Cutting forces and wear analysis of Si_3N_4 diamond coated tools in high speed machining

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ABSTRACT

Si_3N_4 tools were coated with a thin diamond film using a Hot-Filament Chemical Vapour Deposition (HFCVD) reactor, in order to machining a grey cast iron. Wear behaviour of these tools in high speed machining was the main subject of this work. Turning tests were performed with a combination of cutting speeds of 500, 700 and 900 m min^{-1}, and feed rates of 0.1, 0.25 and 0.4 mm rot^{-1}, remaining constant the depth of cut of 1 mm. In order to evaluate the tool behaviour during the turning tests, cutting forces were analyzed being verified a significant increase with feed rate. Diamond film removal occurred for the most severe set of cutting parameters. It was also observed the adhesion of iron and manganese from the workpiece to the tool. Tests were performed on a CNC lathe provided with a 3-axis
dynamometer. Results were collected and registered by homemade software. Tool wear analysis was achieved by a Scanning Electron Microscope (SEM) provided with an X-ray Energy Dispersive Spec- troscopy (EDS) system. Surface analysis was performed by a profilometer.

Keywords: HSM, Turning, Coatings, Diamond, Tool wear

1. Introduction

The use of High Speed Machining (HSM) was increased in the last years for a wide number of materials. This technology assumes particular importance in high competitive industries like automotive and aerospace. Actually, HSM is already used in final die – tools electrodes manufacturing, to Electrical Discharge Machining (EDM) process. These are industry sectors where the lead-time and productivity are the key factors to success. It is important to note that the optimization of the cutting parameters in HSM should not be made taking in account the maximum removal rate, but rather the acceptable compromise between cutting forces and surface quality [1]. The evolution of HSM is due by the enlarge stiffness of the machine structure, the development of new cutting tools materials, including coatings, and the higher control systems accuracy and processing technology [2]. HSM technology is often used in dry cutting mode. This is an important goal, because polluting coolants are not required, with benefits to the environmental aspects [3].

The grey cast iron is a material widely used in many metal-working manufactures such as automotive, pump and machine parts industries. In fact, the lamellar graphite is a precious auxiliary for cutting processes, which allows the use of high-speed cutting with this material [1].

Ceramic tools presents as main characteristics a superior wear resistance at high temperatures, which allows the use of very high-speed cutting with low feed rates, resulting in very high geometrical accuracy and surface quality. HSM technology with rigid machines, combined with ceramic tools, can replace grinding operations in ferrous alloys, increasing significantly the productivity and reducing the product cost [2].

Silicon nitride (Si_3N_4) is one of the ceramic materials used as cutting tools, due to its high hardness, strong compressing strength, very good fracture toughness and exceptional thermal shock resistance [4]. However, the use of selected coatings will allow to a better performance of the ceramic tools and to hinder the tribochemical reactions between Si_3N_4 and iron based alloys [5].

Contrary to the general principle that because of the affinity to carbon, ferrous materials cannot be machined with diamond due to the well-known graphitization phenomena; machining experiments were carried out on industrial environment with a single-edged PCD boring tool [6]. However, diamond coated tools present a different behaviour than PCD tools and were not yet tested in severe turning conditions. Chemical Vapour Deposition (CVD) diamond films are used in silicon nitride tools, due to its excellent mechanical properties. Furthermore, the high thermal conductivity of the diamond contributes to a temperature decrease in the cutting tool surface and low thermal expansion coefficient mismatch

Table 1
Chemical composition of GG25 DIN 1691

C – 3.00%	Si – 2.00%	Mn – 0.60%	*P* �0.10%	*S* �0.05%

Table 2
Properties of Si_3N_4 cutting tool

Density ($g\,cm^{-3}$)	3.254
Hardness (GPa)	15.4 ± 0.3
Toughness ($MPa\,m^{1/2}$)	6.0 ± 0.1
Thermal conductivity ($W\,m^{-1}\,K^{-1}$)	27 (20 °C)–15 (500 °C)
Thermal expansion coefficient (K^{-1})	2.6×10^{-6}–3.0×10^{-6}

