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Analysis of wear of cemented carbide cutting tools during milling operation of gray iron and compacted graphite iron

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ABSTRACT

Cast iron is used to manufacture engine blocks and heads due to its mechanical and physical properties. The thermal conductivity and vibration absorption are some fundamental properties for these applications. Compacted graphite iron (CGI) has higher mechanical strength than gray cast iron and can be a great advantage in these types of mechanical parts. Although mechanical and physical properties are similar for both materials, CGI is considered to have poor machinability compared to gray cast iron, even when compared to alloyed gray cast iron. So it is important to investigate the behavior of the CGI for the most important cutting processes. While CGI Grade 450 is used for cylinder blocks, CGI Grade 350 is proposed for cylinder heads, because of higher thermal conductivity and better machinability. In the present work, two grades of gray iron, used to produce diesel engine cylinder heads, were compared to CGI Grade 350. Machining involves extensive plastic deformation ahead of the tool in a narrow chip zone and friction between the rake face and the chip, and these factors can interact extensively with the tool materials and start the wear mechanism. The investigations of cutting tool wear mechanism became necessary to fit the parameters and reduce the problems of stopping the machine for tool change. This work contributes to a better understanding of wear mechanisms of cutting tools used in milling operation of alloyed gray cast iron and compacted graphite iron using high cutting speeds. The main objective of this work is to verify the influence of the workpiece material and the cutting conditions on tool life and tool wear mechanism. The cutting process used is the dry face milling. Cemented carbide tools of class ISO K coated with Al_2O_3, using the technique of chemical vapor deposition at medium temperature (MTCVD), were used. The main conclusions are that workpiece material strongly influences tool life and tool wear involves different mechanisms. The wear mechanisms observed on the rake face at these conditions were abrasion and adhesion, at the end of tool life. Adhesion was the main wear mechanism at higher cutting speeds.

1. Introduction

The cast iron industry is contentiously making development in the manufacturing processes and also in the material itself. These developments, as a result of demand from the applied areas or cost reduction, result in the technological improvement of a material of long tradition in the automobile industry [1]. The main application of cast iron is in automobile parts which demands improvement in researches to best understand the behavior of these materials according to the manufacturing process. Investments in research and development of new products in this field became a key factor in the market.

In some applications a new material is always a target for improvement in the performance of a product. New materials for engine and head blocks for diesel motors for example, have been developed to help to increase thermal efficiency of the engine with minimal environmental impact. Actually the development of new material to decrease the environmental degradation has been a drive gear in new materials development.

Gray cast iron, the most traditional material applied in the manufacturing of engines blocks and parts, reached the limit of strength, and an increase in the pressure in the chamber is possible only with the increase in the thickness of the engine walls. This means an increase in the weight and a lack of specification [2].

Compacted graphite iron (CGI) is a material that presents properties of thermal conductivity and vibration dumping close to gray

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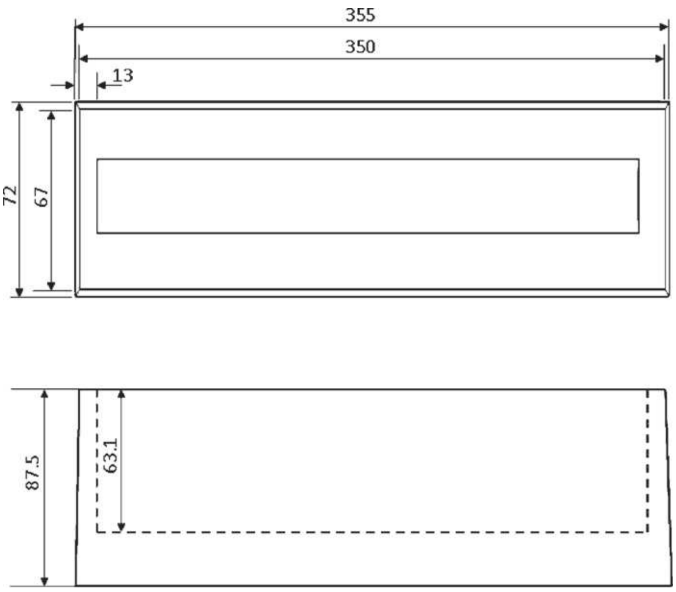


Fig. 1. Workpiece dimensions.

cast iron but has superior mechanical properties. The manufactured parts have therefore, lower weight and better performance which ends in low pollution gases and noise. This material allows a higher pressure in the chamber, leading to a more efficient fuel combustion [3]. However, CGI has poor machinability compared to the gray cast iron, resulting in higher cutting tool wear and loss in productivity [4]. Intense research in the development of this material and the improvement in manufacturing process are therefore necessary.

