Ti-6Al-4V MACHINING WITH SILICON NITRIDE CUTTING TOOLS: A SCIENTIFIC AND TECHNOLOGICAL CONTRIBUTION

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Abstract. *The cientific and technological development is allowing new materials appearance, such as: Ti-6Al-4V alloy, and its alloys, that is widely used in many industries owing offers high strengh, depth hardenability and alevated temperature properties up to 400°C. Titanium alloys are extremely difficultto machine, condidtion that endears its manufacture process and applicability. This paperis proposed with the objective to produze and apply* Si_3N_4 *cutting tools in the Ti-6Al-4V machining. Therefore, a powder mixture composed of the* α*-*Si_3N_4*, AlN and* Y_2O_3 *is homogenized, compacted and sintered at 1900°C for 1h. After sintering, the samples showed relative density, hardness and fracture toughness equal to 98 % of theoretical density, 21 GPa and 5.3* $MPa.m^{1/2}$*, respectively. The phase analysis x-ray diffraction and scanning electron microscopy (SEM) showed presence of* α*-SiAlON and* β*-*Si_3N_4*. After characterization the samples was submitted to machining tests,withoutcoolant, using: Vc=85, 120 and 150* $m.min^{-1}$*, ap=0.5 mm and f=0.05* $mm.rot^{-1}$*. The results this paper showed good performance this cutting tools when machining titanium alloy Ti-64.*

Keywords*:* Si_3N_4*, Ti-6Al-4V, sintering, machining, mechanical properties.*

1. Introduction

In recent years, evolution of the properties of titanium alloys, particularly alloy Ti-6Al-4V has been waking up the interest of several industrials, such as: aeronautic, aerospacial, metallurgical, biomedical and others (Moreira, 2002).

However, success of machining of this alloy depends broadly on domain of the main problems associated to its properties. Among those properties detach its low thermal conductivity, which provides shearing adiabatic conditions, increasing the temperature at the cutting edge of the tool and exit surface. Hence, on machining, the cutting tools wear off very rapidly due to high cutting temperature and strong adhesion between tool and workpiece material (Walter, 1993).

The cemented carbide (WC-Co), cubic boron nitride (CBN), diamond cutting tools has been used to machining of titanium alloy Ti-6Al-4V, but with low cutting speeds about 45$m.min^{-1}$ when using straight grade cemented carbides (WC-Co) (Sandvik, 2000, Dearnley, 1986, Walter., 1993, Narutaki, 1983). Besides the cemented carbides, CBN and diamond cutting tools, others materials also has been used in titanium alloys machining, as silicon nitride ceramics (Si_3N_4), that it appear as promising material to such application, due to the its excellent physical and thermo-mechanical properties (Witting, 2002, Dressler, 1997). The use of Si_3N_4 cutting tools can contribute to decrease the operational costs with increase of the useful life time, no coolant in process, decrease in environmental impact and others.

However, dense Si_3N_4 ceramics are difficult to obtain by solid phase sintering due to its low self-diffusion coefficient. Dense Si_3N_4 ceramics can be obtained by liquid phase sintering using AlN, Al_2O_3, Y_2O_3 and rare earth oxide as additives (Ribeiro, 2000). Such sintering additives facilitate the diffusional phenomena, decreasing the porosity of the material and consequently, improving the densification and mechanical properties of the silicon nitride (Si_2N_4).

The use of rich additives in Al, Y and O ions during Si_3N_4 sinterring results in a solid solution substitutional and/or interstitial, called SiAlONs, that improve hardness, oxidation and creep resistance of the Si_3N_4 ceramics. SiAlONs shows two crystalline phases, α and β, results of the substitution of Si and N by Al and O respectively. Whereas that, Y ion occupy void interstitial in structure, stabilizing in this way the α phase and β at high sintering temperature (Santos, 2004).

Because the titanium alloy is extremely difficult to machine material, this paper had as innovative character, development, characterization and application of Si_3N_4 cutting tools in machining of the Ti-6Al-4V alloy, using different cutting speed, in a dry cutting condition.

2. Experimental procedure

2.1 Materials

The materials used in this work were: α-Si_3N_4 (99.9 % - H. C. Starck - Germany), Y_2O_3 and AlN (Fine grade - H. C. Starck – Germany), Ti-6Al-4V alloy (Embraer) and nitrogen (Type B50 – Air Liquid Brasil S/A).