Table 3
Chemical composition of Si_3N_4 cutting tools

Si_3N_4	89.3%
Y_2O_3	7.0%
Al_2O_3	3.7%

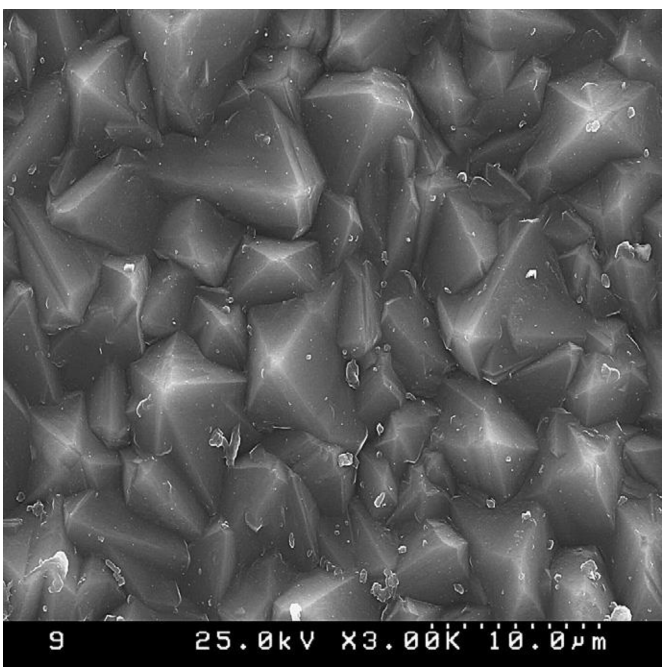

Fig. 1. SEM view of the HFCVD diamond film morphology.

allows obtaining a good adhesion between the CVD diamond film and the ceramic substrate, as a result of a lower interface residual stress at room temperature [7,8]. Effectively, the use of CVD diamond coatings in cutting tools contributes to an enhanced surface hardness and, therefore, a wear tool decreases. However, it is known the catalytic effect of the Fe contained on the lamellar cast iron in contact with diamond, at high temperature. In fact, surface wear of the diamond film/silicon nitride system is a consequence of sp^3 diamond bond degradation as a result of catalytic diamond/Fe reactions during machining operations. Nevertheless, the use of coated tools on severe machining conditions (discontinuous cutting, e.g.) is still restricted, due to insufficient adhesion [9–11].

Despite this, the present work pretends to experiment the same diamond film/silicon nitride tool system under different high-speed cutting conditions of lamellar cast iron. Cutting forces were measured and analyzed during each test, and wear behaviour was verified.

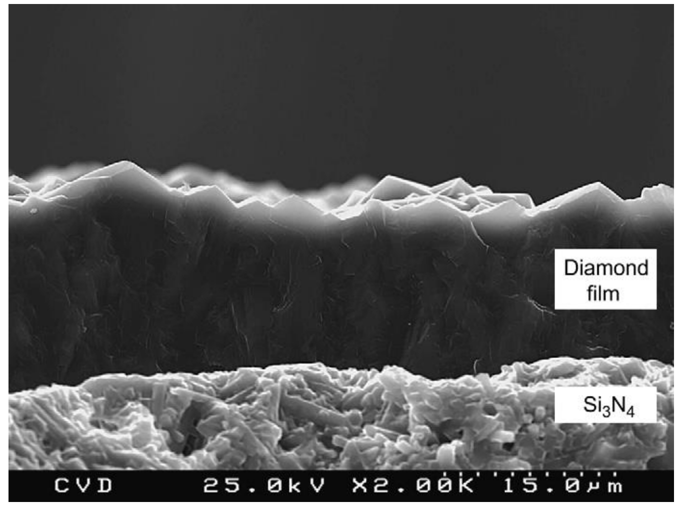

Fig. 2. Cross-sectional SEM view of the HFCVD diamond film on Si_3N_4 tool substrate.

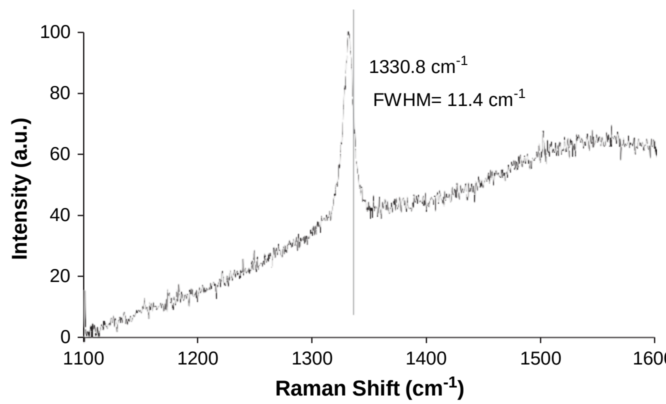

Fig. 3. Micro-Raman spectrum of the HFCVD diamond film.

