Abstract: This paper presents the results of an experimental investigation on the effect of cutting forces on turning gray cast iron with silicon nitride (Si3N4) based ceramic tool. Turning experiments were carried out at five different cutting speeds and feed rates with depth of cut was kept constant. Tool performance was evaluated with respect to tool wear, temperature, surface finish produced and cutting forces generated during turning. The Si3N4 based ceramic cutting tool showed higher performance to increase cutting speed. These results can be associated with good high temperature strength and contains graphite flakes in grey cast iron.
To: Editor-in-Chief:

Professor K.L. Edwards
School of Engineering
University of Derby
Kedleston Road
Derby
DE22 1GB
UK
Ref.: Submission of Manuscript to Materials & Design

Dear Professor Edwards,

We are pleased to submit our paper entitled “CUTTING FORCES IN TURNING OF GRAY CAST IRON USING SILICON NITRIDE BASE CUTTING TOOL” for your considerations.

This is an original contribution for publication at Materials & Design.

My address for further correspondence is the following:

Prof. Dr. José Vítor C. de Souza
Av. dos Astronautas, 1.758, Jd. Granja – CEP: 12227-010 São José dos Campos – SP, Brasil. Tel: 55 (12) 3945-6000 or 55-12-3945-6679
e-mail: vitor@las.inpe.br

Thank you once more for your attention.
sincerely yours,
José Vítor Cândido de Souza
Abstract

This paper present the results of an experimental investigation on the effect of cutting forces on turning gray cast iron with silicon nitride (Si₃N₄) based ceramic tool. Turning experiments were carried out at five different cutting speeds and feed rates with depth of cut was kept constant. Tool performance was evaluated with respect to tool wear, temperature, surface finish produced and cutting forces generated during turning. The Si₃N₄ based ceramic cutting tool showed higher performance to increase cutting speed. These results can be associated at good high temperature strength and contains graphite flakes in grey cast iron.

Keywords: Silicon nitride, Cutting force, Gray cast iron.
1. Introduction

The term ceramics is applied to a range of inorganic materials of widely varying uses. Generally these materials are non-metallic and in most cases have been treated at a high temperature at some stage during manufacture. Ceramics are far less ductile than metals and tend to fracture immediately when any attempt is made to deform them by mechanical work [1]. They are often of complex chemical composition and their structures may also be relatively complex.

Ceramics in recent years have been sought in many applications due to their improved properties like good thermal shock resistance, good high temperature strength, creep resistance, low density, high hardness and wear resistance, electrical resistively, and better chemical resistance [2]. On the negative side, they feature low ductility and fracture toughness at room temperature and standard pressure so that fracture will occur once the atomic linkage forces are exceeded [2]. Therefore in machining test using ceramic materials is a big challenge and quite expensive affair because of their inherent brittleness. Recent work on the machining of compacted graphite iron, Souza, 2004 has confirmed that brittleness of cutting tools ceramics can be a big problem in the quality surface finish [3]. Cutting forces are widely recognized as an optimum performance estimator of machining operations. Many authors, compiled in the trend reports by Van Luttervelt et al. [2] and Ehman et al. [4], have addressed their research work to the prediction and measurement of these forces. Both force modulus and direction are directly related to different aspects of the removal process, with a clear influence on the efficiency of the operation and the quality of the machined part [5].
Thus, cutting force is result of the extreme conditions at the tool-workpiece interface. This interaction can be directly related to the tool wear and, in the worst of the cases, to the failure of the tool [6] and [7]. Consequently, tool wear and cutting forces are related to each other, although that relationship is different for each different wear mechanism (flank, crater, tool breakage). Cutting forces are also related with chatter and process instability [7] and [8]. Chatter results in a loss accuracy of machined parts or in damages of the machines structure.

In order to analyze the different situations that may arise during a machining operation, in this paper the analysis utility, based on the simultaneous measurement of the three orthogonal components of the cutting force ($F_x$, $F_y$, and $F_z$), measured with a dynamometer and the current position of the tool in machining centre, is presented. The performance of turning tests are a main step for turning optimization of gray cast iron.

