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MACHINABILITY ASPECTS CONCERNING PRECISION TURNING OF STEELS

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Abstract: *The aim of this paper is to investigate the influence of feed rate on cutting forces and surface roughness when precision turning various steels using uncoated and coated cemented carbide tools. The workpiece materials used in the experimental work are AISI D2 cold work tool steel, AISI 4140 high strength low alloy steel and AISI 1045 medium carbon steel. The results indicated that, in general, the turning force components increased as feed rate is elevated and the specific cutting force decreases strongly with feed rate when cutting AISI D2 steel, however, for the machining of AISI 4140 and AISI 1045 steels the specific cutting force decreases slightly or remains unaltered as feed rate is elevated. Finally, the surface roughness produced by the two cutting tools was significantly affected by feed rate within the range tested. Best surface finish was obtained when turning the AISI D2 steel followed by AISI 4140 steel. ISO grade K15 uncoated cemented carbide tool presented best overall performance.*

Keywords*: Precision turning, machinability, cutting forces, surface roughness, cold work tool steel.*

1. INTRODUCTION

Machinability is a critical property which affects the production costs in the manufacture of engineering components. Machinability of a material may generally be defined in terms of three principal factors: cutting forces and power consumption, tool wear and machined surface integrity. Thus, a material with good machinability requires low power consumption, promotes low tool wear and produces a satisfactory surface finish without damaging the machined part. Because of the complex nature of the interactions between these parameters, it is difficult to establish quantitative relationships to define the machinability of a given material. In the shop floor, tool life and surface texture are generally considered to be the most important factors for machinability. Furthermore, the material properties possess a significant influence on the success of the machining operation. These properties and other characteristics of the work are summarized in the term machinability, which indicates the relative ease with which a material can be machined using the appropriate tooling and cutting parameters (Lima et al., 2005; Dabnun et al., 2005; Davim and Figueira, 2007; Isik, 2007 e Özel et al., 2007). Stoic et al. (2005) studied the machinability of hard materials subjected to high speed turning and evaluated the influence of the cutting parameters on the machinability index. Surface roughness, tool wear and cutting force components were used to assess machinability. The results suggested that machinability tests performed on mould steel 40 CrMnMo7 present strong influences of machinability criteria. Obtained mathematical models were used for determination of machinability index and optimization of the parameters. Applying floating-point genetic algorithm as an optimization method, it is possible to determine machining parameters with best machinability rate.
Micro-machining is becoming an important fabrication technology due to the increasing demand for miniaturized products in recent years. This is mainly driven by the needs for: greater reductions in size and weight; better efficiency in energy consumptions and higher portability in commercial and non-commercial applications. The value of many products can be substantially increased as their size and weight are reduced. The last decade has shown an ever-increasing interest in higher precision and miniaturization in a wide range of manufacturing activities. Many industrial sectors require micro-components, for instance, telecommunication, biomedical and micro-intelligent technology. Micro-machining by shearing is capable of producing high dimensional and geometric accuracy, surface finish quality and sub-surface integrity at reasonably low cost. Thus, it should be the first choice amongst various manufacturing

processes. Furthermore, conventional machining processes such as turning, milling and grinding have already been well established (Weck et al., 1997; Fang et al., 2003; Fang and Liu, 2004 e Rahman et al., 2005). On the other hand, as the feed rate and depth of cut are reduced, special attention must be paid to the cutting edge preparation, otherwise the chip will not be generated owing to the side flow effect.

Most of the experimental research concerning micro-machining has been conducted on either conventional precision machine tools or prototype machine tools built by researchers. Conventional machine tools used to precision machining have improved considerably with regard to motion accuracy, stiffness and capability. In general, micro-machining is performed on precision machine tools with power and dimensions typical of conventional machines, however, the required power and the work size are much smaller when micro-machining (Chae et al., 2006 e Dornfeld et al., 2006).