2. Experimental

2.1. Workpiece material

The workpiece material was a pearlitic grey cast iron GG25 DIN 1691. The chemical composition is shown in Table 1. The average hardness was 202 HB 2.5/187.5/30. The material used in experimental work had a cylindrical shape, with a diameter of 150 and 200 mm long. All pieces were pre-machined in order to remove the cast skin.

2.2. Cutting tools material

Machining tests were performed with silicon nitride (Si_3N_4) based ceramic tools provided with HFCVD diamond coatings. The material properties and the chemical composition are presented in Tables 2 and 3, respectively.

Ceramic inserts presented a cylindrical shape with 10 mm of diameter and 3 mm of thickness. The tools position was defined by a (negative) rake angle of -10^0 and a clearance angle of 10^0. Tool location was defined by a ‘‘CRSNR 2525 N 09-ID’’ SANDVIK tool holder. The edge geometry was sharp (90^0).

2.3. Surface coating

A homemade HFCVD reactor was used to grown diamond films onto Si_3N_4 tool inserts. All disc shaped substrates were previously

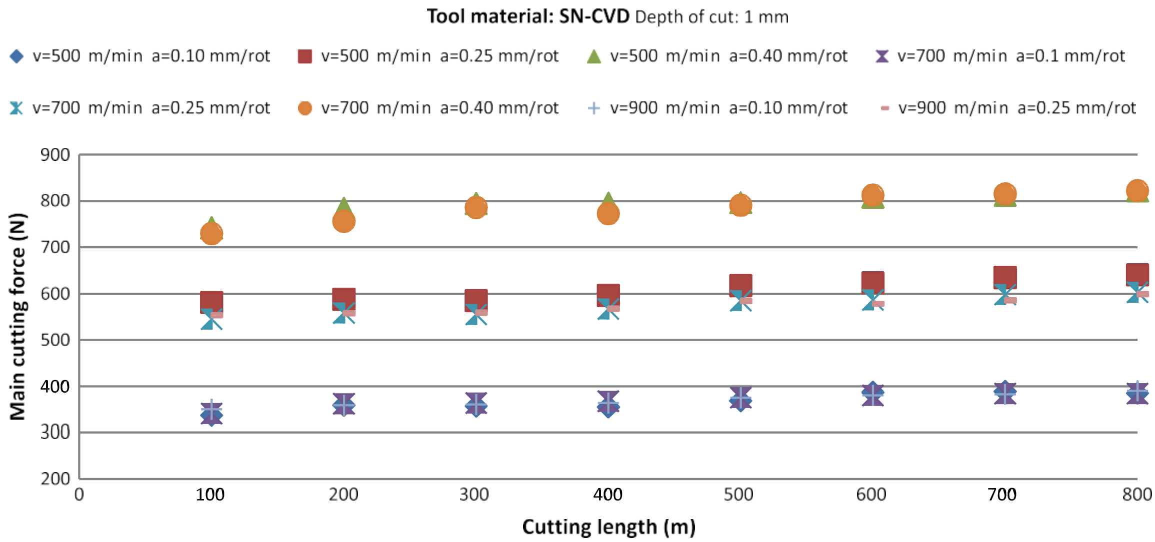

Fig. 4. Main cutting force evolution in turning of GG25 with diamond coated ceramic tool.

scratched in an ultrasonic bath during 1 h in a 1-μm diamond slurry with *n*-hexane. Following, substrates were cleaned in an ethanol bath during 10 min. This pre-treatment was realised in order to increase diamond nucleation and to promote a better adhesion between the diamond film and the substrate.

For diamond synthesis, a set of reactor parameters were used as following: substrate temperature – 800 °C, pressure – 67 mbar, CH_4/H_2 gas feed ratio – 0.015, gas flow – 100 ml min^{-1}, time deposition – 8 h. This set of conditions allowed obtaining a 15-μm diamond film, with a very good morphology, as can see in a Hitachi S-4100 SEM picture presented in Fig. 1. The diamond film thickness value (15 μm) was measured in a SEM cross-sectional view, as shown in Fig. 2. The diamond quality and residual stress of the films were assessed using a JOBIN YVON T-64000 μ-Raman Spectroscope, with a *laser* wavelength of 514 nm. A highly transparent geological type IIa diamond gem was used to calibrate the diamond peak position. The Raman spectrum leads to a diamond film peak of 1330.8 cm^{-1}, with a FWHM (full width at half maximum) of 1332.5 cm^{-1}, as can be seen in Fig. 3. These results permit to conclude that the diamond film was under a light compressive stress effect because the peak deviation observed was around 1.7 cm^{-1} and its quality was high due to the small FWHM registered.

