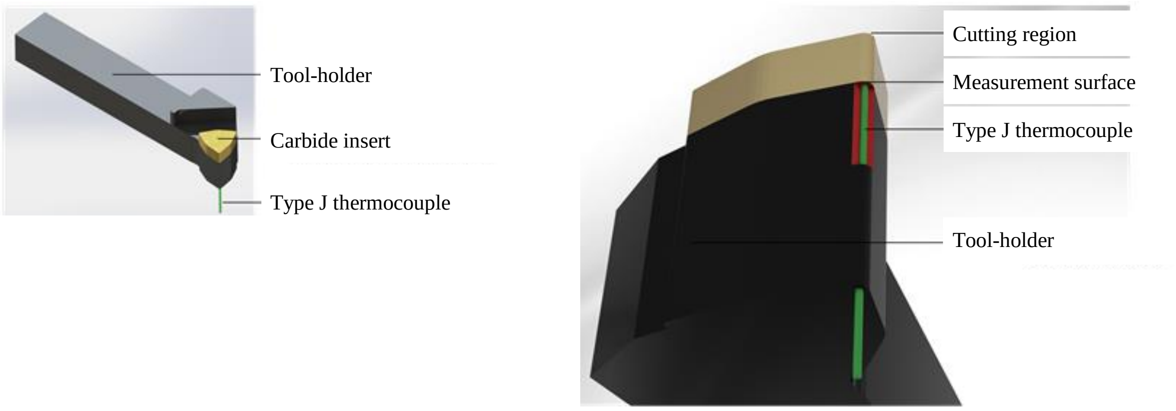


Figure 3. Tool holder and thermocouple scheme.

“Figure 4” presents schematically the connection between the thermocouple type J, the Field-Logger modulus and the computer.

The transversal chip area was measured by the digital microscope USB Dino-Lite model AM-413ZT assisted by the software Dino Capture 2.0. It has resolution of 1.3 megapixels and zoom of 200x. The chip was fixed on a base with a modeling compound which allowing the parallelism between chip surface and microscope. Then the traced polygon chip area was measure through this software.

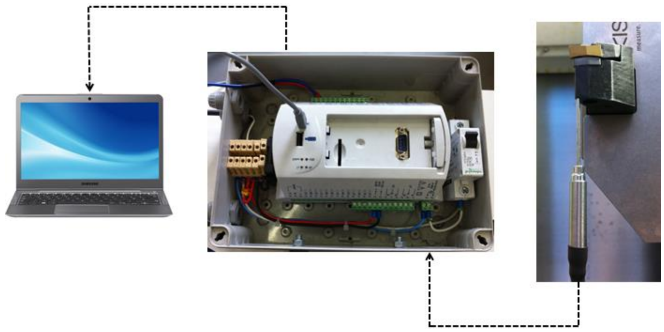


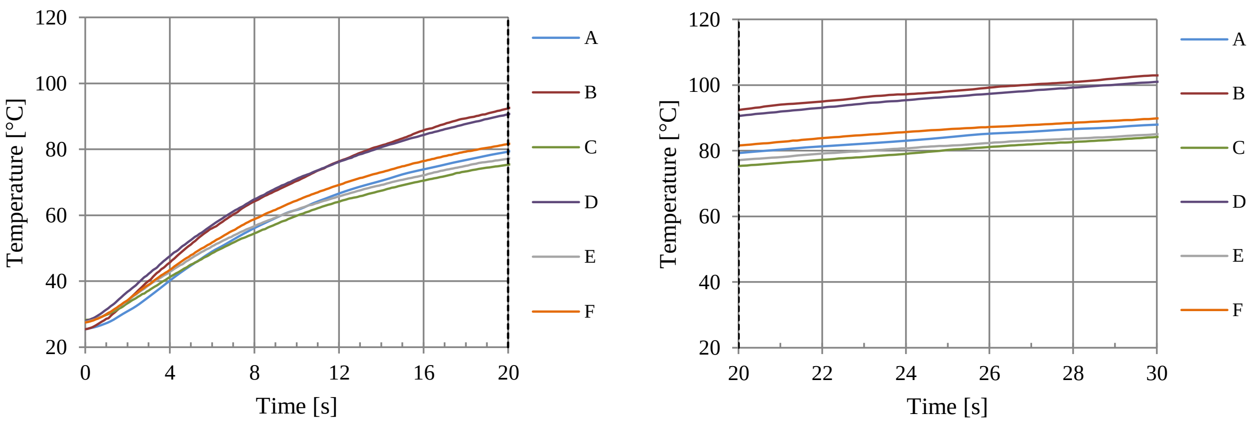
Figure 4. Thermocouple, Field-Logger and computer connection scheme.