Micro-cutting of steel has recently caught research interest with the advent of miniaturized systems using a variety of materials, especially for biomedical applications. The material and geometry of micro-tools are important factors to be considered. The feature size is limited by the size of the micro-tools and tungsten carbide tools are generally suitable for machining a variety of engineering materials. The size and quality of micro-products depends on the properties of the machine tools used to produce them, including their accuracy and their dynamic performance (Chae et al., 2006).

The translation of the wealth of knowledge developed for macro-machining operations to micro-processes is critical, both for the efficient development of practical micro-processes and for the understanding of the limitations of its application. Mechanically removing material using carbide tools can produce countless desired feature shapes and sizes. The micro-cutting process is challenging; however, the experiences learned from macro-processes provide a valuable resource for future micro-machining research (Chae et al., 2006).

The principal difference between conventional and micro-machining resides in the cutting mechanism. In general, the cutting mechanism in conventional machining is mainly shearing of the material ahead of the tool wedge, resulting in chip formation. In contrast, micro-machining relies on more complicated mechanisms depending on the degree of the size effect (Dornfeld et al., 2006). Additionally, in opposition to conventional cutting, micro-machining using depths of cut in the range of micrometers cannot neglect the effect of the tool nose radius. Considerable studies that consider the nose radius in orthogonal cutting have been conducted. When the depth of cut is larger than the nose radius, the effect of the latter may be ignored. However, in micro-machining the nose radius generally affects the cutting mechanism. In spite of that, few research works are reported on this subject matter (Yuan et al., 1996; Kim et al., 1999 e Kang et al., 2007). Kang et al. (2007) presented a cutting force model able to predict the cutting force in micro-end milling, in which the tool nose radius effect is taken into account. In order to validate the mathematical model, experimental tests were performed micro-end milling aluminum with a 200μm diameter cutter.

A considerable amount of investigations has been directed towards the prediction and measurement of cutting forces. The reason for that resides in the fact that cutting forces generated during metal cutting have a direct influence on heat generation and, consequently, on tool wear, surface roughness and workpiece accuracy. Due to the complex tool configurations/cutting conditions of metal cutting operations and some unknown factors and stresses, theoretical cutting force calculations failed to produce accurate results. Therefore, experimental measurement of the cutting forces becomes unavoidable (Wang et al., 2005 e Zaman et al., 2006). On the other hand, surface roughness is predominantly considered as the most important feature of engineering surfaces due to its influence on the performance of the machined component. Compared with conventional machining, however, the quality of micro-parts is much more difficult to be controlled and the quality of micro-components became a relevant aspect of micro-machining (Wang et al., 2005).

Kim et al. (1995) showed analytically the differences in cutting forces between micro-machining processes. In the macro-model, shear takes place along a shear plane; whereas in micro-machining, the shear stress rises continuously around the cutting edge. The analytical orthogonal micro-cutting force model considered the elastic recovery of the work piece along the clearance face of the tool and the plowing effect promoted by the tool edge radius. The authors estimated the elastic effects by simulating the cutting forces based on four separate regions.

The principal aim of this work is to investigate the influence of feed rate on cutting forces and surface roughness when precision turning with uncoated and coated cemented carbide tools under dry cutting. The workpiece materials used in the experiments are cold work tool steel (AISI D2); high strength low alloy steel (AISI 4140) and medium carbon steel (AISI 1045).

2. EXPERIMENTAL PROCEDURE

Precision turning tests were conducted in order to study the influence of feed rate (f) on turning forces (cutting, feed and radial forces) and surface roughness (R_a and R_t parameters). The workpiece materials used were cold work tool steel (AISI D2); high strength low alloy steel (AISI 4140) and medium carbon steel (AISI 1045). Table (1) presents the chemical compositions and mechanical properties of these materials.

Bars with 20 mm diameter and a cutting length of 5mm were turned with uncoated cemented carbide ISO grade K15 without chip breaker (geometry code DCMW 11T3 04) and grade P25 coated cemented carbide (DCMT 11T3 04PF) tools. The coated carbide presented an Al_2O_3 coating on rake face and TiCN coating on the clearance surface (the latter produced by the medium temperature chemical vapor deposition technique). The tools were mounted on a tool holder with geometry SDJCL 2020 K11, resulting in the cutting tool angles indicated in Tab. (2). Tool wear was negligible throughout the experimental program.