2.2 Method

The powder batches were prepared in a planetary mill for 3 hours using ethanol as a vehicle. The suspensions were dried and subsequently sieved. The composition of the powders mixture, as well as its designations is represented in ***Tab. 1.***

Table 1. Code and Composition of the powder mixture prepared.

Code	Composition (wt %)			Green relative density (% of Theoretical)
	α-Si_3N_4	AlN	Y_2O_3	
SAY	82.86	10.63	6.51	59.98 ± 0.20

The green bodies were fabricated by uniaxial pressing under a 100 MPa pressure and subsequent isostatic pressing under a pressure of 300 MPa.. After compactation, samples had 13.36x13.36x7.5 mm dimensions. The green density of the compacts was determined geometrically. 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^{o}C/min up to a maximum sintering temperature of 1900^{o}C, with a holding time for 1 hour. The cooling rate was the same as heat-up rate.

The relative density of the sintered samples was determined by the immersion method in distilled water. The weight loss was determined by before and after sintering measurements. The phase analysis was determined by X-ray diffraction with CuKα radiation and scanning speed equal to 0.02^o/s.

Smoothed and polish samples were submitted to chemical etching in a NaOH:KOH mixture (1:1 at 500^{o}C/10 minutes) to reveal the microstructure. The micrographs of the sintered samples were obtained by the use of Scanning Electron Microscopy (SEM).

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 the crack length created by the Vicker´s indentations. The calculation of the fracture toughness values was done by the relation proposed by Evans et al., valid for Palmqvist type cracks (Silva, 2000).

After characterisation, samples were ground by a diamond wheel into 13x13x4.8 mm dimensions, with negative bevel of 20^o and thickness of bevel equal to 0.08 mm, conform ISO 1832 standard. To development this work cylindrical shape Ti-6Al-4V bar of 87 mm length and 88.30 mm diameter was used.

Machining tests were realized without coolant in a CNC lathe (Romi, mod. Centur 30D). To measure the temperature of the cutting tool to material interface an infrared radiation pyrometer was used. The data used in the machining tests are shown in ***Tab. 2*** (Moreira, 2002). Wear analysis of the cutting tool was determined by performance of cut and flank wear maximum (Vbmax), respectively, it isn't base ISO 3685.

Hence to analyze surfaces of the cutting tool a scanning electron microscopy (LEO-1450 VP) was used.

Table 2. Parameters used in machining tests (Moreira, 2002).

Machining conditions	Cutting parameters		
	Vc (m/min)	f (mm/rot)	ap (mm)
A	85		
B	120	0.05	0.5
C	150		

3. Results and discussions

3.1. Cutting tools manufactured

To obtain ceramic cutting tools it is necessary to combine high relative density and good mechanical properties such as: fracture toughness and hardness that are directly related to the microstructure of the material.

National ceramic cutting tools applied to specific cases is a reality. But, ceramic cutting tools obtaning high hardness and good wear resistance usually has to be accompanied by higher brittleness, if compared to high-speed steel. Such conditions demand an accurate control of machining parameters, aiming to determine the optimum cut states. Aspect of a molded Si_3N_4 cutting tool and its shaving incidence and exit surfaces, before machining tests, is shown in ***Figure 1***.

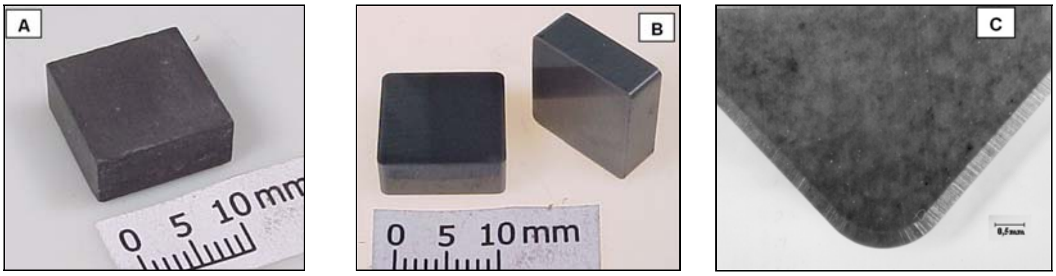

Figure 1. Aspects of molded Si_3N_4 cutting tool and its respectives shaving incidence and exit surfaces, before machining tests: (a) produced tool cutting bit, (b) molded tool cutting bit and (c) Cutting tool bit with surface finish.

