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α-SiAlON: DEVELOPMENT AND MACHINING TEST ON GRAY CAST IRON

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Abstract. The α-SiAlON ceramic cutting tool insert is developed. Silicon nitride and additives powders are pressed and sintered in the form of cutting tool inserts at temperature of 1900 ^{o}C. The physics and mechanical properties of the inserts like green density, weight loss, relative density, hardness and fracture toughness are evaluated. Machining studies are conducted on grey cast iron workpiece to evaluate the performance of α-SiAlON ceramic cutting tool. In the paper the cutting tool used in higher speed showed an improvement in the tribological interaction between the cutting tools and the grey cast iron workpiece resulted in a significant reduction of flank wear and roughness, because of better accommodation and the presence of the graphite in gray cast iron. The above results are discussed in terms of their affect at machining parameters on gray cast iron.

Introduction

Until recently, the development of single phase α-SiAlON ceramics has received little attention. This has primarily been due to the poor fracture toughness and processing difficulties associated with the fabrication of these materials. Conversely, β-SiAlON ceramics are easier to densify than α-SiAlON by pressureless sintering and possess a good combination of properties, among which is the relatively high toughness that arises from the elongated morphology of β-SiAlON grains [1]. It is well established that the presence of elongated grains gives rise to mechanisms such as crack deflection, crack bridging and grain pullout, which improve fracture toughness and reliability [2]. It is well known that α-SiAlON with a composition of $M_xSi_{12-(m+n)}Al_{m+n}O_nN_{16-n}$, where $x=m/v$ and M^{+v}=Li, Mg, Ca, Y and some rare earth elements is generally considered to occur in an equiaxed grain morphology and thus, its toughness is much lower than that of β-SiAlON and β-Si_3N_4 [3]. On the other hand, α-SiAlON has the advantage of a significantly higher hardness than that of β-SiAlON and β-Si_3N_4. There are very few reports on the formation of elongated α-SiAlON grains, but recent studies of different rare earth doped α-Si_3N_4 compositions have revealed that elongated α-SiAlON grains can be formed under certain preparative condition [4 and 5]. Therefore, the formation of elongated α-SiAlON grains was mostly connected with the existence of enough liquid phases during the sintering process. In the present work an additional amount of Y_2O_3/AlN in comparison to the amount in the α-SiAlON composition was chosen to obtain a stable liquid phase and to accelerate the formation of elongated grains.

Gray cast iron properties

The gray cast iron is an important material to automotive industry and its microstructure usually consists of flake graphite and a matrix of pearlite and/or ferrite, which its mechanical properties, machining performance, etc. mainly depend on. The composition of grey cast iron is subject to quantitative changes of its components even so, the mechanical properties of the workpiece obtained should be stable so that the subsequent machining process does not produce any problems [6]. A usual practice in the cast iron manufacturing process is to leave the choice of chemical composition in the hands of the foundryman, who will choose the one which adapts best to the needs of the client, without forgetting, of course, that the requirements of his own foundry installations are determinant in order to obtain the desired properties [7]. The gray cast iron has a pearlite matrix and a tensile strength from 245 MPa and HB 205.

Experimental procedure

Two different Si_3N_4-base compositions were prepared using the following high purity starting powders SNYA1, 85.0 α-Si_3N_4– 5.0 Y_2O_3–10.0 AlN (H. C. Starck) and SNYA2, 80.0 α-Si_3N_4– 8.0 Y_2O_3–12.0 AlN (H. C. Starck) in wt. % to obtain different compositions in the α-SiAlON plane. The starting powders were weighed and milled in water-free ethylic for 4 h. The mixed powders were dried and subsequently sieved. The green bodies were fabricated by uniaxial pressing under at 80 MPa pressure and subsequent isostatic pressing under a 300 MPa pressure. After compaction, samples had showed dimensions 15.36 x 15.36 x 6.5 mm and green density of ~ 58 % by geometric methods. Before sintering, the samples were involved in 70 % Si_3N_4 + 30 % BN as powder bed, and then introduce in a furnace with a graphite heating element (Thermal Technology Inc. type 1000-4560-FP20) in nitrogen atmosphere. The heating rate employed was 25 ^oC/min up to a maximum sintering temperature at 1900 ^oC, with a holding time for 2 hour. The cooling rate was the same as heat-up rate. The density of the samples was measured by the Archimedes method and the weight loss was determined before and after sintering measurements. The surface of the sintered samples was removed (at least 2 mm) and then the phase composition was analyzed by the X-ray diffraction technique using Cu-Kα radiation and scanning speed equal to 0.02 ^{o}/s. The microstructural characterization was performed with a scanning electron microscope. The samples for SEM examination were smoothed and polished samples were submitted to chemical etching in a NaOH **:** KOH mixture (1:1 at 500 ^oC/10 minutes) to reveal the microstructure. The hardness was determined by Vicker´s indentations under an applied load of 20N for 30 s. To statistical reasons, 20 indentations were made to each sample. The fracture toughness has been determined by the measurement of crack length created by indentations. The calculation of the fracture toughness values was done by relation proposed by Evans et al., valid for Palmqvist type cracks [8].