Table 1. Chemical composition in % weight and mechanical properties of work materials.

Work material	C	Mn	Si	Cr	Mo	V	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Hardness (HB)
AISI D2 steel	1.55	0.50	0.30	12.0	0.80	0.90	710 1260	≥320	≥16	260
AISI 4140 steel	0.42	0.65	0.25	1.05	0.20	-	≥770	≥510	≥10	225
AISI 1045 steel	0.45	0.65	0.25	-	-	-	600 720	≥360	≥18	205

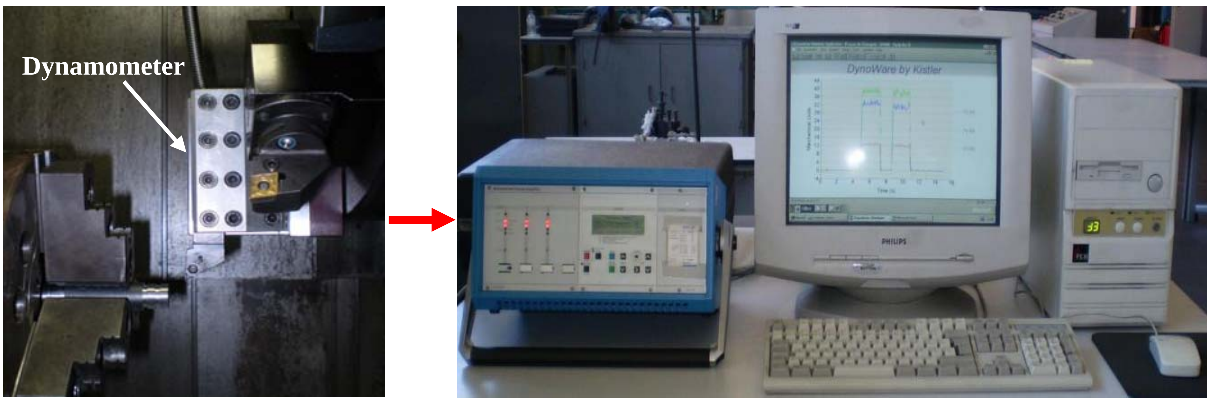
Table 2. Tools geometry.

Tool	Rake angle γ_o (º)	Clearance angle α_o (º)	Cutting edge angle χ_r (º)	Cutting edge inclination angle λ_s (º)	Tool nose radius r_ε (mm)
Uncoated ISO K15 carbide DCMW 11T3 04 H13A	0	7	93	0	0.4
Coated ISO P25 carbide DCMT 11T3 04 PF	6	7	93	0	0.4

Dry turning tests were performed on a Kingsbury MHP 50 CNC lathe with 18 kW spindle power and a maximum spindle speed of 4500 rpm. A Kistler® piezoelectric dynamometer model 9121 with a load amplifier connected to a computer was used for the acquisition of the cutting (F_c), feed (F_f) and radial (F_r) forces, as shown in Fig. (1). Kistler Dynoware® software was used for data acquisition. The specific cutting pressure (K_s) is the ratio of the cutting force to the cross section area of the undeformed chip (feed rate x depth of cut), as indicated in Eq. (1):

$$K_s = \frac{Fc}{S} \quad (1)$$

Where: K_s = Specific cutting pressure (N/mm²)
F_c = Experimental cutting force (N)
S = Shear plane area (mm²)



