STUDY OF THE VARIATION OF MECHANICAL PROPERTIES AND CUTTING FORCES AS AN EFFECT OF MACHINABILITY IMPROVEMENT

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Abstract: The term machinability describes the workpiece aptitude to be machined by metal removal. It is a not inherent characteristic to the workpiece, because of the participation of more variables in the cutting process. Certain chemical elements are usually added in the composition of the steels, in order to reduce the friction between workpiece and tool and to increase the tool life, improving the machinability of the steel. However, these additions can encourage changes in the mechanical properties of the steels, as well as in the heat treatments applied. At the same time, changes in the mechanical properties could modify the cutting requirements, like cutting forces. The sort of cutting process could be a determining factor. A study with two AISI 4140 steels, with different machinability, has been carried out in order to determine differences between the mechanical properties, quenching and cutting forces, when they are machined by a non-continuous cutting process, like milling.

Key words: Machinability, milling, mechanical properties, cutting forces.

1. INTRODUCTION

Modern manufacturing processes are kept under a constant innovation (Raymond & St-Pierre, 2010), with the purpose of improving the productivity rates and reducing the production costs, with no loss of quality in the final product. This behaviour can mean the survival before the present crisis.

In the machining processes, the term machinability refers to the ease with which a metal can be machined to an acceptable surface finish (Degarmo & Black, 1994). Machinability improvements involve the reduction of the tool wear, cutting forces, cutting temperatures, and a better control of the chip. On the whole, machinability improvement can produce a significative improvement of the surface finish.

In the steels, the process of adding non-metallic inclusions, like MnS, and other specific inclusions, causes a series of effects that can improve its machinability. According to the scientific literature, these inclusions are able to reduce the friction between tool and workpiece, due to the formation of a lubricating layer. Thanks to this layer, cutting forces can be reduced, as well as the tool wear mechanisms because of abrasion, adhesion and diffusion (Hamann et al., 1996), (Arrazola et al., 2008), (Bittes et al., 1995).

The study of cutting forces, friction coefficients, lubricants or temperatures in the cutting area (Childs, 2006), (San Juan et al., 2010), (Gaitonde et al., 2008), (Ebrahimi & Moshksar, 2009) let to know if variations in the chemical composition of one steel can produce its machinability improvement.

On the other hand, the elements used in the inclusions can modify the mechanical properties of the steel, as well as the effects of the heat treatments, like quenching. Furthermore, it would be interesting to determine if the change of the mechanical properties has an influence on the machining requirements, like cutting forces.

The present work shows the study of two steels AISI 4140, with different machinability obtained from the addition of non-metallic and specific inclusions.

Literature review shows different researches in which the machinability improvement has been studied in continuous cutting processes, like turning, under orthogonal cutting conditions. Researchers conclude that friction, cutting forces and cutting temperature are lower in the steel with non-metallic inclusions and other specific inclusions (Garay et al., 2008), (Arriola et al., 2011). However, in order to complete the researches, it would be useful to determine if the change of the mechanical properties, caused by the machinability improvement, has the same effect in a non-continuous cutting process, like milling, where the undeformed chip thickness is function of the angular position of the tool, and the tool insert works in cyclical mode.

Changes in the mechanical properties and heat treatments behaviour of two steels with different machinability will be researched, just like cutting forces in slot milling process under orthogonal cutting conditions.

2. NOMENCLATURE

- F_c: cutting force (N).
- F_r: radial force (N).
- R: resultant cutting forces (N)
- f: feed per revolution (mm/rev).
- f_t: feed per tooth per revolution (mm/rev).
- V_c: cutting speed (m/min).
- h: chip thickness (mm).
- φ: angular position of the tooth (deg).
- F_m: maximum load (N).
- R_m: tensile strength (MPa).
- R_p: yield stress (MPa).

3. EXPERIMENTAL SET-UP

3.1 Materials

Two different machinability steels, 42CrMo4 type, with quenched and tempered state, have been used as workpiece materials. These are: AISI 4140 standard and AISI 4140 plus. The chemical composition of both steels is shown in Table 1.

Table 1. Chemical composition (%) of the workpiece materials

Steel	C	Mn	Si	S	Cr	Ni	Al	Cu	Ca
4140 standard	0.40	0.81	0.33	0.026	0.97	0.10	0.023	0.23	-
4140 plus	0.44	0.86	0.23	0.073	1.06	0.20	0.005	0.18	> 15 ppm

The main different between both steels is that in the AISI 4140 plus, it has been induced a machinability improvement effect, by means of MnS inclusions and specific inclusions of $CaO\text{-}MnO\text{-}SiO_2\text{-}Al_2O_3$.
According to previous researches, these inclusions let to reduce the abrasion effect in the tool-chip contact area, as well as the reduction of the friction and the appearance of non-metallic protective layers on the tool.
Table 1 shows the presence of calcium content in the AISI 4140 plus steel as well as high sulphur content.

