# Optimization of finishing face milling of gray cast iron irregular surfaces with ceramic tools

**Jorge Antonio Giles Ferrer**
Centro SENAI - Fundação Romi  Formação de Formadores. Av. João Ometto 118, Jd. Panambi – CEP 13450-510 – Santa Bárbara d´Oeste - SP
E-mail: jorgilfer@hotmail.com

**Anselmo Eduardo Diniz**
Faculdade de Engenharia Mecânica – Unicamp. Rua Mendeleiev, s/n - Cidade Universitária "Zeferino Vaz" Barão Geraldo – Campinas. Caixa Postal 6122 - CEP: 13.083-970
E-mail: anselmo@fem.unicamp.br

**Abstract.** *The main goals of this work were to evaluate the performance of ceramic tool (Sialon) in the finishing face milling of three gray cast iron irregular surface and also to evaluate the performance of this tool with wiper edge in the milling of these surfaces. Tool wear and workpiece surface roughness were measured along the experiments. Aiming to analyze the possibility of replacing the roughing and finishing operations by just one operation, experiments with ap = 1,5 mm were carried out, using a wiper edge as one of the cutter edges, for the ceramic tool. Ceramic tool life was much longer than carbide tool life, even considering that the cutting speed used for ceramic tool was much higher than for carbide. Previously, in the experiments with carbide the end of tool life occurred due to edge chipping, while when ceramic tool was used, tool life was finished due to regular wear. When wiper edge was used, it was possible to replace roughing and finishing operations by just one pass of the tool, with long tool life and keeping workpiece roughness inside the established limit.*

***Keywords***. *milling, gray cast iron, carbide, ceramic, tool wear.*

## 1. INTRODUCTION

A lot of research has been done in face milling operations to establish the best tool-workpiece relative position, cutter diameter in relation to the width of the machined surface, best cutting conditions, direction of cut, and other relevant variables. However, almost all studies were carried out using flat surfaces without interruptions, which is seldom the case in industrial processes. Usually irregularities are found, such as: (a) interrupted surfaces; (b) surfaces with complex geometries; c) surfaces with variable width, where large diameter cutters are used because some parts of the surface are large, leaving the smaller parts of the surface unsuitably machined. In such milling operations, it is very important to define precisely tool geometry and material, cutting parameters, and cut direction, in order to extend tool life. Each cut direction has its limitations, which must be examined depending on the workpiece surface geometry.

Thus, the main goals of this work are: (a) to compare in terms of tool life and workpiece surface roughness the application of silicon nitride based ceramic in the finish milling operation of three different workpiece surface geometries of gray cast iron; (b) to understand the wear mechanism of silicon nitride based ceramic tools in cutting gray cast iron with irregular surfaces; (c) To evaluate the possibility of replacing the conventional operations of roughing and finishing by just one pass of the tool with depth of cut equal to the sum of those used in both operations

## 2. THEORETICAL REVIEW

Ceramic materials generally have good properties as cutting tools, such as high hot hardness, high abrasion resistance, low thermal conductivity and excellent chemical stability. On the other hand, their low toughness restricts their use as cutting tools (Diniz *et al*., 2006). The two main classes of ceramic for cutting tools are aluminum oxide ($Al_2O_3$) based, and silicon nitride based ($Si_3N_4$). For machining gray cast iron, the most widely used ceramic class is the silicon nitride based. Compared to the $Al_2O_3$ class, the $Si_3N_4$ based ceramic has a higher toughness (except compared to whisker reinforced $Al_2O_3$ ceramic), higher hardness, higher thermal shock resistance, but lower chemical stability with respect to iron (Melo *et al*., 2006). The later is the reason why it is used only for gray cast iron machining. This material produces small chips, which do not extensively rub with the tool rake face and, therefore, do not generate much crater wear, which is mainly caused by chemical reaction between chip and tool (diffusion).

The interaction among tool, chip and workpiece usually causes tool wear as well as other damages such as chipping and cracks. The wear/damage mechanisms are built up edge formation, abrasion, diffusion, attrition, thermal and mechanical variation load, and shocks between tool and workpiece (Melo *et al*., 2006). Abrasion is induced when the workpiece material contains hard particles (Yeckley, 2005). Both flank and crater wear may be generated by abrasion, but it is more important in flank wear, since the tool flank face rubs against a rigid element as the workpiece, while the contact between tool rake face and chip involves sliding and seizure/adhesion (Diniz *et al*., 2006). The tool ability to resist to abrasion wear is related to its hardness. The wear land caused by abrasion generally presents scratches parallel to the cutting direction (Melo *et al*., 2006).