The graphite shape in CGI is called worm or compacted. The graphite is interconnected with curved ends and random orientation, which results in higher mechanical strength compared to gray cast iron because this graphite morphology is a barrier to crack propagation [5,6].

The machinability of CGI decreases even more when high cutting speeds are used, increasing heat generation and decreasing tool life. One of the most critical cutting operations in cylinder blocks is the boring of the cylinders encouraging the manufacturers to invest in research to enhance the cutting processes of CGI [7,8]. Three main areas of development can be highlighted: improvement in the machinability, enhancement in the machining process and development of new tool materials [9].

The main objective of this work is to verify the influence of the workpiece and the cutting conditions on tool life and tool wear mechanism. The cutting process used is dry face milling. Cemented carbide tools coated with Al_2O_3 were used. The main conclusions are that workpiece material strongly influences tool life and that tool wear involves different mechanisms.

2. Experimental methodology

Machinability tests were carried out in a face milling operation and flank wear land was measured to monitor the tool life. The milling machine tool model Interact IV manufactured by ROMI was used, with 10 kW of power in the main spindle. A 1.0 mm depth of cut was used, with a feed rate of 0.2 mm/rev/tooth and three cutting speeds: 600, 800 and 1000 m/min. The high cutting speeds were used to decrease tool life and the duration of the tests. The cutting speed is well superior to the ones recommended by the tool maker. The tool insert used was a cemented carbide with specification 1505ZNE-KM K20D and alumina coated (Al_2O_3). This insert is used in the production line to machine cylinder engine blocks

Fig. 2. The milling process used in the experimental work.

and heads. This cemented carbide tool was developed specifically for vermicular cast iron cutting. The tool holder has a specification R365-125Q40-S15M, diameter 125 mm and capacity for 8 inserts.

The cutting parameters were defined according to the production line and also based on preliminary tests carried out in the laboratory. For each cutting condition, the tests were repeated once. The final result of flank wear land is an average of the two tests.

Because the irregular shape all the workpieces were previously machined to have two parallel surfaces before the machinability tests. This was also necessary to remove the surface after the cast process. A layer of approximately 3 mm was removed. Fig. 1 shows the dimensions of the workpiece and Fig. 2 shows the workpiece in the machine tool ready for the milling operation.

All the eight inserts in the tool holder were used for each tool life test. Richetti et al. [10] concluded that the tool life is inversely proportional to the number of inserts in the tool holder. Therefore it was decided to use all the inserts in the tool holder.

The tool life tests were stopped after a defined volume of material removed, 4921.2 cm^3, which corresponds to the machining of five workpieces. Cutting power was monitored during the operation using an appropriated sensor connected to the main electrical motor of the machine tool.

Tool wear was measured using an Olympus stereo microscope with magnification of 45 times and image analysis software. The wear was measured in all the eight inserts and the larger flank wear land was defined as the final wear of the tool after the end of the test. Fig. 3 shows an example of wear of a tool after machining

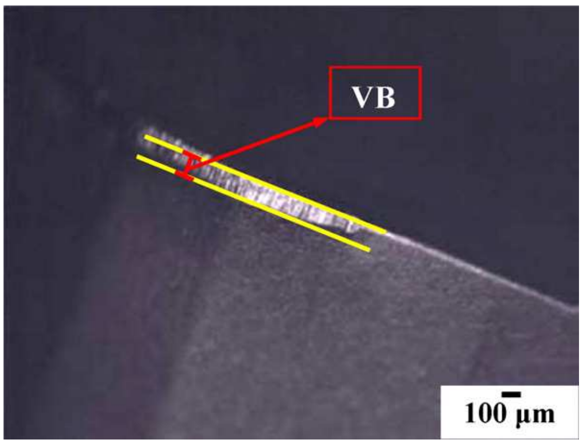


Fig. 3. Flank wear land at a cutting speed of 1000 m/min after machining five workpieces.