3. RESULTS

The results were analyzed evaluating the parameters influence in the temperature detected on the bottom insert surface. The first output data analyzed was the response system time and the validation of the thermocouple type J method for all experiments. Then was analyzed the temperature variation for each one of the six parameters combinations measuring the temperature between cutting times 20 and 30 s and the maximum temperature in the end of the turning process.

3.1 Stabilization Period of Thermocouple, Insert and Sample

In order to determine if the temperature would increase and stabilize in the available length of L = 82.5 mm, the behavior of the generated graphics to the average temperature values for the six combinations of parameters (Tab. 2) was analyzed in the “Fig. 5”. The graphs were analyzed in two situations: “Fig. 5a” from the start point to the thermal system stabilization and “Fig. 5b” from the thermal system stabilization up to 33.8s (lower cutting time).



(a) (b)

Figure 5. Curves to analyze the system response time.

“Figure 5a” presented that the curves increase logarithmically until approximately 20 s for all combinations. After this instant (20 s) it was admitted the system tool holder/insert/workpiece gets thermal equilibrium. “Figure 5b” shows a linear growth from 20 to 30 s. Probably with a higher cutting time the temperature gets higher and will stabilize that, but to prove it is necessary a bigger workpiece and a cutting parameter combination that allow a higher cutting time not available in the experiment.

3.2 Cutting Parameters Influences in Temperature Variation

“Figure 6” shows the temperature variation along the turning process from 20 to 30 s for each parameter combination. The mean and the uncertainty (95% confidence, t = 2.09) for each temperature was calculated.

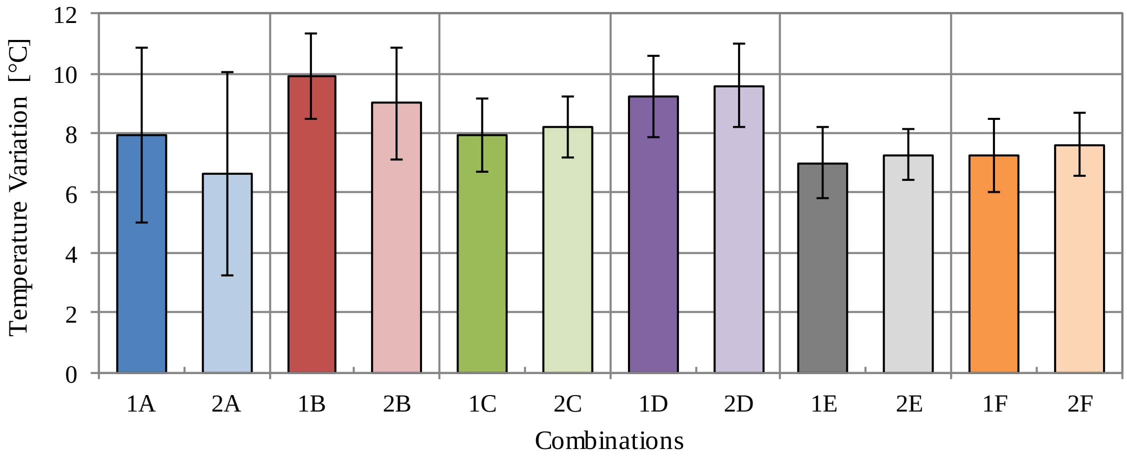


Figure 6. Temperature variation between 20 to 30 s for each parameter combination.