Attrition wear usually occurs under low cutting speeds, when material flow on the tool rake face is irregular, and contact with the tool is less continuous. It can be described as a cyclical adhesion and removal of workpiece/chip material from the tool, which also causes removal of tool particles. Under these conditions, microscopic particles of the tool are pulled out and dragged together with the material flow. The irregular material flow necessary for attrition wear to occur is caused by the sliding zone between chip and tool, by interrupted cutting, irregular depth of cut, and vibration. Areas worn by attrition have a rough appearance (Yeckley, 2005) and (Trent and Wright, 2000).

Diffusion wear is a mechanism involving atom transference between two materials (Trent and Wright, 2000). It is strongly dependent on temperature, solubility among the elements involved in the secondary shear zone, and contact duration (Diniz *et al.*, 2006). Relative speeds between chip and tool are high, and time of contact very low. Because of these facts diffusion may seem unlikely, but seizure zone between chip and tool rake face, and sometimes between workpiece and tool flank face, makes it possible. This zone is not stable and is renewed periodically, keeping the diffusive flow. This wear mechanism is responsible mainly for crater wear in high cutting speeds, because it is on the rake face that the necessary conditions for diffusion occur, i.e., high temperature due to the secondary shear region and the seizure zone, which increases chip-tool contact time. However, after some wear has taken place on the flank face, seizure may occur also on this face and, consequently, diffusion may also be a cause of flank wear. The diffusion wear rate increases with cutting speed. Areas worn by diffusion have a smooth appearance (Yeckley, 2005), (Trent and Wright, 2000) and (Diniz *et al*., 2006).

As previously mentioned, silicon nitride based ceramics have higher hardness than aluminum oxide based ceramics, but lack the chemical stability needed to resist diffusion wear. Chakraborty *et al.* (1990) carried out machining experiments with cast iron with several kinds of ceramic tools. Their results showed that the dominant wear mechanism for $Al_2O_3$ based ceramics was abrasion, while for $Si_3N_4$ based ceramics it was diffusion. In interrupted cutting such as milling, diffusion is harmed, because the tool reaches lower temperatures than in continuous cutting.

Sudden temperature variations generate thermal stresses. For a low toughness material such as ceramic, a cycle of thermal stresses may result in fracture. For ductile materials, a high number of thermal cycles is tolerated before the failure of the part (Melo *et al*., 2006). The tool used in milling operations undergoes thermal shocks in each revolution. The fast heating and cooling of the tool as it enters and leaves the workpiece in each revolution may cause large temperature differences between the edge and the bulk of the insert, causing cracks perpendicular to the edge. These cracks increase, resulting either in chipping or, occasionally, in breakage of the cutting edge (Ferrer, 2006). Another cause for the cracks is the alternate process of expansion and contraction of tool layers, when they are heated and cooled in each revolution (Yeckley, 2005).

Of course mechanical shocks are also frequent in milling, because of the interrupted cutting inherent to it, and this may also generate cracks, chipping and edge breakage. This is why it is necessary to choose a tool with enough toughness and rigid edge and to place the tool in a suitable position in relation to the workpiece, in order to make the shocks less harmful to the tool (Diniz *et al*., 2006). Chipping may also occur when the insert is leaving the cut in each revolution. Pekelharing (1984) investigated the behaviour of the primary shear plane and observed that it rotates and becomes negative when the cutting edge is leaving the cut. He called this process "foot forming". The negative shearing resulting from primary shear plane rotation causes a change in chip velocity, producing stresses along the contact length between the tool rake face and the chip. This is a process of very quick alternation: in a moment, there is tensile stress, and in the next, compressive stress; this causes tool chipping and breakage if it does not have sufficient toughness.

In order to better understand the results of this work, it is necessary to define 'up milling' and 'down milling'. In up milling, the workpiece feed direction is contrary to the cutter rotation at the area of cut. Therefore, chip thickness is zero (when the surface is similar to Workpiece 1 used in this work) when the tool touches the workpiece and increases until the moment it leaves the cut. When the edge starts the cut at chip thickness zero, cutting forces are high, and tend to push the cutter and workpiece away from each other. When the edge penetrates the workpiece, this force changes its direction and the tool pulls the workpiece. Besides, when the edge enters the cut, it has to be forced into the workpiece material, creating a rubbing effect with high friction, high temperatures and often contact with a work-hardened surface caused by the preceding insert. In down milling, the workpiece feed direction is the same as that of the cutter rotation at the area of cut. The chip thickness will decrease from the start of the cut until zero at the end of the cut, when the surface is similar to Workpiece 1 used in this work. Because in down milling the insert starts its cut with a large chip thickness, there is no friction in the tool entrance, and the cutting forces always pull the workpiece into the cutter. However, down milling makes certain demands on the process because the forces tend to pull the cutter along while they hold the workpiece down. If the tool pulls into the workpiece, feed is increased unintentionally, which can lead to excessive chip thickness and edge breakage. To overcome this, the machine tool must not have back-lash in the table feed system. Therefore, down milling is preferred wherever the machine tool, fixture and workpiece will allow (Melo *et al*., 2006).