3.2. Relative density and linear shrinkage

Relative density and linear shrinkage of the sintered samples are shown in ***Tab. 3***. Sintering conditions used, aided by additive system provide to obtaining ceramic with high linear shrinkage and relative density. The liquid phase formed during sintering is probably another condition that allowed a ceramic with such properties. Because, its intensified particle rearrangement and reprecepitation-solution mechanisms.

Table 3. Relative density and linear shrikage of sintered samples.

Code	Physical properties	
	Relative density (% of theoretical)	Linear shrinkage (%)
SAY	98.03 ± 0.54	15.26 ± 0.36

3.3. Phase analysis of the sintered samples

X-ray diffraction patterns of the sintered samples are shown in ***Fig. 2***. Observing the results shown in this figure, presence of α-SiAlON, β-Si_3N_4 and $Y_2Si_3N_4O_3$ phases has been noted. However, with predominace of α-SiAlON phase, shows the efficiency of additive system in stabilization of α-Si_3N_4 phase and transformation to α-SiAlON.

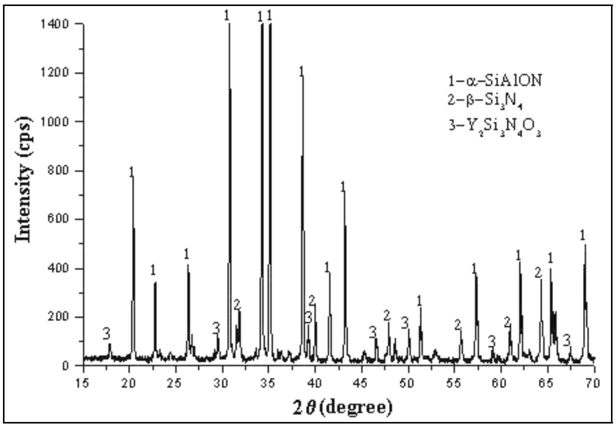

Figure 2. X-ray diffraction patterns sample sintered.

3.4. Microstructural analysis of the sintered samples

Micrograph of the sintered sample is shown in ***Fig. 3***. A homogeneous microstructure with elongated grain morphology, characteristics of α-SiAlON different, possibly reflecting in good hardness and fracture toughness, it is observed in Figure 3.

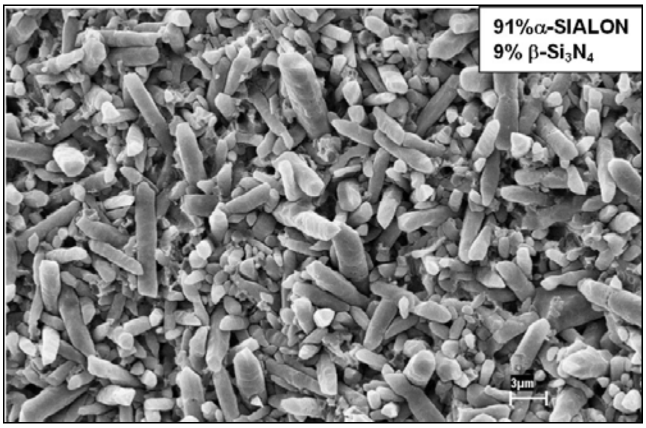

Figure 3. Micrograph of the sintered sample.

3.5. Hardness and fracture toughness

Fracture toughness and hardness of the sintered samples are shown in ***Tab. 4***. High hardness values is related to predominance of α-SiAlON phase, which shows hardness higher to the β-Si_3N_4. Whereas, fracture toughness results is directly related to the α-SiAlON and β-Si_3N_4 amount, that can activate toughening mechanisms, depending on the aspect ratio (length:diameter) of the presents phases.

Table 4. Hardness and fracture toughness of the sintered samples.

Code	Mechanical properties	
	Hardness (GPa)	Fracture toughness ($MPa.m^{1/2}$)
SNAY	21.36± 0.21	5.28 ± 0.12

3.6. Influence of the machining parameters in wear of cutting tool and surface of the piece machined

In ***Fig. 4*** the influence of the cutting length and time on flank wear for the different conditions analyzed. The better results to cutting length and time is noted for Vc=85 m/min, but it is condition that presents greater flank wear. This behavior probably can be explained because to increase of cutting time, providing larger shaving and heat accumulation on cutting edge, due the low thermal conductivity of the titanium alloy Ti-6Al-4V, raising this way shearing adiabatic conditions.