Cutting performance

All experiments were carried out on a computer numerical control lathe (CNC-Romi, Mod. Centur 30D) under dry cutting condition. The sintered α-SiAlON were cut and ground to make SNGN120408 (12.7 mm×12.7 mm, 4.76 mm thickness). A tool holder of CSRNR 2525 M 12CEA type was used for the cutting experiments. The cutting performance of the α-SiAlON tools was tested by machining gray cast iron, using composition of the best mechanical properties. The cutting tests for machining of gray cast iron were performed at cutting speed of 150, 230, 700 m/min with a feed rate of 0.30 mm/rev and a depth of cut of 1.0, 2.0 and 2.0 mm. The dimension of work material was about 105 mm in diameter and 300 mm in length. The wear of the tools was determined by measuring the wear depth on the flank face by using a SEM (LEO-1450 VP) at more than four points of flank face and the average of them was taken as a nominal flank wear depth. Flank wear of 0.3 mm (ISO 3685) and variation abrupt of R_a and R_y has been used as end tool life criterion. The surface roughness of the machined work piece was measured using a surface roughness meter with a cut-off length of 0.8 mm and sampling length of 5 mm (Mitutoyo Surftest 402 series). To measure at temperature workpiece/cutting tools was used an infrared pyrometer.

Results and discussion

Sintering

The relative densities, weight loss, green density and theoretical densities were determined in individual samples, are listed in Table 1.

Table 1. Theoretical, green and relative densities and weight losses of the sintered samples

Sample	Theoretical density [g/cm^3]	Green density [%]	Relative density [%]	Weight loss [%]
SNYA1	3.32	58.6 ± 1.3	97.92 ± 0.22	2.10
SNYA2	3.50	57.7 ± 1.4	98.75 ± 0.16	1.97

The densification behavior of both samples was also similar. The relative densities of SNYA2 sample were slightly higher, while the weight loss during the sintering was slightly smaller than that of SNYA1 sample. This behavior demonstrates the viability of using Y_2O_3/AlN as sintering additives. It is supposed that the temperature of liquid phase formation using Y_2O_3/AlN as additives is slightly lower if compared to the other additives systems [9]. However similar sintering activity for the both sample compositions is expected because of same additives only different amount. Furthermore, the weight losses during the sintering of both powder compositions of about 2 % are quite acceptable for the fabrication of high-performance ceramic materials and are in agreement with the results presented by Shin and Kim [10]. Thus, the sintering parameters applied are adequate to produce ceramics cutting tools at high density. The isothermal holding time for 2 h at 1900 °C during sintering reduced the effects of a nonuniform densification, typically observed in α-SiAlON ceramics, characterized by porosity gradient between the surface and center region of the samples [11].

X-ray difractometry

In this work, samples with Y_2O_3 and AlN as sintering additives were densified completely, which is coincident with the results presented by Santos et al.[9]. The SNYA1 samples sintered show present β-Si_3N_4 as the main majority phase. The randomly distributed grains of Si_3N_4 ceramics fabricated by N_2 pressure sintering lead to isotropic mechanical and physic properties, which is different from that, prepared by hot-pressed method [12]. But $Y_2Si_3O_3N_4$ formed during the sintering process was found to greatly decrease the properties of the samples, like Hardness Vickers, fracture toughness and others. The formation of this phase can be explained by the following reaction equation.

$$Y_2O_3 + Si_3N_4 \rightarrow Y_2Si_3O_3N_4 \quad (2)$$

The relative intensity of peak β-Si_3N_4, α-SiAlON and peak $Y_2Si_3O_3N_4$ together reflect the relative amount of the three phases after sintering. The relationship between the amount of additive and the properties of the samples is evidence in SNYA2 that present α-SiAlON as the main matrix phase that increase of properties mechanical and phase $Y_2Si_3O_3N_4$ disappears. However the sintering temperature at 1900 ^{o}C with 20 % of additives were an effective procedure to remove this phase ($Y_2Si_3O_3N_4$), which results in the improvement of the properties mechanical. The relationship between the amount of additive and the properties of the samples is showed in Table 2.

Mechanical properties

The results of the sintered samples are shown in Table 2. The results was hopeful, which present the average grain sizes, aspect ratios, Vicker's hardness and fracture toughness to SNYA1 and SNYA2.