In this paper was focus, three case studies will be shown. Process of manufacture cutting tools, characterization and finally apply in turning tests. However it must be remarked that the system has been developed only for running machining tests and diagnostics, since in an industrial environment dynamometric devices such as the one here used are not applied because of their high cost.

1.2. Machinability of gray cast iron

The presence of graphite particles in gray cast iron, renders this material to have good machinability by nearly all criteria, especially when compared to steels. Low rates of tool wear, high rates of metal removal, relatively low cutting forces and power consumption are the characteristics of cast iron. The surface of the machined cast iron, however, is rather matt in character. When machining gray cast iron the graphite
particles determine cutting forces and surface roughness while the matrix determines the tool life [9] and [10].

When a steel part is replaced with ductile iron, better machinability is considered to be the most important gain. Although there is no definite information in the published literature that gray cast iron has better machinability than steels, data obtained from manufacturers like General Motors shows that parts manufactured from gray cast iron leads to improvement in tool life by 20–900% when compared to the heat treated forged steels. Very fine surface finishes can be obtained on gray cast iron. For machining gray cast iron, it is possible to find some practical cutting parameters value from the machining handbook [11], [12] and [13].

1.3. Surface finish

One of the important parameters in evaluating the performance of a cutting tool is the surface quality it produces on the machined work piece. It is well known in turning, the surface quality largely depends upon the accuracy of replication of cutting nose on the work surface. An ideal tool material is the one which can ensure high fidelity of its nose replication, thereby ensuring good control over the surface quality [14]. The advantage of machining using ceramic cutting tools is generally seen in higher levels of surface finish obtained compared to that of other conventional tools such as cemented carbides. While dimensional accuracy is controlled by flank wear of the turning tools, the surface quality largely depends upon the stability of the cutting nose. Therefore the variation of surface roughness with cutting speed it will be presented in this paper.
1.4. Influence of cutting force in the work material

The ceramic cutting tools have an advantage in the machining of hard work piece materials. The variation of main cutting force with cutting speed on machining steel (45HRC) using Ti\([C,N]\) mixed alumina ceramic cutting tool is presented in paper [15]. In this paper it can be noted that the cutting forces of the ceramic cutting tool decrease with cutting speed. The decrease of cutting force with respect to cutting speed when using Ti\([C,N]\) mixed alumina ceramic cutting tool shows that this type of ceramic cutting tool can machine the work piece material with high speed and at low cutting forces. The lower cutting forces result in a lower distortion of work piece [15], which improves the surface finish while machining with the ceramic cutting tools.

In general the ceramic cutting tool materials produce good surface finish for harder work piece materials. The surface finish of the work material improves with cutting speed. Wuyi Chen et al. reported that surface finish was improved with increasing cutting speed during machining medium hardened steel using CBN tools [16]. It was reported that the ceramic tools exhibited superior performance as compared to the carbide tools, especially at higher machining speeds, both in terms of tool life and surface finish of the work-piece [17].

2. Materials and experimental procedure

The composition of Si\(_3\)N\(_4\) ceramics were prepared 77.90Si\(_3\)N\(_4\)– 4.8Y\(_2\)O\(_3\)–4.80CeO\(_2\)–10.0AlN– 2.50Al\(_2\)O\(_3\) (in wt.%) was produced and characterization. In this work, they were produced using powders of \(\alpha\)-Si\(_3\)N\(_4\) (H.C. Starck, Germany, \(d=3.2\) g/cm\(^3\)), \(\alpha\)-Al\(_2\)O\(_3\) (Alcoa Chemicals, Brazil, \(d=3.98\) g/cm\(^3\)), Y\(_2\)O\(_3\) (H.C. Starck, \(d=5.03\) g/cm\(^3\)), CeO\(_2\) (H.C. Starck, \(d=2.70\) g/cm\(^3\)) and AlN (H.C. Starck, \(d=3.26\) g/cm\(^3\)).
Suspensions comprising 100 g of appropriate powder mixture were prepared. The suspensions were planetary-milled in an Al₂O₃ cube (i.e., milling container) for 3 h, using 250 g of Si₃N₄ balls of different sizes. The weight loss of the Si₃N₄ balls and the cube was always measured. The results indicated that the contamination level introduced in this stage was <0.2 %. After drying (100 °C, 24 h), the powders were sieved (100 mesh). Samples (16.36mm x 16.36mm x 7.5mm) were prepared by uniaxial pressing (50 MPa) following by isostatic pressing (300 MPa, 2 min). The green samples were embedded in a mixture of powders of Si₃N₄ and BN (70: 30 weight ratio) inside a graphite crucible and sintered at 1850 °C for 2 h, in nitrogen atmosphere (0.1 MPa) with a heating rate of 25 °C/min.