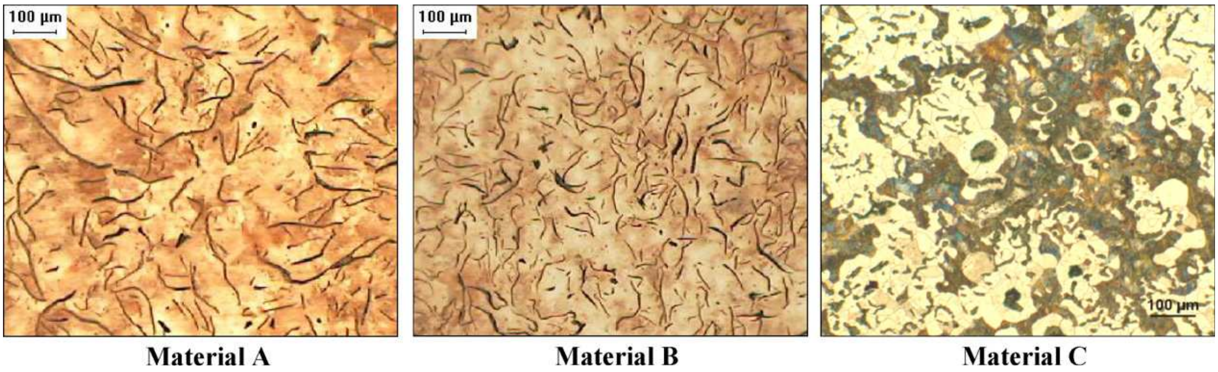


Fig. 4. Microstructure of the workpiece materials.

Table 1
Mechanical properties of the workpiece materials.

Properties	Material A	Material B	Material C
Tensile strength (MPa)	226	250	372
Hardness (HB)	216.4	223.5	174.9
Pearlite microhardness (HV 01)	320.3	330.1	341.6
Thermal conductivity (W/m K)	50	45.5	37

five workpieces at a cutting speed of 1000 m/min. The worn tools were analysed in a scanning electron microscope to identify the predominant type of wear mechanisms. Energy dispersive X-ray spectroscopy (EDX) was used for chemical characterization.

Table 1 presents some mechanical properties for the three materials used in the tests. Material A is the gray cast iron alloyed with CrCuSn (grade 200) and material B alloyed with CrCuSnMo (grade 250). The third material, C, is a vermicular cast iron grade 350 [11,12]. Those three materials are used for cylinder heads on diesel engines.

The microstructures for these three materials are presented in Fig. 4. It is possible to observe that lamellar graphite is randomly distributed in a pearlitic matrix. Table 2 presents some information of the microstructure according to the material producer. CGI Grade 350, material C, has 40–45% ferrite in the matrix, showing lower hardness than gray iron grades.

3. Results and discussion

Fig. 5 presents the results of tool flank wear land for all three materials and three cutting speeds used. These are the average of two sets of tests. Five workpieces for each condition and material were machined in each test.

At cutting speed of 600 m/min, material C, CGI, is the most difficult material to cut while material A had the best machinability, considering tool flank wear land as a machinability criterion. This can be due to the morphology of the graphite, which are similar for material A and B. The graphite flakes facilitate crack propagation on the primary shear plane and can also act as a lubricant at the tool/work interface. These results are also supported by the tensile strength of the three materials (Table 1). However, for the highest cutting speed, 1000 m/min, both materials A and C had similar machinability using the same criterion. The average tool flank wear when machining these materials were about 200 μm. According to Tables 1 and 2 the mechanical resistance of material C is higher than A, however material A is harder than C and its microstructure is entire pearlite while C has 44% of ferrite. These properties are affected by temperature, which increases with cutting speed. The balance between these two mechanical properties affects machinability.

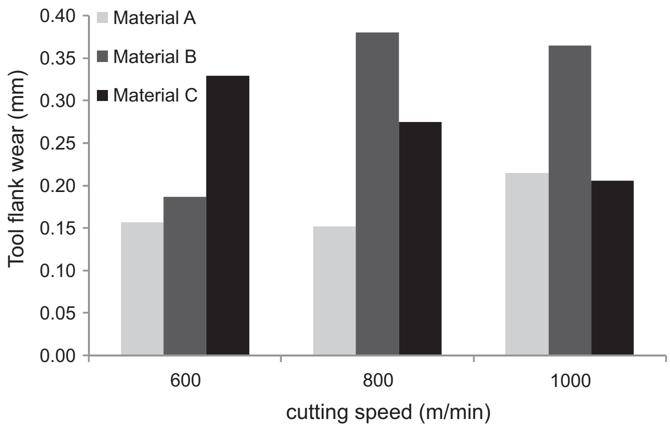


Fig. 5. Tool flank wear for all materials and cutting speeds.

