Si₃N₄ Ceramic Cutting Tool Sintered with CeO₂ and Al₂O₃ Additives with AlCrN Coating

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Ceramic cutting tools are showing a growing market perspective in terms of application on machining operations due to their high hardness, wear resistance, and machining without a cutting fluid, therefore are good candidates for cast iron and Nickel superalloys machining. The objective of the present paper was the development of Si₃N₄ based ceramic cutting insert, characterization of its physical and mechanical properties, and subsequent coating with AlCrN using a PVD method. The characterization of the coating was made using an optical profiler, XRD, AFM and microhardness tester. The results showed that the tool presented a fracture toughness of 6.43 MPa.m$^{1/2}$ and hardness of 16 GPa. The hardness reached 31 GPa after coating. The machining tests showed a decrease on workpiece roughness when machining with coated insert, in comparison with the uncoated cutting tool. Probably this fact is related to hardness, roughness and topography of AlCrN.

Keywords: *AlCrN, ceramic cutting tool, mechanical properties, coating*

1. Introduction

Generally, unconventional or advanced machining processes are used only when no other traditional machining process can meet the necessary requirements efficiently and economically. It is important to note that most of advanced machining processes incur relatively higher initial investment, maintenance, operating, and tooling costs. Beyond that, the optimal choice of process parameters is essential to increase the efficiency of the process[1]. The machining is a major manufacturing process and plays a key role in the creation of wealth. Machining operations consumes a large amount of money annually worldwide. Over US$ 100 billion is spent annually worldwide on metal part finishing processes such as turning, milling, boring and other cutting operations. It is also known that the machining industry converts about 10% of all the metal produced into swarf (wastage). It is envisaged that up to 20% savings should be possible by using the correct choice of tooling and machining conditions[2].

The highest machining costs are found on high technology industries like aeronautics, aerospace, automobile, among others, that uses difficult-to-cut alloys. In the manufacture of these materials it is necessary to use specific cutting tools like cubic boron nitride (CBN), and hard coated tools (diamond, titanium nitride), that present a high wear resistance[3]. However, the high cost of these cutting tools is a negative factor of them.

The materials used in the fabrication of ceramic cutting tools present important properties like: a) high hardness, b) good chemical stability, c) stable mechanical properties on high temperatures, and d) high wear resistance. Brittleness is the key propertie that needs to be improved and this can be achieved with the use of additives that enhance the fracture toughness[4].

Recently, machining tests on gray and vermicular cast iron showed the advances on the properties of Si₃N₄ based ceramic cutting tools. It was possible by the combination of properties like mechanical resistance on high temperatures, fracture toughness, wear resistance and chemical stability[5].

Several researchers have established that hard coatings deposited on tool, by different physical vapor deposition methods (PVD), can dramatically change its performance. In most cases, AlCrN coating not only help reducing the wear and increasing the tool life but also improve strength and chemical inertness, reduce friction, and improve the stability at high temperatures[6].

Dry machining will be considered as a necessity for manufacturing industries in the near future and it is ecologically desirable. Companies will be compelled to consider dry machining to enforce environmental protection laws for occupational safety and health regulations. The advantages of dry machining include: non-pollution of the atmosphere (or water); no residue on the swarf which will be reflected in reduced disposal and cleaning costs; no danger to health. Moreover, it offers cost reduction in machining[7]. Dry turning tests were chosen in this work.

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Among the factors that influence the workpiece surface roughness are: the process parameters (cutting speed, feed rate, etc.), friction in the cutting zone, system vibrations, cutting force variations, workpiece hardness, cutting tool material, and roughness and geometry of the cutting edge[8]. The effect of cutting edge roughness on the workpiece roughness will be discussed here.

In this paper, it will be shown the development of a new Si_3N_4 based ceramic cutting tool, sintered with CeO_2 and Al_2O_3 additives used to reduce the insert cost and improve fracture toughness, as well as, the AlCrN coating used mainly to enhance the superficial hardness. There were also made turning tests on gray cast iron.