3.2 Metallographic and microstructure analysis

In order to prove the presence of the non-metallic inclusions, a metallographic analysis of both steels were carried out. Figure 1 shows the metallographic appearance of a longitudinal section of the AISI 4140 standard steel. It is possible to appreciate the presence of MnS deformed in the direction of the rolling process.

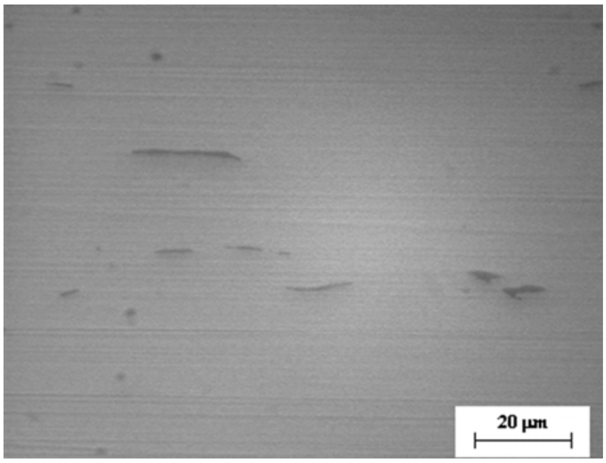

Fig. 1. Metallographic image (AISI 4140 standard steel)

In the case of the AISI 4140 plus steel, Figure 2 shows a higher content of deformed MnS, as consequence of the addition of sulphur in order to improve its machinability.

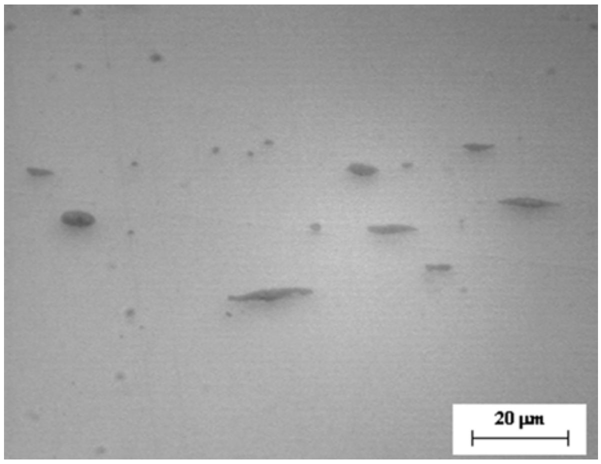

Fig. 2. Metallographic image (AISI 4140 plus steel)

Afterwards specimens of both steels were treated with *nital*, in order to reveal the microstructure. Both steels show a partially tempered martensite microstructure, with no significant differences between both. In Figure 3 and Figure 4 it is possible to recognize needles of untransformed martensite (marked with white arrows).