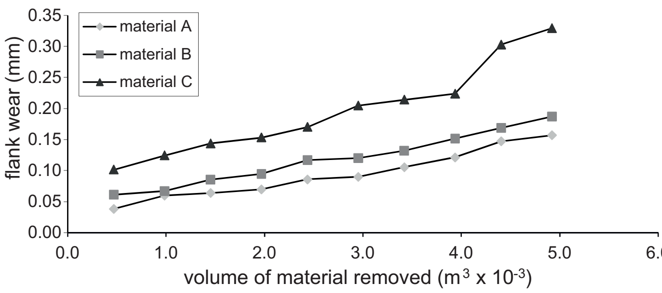


Fig. 6. Tool wear evolution for all materials at the cutting speed of 600 m/min.

Table 2
Characteristics of the microstructure of the workpiece materials.

Material	Matrix	Graphite			
		Shape	Type	Size	Nodular
A	Pearlitic 100%	I	A	4–5	–
B	Pearlitic 100%	I	A	4–5	–
C	Pearlitic with 44% ferrite	III–VI	–	–	15%

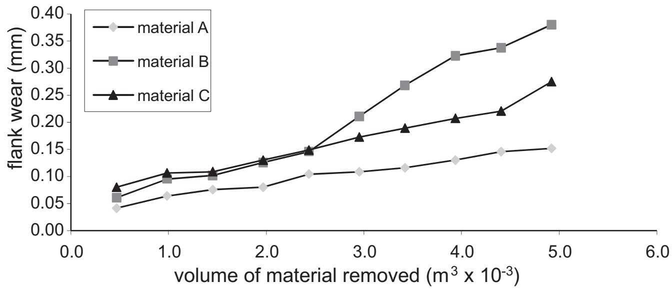


Fig. 7. Tool wear evolution for all materials at the cutting speed of 800 m/min.

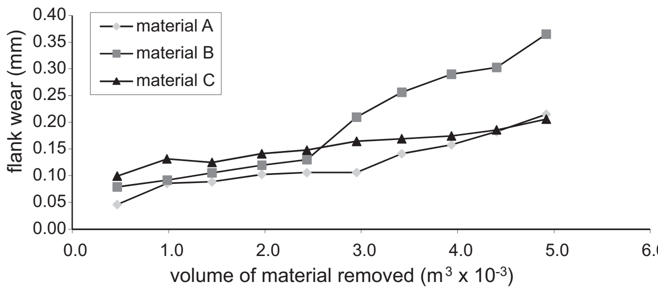
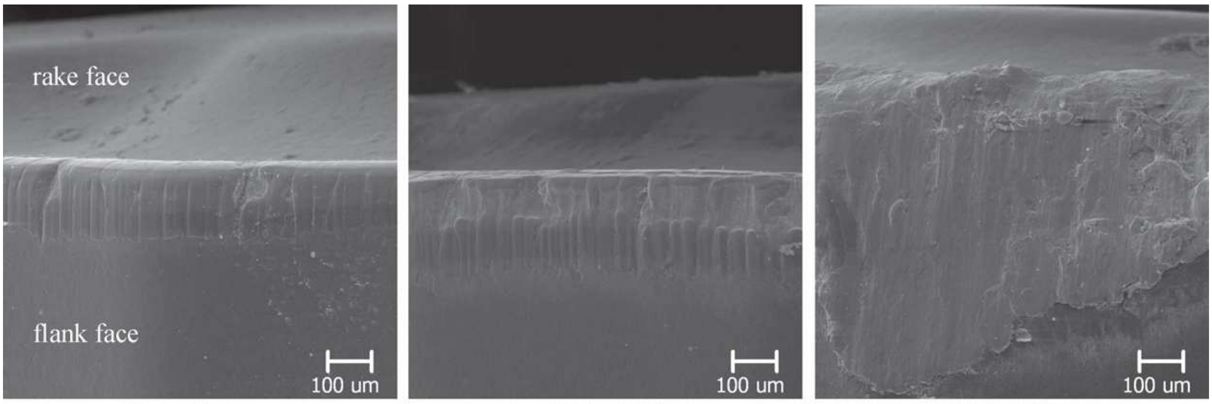
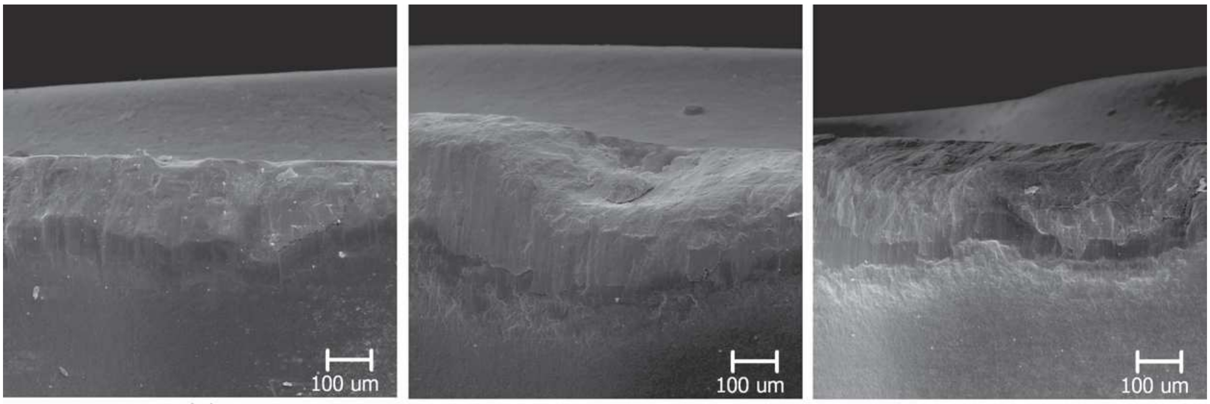