In a face milling operation it is recommended that the radial depth of cut ($a_e$) be larger than half the tool diameter (D), in order to minimize edge-workpiece shock in down milling. When $a_e < D/2$, the tool begins the cut with the outermost cutting edge subjected to the first contact, making tool chipping and breakage easier. When $a_e > D/2$, the initial contact is further in along the cutting edge, where support is better. In the cut of Workpiece 1 of this work, due to its geometry, a large portion of the cut is carried out with $a_e < D/2$. Therefore, the cutting tool must have enough toughness to withstand these shocks.

## 3. MATERIALS, METHODS AND EXPERIMENTAL PROCEDURES

Several milling experiments were carried out on gray cast iron GG25 workpieces with 193-226 HB hardness, 3.12% carbon and 2.2% silicon, presenting perlitic structure with small areas of ferrite and graphite (graphite type A).

Three different workpiece shapes were machined, with the same geometry of an air compressor carcass of a bus brake system. They were chosen for their typical milling problems, and are shown in Figures 1 to 3. The elliptical surface (Figure 1) will be referred to as "Workpiece 1", the square surface (Figure 2) as "Workpiece 2", and the irregular surface (Figure 3) as "Workpiece 3". Workpiece 1 makes the up milling process damaging to the tool, because the entrance of the edge into the workpiece in each revolution is done with chip thickness zero, causing the high wear rate already mentioned. Down milling also has problems in this kind of workpiece, because in most cases the tool center line is outside the surface being machined, making the tool-workpiece shock damaging, as mentioned earlier. Down milling was the direction chosen for the experiments in this workpiece. In the milling of Workpiece 2, the cutting edge hits the surface twice during most of the cutting, increasing the tendency to edge chipping/breakage. Workpiece 3 is the one which presents the smallest cut width variation and in roughly 75% of the cutting time, the tool stays with its center line outside the workpiece. Each experiment were carried out twice.