2.2. Characterizations

To remove any possible superficial layer formed at the surface of the samples during sintering, the sintered samples were rectified and then polished until mirror finishing at both sides. After cleaning in ultrasonic bath with acetone and then with distilled water, the samples were stored in an oven of 100 °C to avoid water uptake from atmospheric humidity.

Relative density of the samples after sintering was determined by Archimedes method, correlating with the theoretical density of the mixtures. The weight loss was determined by measurement of weight, before and after sintering. The phase composition of the sintered samples was determined by X-ray diffraction analysis (Phillips PW1380/80), using CuKα radiation, slow scanning and 0.02 °/s step. The microstructures were observed by SEM investigations of polished surface after having them chemically etched by molten NaOH/KOH mixtures at 500 °C for 5 min.
Hardness was determined by Vickers indentations under a load of 20 N, for 30 s. 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 [18].

2.3. Cutting performance

All experiments were carried out on a computer numerical control (CNC) lathe (Romi, Mod. Centur 30D) under dry cutting condition. The ceramic insert were cut and ground to make SNGN120408 (12.7 mm×12.7 mm, 4.76 mm thickness, 0.08 mm nose radius and 0.2 mm×20° chamfer) Fig.1.

Figure 1

A tool holder of CSRNR 2525 M 12CEA type (offset shank with 15° [75°] side cutting edge angle, 0° insert normal clearance and 25 mm×25 mm×150 mm) was used for the cutting experiments. The cutting performance of the silicon nitride base tools was tested by machining gray cast iron. The Chemical composition and mechanical properties of the gray cast iron were given in Table 1.

Table 1

The cutting tests for machining of gray cast iron were performed at a cutting speed of 180, 240, 300, 360, 420 m/min with a feed rate of 0.12, 0.23, 0.33, 0.40, and 0.50 mm/rev and a constant depth of cut of 1.0 mm. The dimension of work material was 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 were measured using a toolmakers microscope. To complete analysis of tool life was considered at finish surface (Ra and Ry) using a surface roughness tester (Mitutoyo Surftest 402 series 178)
was adopted and to measure at temperature work-piece/cutting tools was used an infrared pyrometer. Flank wear of 0.3 mm (ISO 3685) and variation abrupt of Ry has been used as end tool life criterion. A three-force component analogue dynamometer capable of measuring cutting forces during turning was utilized in test. A computer connection for data acquisition was also made and calibrated. The analogue data can be evaluated numerically on a computer and when required can be converted back to analogue. A schematic illustration of measured forces is given in Fig. 2 [19].

Figure 2

The machining tests on grey cast iron work piece were chosen because the ceramics are generally used to machine cast iron [20]. Grey cast iron contains graphite flakes and it is widely used in the manufacturing industry [21].

3. Results

3.1. Properties of cutting tools

The relative density of the specimens after gas-pressure sintering process presented values higher than 98.12 ± 0.14 % for this composition, demonstrating that dense ceramics were obtained. Phase analysis by X-ray diffraction revealed only the presence of $\beta$-Si$_3$N$_4$ indicating that the $\alpha$-$\beta$-Si$_3$N$_4$ transformation has been completed and, furthermore, that the additives formed an amorphous intergranular phase Fig.3.