Fig. 8. Tool wear evolution for all materials at the cutting speed of 1000 m/min.



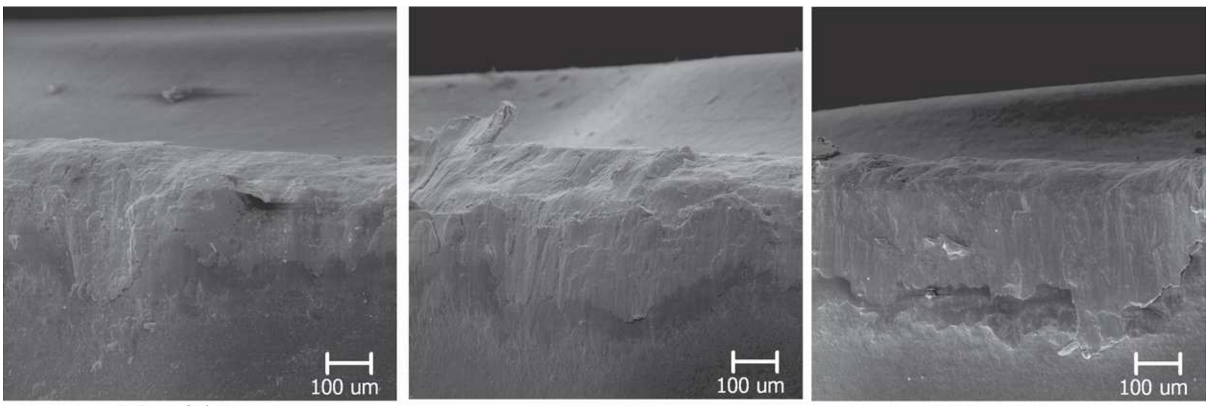
Material A Material B Material C

Fig. 9. Tool flank wear at cutting speed of 600 m/min.



Material A Material B Material C

Fig. 10. Tool flank wear at cutting speed of 800 m/min.



Material A Material B Material C

Fig. 11. Tool flank wear at cutting speed of 1000 m/min.

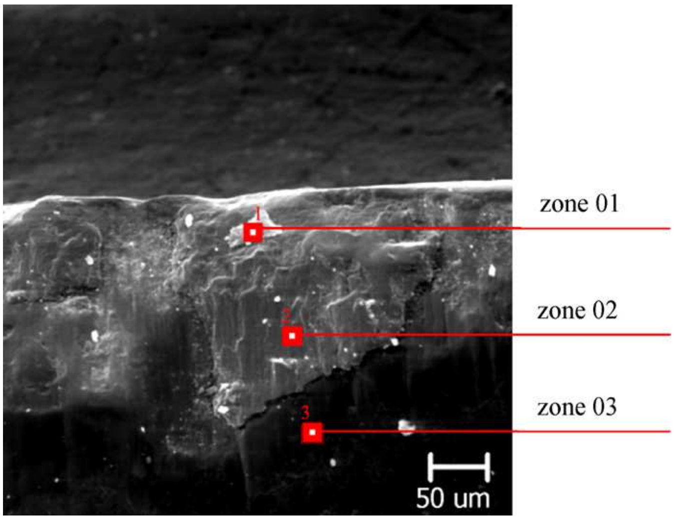


Fig. 12. Tool cutting edge after machining material A at cutting speed of 800 m/min.

The graph at Fig. 5 also suggests that for material C increasing cutting speed results in decreasing tool wear rates. The reason for that behavior is not clear. Material A and C shows the typical trend of increasing tool wear rates with increasing cutting speed; material B has the highest influence on tool flank wear when increasing cutting speed. The increase in cutting speed means increase in the heat generation and the temperatures on the cutting zone. The hardness of material B is higher than the others materials and it contains molybdenum.

