Vacuum 82 (2008) 1415–1420

Contents lists available at ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum

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

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Keywords:
HSM
Turning
Coatings
Diamond
Tool wear

A B S T R A C T

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 Spectroscopy (EDS) system. Surface analysis was performed by a profilometer.

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 metalworking 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

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0042-207X/$ – see front matter
doi:10.1016/j.vacuum.2008.03.065

Table 1
Chemical composition of GG25 DIN 1691

C – 3.00%	Si – 2.00%	Mn – 0.60%	$P \leq 0.10\%$	$S \leq 0.05\%$

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%

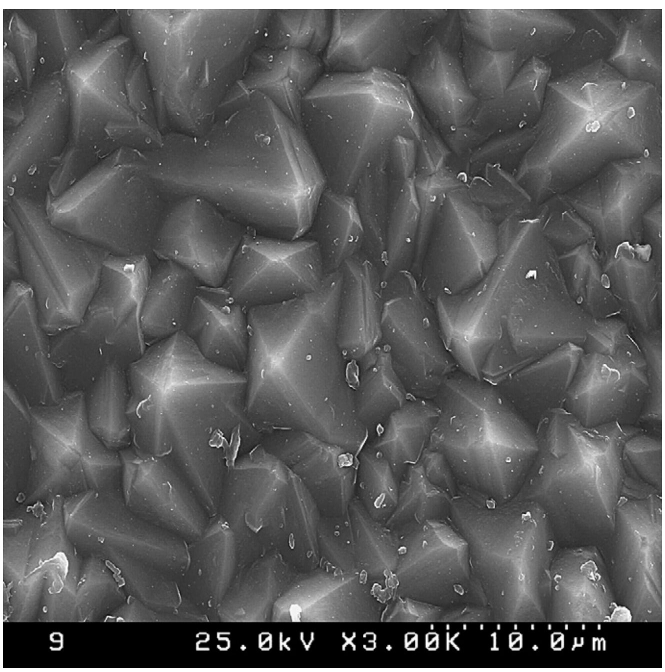

Fig. 1. SEM view of the HFCVD diamond film morphology.

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.

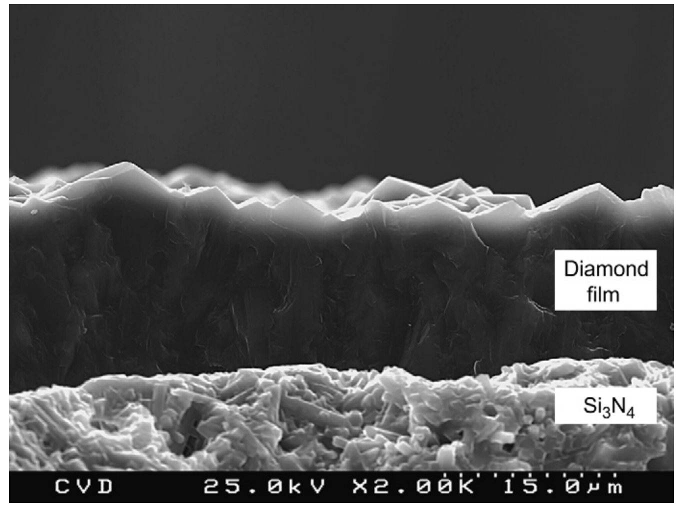

Fig. 2. Cross-sectional SEM view of the HFCVD diamond film on Si_3N_4 tool substrate.

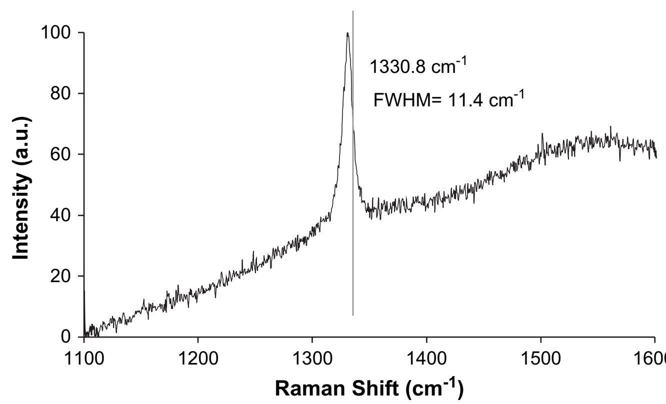

Fig. 3. Micro-Raman spectrum of the HFCVD diamond film.

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 $-10°$ and a clearance angle of 10°. Tool location was defined by a "CRSNR 2525 N 09-ID" SANDVIK tool holder. The edge geometry was sharp (90°).

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