"Figure 7" shows the percentage temperature variation when the feed-rate (*f*) is increased from 0.1 to 0.2 mm/rev. keeping the cutting speed (v_c) constant. It was possible to notice the temperature increased while the *f* was increased 30%, 17% and 4% for the cutting speed of v_c = 60, 80 and 100 mm/min, respectively. The possible explanation for this fact is because as higher is the *f as* greater is the material removal rate (Q) and as upper is the generation of thermal energy (Trent e Wright, 2000). Moreover, Machado *et al*., 2011, say that the amount of heat generated during the turning increases directly with the cutting force (F_c). As the F_c increases with the *f*, a higher *f* rise the heat generated.

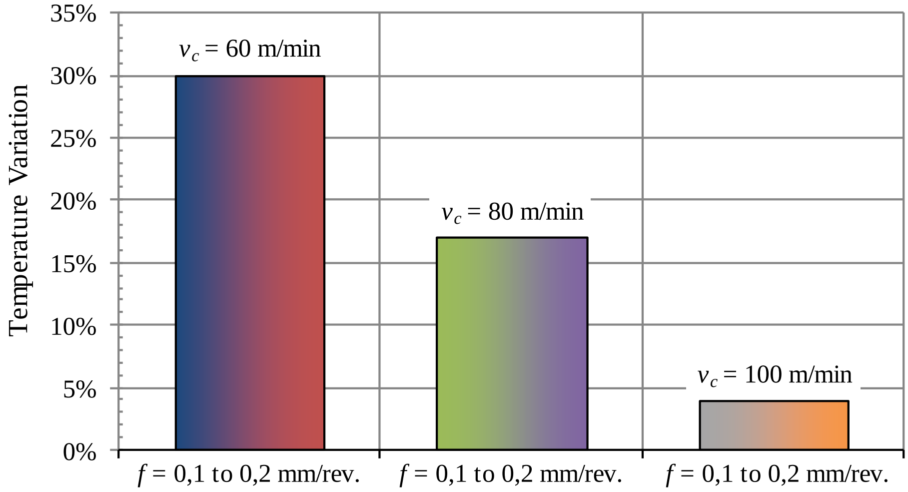


Figure 7. Percentage temperature variation for three cutting speeds while the feed-rate is increased 100%.

"Figure 8" illustrate the percentage variation of temperature when the cutting speed (v_c) increases from 60 to 80 m/min and from 80 to 100 m/min keeping the feed-rate (*f*) constant. When *f* = 0.1 mm/rev. and the cutting speed was increased from 60 to 80 m/min (33,3%) the measured temperature increases 11%, while the cutting speed was increased from 80 to 100 m/min (25%) the measured temperature decreases 11,5%. When *f* = 0.2 mm/rev., the first cutting speed variation decreases the measured temperature 0.5% and the second decreases the measured temperature 21%.

Diniz *et al*., 2010, mentioned that the percentage of total heat dissipated by the chip increases if the cutting speed also growths, in other words, the heat generated that flows to tool decreases when increasing the cutting speed. Furthermore, when the cutting speed increases, the friction coefficient between chip and tool decreases in consequence the chip slide easier through the tool. In other hand, a decreasing the cutting speed promotes an increasing in the friction coefficient between chip and tool, consequently the heat generated also increases. This friction makes the workpiece material stick on the tool as shows in the "Fig. 9".

Other hypothesis for the temperature decreases is the reduction of the chip deformation with the increase of the cutting speed: as lower is the material deformation on the primary zone, minor is the heat generated. "Figure 10" shows the chip transversal area generates with feed-rate *f* = 0.2 mm/rev. in three different cutting speeds.

The transversal section area on the undeformed chip is calculated by $A = a_p \cdot f = 0.1\ \text{mm}^2$. The deformation can be quantified by the coefficient between the measured area and the theoretical area (A), so it is possible to conclude that higher deformation energy is generated with v_c = 60 m/min (R_{60} = 2.24) consequently higher heat is generated and the reverse phenomena is also valid.