It must be highlighted that the tests were stopped after machining five workpieces. Fig. 5 suggests a decrease on tool flank wear with cutting speed, but the machining time depends on the cutting speed, which are different. Figs. 6–8 show the relationship between tool flank wear and volume of material removed for all three materials and cutting speeds used. At the cutting speed of 1000 m/min, both wear curves for materials A and C are similar and have close flank wear values. All curves have similar shape with exception for material B at cutting speeds of 800 and 1000 m/min.

According to the results the alloyed gray cast iron CrCuSnMo (material B) is the most difficult material to machine at cutting speeds of 800 and 1000 m/min. The alloying elements in the matrix of both gray cast iron affect machinability. Chromium at quantities over 0.3% can precipitate and form complex carbides. These carbides will also increase the resistance and hardness of the material. Copper and tin are pearlite stabilizers, the last being used in small amounts. The effect of most alloying elements is to increase the quantity of the pearlite and decrease the distance between the lamellas (resulting in a fine pearlite). Alloying elements can also increase the hardness of the ferrite [2]. These effects suggest that poor machinability can be obtained in an alloyed gray cast iron compared to CGI. The difference in chemical composition between material A and B is the presence of molybdenum. This element can form eutectic carbides which affect the strength and can be a key factor affecting machinability.

In metal cutting four types of wear can be identified: abrasion, adhesion, diffusion and oxidation. The predominant type depends on temperature which means depends on cutting speed. In general, the abrasive wear can occur for any cutting speed, while adhesive wear is concentrated at lower cutting speeds. At high cutting speed diffusion and oxidation effects are more important [13]. Examination of tool surfaces used in the tests can give important information about the wear mechanism. Figs. 9–11 present some scanning electron microscope (SEM) micrographs of the cutting tool inserts. It is possible to identify two wear mechanisms: abrasion and adhesion.