2. Materials and Methods

Silicon nitride powder 79.00 wt. (%), with an average particle size of 0.8-1.0 μm, was mixed with 7.70 wt. (%) of cerium oxide powder, with an average particle size of 1.20 μm, and 13.30 wt. (%) of aluminum oxide powder, with an average particle size of 1.12 μm. The blended powders were mixed with ethylic alcohol and uniaxially cold pressed to a square shaped compact at 80 MPa and isostatic pressing under a 300 MPa pressure. The green compacts were sintered at 1850 °C in nitrogen atmosphere (1.5 MPa) for 2.0 hours. The sintering was carried out at a heating rate of 15 °C/min from room temperature to 1500 °C and at this stage some volatile elements was totally removed from the compacts. Then, the sintering was carried out at a heating rate of 20 °C per minute from 1500-1850 °C, with a holding time for 2 hours. The sintered specimens were slowly cooled in the furnace to room temperature. Subsequently, it was cut and ground to make SNGN120408 (12.7 × 12.7 mm, 4.76 mm thickness, 0.8 mm nose radius and 0.2 mm × 20 chamfer). The XRD analysis was carried out using a computer controlled diffractometer, using CuKα radiation (wavelength 1.5406 Å). The densities of the specimens were determined using the Archimedes principle. The hardness was evaluated using a Vickers Hardness Tester Machine with a load of 20 N. The Fracture toughness was calculated by the crack length emerging from the indentation marks, using the equation proposed by Evans and Charles for Palmqvist shaped cracks[9].

AlCrN coating was made using a PVD method[10]. To evaluate the arithmetic average roughness (Ra) and surface topography of the inserts, with and without AlCrN coating, it was used an optical profiler from VEECO, model WYKO NT1100. In order to observe, in details, the morphology of the AlCrN grains, it was used an atomic force microscope (AFM) from VEECO (Multimode V). AlCrN phase was identified by grazing incidence X-ray diffraction (GIXRD – omega = 2°) and coating hardness was made using 0.07 N loads, eliminating the influence of the substrate on the results. Figure 1 and 2 show uncoated and AlCrN coated cutting tools, respectively.

After the characterization of the inserts (with and without coating), they were submitted to dry turning tests on gray cast iron in a computer numerical control (CNC) lathe (Romi, Mod. Centur 30 D) under dry cutting condition, in order to evaluate coated and uncoated cutting tools performance.

A tool holder of CSRNR 2525 M 12CEA type (offset shank with 15° [75°] side cutting edge angle, 0° insert normal clearance and 25 × 25 × 150 mm) was used for the cutting experiments. The cutting tests were performed at a cutting speed of 300 m/min, with constant feed rate of 0.33 mm.rev⁻¹ and cutting depth of 1.0 mm. For each condition, the cutting test was repeated twice. Initially, the work material had a cylindrical shape, with 105 mm in diameter and 300 mm in length. Three surface roughness measurements were taken, distant from each other by 120° in the cylindrical work material, after each pass. For that, it was used a surface roughness meter (Mitutoyo Surftest 402 series 178). For each pass, the average and
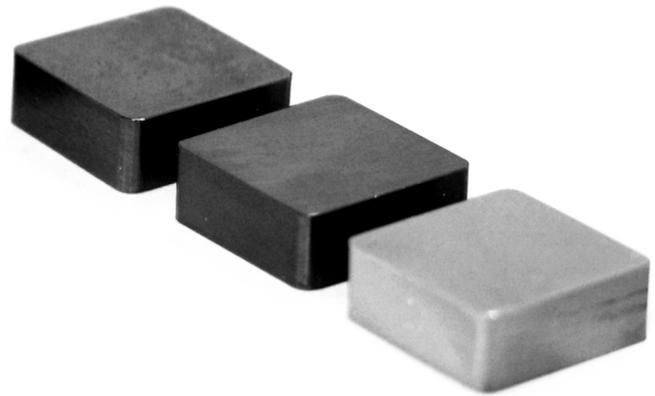