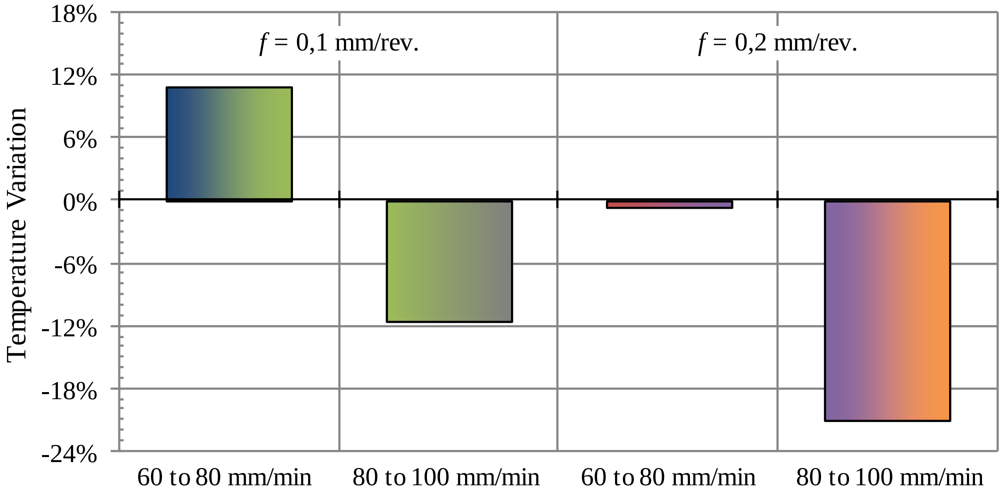
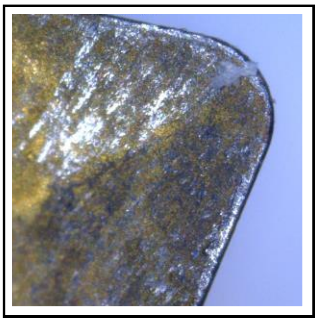
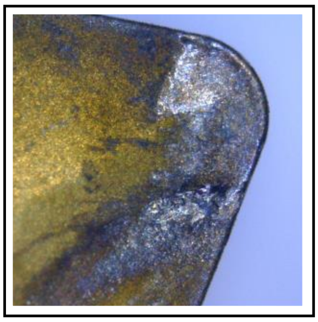


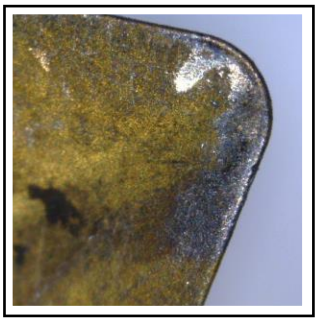
Figure 8. Percentage temperature variation for each feed-rate while the cutting speed is increased 33.3% and 25%.



(a) v_c = 60 m/min

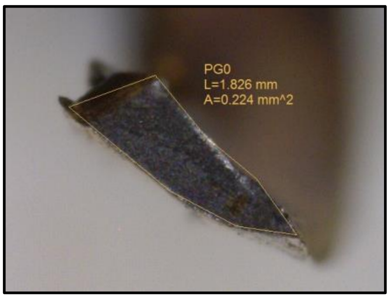


(b) v_c = 80 m/min

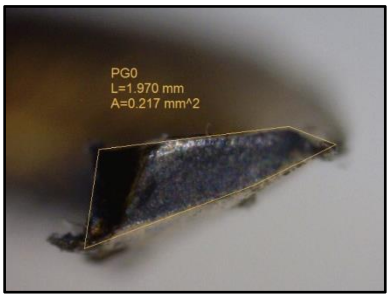


(c) v_c = 100 m/min

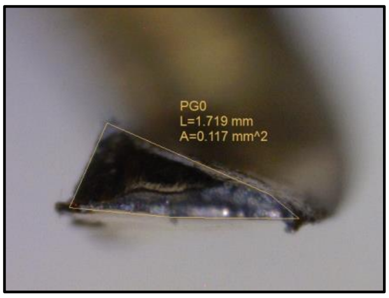
Figure 9. Relief surface images obtained by AM-413ZT digital microscope (zoom 200x).