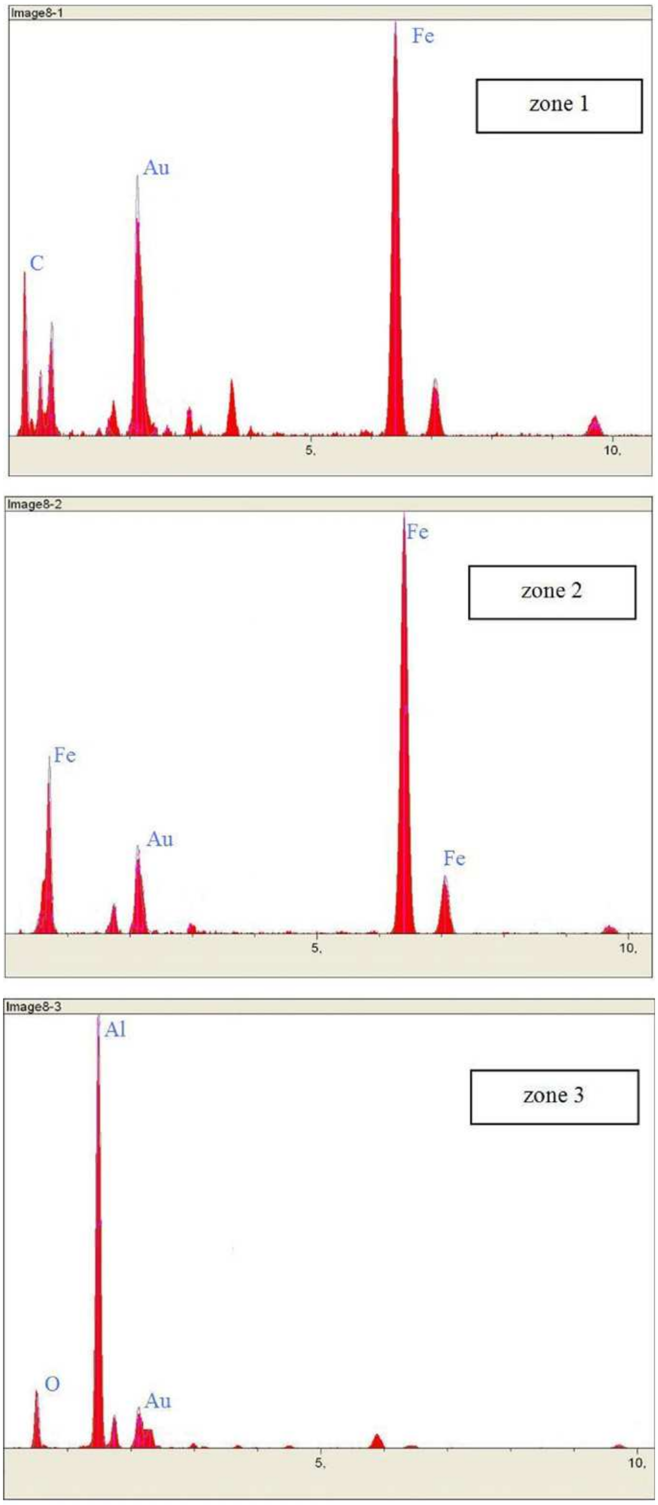


Fig. 13. Result of EDS analysis of three regions of cutting tool of Fig. 11.

For the cutting speed of 600 m/min and materials A and B, Fig. 9 shows some scratch marks on flank face, which can be due to abrasion, the main wear mechanism for these materials at this cutting speed. Material C in all three cutting speeds and material B for 800 and 1000 m/min, adhesion of workpiece material on tool surfaces suggests adhesive wear as the main mechanism. However, a more deep investigation about the adhered material on the cutting tool is needed. The observations in this work only gave evidences of more strong adhesion of material B, which is the gray iron containing Mo.

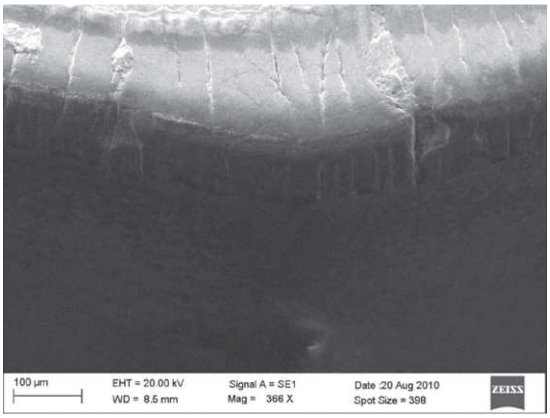


Fig. 14. Tool cutting edge after machining material A at 600 m/min.

The tool insert presents a strong adhesion of workpiece material. Fig. 12 shows a SEM view of a tool flank face used to cut material A at a cutting speed of 800 m/min. Three zones in the tool wear surface were analysed using EDX spectra. The results are shown in Fig. 13. In zone 1 a high concentration of iron and carbon was observed, which can suggest adhesion of the workpiece material. Iron is also the main chemical element detected in zone 2 in the same figure. Other chemical elements detected in zone 2 are: carbon, silicon and sulphur. These are chemical elements present in the composition of the gray cast iron. The EDX spectrum of zone 2 is strongly indicating adhesion between workpiece material and tool material.

In zone 3 the following elements are detected on the coating: aluminium and oxygen (probably forming Al_2O_3). This zone has no wear, however some chemical elements of the workpiece material (iron, carbon and silicon) were also detected in the EDX spectra. Little adhesion between workpiece and tool material is also occurring in this zone.

It is important to notice that the cutting speed of 1000 m/min can be considered high speed cutting (HSC) for these materials and cutting process. A cutting speed of 400 m/min is recommended by