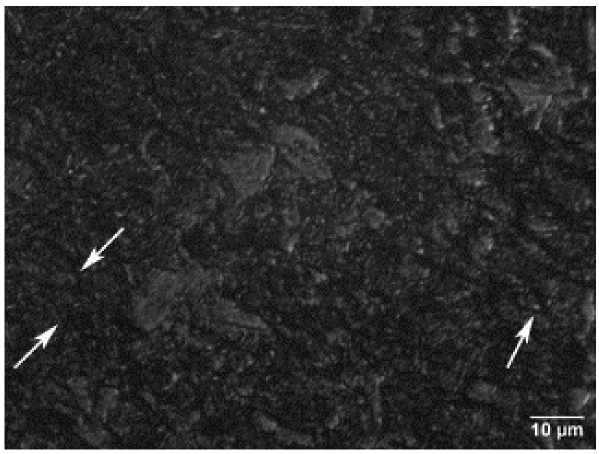

Fig. 3. Microstructure of the AISI 4140 standard steel

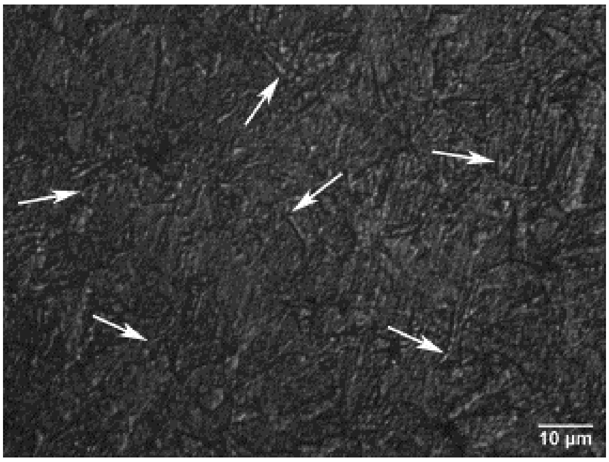

Fig. 4. Microstructure of the AISI 4140 plus steel

3.3 Mechanical characterization

Workpiece materials were suministred by the steel manufacturer with a form of cylindrical bar of 85 mm of diameter. In order to determine differences in the ability of both steels to be hardened in depth by quenching, the bar was divided in 7 parts. One of them was obtained from the center of the bar, and the others were obtained from the periphery of the bar (Fig. 5).

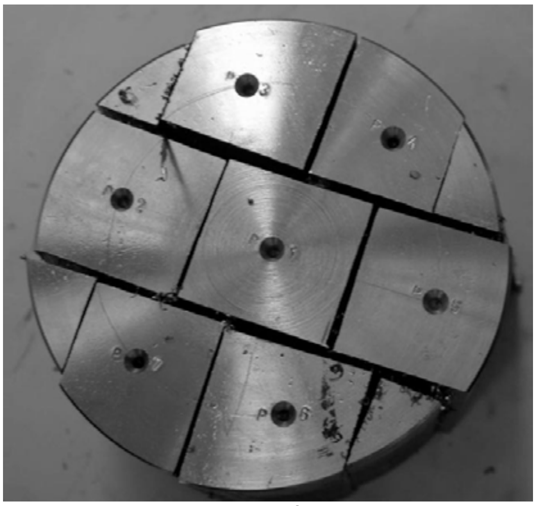

Fig. 5. Division of the steel bar

Every part was machined by a lathe in order to obtain a cylindrical test specimen, with the dimensions shown in Figure 6.

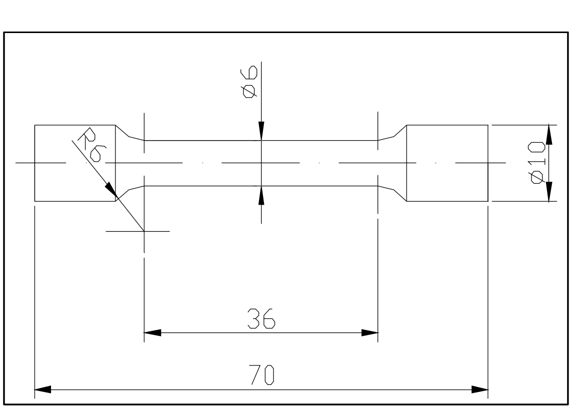

Fig. 6. Tensile test specimen dimensions

Figure 7 shows the obtaining process of the test specimens, from the original cylindrical bar.

Fig. 7. Division of the steel bar

With the aim of characterizing the mechanical properties of the workpiece materials, series of tensile tests were carried out, by means of an electromechanical test machine, with a calibrated load cell and a calibrated extensometer (Fig. 8). Tests were developed according to the standard EN 10002-1:2001, with a speed of 5 mm/min.

Fig. 8. Tensile test set-up

3.4 Cutting forces measurement

The tensile tests try to find out if the machinability improvement, by means of inclusions, produces significant differences in the mechanical properties of both steel. Afterwards, the objective is to determine if these differences can cause variances in the cutting behaviour of both steels, when both are machined by a non-continuous cutting process. With this purpose, cutting forces during milling have been studied.

Slot milling tests were carried out on specimens of both steels, with dimensions of 150 mm length, 60 mm width and 3 mm thickness, under orthogonal cutting conditions (Fig. 9).