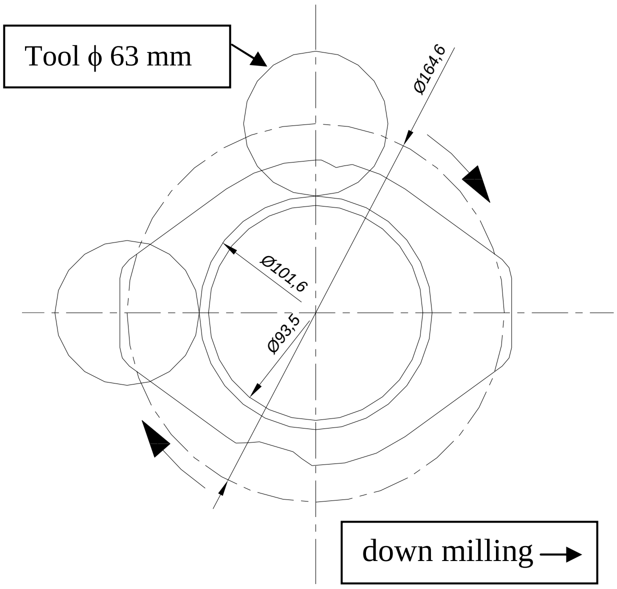

Figure 1 - Workpiece 1 scheme and feed direction used in the experiments

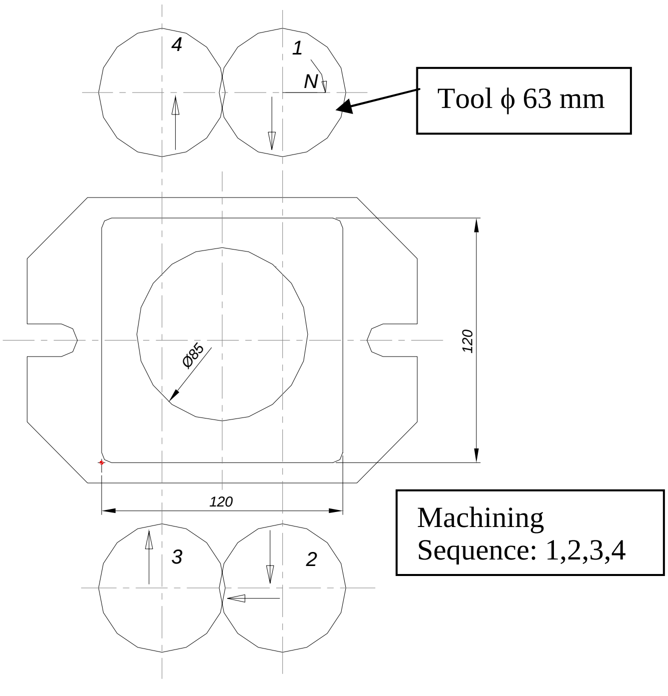

Figure 2 - Workpiece 2 scheme and feed direction used in the experiments

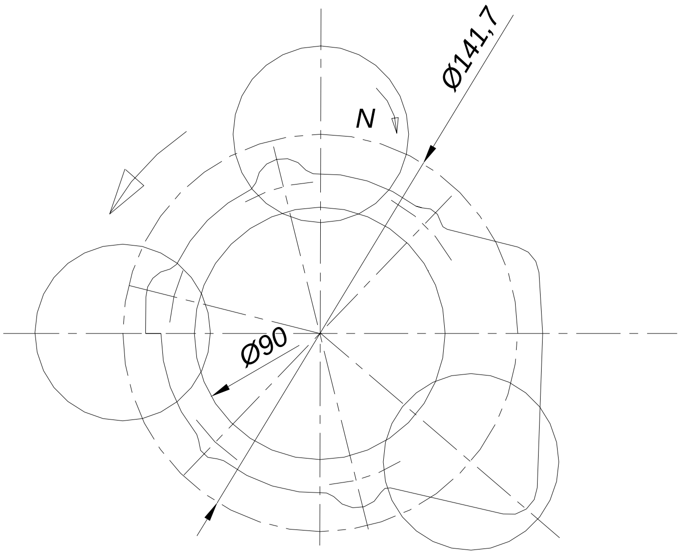

Figure 3 - Workpiece 3 scheme and feed direction used in the experiments

The machine tool used in the experiments as a vertical machining center with power of 20 CV in the main motor, and maximum tool rotation of 6,000 RPM. Tool wear and workpiece surface roughness were measured several times during the experiments. For this, the experiments were interrupted and the tool was taken to an optical microscope with 90 times magnification, connected to a photographic camera, in order to measure flank wear. In the same interruption, the workpiece was taken to a surface roughness tester. After the experiments, the cutting edges were taken to a Scanning Electronic Microscope with EDS system, to take tool pictures allowing the analysis of wear mechanisms.

All surfaces were machined with the same tool geometry, since this is usual practice in brake system manufacturers. Therefore, the tool had to have an entering angle of 90° due to the wall of Workpiece 1, which had to be contoured by the tool during the cutting. The tool had to have a diameter of 63 mm to machine Workpiece 3 and the larger diameter of the ellipse of Workpiece 1, but this caused the tool center line to stay outside the surface during the machining of the smaller diameter of the ellipse. The cutter used in the experiments had with 63 mm of diameter, 8 cutting edges, positive radial rake angle, and negative axial rake angle. Silicon nitride ceramic inserts had no coating. No cutting fluid was used in the experiments.

The tool life criterion was either flank wear of $V_{B\ max}$ = 0.2 mm in at least 3 of the 8 cutting edges (i.e., each experiment continued until 3 cutting edges reached this value of flank wear) or workpiece surface roughness reached ($R_{a\ máx}$ = 3,2 μm). In all experiments, depth of cut ($a_p$) was 0.5 mm (except that with wiper insert), feed per tooth ($f_z$) was 0.1 mm and cutting speed ($V_c$) was 1000 m/min.

Flank tool wear and surface roughness were measured each 20 tool passes. Roughness was measured in several points of the surfaces. In workpiece 1, the highest roughness was got in its larger diameter. In Workpiece 2 the largest roughness value was got in the diagonal of the square and in workpiece 3 in the largest width of the surface.

Based on the results of preliminary experiments, down milling was used in the cut of Workpiece 1 (Figure 1) and Workpiece 2 ( Figure 2), and up milling was used in Workpiece 3 (Figure 3).

## 4. RESULTS AND DISCUSSIONS

### 4.1 – Experiments with regular inserts

Figure 4 shows flank wear against volume of chip removed ($V_{Bmed}$) up to the point the tools reached their end of life. The workpieces in which tool lives were the longest were 2 and 3. However, all tool lives were much longer than those which could be reached with carbide tool in this cutting speed (Ferrer, 2006).