Figure 1. Photograph of silicon nitride based insert.
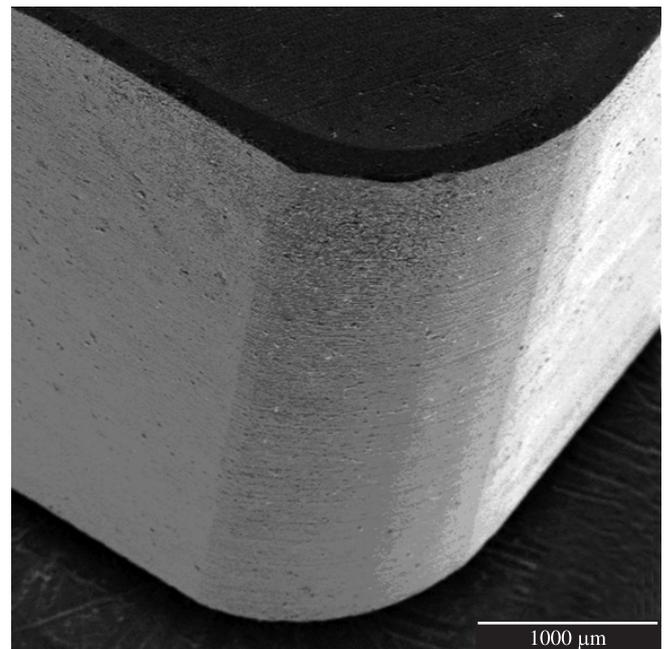

1000 μm

Figure 2. SEM micrograph of AlCrN coating deposited on ceramic cutting tools.

standard deviation surface roughness were calculated. The average temperature was measured with a non-contact infrared pyrometer, with laser dot sighting pointed in the cutting nose. The pyrometer was fixed in the carriage at 20 cm from cutting edge. All machining tests were supported by ISO 3685. The chemical composition and mechanical properties of the gray cast iron are given in Table 1. In the Figure 3, it can be seen the etched microstructure of gray cast iron (optical microscope) with a pearlitic structure matrix, and a distinct lamellar graphitic flakes. It also presents, in a small amount, an iron phosphide eutectic (light regions) and manganese sulphide stringers (darker grey circular features less than 5 μm in diameter).

3. Results and Discussion

3.1. Cutting tool properties

The relative density (measured density compared to theoretical density) of the sintered tools was 98.34%. The fracture toughness and hardness were respectively 6.43 MPa.m$^{1/2}$ and 16 GPa. According to the X-ray diffractogram showed on Figure 4a, few reminiscent α-Si_3N_4

Table 1. Chemical composition and mechanical properties of gray cast iron used for cutting test.

Chemical composition of gray cast iron								
C	S	P	Si	Mn	Cu	Cr	Ni	Mo
3.04	0.11	0.068	2.58	0.42	0.05	0.07	0.02	0.005
Mechanical properties								
Hardness HB			Tensile strength MPa			Fatigue strength MPa		
205			245			100		
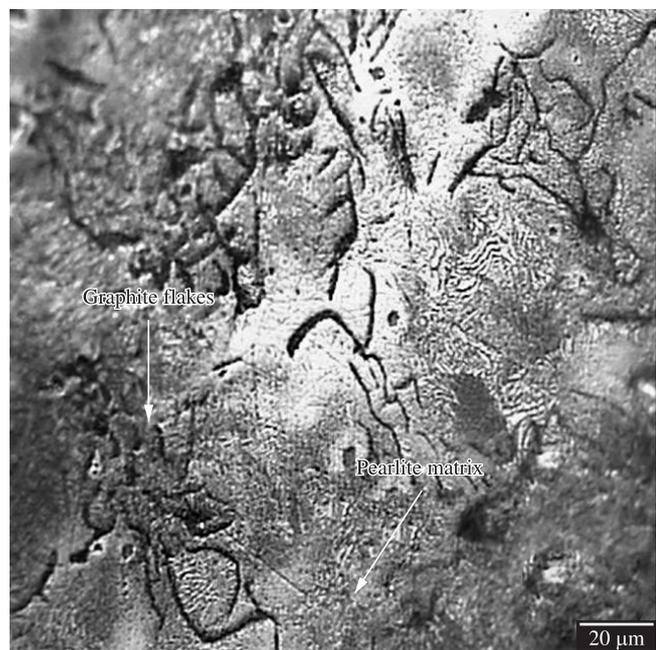
Figure 3. Microstructure of gray cast iron (optical microscope).