The flank wear to all conditions has been higher at ISO 3865 standard. But, the cutting tools presented good performance, even with wear happening in intense mode, proving the properties of cutting tools, that didn't exhibit catastrophic flaws, supporting the intense loads during realization these tests. In figure 4 is observed that the better cutting speed is Vc=180m/min, condition the which confirm a good performance this cutting tools in higher speed to conditions this paper.

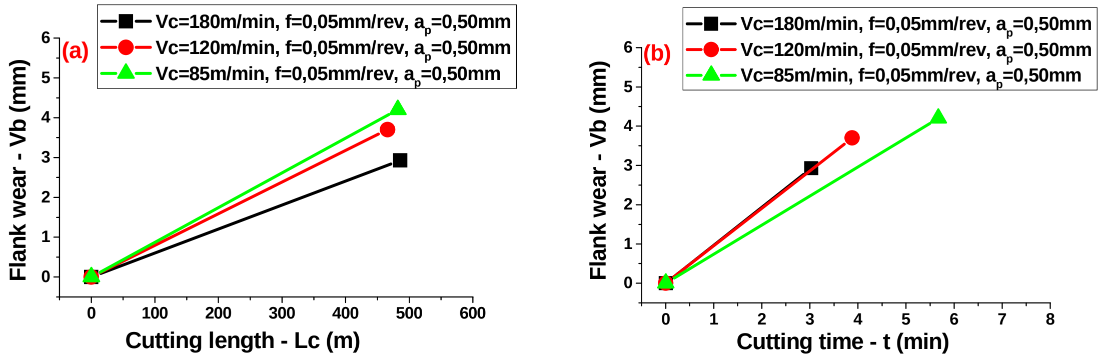

Figure 4. Influence of cutting length, cutting time in flank wear to different machining conditions.

The influence of cutting length on cutting speed has noted in ***Fig. 5 a***. In this figure, the better condition was Vc=85 m/min, whereas to others conditions, the high temperatures (***Fig. 5b***), mechanical pressure and dynamics loading during Ti-6Al-4V machining associated the high reactivity of the Ti with the material of cutting tool are main responsible by wear and damages occurred on cutting tools, caused decrease of the useful life of cutting tool.

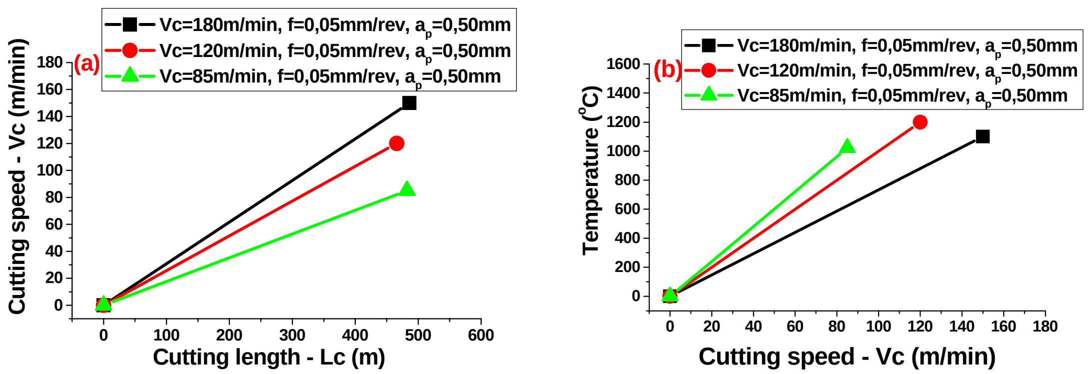

Figure 5 Influence of the cutting length, cutting speed and different machining conditions on flank wear of Si_3N_4 cutting tools and temperature of the piece-tool interface.