Figure 3

The specimen investigated yielded ceramic materials of high hardness, more than 18.65 ± 0.15 GPa and the fracture toughness values are near to 5.96 ± 0.12 MPa m$^{1/2}$. These results can be attributed to several factors such as the high relative density, the
complete $\alpha$-$\beta$-Si$_3$N$_4$ transformation, but mainly due to microstructural aspects Fig.4 [22 and 23].

**Figure 4**

The mass loss during the sintering was about 2.50 % sample. This behavior demonstrates the viability of using Y$_2$O$_3$–CeO$_2$–AlN–Al$_2$O$_3$ as sintering additive, promoting important sintering activity for the composition. Thus, the sintering parameters applied are adequate to produce ceramics cutting tools at high density.

### 3.2. Variation of machining forces with cutting speed

The variations of machining forces with cutting speed in shown in Fig. 5. It is seen that after an initial rise, the cutting force component decrease in magnitude as the cutting speed increases. With low cutting speed, the cutting wedge tends to plow on the work surface, resulting in higher order cutting force, but as the cutting speed increases, the cutting becomes more or less steadier, with a consequent reduction in cutting force component.

**Figure 5**

From the Fig. 5, it can be seen that the cutting force component was greater than the thrust force component by a considerable margin. These results were in agreement Lanna, 2004 and indicate that the material removal has occurred in ductile manner without fracture thus preventing the occurrence of a brittle material removal [24]. The effect of variations in operating parameters may be seen in cutting forces and surface temperatures, but knowledge of what takes place internal to the workpiece is extremely desirable.
During machining, a considerable amount of temperature rise occurs in the cutting zone Fig. 6 and 7.

**Figure 6**

**Figure 7**

This heat has to be normally dissipated by the work-piece, tool, chip and the surroundings. But in gray cast iron machining, since the work-piece is a good conductor of heat, a major portion of the heat developed at the cutting zone has to be dissipated by the tool and chip. Therefore, the dependence of temperature on cutting speed will exert a greater influence on the tool performance especially at higher speeds. With 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. As the cutting speed increases, the cutting becomes steadier with a consequent reduction in cutting force components. The decrease in cutting forces above a cutting velocity of 300 m/min can be attributed to the possible thermal degradation of the gray cast iron. The other two components of the machining force, namely, the thrust and feed forces also exhibited a similar trend.

### 3.3. Variation of machining forces with feed of cut

The effects of the variations of the feed of cut on the machining forces were studied using the cutting velocity of 300 m/min, and with a tool having a negative rake angle of 20°. The variations of machining forces with the variation in feed of cut are shown in Fig. 8.

**Figure 8**
All the three components of the machining force are seen to increase with the feed of cut. The cutting force dominates over the thrust and feed force components clearly indicating the material removal by plastic deformation.

3.4. Surface roughness

Surface finish was shown to be improved by increasing cutting speed (Fig. 9), though the improvement was very limited.

Fig. 9

Producing a better surface finish at higher cutting speed is not something unusual in metal cutting [25]. It is observed that the surface finish is not affected by the increased tool flank wear. In all cutting conditions, the variation of surface finish with the flank wear is insignificant. The surface roughness values remained almost constant although the flank wear increased with the increase of time to feed and depth of cut constant. However, the magnitude of surface roughness is higher for lower cutting speed. When increase cutting speed and feed rate constant (0.33 mm/rev), surface finish even improved with the increase of flank wear (Fig. 10).

Fig. 10

However in this paper observe that increasing wear of cutting tool improved the roughness of the workpiece. These results have been common when using ceramic cutting tools on machining gray cast iron [26].

3.5. Flank wear

Fig. 11 shows the flank wear progression with increasing cutting length for \( V_c = 300 \) m/min, feed rate of 0.33 mm/rev and depth of cut was kept constant at 1.0 mm.
Flank wear measurements were taken at an interval of every 1500 m length cut. With the workpiece diameter of 105 mm and employed depth of cut of 1 mm, when the tests were stopped when the maximum flank wear value ($VB_{\text{max}}$) exceeded 0.3 mm. In this was represent one micrographs of cutting tools that use in machining longer time because in others conditions flank wear exhibited low and similar wear behaviors at all cutting speeds Fig. 12. In this Figure can be seen more clearly the average flank wear ($VB_{\text{max}}$), in which shows the in Fig. 11 by the corresponding maximum cutting length (in m).