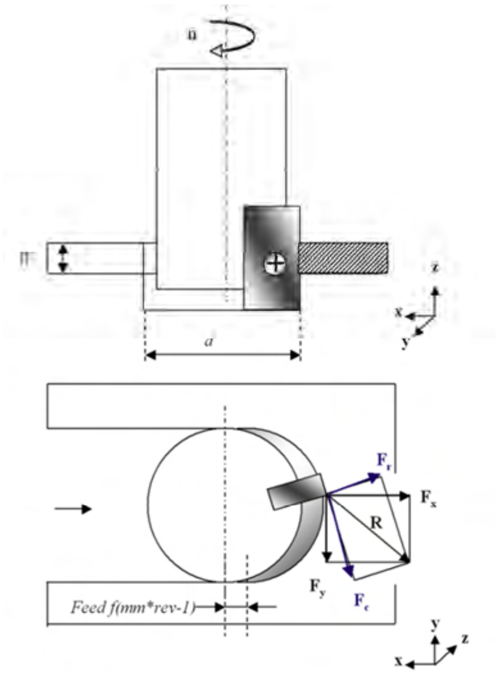

Fig. 9. Orthogonal cutting forces in slot milling

The equipment employed to measure cutting forces includes a Kistler 9124 rotating dynamometer for measuring the three force components associated to a reference system (F_x, F_y, F_z) fixed to the dynamometer, and a multichannel portable data acquisition system, 12-bit type WaveBook 512, with a Simultaneous Samples & Hold card, which allows a high speed sampling and reduces the out-of-phase between acquisition channels. Data processing was carried out by means of DasyLab.

For studying the cutting forces it is more suitable to determine the forces in a reference system fixed to the tool insert, instead of the dynamometer, in order to calculate the force perpendicular to the rake face of the tool (F_c) and the parallel one (F_r). When the reference point of the dynamometer goes through the stator, a signal is generated, so that, through the measurement of the time between this signal and the beginning of the cutting forces, the angle η, which determines the angular position of the tool related to the dynamometer (Fig. 10), is calculated.

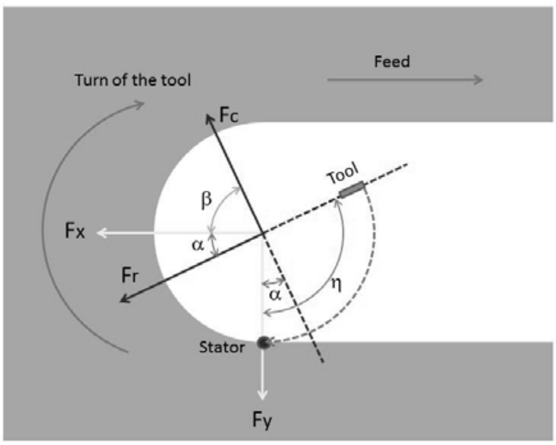

Fig. 10. Angular relationship of the systems of reference

With the angular relationship shown in Equation 1 and Equation 2, it is possible to determine the reference change matrix shown in Equation 3, which allows the direct evaluation of the force components in a single-edge tool: cutting force (F_c), radial force (F_r) and axial force (F_z).

$$\alpha = \eta - \frac{\pi}{2} \qquad (1)$$

$$\beta = \frac{\pi}{2} - \alpha \qquad (2)$$

$$\begin{pmatrix} F_c \\ F_r \\ F_z \end{pmatrix} = \begin{pmatrix} \cos\beta & -sen\beta & 0 \\ sen\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix} \qquad (3)$$

The study of axial force F_z allows to identify the goodness of the orthogonal milling hypothesis: the force system can be considered as orthogonal when obtained values of this component are lower than 5% of force R (Fig. 9). With this condition, F_z is not significant relative to F_c and F_r, and a two dimensional system of forces is considered.

The milling tests were carried out with a NC A-16 milling machine. Tool diameter was 20 mm, with a TPKN 1603 PPTR-42 IC328 single tool insert with the following angles: cutting angle 90º, main rake angle 0º, axial rake angle 0º and radial rake angle 0º. Since it has been used a single insert, the feed per tooth per revolution (f_t) coincides with feed per revolution (f).

Machining tests were carried out without lubrication and a new cutting edge of the tool insert was used in every test.

The study of cutting forces was carried out with a cutting speed (V_c) of 200 m/min, and four feed per tooth per revolution: 0.05, 0.10, 0.15 and 0.20 mm/rev.

Figure 11 shows the temporal evolution of F_c and F_r, in one tool revolution. As it can be observed, both signals have a significant noise, due to the oscillations of the tool insert in the cutting revolution. During one revolution, in the first 90º the tool insert is machining under up-face milling condition, after this, from 90º until 180º the process is down-face milling, and, finally, in the last 180º, the tool insert is turning in empty mode.

In order to reduce the dynamic problems related to the high sensitivity of the signals when a rotating dynamometer is used, it was applied a signal filtering to data acquisition. A low-pass Butterworth digital filter, with order 2, was applied to the previously obtained cutting and radial forces, in order to suppress the frequency noise, as it is shown in Figure 12.