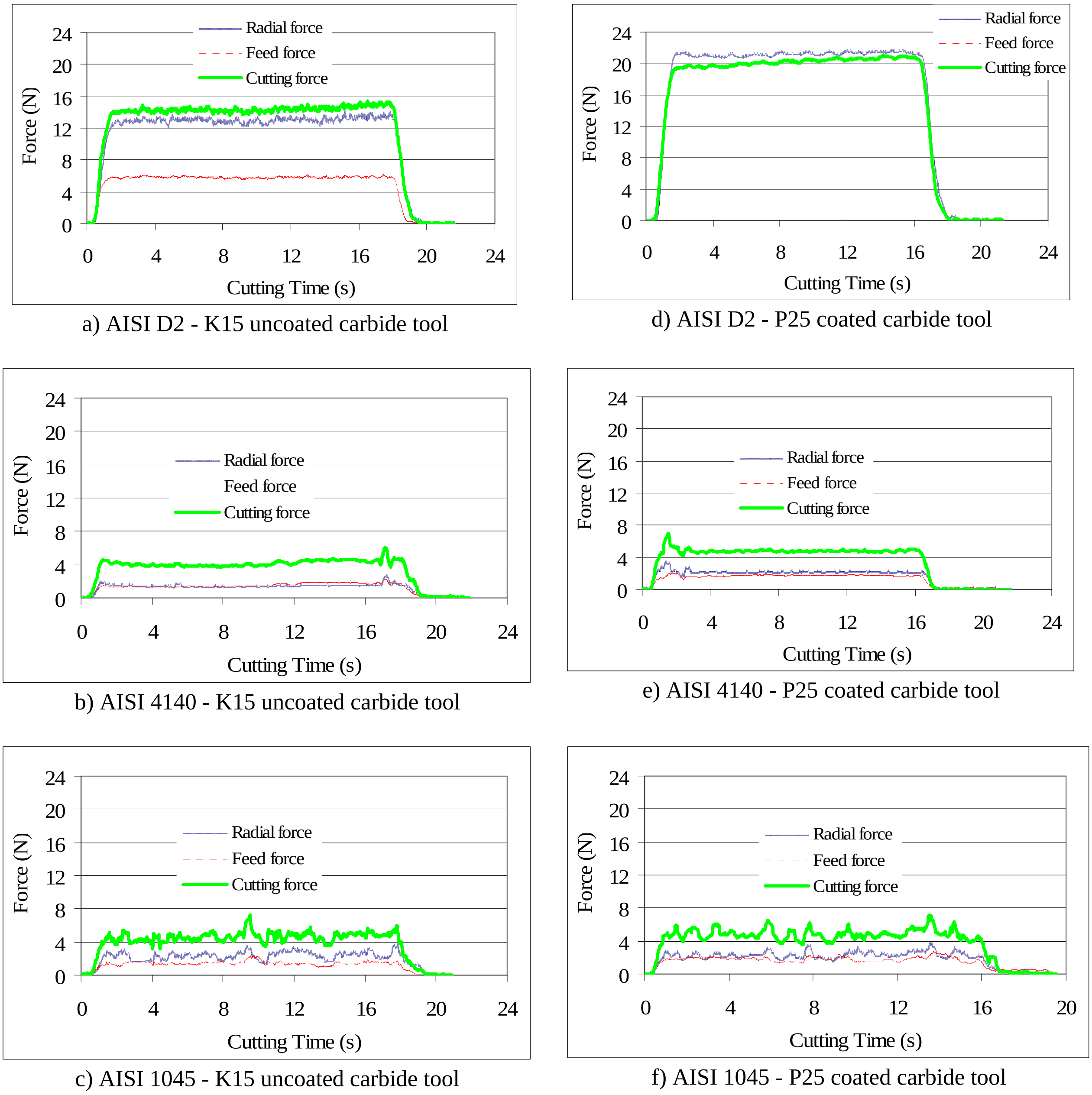
Charge amplifier PC

Figure 1. Three component (F_c, F_f and F_r) turning forces data acquisition system.

The surface roughness parameters R_a and R_t were assessed in accordance to ISO 4287/1 standard, using a Hommeltester T1000 profilometer connected to a computer with Hommeltester Turbo-Datawin software. An average value of six measurements was used to assess the surface roughness under each cutting condition. The experimental work was conducted at constant values of cutting speed (v_c= 100 m/min) and depth of cut (a_p= 100 μm). The following feed rate (f) values were tested: 10, 20, 40 and 80 μm/rev. Owing to the fact that the experimental work was conducted on a conventional CNC lathe, preliminary tests were conducted in order to check the accuracy of the machine tool. These tests indicated a diameter repeatability of ±1μm (measured with a digital micrometer with 1μm resolution).