2.4. *Cutting operations*

All cutting operations were carried out using a TARI SEIKI CNC lathe. Turning speed was automatically adjusted as a function of the workpiece diameter, in order to maintain constant the cutting speed. Tests were performed at different cutting speeds of 500, 700 and 900 m min^{-1} and feeds of 0.1, 0.25 and 0.40 mm rot^{-1}, in a 3 X 3 matrix cutting conditions. The depth of cut of 1 mm was kept constant in all tests. The length of cut for each tool edge was 800 m. All the tests were carried out in dry and continuously turning conditions. The three orthogonal components of the cutting force (F_c – main cutting force, F_a – feed force and F_p – depth of cut force) were acquired by a Kistler model 9257BA dynamometer, connected to a PC provided with a homemade data acquisition software by a signal Amplifier/Conditioner model 5233A1 with an A/D PCMCIA converter. Signal data were stored in data files to posterior analysis.

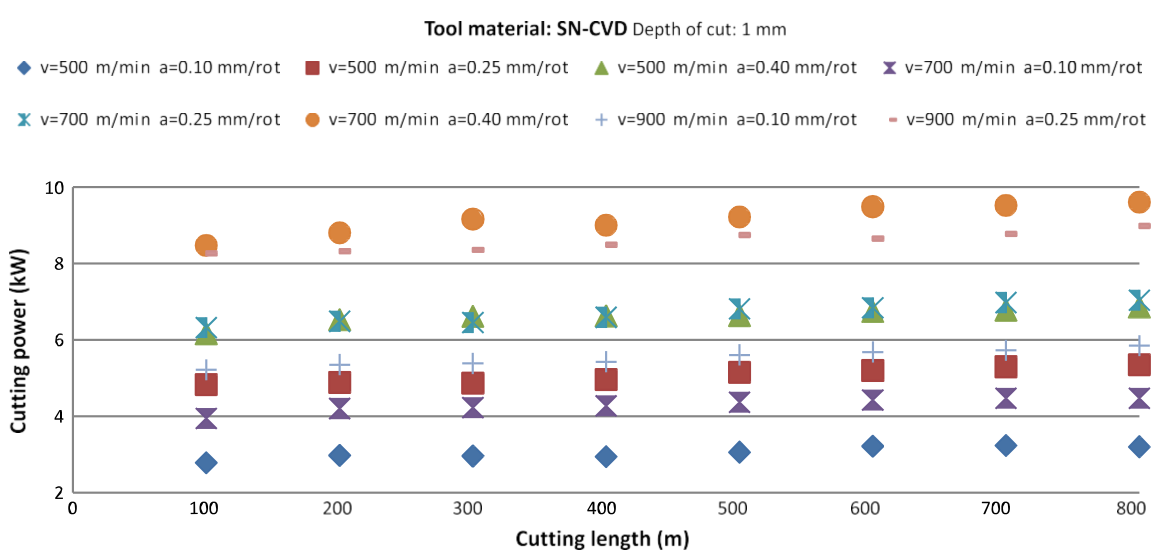

Fig. 5. Cutting power evolution in turning of GG25 with diamond coated ceramic tool.