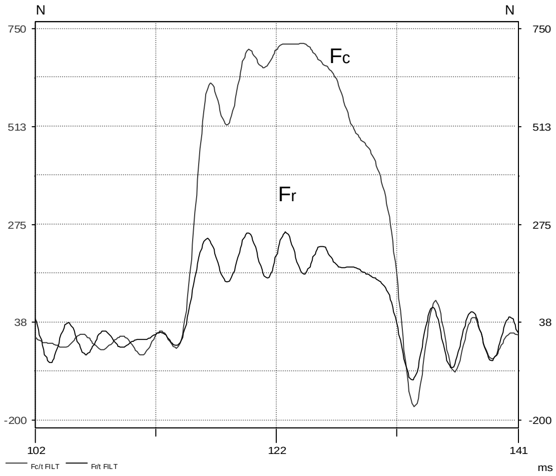

Fig. 11. F_c and F_r vs. time, without filtering

As it is shown in Figure 12, during one revolution of the tool, cutting forces are changing. At the beginning, F_c and F_r are oscillating around cero. During the first part of the revolution, both forces increase at the same time that the undeformed chip thickness put up, until this catch up its maximum value, coinciding with the maximum value of cutting forces. Afterwards, both cutting forces decrease, as undeformed chip thickness, until the end of the slot milling, where cutting forces come back to oscillate around cero.

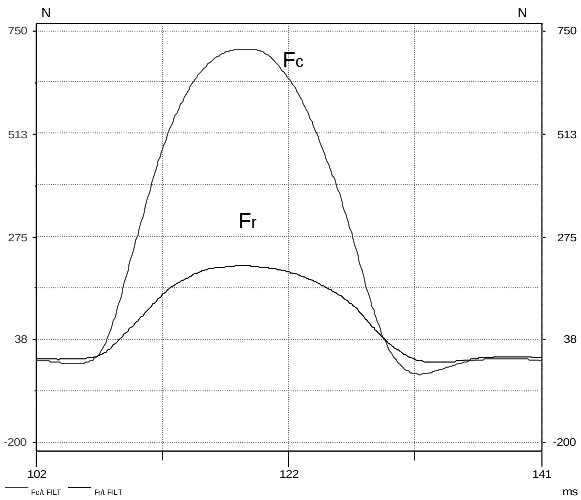

Fig. 12. F_c and F_r vs. time, with a low-pass (50 Hz, order 2) Butterworth filter

4. RESULTS

4.1 Mechanical properties

The mechanical properties studied were: maximum load (F_m), tensile strength (R_m) and yield stress (R_p).
Numerical results obtained from the tensile tests of the AISI 4140 standard steel specimens are shown in Table 2. The subscript 1 refers to the specimen obtained from the center of the cylindrical bar.
Analysing the results it is possible to appreciate that, in every mechanical property, all the values corresponding to the specimen obtained from the center of the bar, were lower than the obtained ones from the periphery. This effect is due to the ability of penetration of the heat treatment in the studied steels.

Table 2. Mechanical properties (AISI 4140 standard)

Property:		F_m (N)	R_m (MPa)	R_p (MPa)
Specimen	S_1	23475.25	798.03	618.00
	S_2	25508.85	876.30	639.05
	S_3	25443.08	887.99	638.39
	S_4	25453.20	890.70	652.39
	S_5	24634.87	851.86	632.81
	S_6	25486.67	885.98	662.90
	S_7	25308.36	877.46	639.90
Average:		25044.33	866.90	640.49
Std. Deviation:		756.86	33.03	14.23

With the purpose of grouping all the values obtained from the periphery of the bar, the average of the peripheral specimens was calculated. Table 3 shows the comparison between the mechanical properties obtained from the center of the bar and the averaged values from the periphery, in the case of the AISI 4140 standard steel.

Table 3. Center vs. peripheral specimens results (AISI 4140 standard)

Property:	F_m (N)	R_m (MPa)	R_p (MPa)
Center:	23475.25	798.03	618.00
Periphery (average):	25305.84	878.38	644.24

Differences between center and periphery show reductions for the center specimen, close to 8% in the maximum load, 10% in the tensile strength and 4% in the case of the yield stress.