3. RESULTS AND DISCUSSION

Figure (2) illustrates typical results related to the three component turning force for each tool material as cutting time elapses, employing a constant feed rate of 10 μm/rev. It can be noticed that, in general, the AISI D2 steel presented highest turning forces values due to its higher hardness. For a feed rate of 10 μm/rev, the turning forces values for AISI 4140 and AISI 1045 steels were similar, irrespectively of the tool grade used. Low radial force values were expected owing to the cutting edge angle value of 93^o, nevertheless, due to the fact that the depth of cut used was considerably smaller than the tool nose radius, the effective cutting edge angle was drastically reduced, thus causing the elevation of the radial force.



a) AISI D2 - K15 uncoated carbide tool

d) AISI D2 - P25 coated carbide tool

b) AISI 4140 - K15 uncoated carbide tool

e) AISI 4140 - P25 coated carbide tool

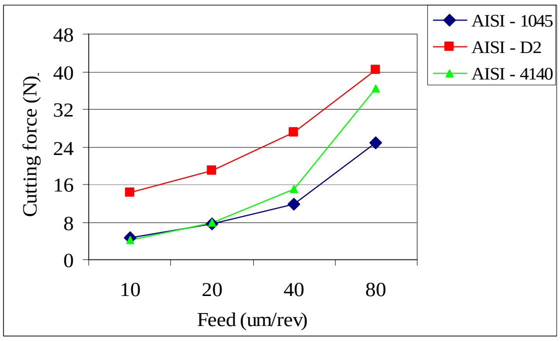
c) AISI 1045 - K15 uncoated carbide tool

f) AISI 1045 - P25 coated carbide tool

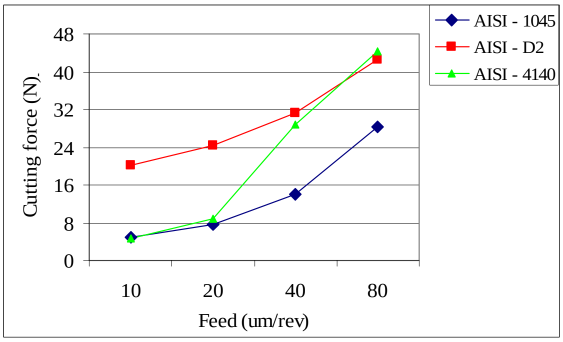
Figure 2. Turning forces evolution when cutting AISI D2; AISI 4140 and AISI 1045 steels at v_c= 100 m/min, f = 10 μm/rev and a_p = 100 μm using uncoated (K15) and coated (P25) cemented carbide tools.

Additionally, the forces recorded when turning with P25 coated carbide tool were higher compared to K15 uncoated carbide tool, especially in the case of the AISI D2 steel. The differences between the tools are related to the substrate, coating and geometry (rake angle value and the presence of chip breaker), therefore, the fact that the coated carbide tool with chip breaker (P25) generated higher forces suggests that the chip breaker is ineffective for the feed rate and depth of cut values tested. The coated cemented carbide tool was expected to provide lower force values owing to both its positive rake angle (γ_o= 6^o) and the presence of the film, however, this was not the case. A possible reason for that may be attributed to the superior surface finish of the rake face of the uncoated insert and to the cutting edge sharpness (smaller hone radius), as reported by Yuan et al. [15]. Therefore, one can conclude that, in general, the plain carbide tool with rake angle of $\gamma_o=0^o$ and without chip breaker was the most effective tool in reducing the turning forces. The turning forces results for the AISI 1045 steel presented larger scatter in comparison to the other work materials. Finally, the behavior of the turning forces did not change significantly as feed rate was elevated, therefore the remaining results showing the influence of cutting time will not be presented.