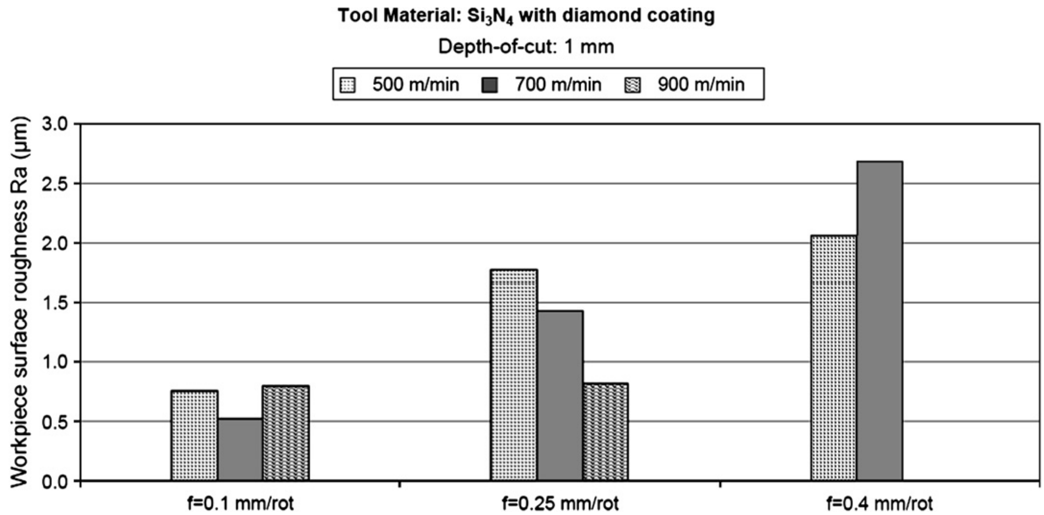

Fig. 6. Surface roughness evolution with feed rate for diamond coated ceramic tool.

2.5. *Wear and roughness analysis*

A MAHR M1 profilometer was used to measure surface roughness at the end of each test. SEM JEOL JFM63 01 F (provided with EDS system) and optical OLYMPUS BX51M microscope provided with an OLYMPUS 12.5 MPixels digital camera were utilized to measure and analyse tool wear.

3. Results and discussion

3.1. *Cutting force*

The evolution of main cutting force (F_c) is shown in the graphic of Fig. 4. It can be observed that cutting speed does not influence this force (F_c). By the other hand, the feed promotes a great increment of the same force. The maximum value of F_c obtained was 823 N for the following parameters: v >0.1/>500 or 700 m min^{-1}, f >0.1/>0.4 mm rot^{-1} and doc >0.1/>1 mm.

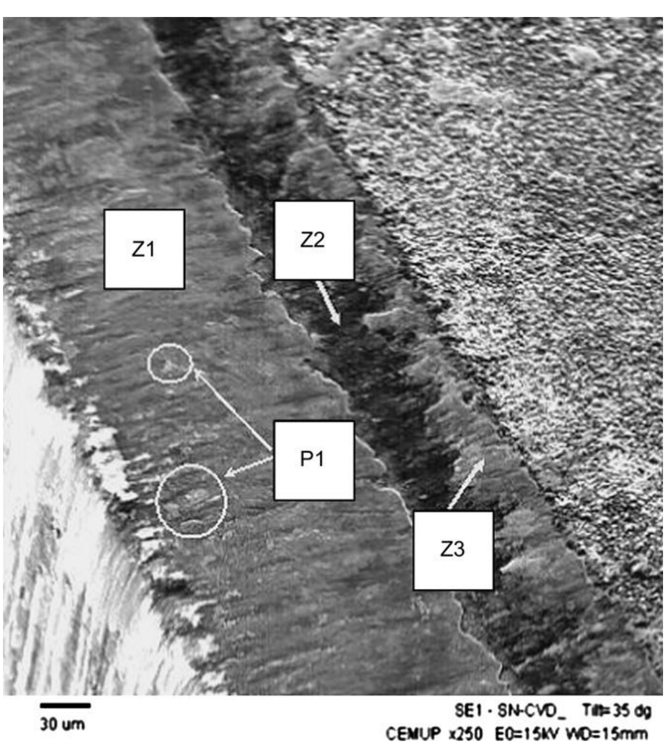

Fig. 7. Top view of rake face of a diamond coated ceramic tool divided in four areas.

3.2. *Cutting power*

Cutting power is one of the most useful parameter in industrial applications, because it makes possible the correct selection of the machine-tool to a certain machining process and also permits the monitoring of tool wear. This parameter is given by the following equation:

$$P_c = \frac{F_c \times v}{60}$$

where P_c (W) represents the cutting power, F_c (N) the main cutting force and v (m min^{-1}) the cutting speed. Fig. 5 presents the cutting power evolution with the cutting length. It can be noted that the cutting power increases with the cutting speed and feed, being verified that the maximum value was 8.9 kW for a v >0.1/ >700 m min^{-1} and a f >0.1/>0.4 mm rot^{-1}.

3.3. *Roughness*

As presented in Fig. 6, the roughness increases with feed, for cutting speed of 500 and 700 m min^{-1}, as expected. However, for 900 m min^{-1}, the value remains approximately constant between a ¼ 0.1 and a ¼ 0.25 mm rot^{-1}. These apparently incongruent results can be attributed to the characteristic microstructure of the grey cast iron.