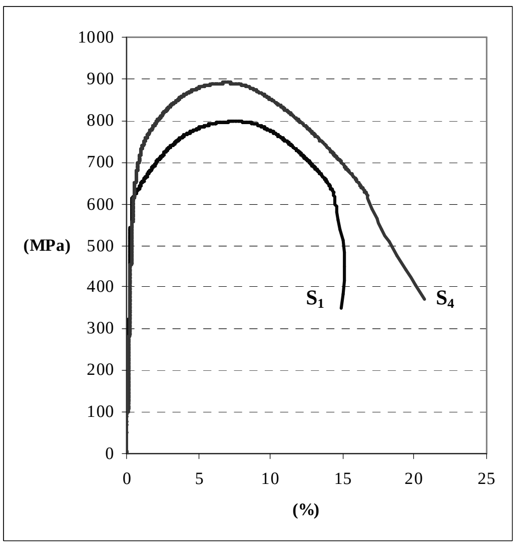

Fig. 13. Stress-strain curves (AISI 4140 standard steel)

Figure 13 shows the maximum stress-strain curve (belonging to the specimen number 4, from the periphery of the bar), and the minimum stress-stain curve (belonging to the specimen obtained from the center of the bar), in the case of the AISI 4140 standard steel.

A similar effect on the reduction of the mechanical values in the center specimen of the bar was observed in the case of the AISI 4140 plus steel, except for the yield stress. Table 4 shows the tensile tests results.

Table 4. Mechanical properties (AISI 4140 plus)

Property:		F_m (N)	R_m (MPa)	R_p (MPa)
Specimen	P_1	26730.39	923.11	754.45
	P_2	27512.19	935.26	730.84
	P_3	27986.22	961.40	758.19
	P_4	27923.15	954.25	749.32
	P_5	27304.54	929.42	733.29
	P_6	27917.01	945.31	731.32
	P_7	28452.71	954.71	742.66
Average:		27689.46	943.35	742.87
Std. Deviation:		559.23	14.41	11.40

In this case, the differences of the maximum load and tensile strength, between the center and the periphery of the bar, were close to 4% and 3%, respectively. Yield stress turned out to be 2% high in the specimen of the center, on the contrary (Table 5).

Table 5. Center vs. peripheral specimens results (AISI 4140 plus)

Property:	F_m (N)	R_m (MPa)	R_p (MPa)
Center:	26730.39	923.11	754.45
Periphery (average):	27849.30	946.73	740.94

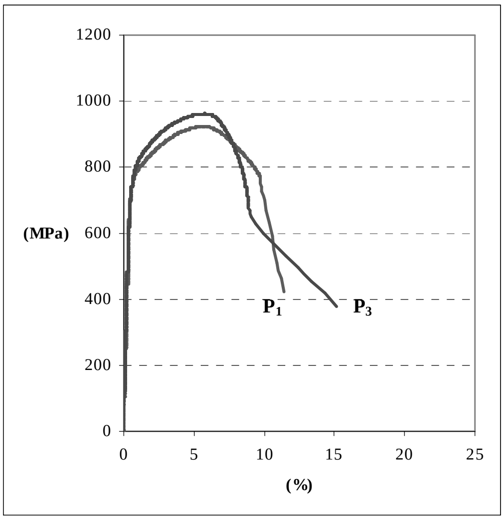

Fig. 14. Stress-strain curves (AISI 4140 plus steel)

Figure 14 shows, for the AISI 4140 plus steel, the same behaviour in the evolution of the stress-strain curve, obtained with the AISI 4140 standard steel. Now, it is possible to appreciate that maximum and minimum strain-stress curves are nearby, as well as a reduction of the elongation in comparison with the stress-strain curve of the AISI 4140 standard steel.

Making a comparison of both steels with different machinability, it is possible to point out the next evidences:

- In the case of the AISI 4140 plus steel, mechanical values obtained from the tensile tests, were higher than the obtained ones from the AISI 4140 standard steel. Maximum load, tensile strength and yield stress were, with regard to the center specimen, 14%, 16% and 22% higher, respectively; and with respect to the average of the peripheral specimens, they resulted 10%, 8% and 15% higher, respectively.

- The highest difference between the mechanical properties of the center specimen and the average of the peripheral specimens were found in the AISI 4140 standard steel,

4.2 Cutting forces

The graphs represented on the Figure 15 and Figure 16, show the temporal evolution of the resultant force, calculated through the modulus of the filtered cutting forces (F_c, F_r). This force has been characterized for each feed per tooth and revolution, in the study of the AISI 4140 standard and AISI 4140 plus steels, respectively.

As it is shown, in both cases, when feed per tooth per revolution increases, the modulus of the cutting forces raises, due to the rise of the undeformed chip thickness, which depends on the angular position of the insert (φ) and on the feed per tooth per revolution, according to Equation 4.

$$h(\varphi) = f_t \cdot sen(\varphi) \qquad (4)$$

The maximum values averaged of the resultant of the cutting forces are shown in Table 6, calculated for each cutting test.