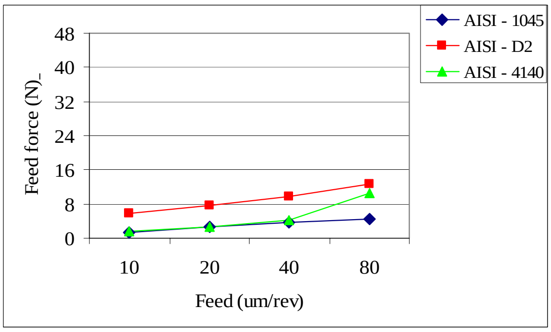
Figure (3) gives the effect of feed rate on the average cutting, feed and radial forces and specific cutting force for the three workpiece materials using both tools. The cutting and radial force values increase drastically with feed rate and the feed force component increases slightly. It can be noticed that, in general, the AISI D2 steel presented the highest cutting force values, followed by the AISI 4140 steel and finally by the AISI 1045 steel. During the machining of AISI 4140 steel with the uncoated tool, a steep increase in all forces was observed when feed rate was elevated from 40 to 80 μm/rev. In the case of the coated carbide, this sudden increase was noticed when feed rate increased from 20 to 40μm/rev. The AISI 4140 and 1045 steels presented approximately the same force values for feed rates of 10 and 20μm/rev. Again, the coated cemented carbide tool presented higher force values under all cutting conditions. Figures 3d and 3h show the influence of feed rate on the specific cutting force (K_s) when turning with uncoated and coated carbide tools, respectively. It can be seen that the specific cutting force decreases as feed rate is elevated, particularly when cutting the cold work and medium carbon steels. In contrast, the specific cutting force recorded when turning the AISI 4140 steel with the coated carbide tool increased drastically as feed rate was elevated from 20 to 40μm/rev. This behavior is probably owed to highest yield strength of the AISI 4140 steel (≥510 MPa), therefore, presents inferior elongation (≥10%), contemplating strongly when used higher feed rate, also supplying high value of cutting force. In condition low feed rate, AISI 4140 steel has behavior similar to AISI 1045.