and β-Si_3N_4 phase was identified in the sintered insert indicating that the sintering parameters were adequate to produce β phase, which presents important properties like high density, toughness and hardness. It was observed that the use of Al_2O_3 and CeO_2 additives (dissolution and precipitation; low volatilization,) promoted the formation of β-Si_3N_4 phase, and the fracture toughness and hardness values are characteristics of this phase[11]. Figure 4b presents the X-ray diffraction pattern of the coating, obtained with a grazing incident X-ray beam. It was observed the presence of the AlCrN phase.

The substrate of the insert is β-Si_3N_4 with a hardness of 16 GPa. The AlCrN coating presents a hardness of 31 GPa, so the surface hardness of the insert was increased.

3.2. Surface morphology of the tool

Figure 5a shows the surface morphology (optical profiler) of the β-Si_3N_4 sintered tool after grinding (0.1 μm grid size). It can be observed the grooves made from the (0.1 μm) diamond grinding wheel (narrow indicate the grinding direction). It is important to mention that these grooves can act as a stress raiser during turning process, favoring premature tool failure. The Figure 5b presents the surface topography of the AlCrN coated tool. The arithmetic average roughness (Ra) for the uncoated tool was 428 ± 13 nm, and for coated specimen was 323 ± 12 nm. It can be seen that, after coating, peaks and valleys are smoother compared to the uncoated sample.

Figure 6a presents the surface topography (AFM) of the uncoated tool, showing clearly the grooves from grinding step (narrow indicate the grinding direction). Figure 6b shows the surface morphology of the AlCrN coated tool. It was observed that AlCrN grains exhibited a round shape and an equivalent average diameter of approximately 1 μm.