3.4. *Tool wear*

No diamond film delaminations were observed in the surface tools in SEM observations after the tests. The high temperatures developed on the cutting zone provoke diamond coating graphitization, with consequent film loss during the machining operations. This kind of phenomenon occurs when the temperature is higher than 730 °C. SEM observations of the cutting tools rake face in different zones were revealed abrasion, diffusion and adhesion wear. Fig. 7 presents a typical worn rake face. In this picture, four different areas were identified. Area Z1, near the cutting edge, presents abrasion wear and diffusion phenomena, due to the high temperatures developed in this zone. This area also presents adhesion wear

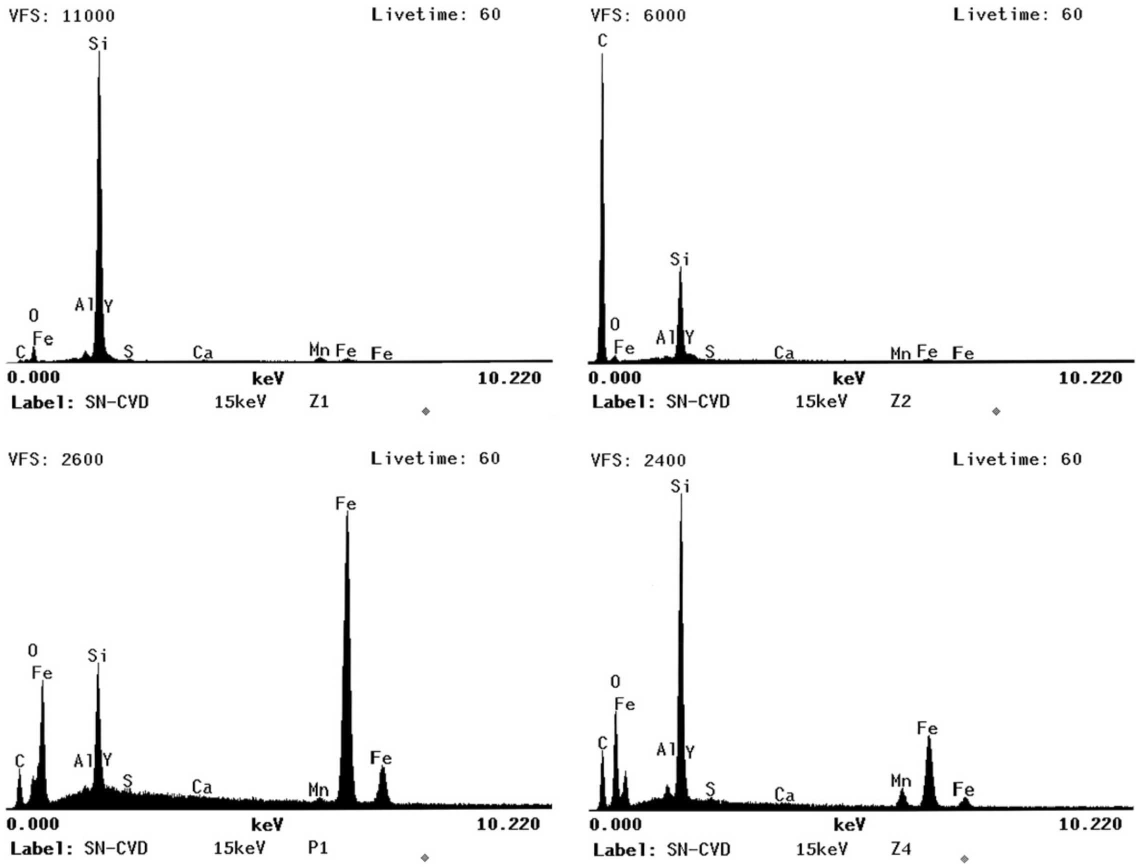

Fig. 8. EDS microanalysis of each area represented in Fig. 7.

in some located areas, identified by P1. In the EDS spectra of this area it is possible to observe the presence of Fe and Mn, from the workpiece. After the film loss as a result of graphitization, abrasion origins a flat wear zone (Z1), as observed in Fig. 7. In the area Z2, the presence of carbon is evidenced by the EDS spectra (Fig. 8). In the area Z3, the wear evolution was retarded by the diamond film presence where, presumably, the developed temperature was not so high. In this area, where the chip flux was not so continuous, the adhesion mechanism was also verified. This lower chip flux provokes a workpiece material transfer to the tool rake face. The temperature developed was lower and the graphitization phenomenon was almost inexistent. In Fig. 9 it is possible to observe the adhesion and abrasion mechanisms on the flank face. The wear of this face (VB) was measured for all cutting tools being verified that it was increasing with the cutting speed and mainly with the feed rate, as shown in Fig. 10.