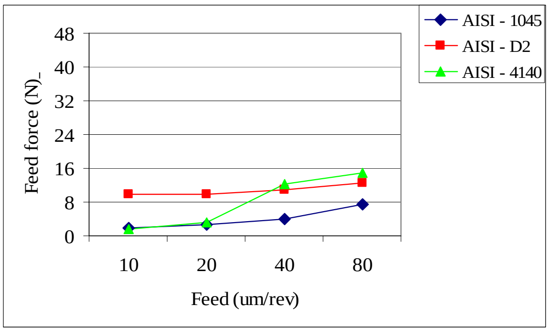
a) K15 uncoated carbide tool



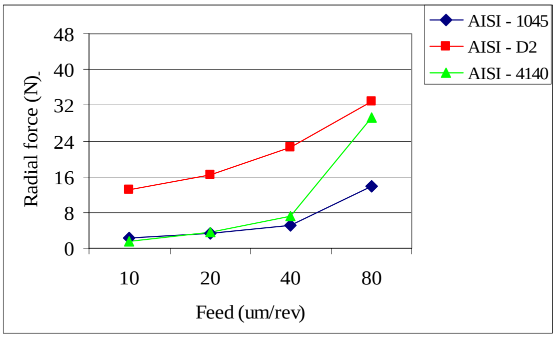
e) P25 coated carbide tool



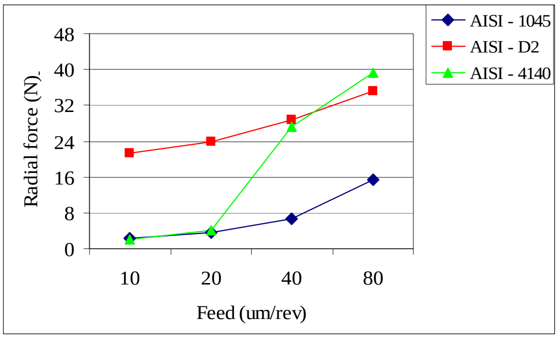
b) K15 uncoated carbide tool



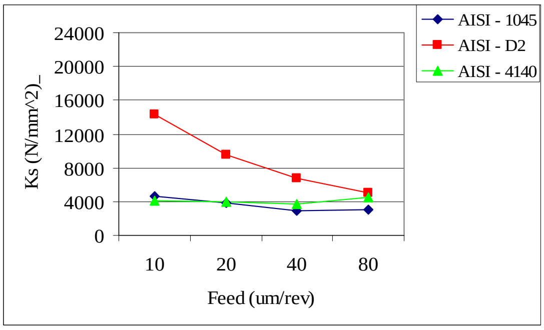
f) P25 coated carbide tool



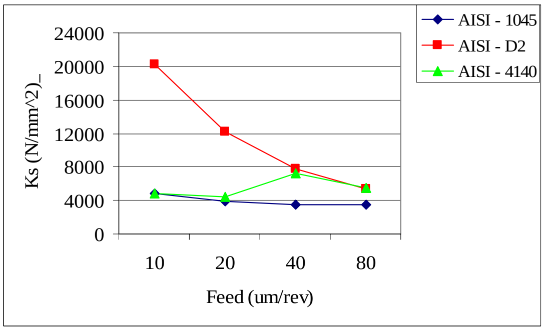
c) K15 uncoated carbide tool



g) P25 coated carbide tool



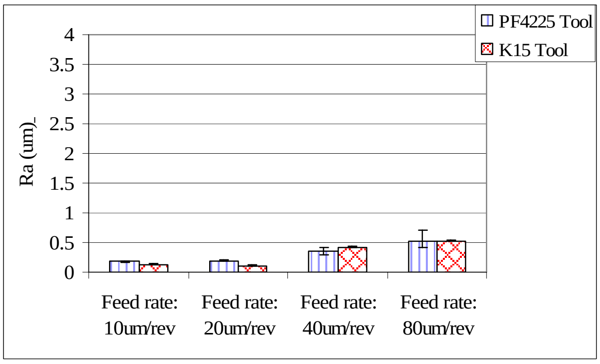
d) K15 uncoated carbide tool



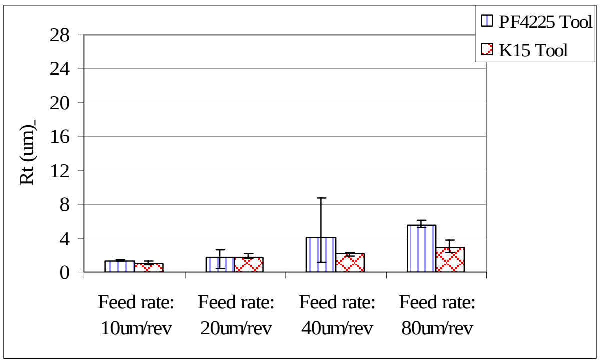
h) P25 coated carbide tool

Figure 3. Effect of feed rate on turning forces and specific cutting force when machining AISI D2; AISI 4140 and AISI 1045 steels at v_c = 100 m/min and a_p = 100 µm using uncoated (K15) and coated (P25) cemented carbide tools.

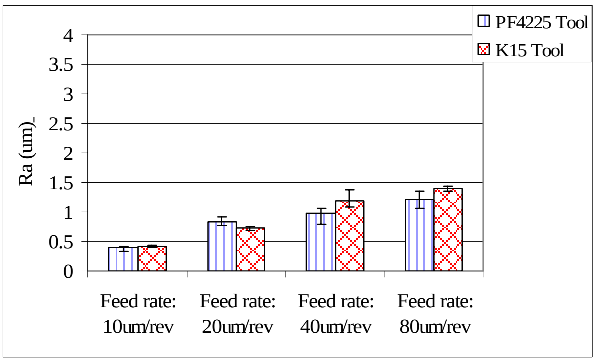
Figure (4) shows the evolution of surface roughness as a function of feed rate and tool material. Figures 4a), 4b) and 4c) present the results concerning the R_a values for the three work materials, whereas Figures 4d), 4e) and 4f) show these findings related to the R_t values. Although many factors affect the surface texture of a machined part, feed rate is the most significant cutting parameter. As far as the work materials are concerned, it can be observed that in spite of the higher force values recorded, lower surface roughness was obtained when turning AISI D2 steel due to its higher hardness and probable inferior ductility, followed by AISI 4140 and 1045 steels, in this order. These results suggest that the stiffness of the machine tool is sufficient to withstand the stresses imposed during the operation without deteriorating the surface finish. In general, the uncoated cemented carbide tool provided lower R_a and R_t values in comparison to coated cemented carbide tool. The surface roughness produced by the two cutting tools was significantly affected by feed rate within the cutting range tested.