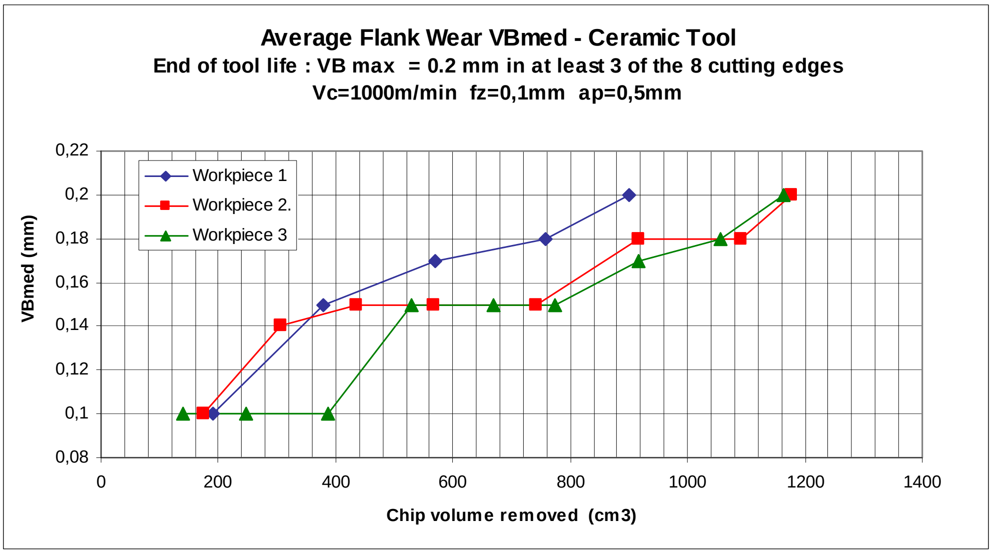

Figure 4 – Average flank wear against volume of chip removed for the three workpieces

### Tool wear/tool damage analysis – workpiece 1 – down milling

This experiment presented end of tool life due to flank wear and not due to the increase of surface roughness. Attrition was not among the wear mechanisms. In the border of the wear land (point 2 of Figure 5), mainly Fe from the workpiece material is present. On the other hand, there are some indications of diffusion wear: the wear land is smooth, tool temperature was very high due to the high cutting speed used, and the tool material did not have a high chemical stability with respect to iron. It is impossible to affirm that diffusion was the basic cause of this tool wear since we do not have temperature data to support this affirmation, but based on these clues, it can be supposed that diffusion of Fe from the workpiece/chip material weakened the very hard and resistant ceramic cutting edge. This very shallow layer of Fe was removed by the friction with the workpiece, producing flank wear, but it remained in the border of the wear land, causing the wear to increase further.

Table 1 shows the EDS analysis results, where it can be seen that the wear land (point 1 of Figure 5) did not have any points of iron from the workpiece, although in the wear land border (point 2) there was a strong Fe diffusion. No abrasive scratches could be seen on the wear land. The low chemical stability of the $Si_3N_4$ based ceramic made diffusion possible even on flank face, what is not usual for the machining with other kind of cutting materials.

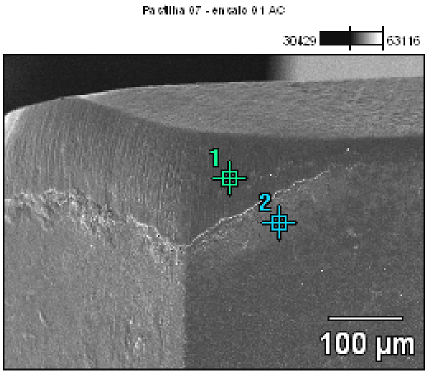

Figure 5 - Ceramic tool cutting edge in the end of tool life - Workpiece 1 (x200) - MEV (20 kV)

Table 1- EDS analysis of the wear land, according to Figure 5 - Weight concentration %

| | Si | Mn | Fe | Zn |
|---|---|---|---|---|
| Cutting edge 07 - test 01 - P1 | 51.39 | 6.74 | | |
| Cutting edge 07- test 01 – P2 | 11.02 | | 46.42 | 17.24 |

### Tool wear/tool damage analysis – workpiece 2 – up milling

It is important to point out that in around 30% of the cutting time two shocks of edge and workpiece occurred in each tool revolution and no zero chip thickness happened. This situation is very favorable, because it minimizes abrasion wear. In the other hand, foot forming phenomenon is negligible, since chip thickness in the edge exit from the workpiece in each revolution is small and its maximum value is just got in two moments of the workpiece cut.