The alloy Ti-6Al-4V machining with Si_3N_4 cutting tools has been shown in ***Fig. 6a***. An aggressive behavior during machining this alloy can be observed, explaining high wear suffered by cutting tool, conform previous results (***Fig. 4 and 5***) and micrographs illustrated in ***Fig. (6b-6d)***. In all conditions analized, observe predominance of abrasion, followed strong adhesion, which probably during machining resulted in others wear types, as chipping and crater, see ***Fig. 6b***. Such these mechanisms are directly related to machining conditions, that provided the increase the temperatures at the cutting tools of the tool, contributing this mode for activation of the same mechanisms, due probably of chemical interaction between the Si_3N_4 cutting tools and piece machined (Ti-6Al-4V alloy). These results are superior at found in literature when of the used cemented carbides (WC-Co). In recent paper (Che-Haron, 2005), utilized cemented carbides, with cutting speed of 60, 75, 100m/min, at obtained about 5minutes to cutting speed of 60m/min, to 75, 100m/min the time is loss than 1minutes. However (Che-Haron, 2005), obtained the better surface finish, owing at a lower cutting speed (Che-Haron, 2005).

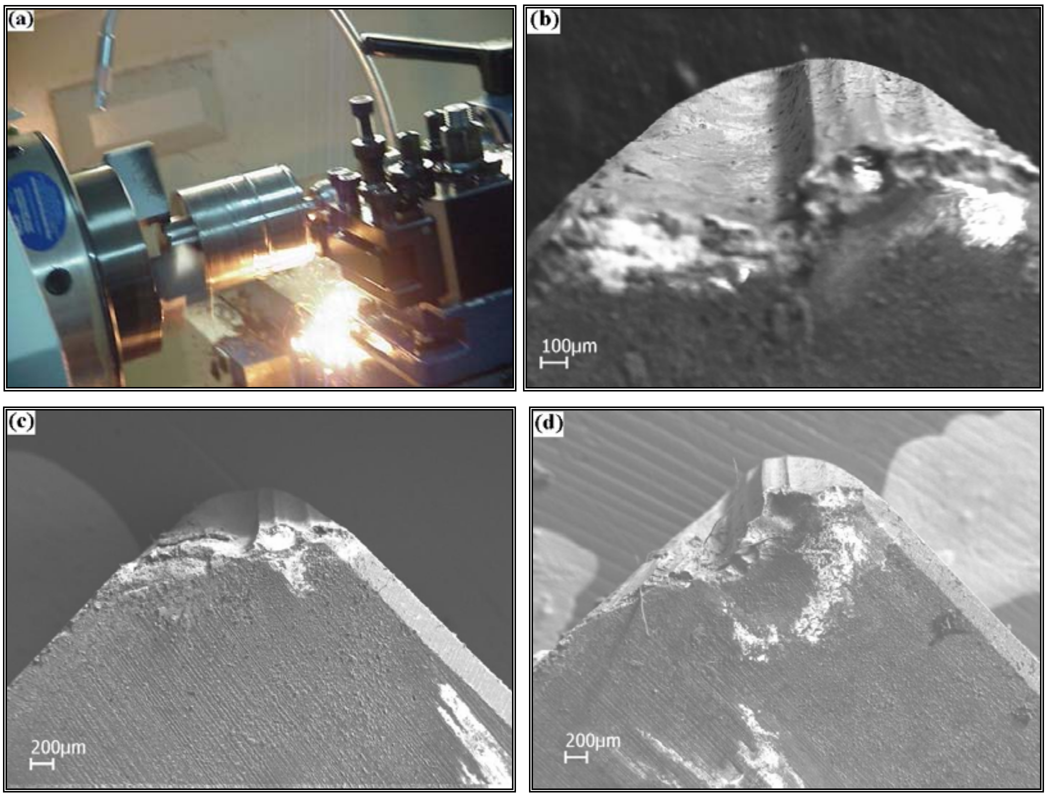

Figure 6. Machining of alloy Ti-6Al-4V (a), micrography of Si_3N_4 cutting tool: (b) Vc=85m/min, Lc_{max}=482 m, Vb_{max}=4,2 mm, (c) Vc=120 m/min, Lc_{max}=466 m, Vb_{max}=3.7 mm, (d) Vc=150 m/min, Lc_{max}=456 m, Vb_{max}=2.93 mm.

4. Conclusion

The silicon nitride (Si_3N_4) cutting tools showed good physical and mechanical properties, that during alloy Ti-6Al-4V machining produced considerable results, such as cutting length equal to 482 m. However these results it isn't found in literature, intensifying the cientific and technological informations referring to the machining process this titanium alloy Ti-6Al-4V with cutting tools ceramics.

5. Acknowledgements

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