(a) v_c = 60 m/min



(b) v_c = 80 m/min



(c) v_c = 100 m/min

Figure 10. Traced polygon in transversal section images acquired by AM-413ZT digital microscope and assisted by the software DinoCapture 2.0 (zoom 200x).

Taking the hypothesis described by coefficient between areas, it is possible to say even increasing the heat generation due to increase of the material removal rate (Q) the tool not necessarily experienced a high temperature, because the heat removal mechanisms, mainly the chip, helped a lot with heat dissipation.

"Figure 11" illustrates the graphs of the cutting speed influence, the feed-rate and the combination between both in the temperature for the time from 20 to 30 s. It is possible to notice that the feed-rate was the input parameter with more influence (20.2%) in the temperature during 20 and 30 s. The cutting speed influence was moderated (9.5%) and the combined effect (v_c and *f*) showed the lower influence (4.6%) in the temperature.

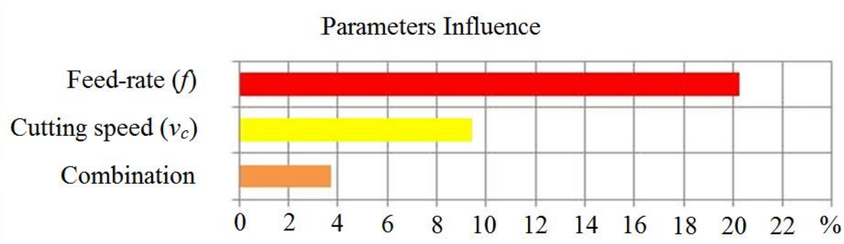


Figure 11. Percentage influence of the input parameters in the temperature for the time between 20 and 30 s.

"Figure 12" illustrates the temperature variation reached in the process during the time 20s and the end of the cut. In other words, the graph shows the variation between the higher temperature and the initial temperature for each parameter combination of "Tab. 2". The average and the uncertainty (confidence of 95%, t = 2.09) of each temperature was calculated taking 10 points for each test submitted in the same turning conditions.

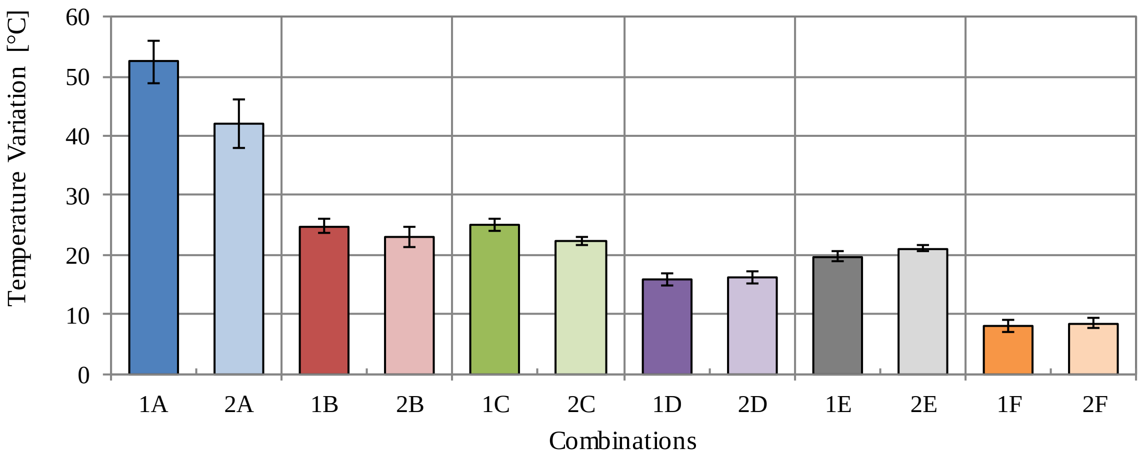


Figure 12. Temperature variation for the time between 20s and cutting time (t_c) for each parameter combination of "Tab. 2".

It is possible to detect in all combination presented at "Fig. 12" that as higher is the cutting speed (v_c) as lower is the temperature variation measured by the system – exception in **D** combination. Likewise, it is likely to observe as higher is the feed-rate as lower is the temperature variation. One hypothesis is: as the feed-rate increases the turning process time decreases significantly generating lower contact time between tool and workpiece, and consequently, the maximum measured temperature decreased.