It is clearly seen that flank wear rate curves is linear with cutting length indicating that cutting tools have had long life was agreement [19].

4. Conclusions

The results of turning of gray cast iron using silicon nitride base tools were presented. The effect of cutting speed and feed of cut on machining forces were analyzed. Studies have indicated that:

1. The $\text{Si}_3\text{N}_4$ based ceramic cutting present important performance in high-speed turning of gray cast iron. The low wear of the insert suggests that this tool is suitable for machining gray cast iron.

2. The cutting process becomes more and more stable as the speed increases. The accommodation during cutting at the highest speed can be better. This might suggest that high-speed machining is more and more stable for the tool–work–machine system under consideration, with decrease in the force components up to speed of 300 m/min.
3. As the feed of cut is increases the machining forces also increase.

4. Several it is possible observe that all the two components of the roughness are seen to decrease with the length of cut.

5. Surface finish of the work part is not influenced by the tool wear. However, increasing speed, feed or depth of cut does influence the surface finish.

6. The cutting force decreases with increasing cutting speed owing to the high temperatures generated at the cutting zone. The decrease in the cutting force obtained with Si$_3$N$_4$ based ceramic cutting tool is more to machining gray cast iron. This, together with the results obtained for flank wear and surface roughness, indicates that, among many tools Si$_3$N$_4$ will have the most suitable tool, for turning of gray cast irons at high cutting speeds.

Acknowledgement

The authors would like to thank for financial support by CAPES and FAPESP.

References


**List of captions for illustrations**

Fig. 1. Photograph of silicon nitride based insert.

Fig. 2. Force components measured in turning tests [26].

Fig. 3. XRD pattern of sintered ceramic cutting tool, using Cu K$\alpha$ radiation.

Fig. 4. Microstructure of cutting tools.

Fig. 5. Typical variation of machining forces with cutting speed.

Fig. 6. Temperature vs feed to $v_c = 300$ m/min.

Fig. 7. Temperature vs cutting speed to $f = 0.33$ mm/rev.

Fig. 8. Forces vs feed to $v_c = 300$ m/min.

Fig. 9. Surface roughness vs cutting speed to $f=0.33$ mm/rev, $a_p=1.0$ mm.

Fig. 10. Surface roughness vs cutting speed to $f=0.33$ mm/rev, $a_p=1.0$ mm.

Fig. 11. Flank wear vs cutting length $v_c = 300$ m/min, $f=0.33$ mm/rev, $a_p=1.0$ mm.

Fig. 12. Micrograph of cutting tool after machining to cutting length of 7500 m.

**List of captions for table**

Table 1. Chemical composition and mechanical properties of gray cast iron used for cutting test (Hick, 2000)
Fig 3

Intensity (a.u.)

2θ (°)

β- Si$_3$N$_4$

a- Y$_3$Al$_5$O$_{12}$

α-Si$_3$N$_4$

β - Si$_3$N$_4$

α - Si$_3$N$_4$
Fig7

Temperature vs. Cutting speed

Temperature x Cutting tools to f=0.33mm/rev

Temperature (°C)
Cutting speed (m/min)
Roughness Ra (µm) vs. Cutting speed Vc (m/min) for cutting tools to f=0.33 mm/rev.
Roughness $R_y$ vs Cutting tools $V_c$ for $f=0.33\, \text{mm/rev}$

- Roughness $R_y$ (µm)
- Cutting tools $V_c$ (m/min)

![Graph showing the relationship between roughness and cutting speed for a specific feed rate](image-url)
Flank wear (mm) vs. Cutting length (m)

- Cutting speed $V_c = 300$ m/min
- Feed rate $f = 0.33$ mm/rev
- Depth of cut $a_p = 1.0$ mm
### Chemical composition of gray cast iron

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### Mechanical Properties

- Hardness HB 205
- Tensile strength MPa 245
- Fatigue strength MPa 100