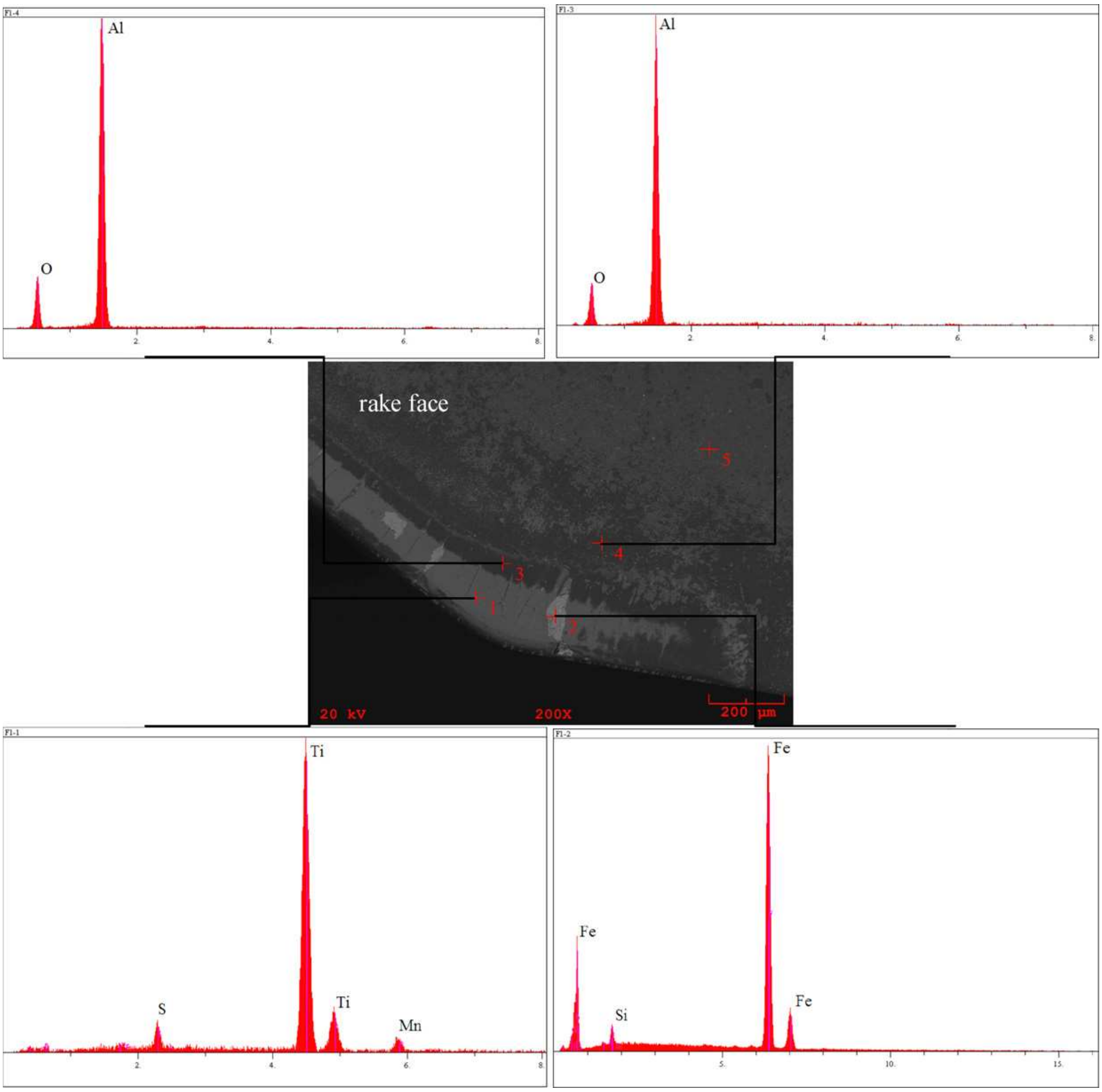


Fig. 15. EDX spectra of tool rake face after machining material A at 600 m/min.

the tool maker. The material behavior at such conditions of high temperature and strain rate is not known. It is important also to measure the thermal properties of the workpiece materials. The thermal conductivity for example, can be one of the most important properties affecting tool wear.

Thermal fatigue in cemented carbide tools occurs frequently in interrupted cutting such as the milling operation used in this work [14]. Thermal fatigue in cutting tools is evidenced by the development of cracks running along the rake and flank faces perpendicularly to the cutting edge [15]. Fig. 14 shows an SEM micrograph of a tool cutting edge after machining material A at cutting speed of 600 m/min. There are some cracks perpendicular to the cutting edge, which is a characteristic of damage caused by cycling variation of temperature. Some cracks are deep enough to be filled by material from the workpiece material. An EDX analysis of the tool rake face can reveal the main chemical elements in this wear surface, Fig. 15.

The EDX spectra of zone 1 of Fig. 15 reveal the presence of Ti. The cemented carbide tool used has two coatings. The inner one is TiCN, and therefore, the Ti detected is due to this coating.

4. Conclusions

Two grades of gray iron, alloyed with CrCuSn (grade 200) and with CrCuSnMo (grade 250), and vermicular cast iron grade 350 were machined using milling operation. The tool performance was analysed by means of tool wear and wear mechanisms. Based on the results obtained, the following conclusions can be drawn:

- The CGI, material C, presented poor machinability at cutting speed of 600 m/min. Tool flank wear can be more than 100% higher for CGI than alloyed gray iron.
- At the higher cutting speeds of 800 and 1000 m/min, the CrCuSnMo alloyed gray iron, material B, is the worst material to cut. Tool flank wear was about 85% higher than when CGI in machined.
- The CGI and the CrCuSn alloyed gray cast iron have similar machinability at cutting speed of 1000 m/min.
- Flank wear was the main type of wear for all conditions and materials. The wear mechanisms observed at these conditions were abrasion and adhesion. Adhesion was the main wear mechanisms at higher cutting speeds.

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