Tool life end occurred due to flank wear and not due to workpiece roughness. The main wear mechanism was diffusion, similarly to what occurred in the experiments on workpiece 1. In the wear land (point 1 - Figure 6), there was no presence of iron from the workpiece and in their border (point 2) there was a strong diffusion of Fe, what decreased its wear resistance and caused flank wear to increase by the contact with the workpiece. Interesting to note that, even machining a workpiece in which the tool hits against the workpiece twice in each revolution and with a very high cutting speedd, which make the force of the impact even higher, there was no edge chipping. Therefore, it can be concluded that the supposedly ceramic low toughness is not true at least for this kind of ceramic.

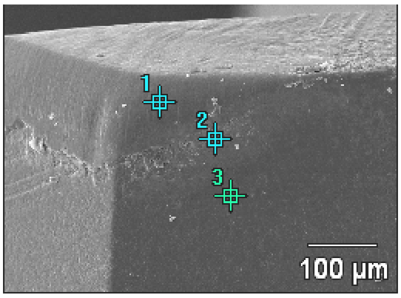

Figure 6 - Ceramic tool cutting edge in the end of tool life - Workpiece 2 - (x200) - MEV (20 kV)

### Tool wear/tool damage analysis – workpiece 3 – up milling

In this workpiece, in roughly 80% of the cutting time, the cutter center line was outside of the workpiece, making the edge first contact with the workpiece supposedly unsuitable, mainly in high cutting speed.

The main wear mechanism was again diffusion, like what occurred in the experiments of the other workpieces. There was no chipping in any edge of the tool. On the wear land and on its border (points 3 and 2 of Figure 7) there was a small presence of Fe from the workpiece. Table 2 shows the EDS analysis results.

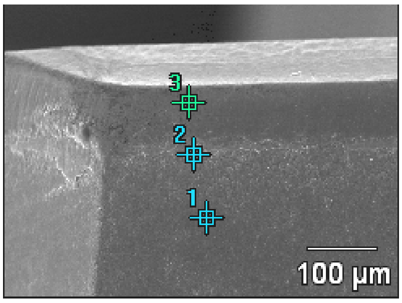

Figure 7 - Ceramic tool cutting edge in the end of tool life - Workpiece 3 –MEV (20 kV)

Table 2- EDS analysis of the wear land, according to Figure 7 - Weight concentration %

| | Al | Si | Mn | Fe | Zn |
|---|---|---|---|---|---|
| Cutting edge 02 - test 03 - P2 | | 89.05 | | 6.08 | 4.86 |
| Cutting edge 02 - test 03 - P3 | 0.10 | 89.90 | 4.10 | 5.90 | |

### Workpiece Surface Roughness

Figure 8 shows the surface roughness values on the workpieces used in the experiments. In workpiece 1 the roughness value used was that got in the largest diameter of the ellipse. It can be seen in this figure that the increase of surface roughness with the volume of chip removed was not as steep as the increase of tool wear shown in Figure 4. It was observed through the optical microscope during the experiments that the secondary edge wear was less intense than the wear which occurred in the main cutting edge. Therefore, as roughness increase depends on the wear of the secondary edge, its increase was not so high.

In the experiments carried out on the Workpiece 2, it was observed that the roughness in the diagonal of the square was higher than in its center line, what was expected due to the higher chip thickness in the diagonal. Moreover, the roughness in the entrance diagonal was higher than in the exit diagonal and both have the same chip thickness. This occurred due to the fact that in the exit the tool was better supported by the worpiece than in the entrance. Figure 8 shows the average roughness values (Ra) in the entrance diagonal. The roughness increase with the volume of chip removed was higher than what happened in workpiece 1 and during the experiments it could be noted that the secondary edge wear was not negligible.

For Workpiece 3, the roughness values measured in all the points of the surface were similar, despite the difference in chip thickness. Figure 8 shows the average roughness measured in the region of the highest chip thickness. This workpiece had the highest roughness increase with chip volume, due to a higher increase on the secondary edge wear.

The roughness values obtained in all workpieces was much lower than the limit value demanded in this kind of workpieces (Ra = 3.2 μm), which indicates either that these tools could go on working, even further than the wear limit established in this work or that a higher value of feed per tooth could be used in order to make the process faster.