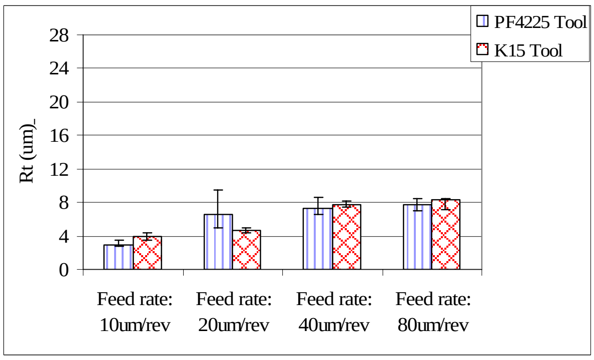
a) R_a - AISI D2



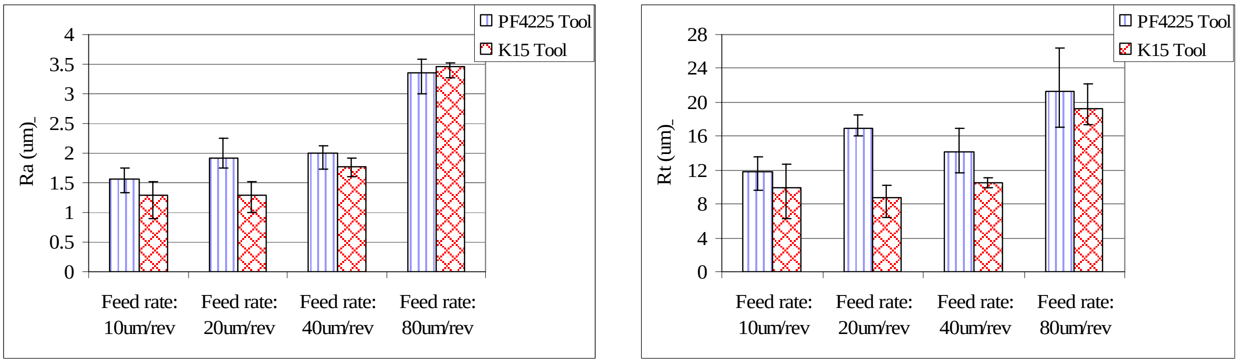
d) R_t - AISI D2



b) R_a - AISI 4140



e) R_t - AISI 4140



c) R_a - AISI 1045

f) R_t - AISI 1045

Figure 4. Effect of feed rate and tool material on the machined surface roughness after turning AISI D2; AISI 4140 and AISI 1045 steels at v_c =100 m/min and a_p = 100 μm.

4. CONCLUSIONS

Based on the experimental results presented, the following conclusions can be draw from precision turning of AISI D2, 4140 and 1045 steels with uncoated and coated carbide inserts:

- In spite of the high cutting edge angle tested, the cutting force component presented highest values, followed by the radial and feed forces. The forces increased with feed rate and, in general, the uncoated (K15) cemented carbide tool was responsible for lower force values regardless of the work material tested.
- The specific cutting force decreased drastically as feed rate was increased when cutting the AISI D2 steel. However, when machining AISI 4140 and 1045 steels, this reduction was smooth or negligible. The AISI D2 steel presented higher K_s values irrespectively of the cutting tool tested.
- The surface roughness produced by the two cutting tools was significantly affected by feed rate within the range tested. Better surface finish was produced when turning the AISI D2 steel followed by AISI 4140 steel. The uncoated carbide insert presented better overall performance.

5. ACKNOWLEDGEMENTS

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