Table 2. Microstructural characteristics and mechanical properties of the sintered samples

Sample	Aspect ratio	Average grain size [µm]	Vicker's hardness [GPa]	Fracture toughness K_{IC} [MPa $m^{1/2}$]
SNYA1	5.6	4.8	18.90±0.29	5.92±0.24
SNYA2	5.1	4.2	21.52±0.18	5.45±0.12

Accordance average grain both samples present similar microstructures for SNYA1 (higher grains) and SNYA2 (lower grains) samples Table 2. The images exhibit elongated α-SiAlON grains, with an average grain size of about 4.0-4.2 µm and aspect ratios higher than 5 µm, thus confirming the formation of α-SiAlON with an elongated microstructure by the gas pressure sintering (GPS) process. In a previous work [9], the formation of the elongated α-SiAlON grains was explained by the reduction of the driving force for the nucleation. Agreement, Santos et. al.(2004) the formation of elongated grains is directly related to the sintering parameters, time, temperature and isothermal holding time, as well as to the characteristics of the starting powders, such as composition and amount of additives used. It can be concluded, that for additives used, namely Y_2O_3/AlN in different amount lead the activation energies for nucleation and growth of elongated grains should be similar, since the sintering parameters were the same for both compositions and the microstructures show very similar features. The results of mechanical properties of both investigated samples yielded of α-SiAlON ceramic with Vicker's hardness higher than 18.90 GPa and a fracture toughness of 5.4 MPa $m^{1/2}$. The high fracture toughness, caused by high degree of crack deflection, is consistent with the large grains and high aspect ratios Table 2. The similarity of the microstructural features, especially the formation of elongated α-SiAlON grains and the presence of small residual amounts of an intergranular glassy phase should be the determining factors for the SNYA2 samples present higher mechanical properties.

Tool life

The effects of various types of tool wear on tool life at different cutting speeds are analyzed. The maximum allowable machining time is calculated from the flank wear, crater wear, and notch wear models or fracture using the respective tool rejection criterion. Therefore the tool wear affects tool life, quality of the machine surface, its dimensional accuracy and consequently the economics of cutting operations. The variation of flank wear of the α-SiAlON cutting tool with respect to machining time is shown in Fig. 1A. This figure we can be noted that flank wear of α-SiAlON is lower to high speed because there is the better accommodation between cutting tool/workpiece, it can be confirmed in the Fig. 2C. During on turning gray cast iron the stability of the α-SiAlON cutting tool is favored in the presence of a lubricating phase, like graphite flakes. The presence of a self-lubricant becomes of further help. Lubricant particles are expected to prove better wear behavior and better cutting tools performance. Analyzing Fig. 2A and 2B, it is possible to suppose that lower cutting speed provides minor adhering capability to the lubricant particles on the sliding surfaces required for smearing and lubricating film formation is slow causing increasing wear rate and possible vibrations could be attributed to the increased severity which evident surface damage. However in these figures we can observe chipping of α-SiAlON cutting tools due to lower order cutting velocity, the cutting wedge of the tool tends to plow on to the work surface resulting in a marginally higher order force. The increased of cutting speed the graphite lubricant indicates more effective film formation presenting decrease flank wear and surface roughness. The reports results of α-SiAlON properties and machining parameters is possible tell that α-SiAlON cutting tools present unique results when machining gray cast iron. Therefore it credits can be associated at contains graphite flakes in grey cast iron. In Fig. 2A and 2B, shows at micrographics of the cutting edge chipping seen to speed machining 150 and 230m/min. The important relation between chipping and speed is shown by Fig 3A and 3B in roughness graphics.

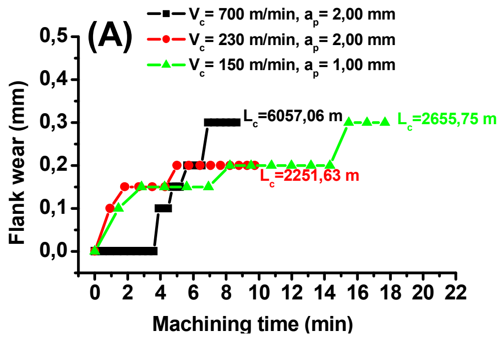

Fig. 1A - Flank wear vs machining time.

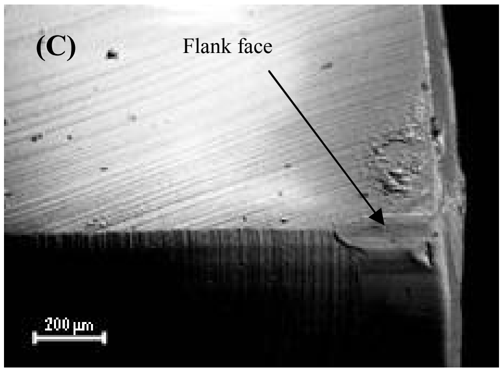

Fig. 2(C) - Flank wear growth at 700 m/min.