3.3. Turning tests

In the turning tests, for both coated and uncoated tools, it was not verified wear or cracks on the cutting edge of the inserts, using an optical tool makers microscope without removing the inserts out of the cutter and after each three pass. It was not observed also delamination of the AlCrN coating during machining.
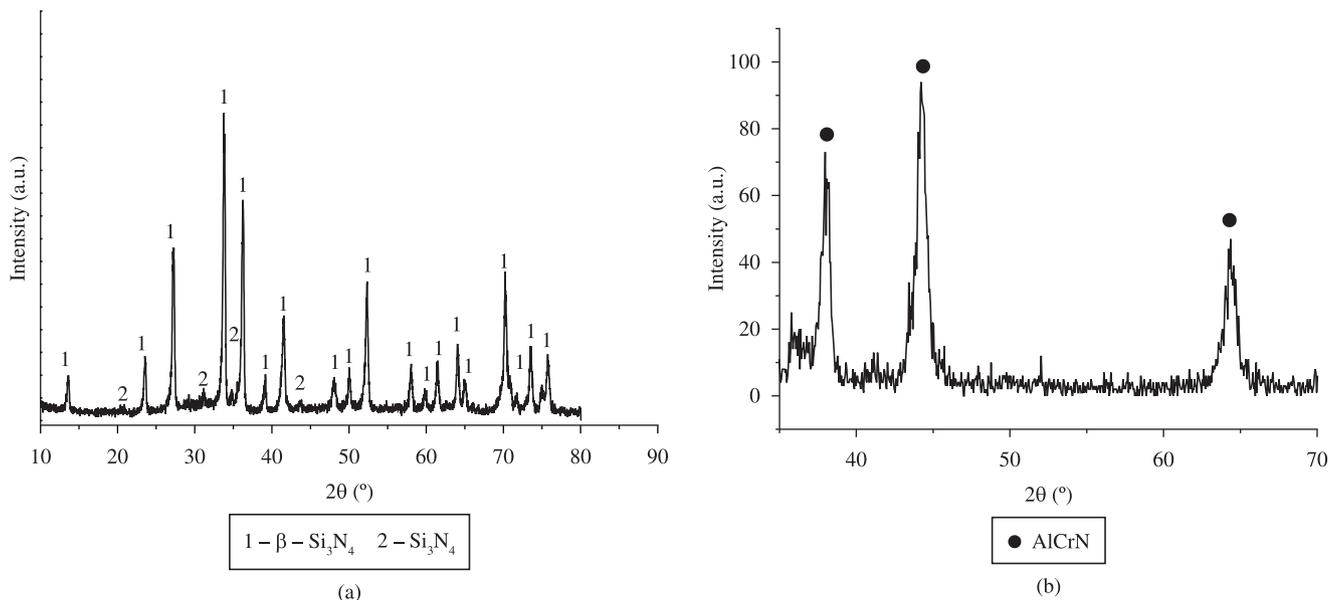