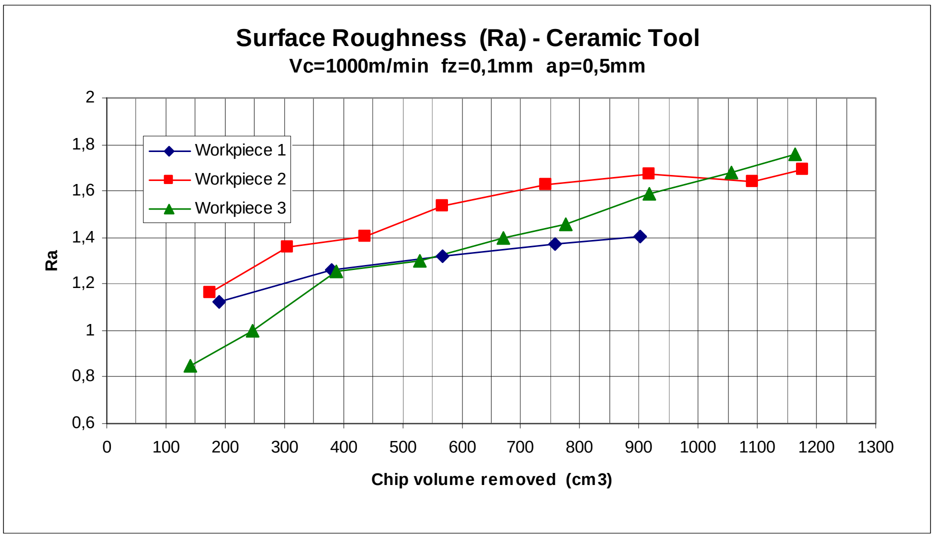

Figure 8 – Surface roughness (Ra) in all workpieces

## 4.2 - Experiments with wiper inserts

A second strategy was used in one of the experiments: a wiper edge was inserted in the cutter (the 7 other edges were regular) 0.03 mm more advanced than the others. The plane phase of the wiper insert (bs) was 5.2 mm. The experiments with this cutter with wiper edge had depth of cut $a_p$ = 1.5 mm and, due to the lack of machine tool power, tha cutting speed had to be reduced to 700 m/min. The goal of these experiments was to verify whether it was possible to replace both operations (rough and finish) by just one removing the sum of depth of cut of those two. Figure 9 shows the average tool flank wear (average of the seven edges excluding the wiper insert) against volume of chip removed. The wear growth had the same behavior in the cutting of all workpieces. It can be seen, comparing this figure with Figure 4, that the volume of chip removed per tool life (moment when the flank wear was 0.2 mm) was much bigger in the experiments with wiper insert. Of course, the smaller cutting speed and the higher depth of cut used in this work contributed to this result, but it is sure that this long tool life obtained makes the use of wiper insert feasible, mainly taking into account that two operations were replaced by just one (just one tool made the work of two).

There is no space to show the SEM pictures and EDS analysis results of the inserts used in these experiments, but it can be said that the wear mechanism did not change, i.e., there was no chipping in the edges and diffusion was the main wear mechanism. Moreover, the flank wear of the wiper edges was not larger than the wear of the regular inserts as it could be supposed.

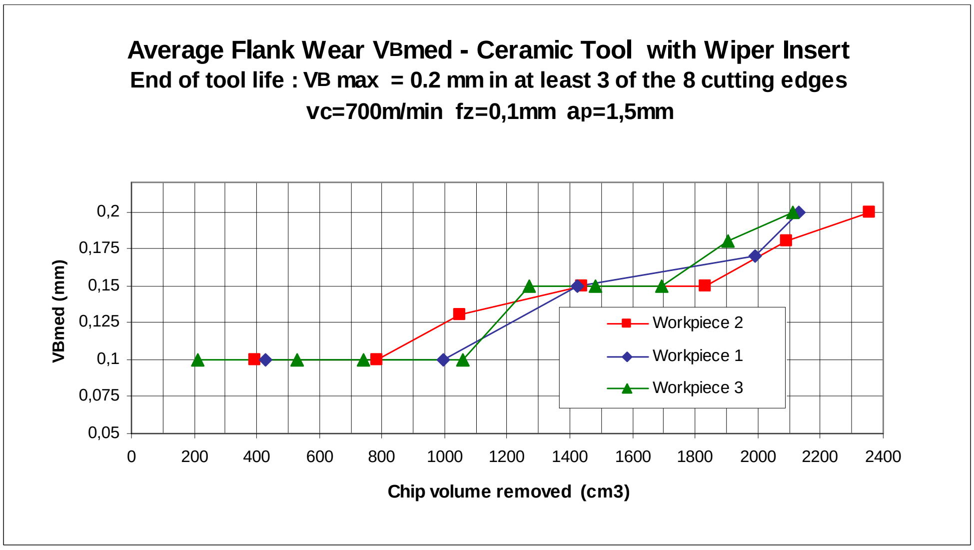

Figure 9 – Average flank wear ($V_{Bm}$ ) against volume of chip removed using wiper insert