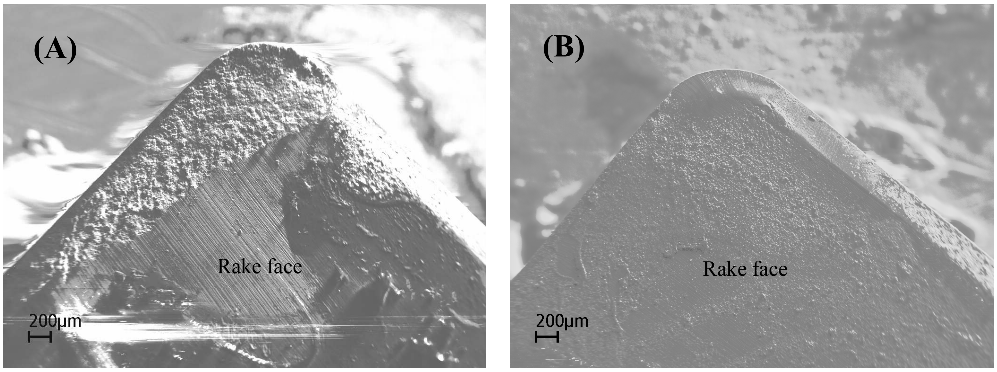

Fig. 2. Photomigraphics of chipping: 2(A), at 150 m/min and 2(B), at 230 m/min

Surface finish

Surface finish is controlled by flank wear of turning tool, the surface quality largely depends upon the form stability of the cutting nose. In this work confirm concept above. The roughness parameters values showed important variations despite the fact that the initial conditions of the surface as well as the workpiece properties were the same. The correlation between changes in the roughness parameters and the cutting speeds can be seen in Fig. 3A and 3B. These changes are different for three types of cutting speeds. For, cutting speed 700 m/min the decrease on surface roughness is greater than for the cutting speed 150 and 230 m/min, but in three cases, there is a similar relationship between the roughness and the cutting speeds. This is of particular importance on the performance of SiAlON tool. Taking into account the high density and hardness of this tool it will cause a not accelerated wear of the tool surface to higher speed. Supplementary investigations and literature [13] show that an increase in the quality of the surface of gray cast iron is related to graphitization during machining due to at thermochemical action in workpiece/tool interface. A change in surface roughness after some time is due to higher temperature of 760 ^{o}C and machining parameters. It can be noted that the α-SiAlON tool produced better surface finish with the increase of cutting speed. The surface finish produced using α-SiAlON cutting tools is due to important mechanical properties resulting in better form to stability of the cutting nose.

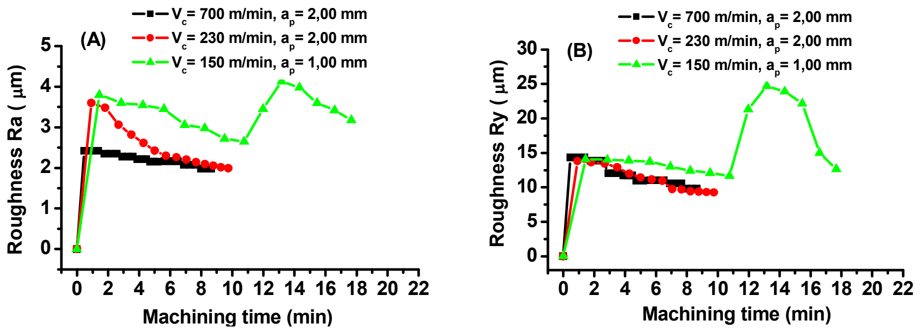

Fig. 3A and 3B- Surface roughness (R_a and R_y) vs cut length.

Conclusion

The α-SiAlON cutting tool insert has been developed in the laboratory and its machining performance on grey cast iron workpiece has been promising with important value of cut length, low roughness and flank wear for higher cutting speed. Therefore was observed that at low cutting speed of 150 and 230 m/min dry machining did not offer any advantage. However, at higher cutting speed (700 m/min), it significantly reduced the tool flank wear and increased the tool life. This study also brought out some interesting and useful observations for future researches in development, manufacture and machining test with α-SiAlON cutting tools. For example, increase cutting speed to provide some direct correlation with flank wear or surface roughness. Thus, the inclusion of parameters, for prediction of surface roughness and tool wear as was successfully done for the prediction of tool life in machining gray cast iron may be advisable in the present case. The results obtained are encouraging and dry machining can be a good environment friendly option for manufactures process. In future work we will concentrate in optimizing the process parameters of development, characterization, manufacture and dry machining process using α-SiAlON cutting tools on turning of others materials.

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