Figure 4. X-ray diffraction pattern for: a) Si_3N_4 tool; and b) AlCrN coated tool (GIXRD).
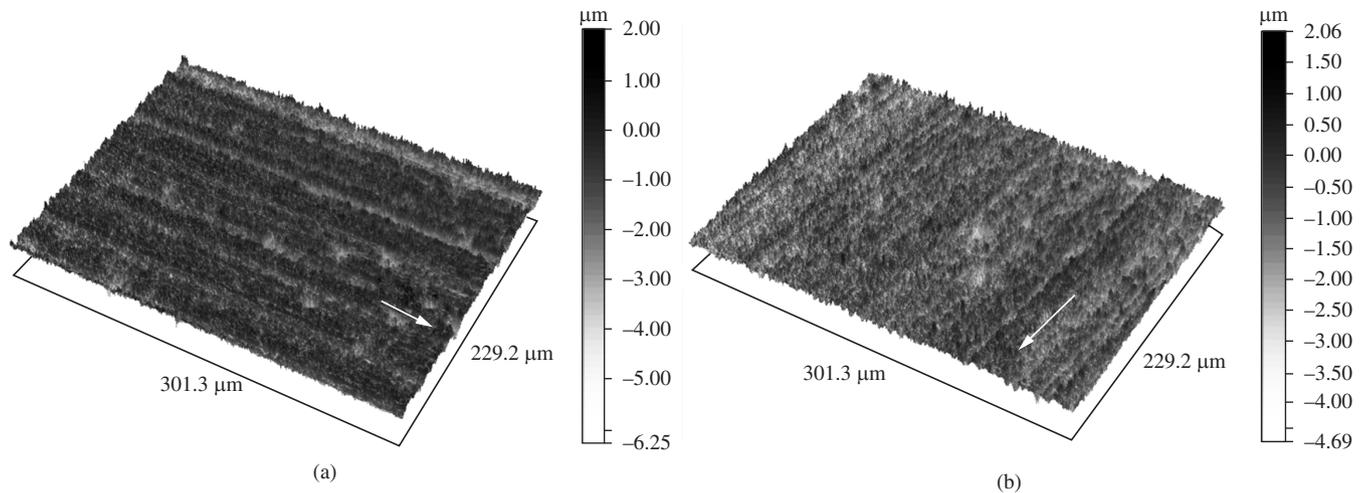
Figure 5. Optical profiler images of a β-Si_3N_4 cutting tool: a) grounded, and b) AlCrN coated.
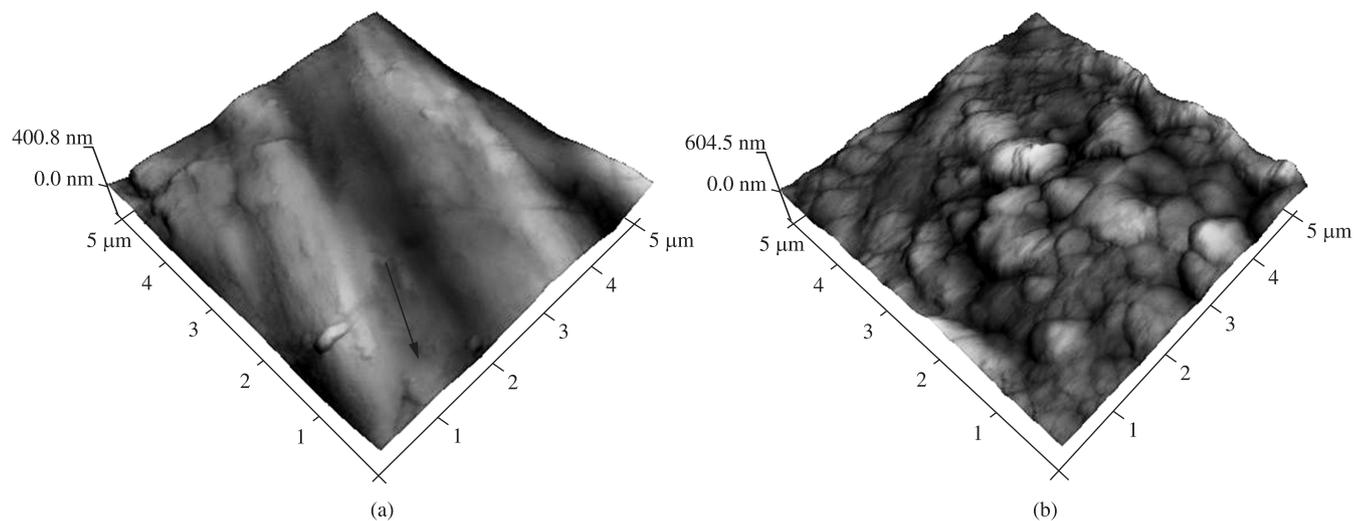

Figure 6. AFM images of the cutting tool surface: a) grounded, and b) AlCrN coated.

3.3.1. Surface roughness

The profile of the workpiece surface roughness can be considered as successive movements of the tool profile at intervals of feeds. A surface with a high finishing quality is difficult to achieve because of tool fracture, pull-out of particles and other failures during machining process. The results showed that the surface finish quality was better when using an insert with AlCrN coating (below 2.3 µm) due to the small grain size of coating, higher hardness, regular (homogeneous) topography and no flank wear. It was observed that when using uncoated ceramics cutting tools, the workpiece surface exhibited a higher surface roughness (upper than 2.8 µm) due to irregular topography of its cutting edge, Figure 7.

The results showed in Figure 7 also indicate that surface roughness increased substantially until a specific time. This can be attributed mainly to an accommodation period of the cutting tool with the workpiece. For both cutting tools, it was noted that surface roughness decreased, after that specific time mentioned above, possibly due to the graphite adhesion in the nose, promoting smoothening of workpiece surface. This graphite possibly acts as a solid lubricant (lower friction coefficient between the tool and the workpiece) and protects the tool from flank wear.

The total cutting length for both tools was near 3500 m, in a total turning time of about 12 minutes. These tools are suitable for finishing operations on gray cast iron.