"Figure 13" presents the measured temperature average for the workpieces 1 and 2 for each parameter combination given the cut length L = 82.5mm.

Analyzing the results given in the time from 20 to 30 s (Fig. 6) and the temperature variation given the time between 20 s and cutting time (t_c) for each combination (Fig. 12), it was perceive a contradiction in the temperature variation when changed the feed-rate (*f*). In the first case, as higher was the *f* as higher was the temperature. In other hand, in the second case, as higher was the feed-rate as lower was the maximum temperature. By the "Fig. 13" is possible observe this fact, where the **B**, **D** and **F** combinations got higher temperature faster but does not get so high temperatures when compared with the **A**, **C** and **E** combinations, respectively, because the cutting operation was concluded faster. Emphasizing, the measured temperature does not, necessarily, represent the temperature in the interface tool/workpiece. This result suggests that when using the maximum feed-rate permitted by the insert, higher will be the rising temperature rate, in other words, the temperature gets higher levels in shorter times. However, as all workpieces had the same length L=82.5mm, the maximum temperature decreases as the cutting time (t_c) reduces.

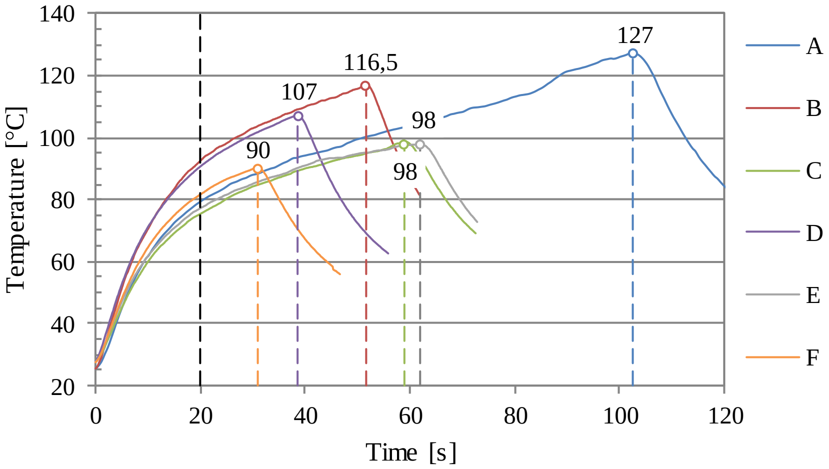


Figure 13. Temperature vs all parameter combination used in the.

Comparing the extremes, **A** (v_c = 60 m/min; f = 0.1mm/rev.) and **F** (v_c = 100m/min; f =0.2 mm/rev.) combinations, is possible perceive a reduction in the cutting time (t_c) from 112.5 s to 33.8 s (232.8%). Moreover, the material removal rate (Q) increases 233.3% with reduction on the temperature variation from 47 °C (**A**) to 8 °C (**F**) or 487.5%.

4. CONCLUSIONS

The paper got successful conclusions about the temperature variation during the turning process of AISI 420C hardened stainless steel.

Analyzing all parameters combination used, the **F** combination (depth of cut a_p = 0.5 mm, cutting speed v_c = 100 m/min and feed-rate f = 0.2 mm/rev.) presented the best results along the experiments. This combination produced the lower temperature variation and the higher material removal rate with shorter cutting time. The variance test shows that the feed-rate (f) has higher impact in the temperature variation than the cutting speed (v_c).

The increase of temperature when the feed-rate (f) is increased probably because as higher is the f *as* greater is the material removal rate (Q) and as upper is the generation of thermal energy ted. For the increase of the cutting speed (v_c) in some cases (When f = 0.1 mm/rev with increase of 80 to 100 m/min and for f = 0.2 mm/rev and both variations of 60 to 80 m/min and from 80 to 100 m/min) the measured temperature decreases probably because total heat dissipated by the chip increases if the cutting speed also growths decreasing the heat on the tool. Also this increase can decrease the friction coefficient between chip and tool.

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