Table 6. Maximum value of the resultant of the cutting forces

f_t (mm/rev)	$\left\|R_{F_c,F_r}\right\|$ (N)	
	4140 standard	4140 plus
0.05	188	219
0.10	414	459
0.15	542	576
0.20	619	662

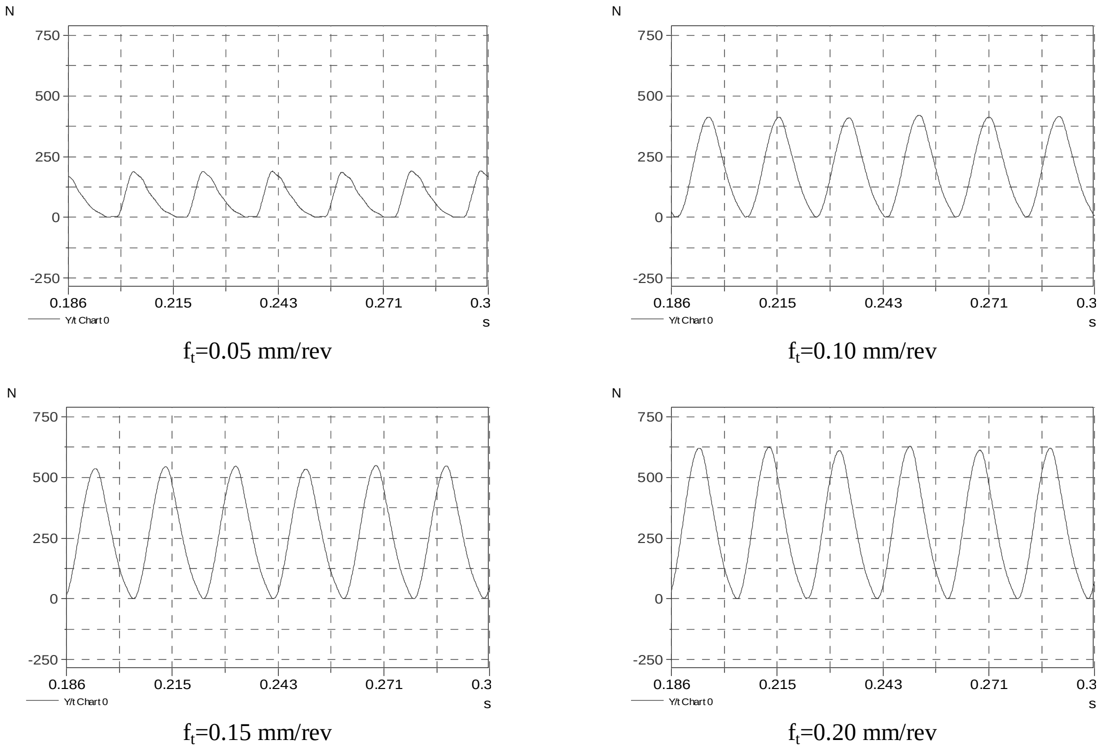

Fig. 15. Modulus of F_c and F_r vs. time, AISI 4140 standard steel, (V_c=200 m/min)