3.3.2 Machining temperature

The determination of the maximum temperature and temperature distribution along the rake face of the cutting tool is of a particular importance because of its controlling influence on tool life, as well as, the quality of the workpiece. A great part of research on thermal aspects of metal cutting operations has been concentrated on predicting the temperature on the interface zone and obtaining the temperature distributions in the cutting tool and chip. However, there is no general agreement on the procedures for estimating the average temperatures on the shear plane and the tool-chip interface.

In this paper the results obtained, give a clear idea about the values of temperature achieved at the tool-chip interface, for both cutting tools (AlCrN coated/uncoated). Figure 8 shows that as the insert gets in contact with the workpiece, the temperature raises rapidly. For the uncoated cutting tools, it can be seen that the temperature rises until a maximum of about 695 °C, and for coated insert the maximum temperature is approximately 770 °C. The temperature variation
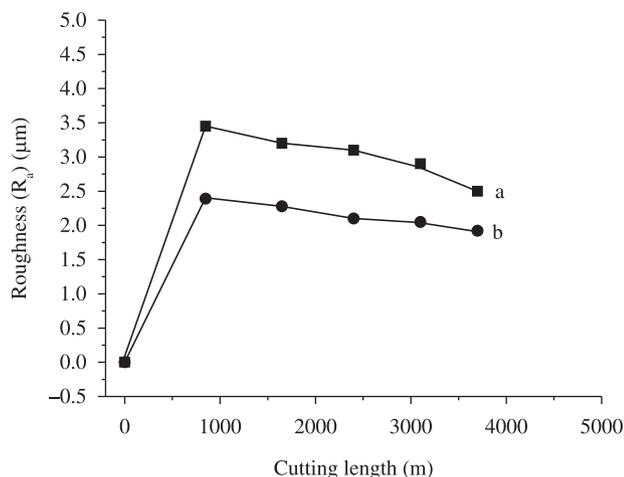
Figure 7. Workpiece roughness vs. cutting length, for β-Si₃N₄: a = uncoated; and b = AlCrN coated.
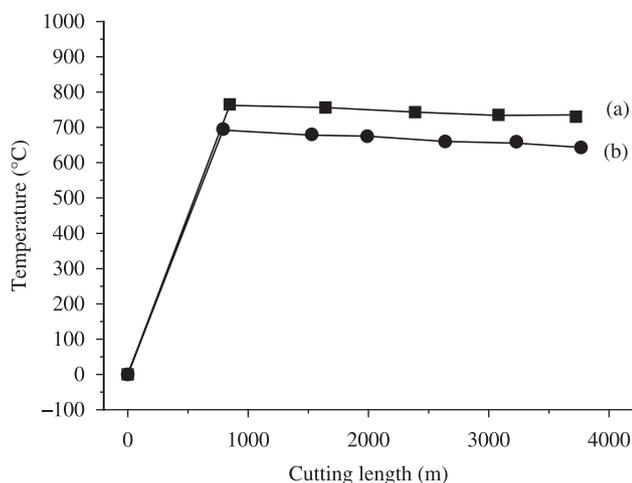

Figure. 8. Temperature vs. cutting length, for: a = AlCrN coated; and b = uncoated.

on Figure 8 shows that tribological behavior (friction components) is different for AlCrN coated and uncoated inserts. There are differences of about 40-50 °C between the highest and the smallest temperature, independent of cutting tools used. Both cutting tools keep their physical and mechanical properties stable for the reached temperatures during tests.

4. Conclusions

It can be concluded that, using the experimental methodology presented here, it was possible to develop new β-Si₃N₄, using Al₂O₃ and CeO₂ as additives, with and without AlCrN coating ceramic cutting tools, suitable for finishing operations on gray cast iron.

The AlCrN coating promoted, compared to the uncoated insert, an increase on the hardness of the surface cutting tool, a better tribological behavior and consequently a smoother surface (lower roughness) on the gray cast iron workpiece surface after machining tests.

Both uncoated and coated inserts did not present wear or cracks after turning, for the used machining conditions.

Acknowledgements

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