Figure 10 shows the average roughness values (Ra) of the workpieces machined with wiper inserts using $a_p$ = 1.5 mm. It is important to note that when the tools reached the end of their lives due to the flank wear ($V_B$ = 0.2 mm), all the kinds of workpiece had roughness values very similar and lower 0.65 µm, value three times lower than that obtained without wiper insert and much lower than the limit demanded in this kind of workpiece (air compressor carcass) which is $R_a$ = 3.2 µm. This result once more sustain the affirmation made earlier that the replacement of two operations (rough and finish) by just one pass is feasible. Moreover, the variation of roughness values along the experiments was very small and independent of the tool wear growth. This fact was possible due to the small wear of the wiper insert, mainly on its secondary edge. This result shows that either, the experiments could go longer up to a higher flank wear value, or the feed per tooth value could be higher, without passing the limits of workpiece surface roughness.

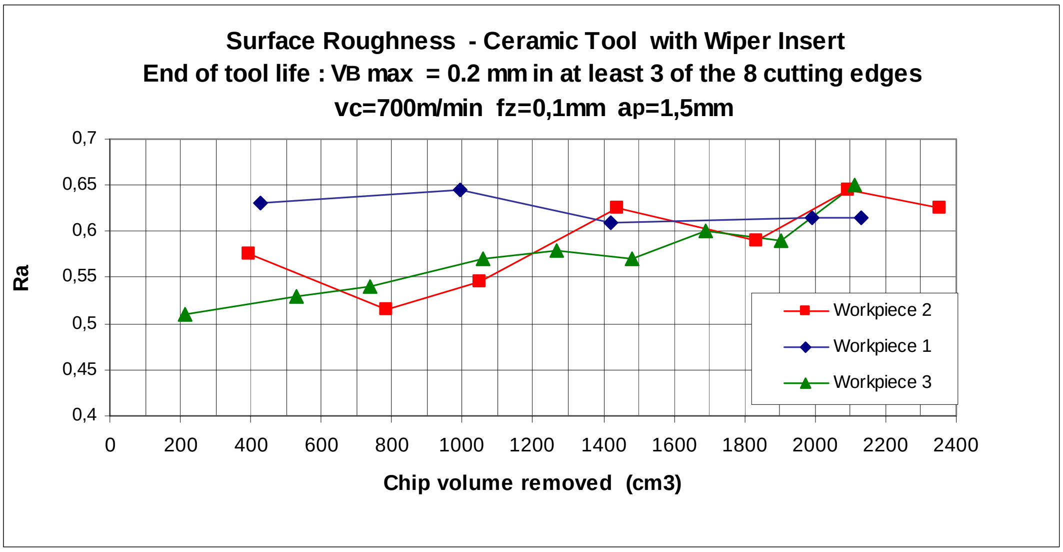

Figure 10 – Average surface roughness of the workpieces machined with wiper insert cutter

## 5. CONCLUSIONS

Based on the results of this work, it can be concluded for the finish face milling of irregular surfaces using $Si_3N_4$ tool that:

- Attrition was not among the wear mechanisms. There are some indications of diffusion wear: the wear land is smooth, tool temperature was very high due to the high cutting speed used, and the tool material did not have a high chemical stability with respect to iron. It is impossible to affirm that diffusion was the basic cause of this tool wear since we do not have temperature data to support this affirmation, but based on these clues, it can be supposed that diffusion of Fe from the workpiece/chip material weakened the very hard and resistant ceramic cutting edge. This very shallow layer of Fe was removed by the friction with the workpiece, producing flank wear, but it remained in the border of the wear land, causing the wear to increase further.
- Chipping never occurred, indicating that this kind of ceramic material presents enough toughness to withstand this kind of operations on irregular surfaces.
- The increase of workpiece roughness with the volume of chip removed using regular inserts was not very large due to the small value of wear on the secondary cutting edge.
- In the experiments with wiper inserts, the roughness values obtained were around three times smaller than those obtained with regular inserts.
- Tool lives of the cutters using wiper inserts were long enough to indicate that the substitution of two operations (rough and finish) by just one operation with the sum of depth of cut of those two using wiper inserts is feasible. Moreover, when wiper inserts were used the roughness values were very small showing that either the flank wear used to establish the end of tool life could be larger or the feed per tooth value used could be much higher.

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