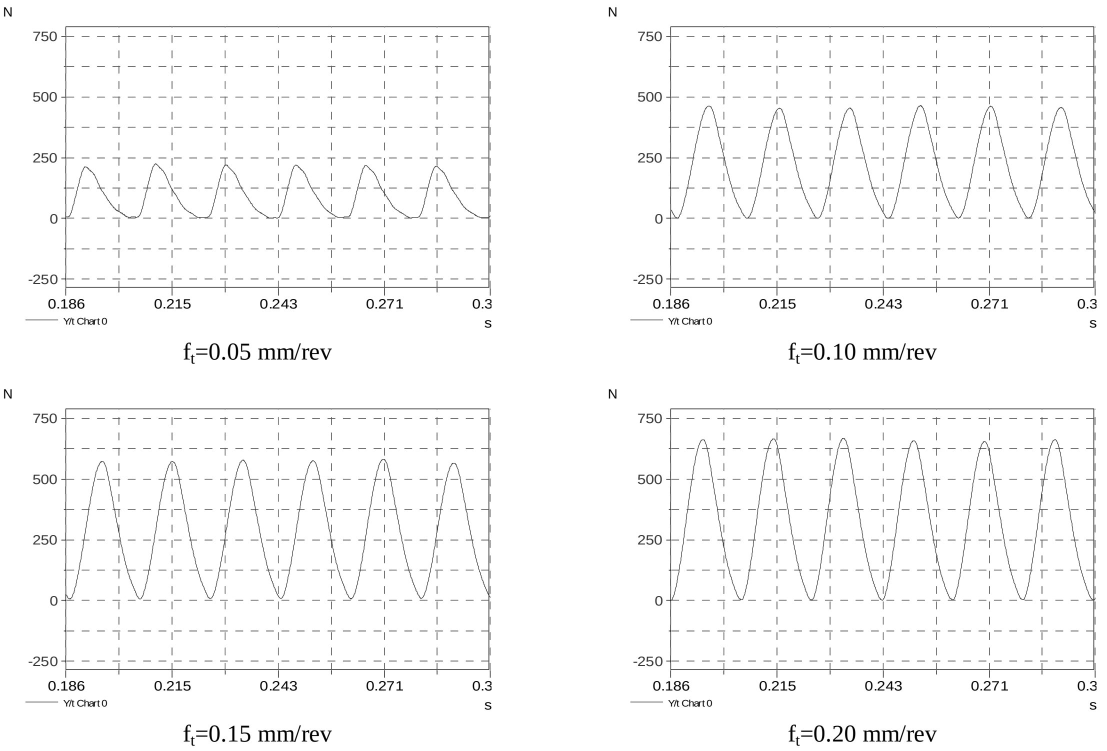

Fig. 16. Modulus of F_c and F_r vs. time, AISI 4140 plus steel, (V_c=200 m/min)

The comparison of the modulus of the cutting forces, obtained with both steels, shows that the steel with the machinability improvement demands a higher cutting force than the standard steel in all the machining tests (Fig. 17). This result supposes an opposite effect to the expected one in the literature review, where the machinability improvement by means of the addiction of non-metallic and specific inclusions must reduce the cutting forces as consequence of the easier shearing and lower-tool friction (Hamann et al., 1996). However, since it has been shown, the mechanical properties of the AISI 4140 plus steel are higher than the obtained ones for the AISI 4140 standard steel. This fact seems to be significant in order to determine the force requirements for a non-continuous cutting process, like milling.

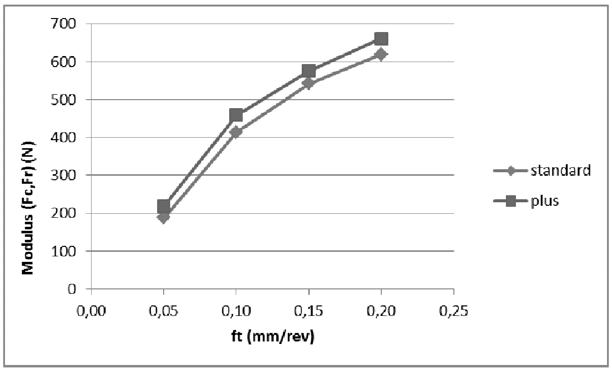

Fig. 17. Maximum values of the modulus of F_c and F_r vs. f_t (V_c=200 m/min)

5. CONCLUSIONS

Mechanical properties of two AISI 4140 steels have been studied. One of these steels has non-metallic and specific inclusions, which have been induced in order to improve its machinability. However, this sort of inclusions causes changes in the mechanical properties. As it has been shown, yield stress and tensile strength increase due to the influence of the elements of the inclusions, as well as the elongation has been reduced.

Furthermore, another significant effect achieved is related to the behaviour of the steel to the heat treatments applied. Both steels have moderate hardenability, for this reason as depth from the periphery goes on, the values of the mechanical properties decrease. However, it has been found that this reduction is lower in the steel with machinability improved than in the standard steel. The penetrative effect of the quenching is higher in the AISI 4140 plus steel than in the AISI 4140 standard, due to a high content of C and other alloy elements (Mn, Mo and Cr) that improve the machinability of the steel as well as help to penetrate the quenching effect.

With regard the cutting requirements, in the literature review, the study of the cutting forces in this sort of steels has always been carried out by means of a continuous cutting process (turning), in which the undeformed chip thickness and the cutting forces are constant during the cut. In that situation, cutting forces are lower in the steel with machinability improved. However, milling is a non-continuous cutting process, in which the undeformed chip thickness and cutting forces depend on the angular position of the tool, and in this situation, the steel with non-metallic and specific inclusions demands a higher cutting force than the standard steel. This fact is an experimental evidence to prove that the cutting process is an important part to define the machinability of steels, since the addition of inclusions can reduce the cutting force requirements, when the steel is machining by a continuous cutting process, or increase them, when the process is non-continuous, like milling.

6. ACKNOWLEDGMENT

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