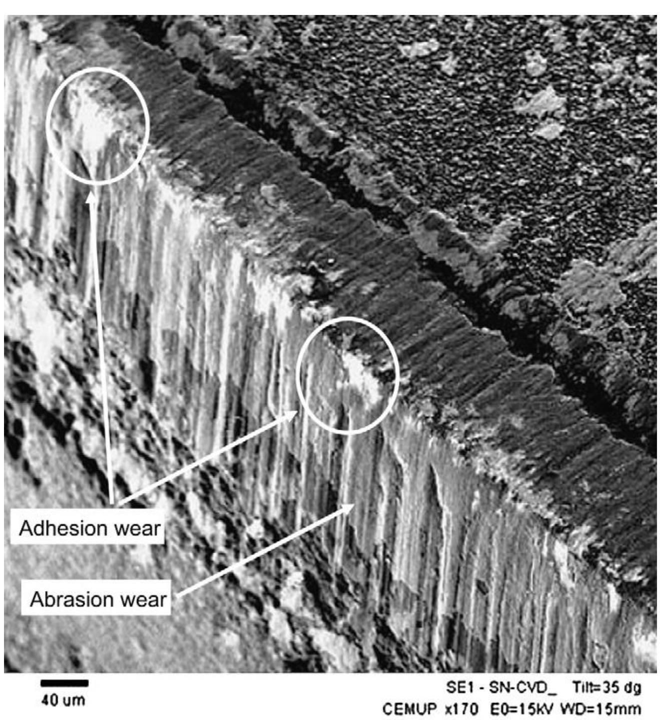

Fig. 9. Flank face where it is observed abrasion and adhesion wear mechanisms.

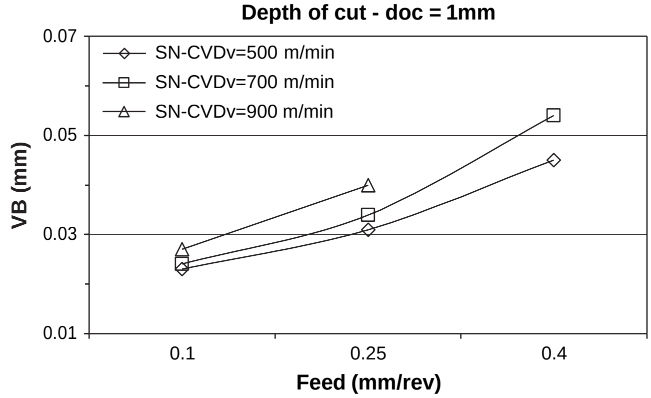

Fig. 10. Flank wear value as a function of feed of a diamond coated tool.

4. Conclusions

Based on these experimental results, the following conclusions can be drawn.

The increase of the main cutting force was linked to an increase of the feed rate. However, cutting speed does not present a significant contribution to the main force evolution, for the same feed and depth of cut values.

High temperatures often occur in HSM in the cutting zone. Because of this, it was verified chemical and diffusion reactions between tool and workpiece material. As a result of these reactions, wear phenomena was verified.

The roughness trend is to increase clearly with feed rate increase at 500 and 700 m min^{-1}. However, the cutting speed does not seem to influence coherently the surface quality. At 900 m min^{-1}, only a slight evolution was verified. This behaviour may be attributed to the heterogeneity of the grey cast iron microstructure or to a more rapid and intense wear of the tool.

No film delamination occurs during the machining operations, revealing a very good adhesion between the HFCVD diamond film and the silicon nitride substrate.

The first phenomenon observed was the diamond film graphitization, stimulated by the high temperature developed on the cutting zone. As a result of this fact, the diamond film had been lost, remaining the ceramic substrate in direct contact with the workpiece. In spite of this, it seems that the diamond films hinder the flat zone wear evolution and, also, the flank face wear. The wear verified in the flank face (VB), was increasing with the cutting speed and, mainly, with the feed rate.

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