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RESEARCH ON TOOL WEAR EVALUATION IN GRAPHITE MILLING

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Abstract: The paper was developed as part of a collaboration between the Technical University of Cluj-Napoca – Faculty of Industrial Engineering, Robotics and Production Management – and Guhring SRL Company. The aim of this study is to implement a milling technology for graphite machining, as Guhring did not previously possess this capability. The objectives of the research include the development of improved tool geometry and coating for graphite milling, focusing on optimizing cutter design, enhancing coating performance, and minimizing tool wear during the machining process.

Key words: Graphite milling, milling tools, geometry, tool wear, measurements

1. INTRODUCTION

The purpose of this research was to test several types of diamond-coated milling cutters in order to determine their durability when machining graphite, specifically the ELLOR+25 material. These tests were conducted with the aim of improving the geometry of the cutters used in this experiment. By employing various devices and optical instruments, the geometry of the milling cutters was measured before and after use, at different intervals, thereby allowing for the analysis of the coatings and their wear.

Milling is a chip-removal process that generates complex surface geometries using multi-edge rotary cutters. Unlike turning or drilling, milling features a discontinuous cutting action, combining the tool's rotary motion with linear, circular or combined feed motions of the tool and/or workpiece. It can machine both internal and external surfaces, either profiled or unprofiled. Milling methods are classified as cylindrical, face, or peripheral-face, depending on tool geometry and the engagement of cutting edges. [1]

1.1 Surface Coating Methods Applied in Milling Tool Production

The key property of cutting materials is hardness, which must exceed that of the workpiece and it generally decreases with temperature. Therefore, tool materials are engineered for

hardness, chemical stability and wear resistance through heat treatments, coatings and structural modifications. Coatings enhance cutting speed, reduce friction and temperature and improve hardness and surface quality. In industry, two main types are used for carbide inserts: PVD (TiN, TiCN, TiAlN) and CVD (TiC-TiN, TiC-Al₂O₃-TiN). TiC provides high hardness and abrasion resistance, TiN offers low friction and stability, Al₂O₃ acts as a thermal barrier, TiCN combines TiC/TiN properties and TiAlN enables PVD deposition with added thermal resistance. [2]

1.2 Graphite – Properties and Areas of Use

Graphite is a naturally occurring carbon mineral found in metamorphic rocks, crystallizing mainly in a hexagonal system but also in rhombohedral or amorphous forms. Its structure consists of hexagonal layers of covalently bonded carbon atoms, while adjacent layers are held by weak van der Waals forces, leading to its anisotropic behavior.[3]

Figure 1.1 shows the hexagonal structure of graphite with basal planes, where the atoms within each layer are bonded through stable covalent hexagonal bonds. However, adjacent layers are held together by weaker ionic-like (van der Waals) forces, which are much more labile. This variation in bonding strength and direction results in the anisotropic behavior of graphite.

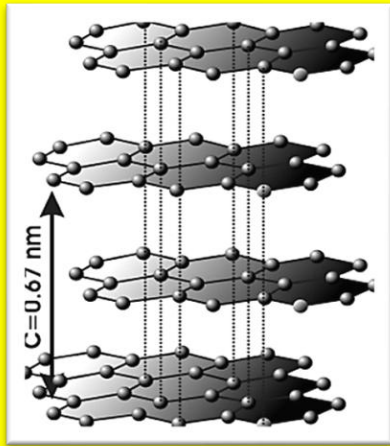


Figure 1.1 Hexagonal Structure of Graphite

Graphite forms naturally through the metamorphism of carbon-rich rocks and occurs as flake, amorphous, vein, or lump types. It is widely used in industry: natural graphite is found in furnace linings and crucibles, synthetic graphite in steel-recycling electrodes, while both forms are used in automotive components, carbon brushes, insulation, and lubricants.[4]

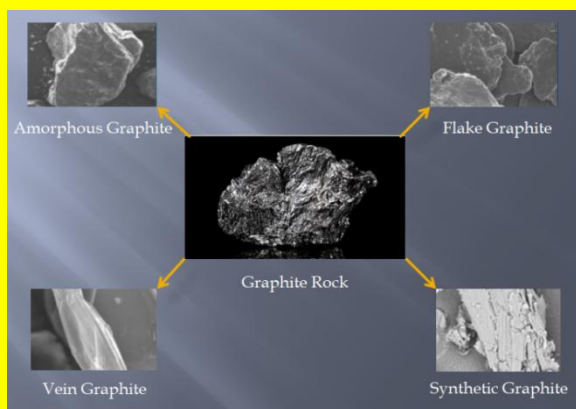


Figure 1.2 Types of graphite

1.3 Properties of ELLOR+25 Graphite

Graphite is the preferred material for EDM electrodes due to its machinability, thermal shock resistance and low thermal expansion, which ensures dimensional stability. The experiment used ELLOR+25 graphite, a grade supplied by Mersen, with cutting parameters recommended by the manufacturer [5].

Table 1.1

Cutting parameters for ELLOR+25 graphite milling process

Milling	Spindle Speed m/min	Feed per Tooth mm
Roughing	800-1000	0.1-0.8
Finishing	1000	<0.09

The surface roughness which is achievable on this material ranges between 1.6 and 3.15 Ra [μm].

2. SPECIFIC CHARACTERISTICS OF THE MILLING PROCESS FOR GRAPHITE MACHINING WITHIN THE EXPERIMENT

2.1 Types of Milling Cutters Used in Graphite Machining

For graphite machining, solid carbide end mills with two or more cutting edges are predominantly used, often coated with diamond. This coating provides up to ten times longer tool life compared to conventional coatings. In general, these end mills significantly increase productivity and reduce costs, as they require fewer tool changes and can produce precision components at high feed rates.

End mills are classified according to their mounting method into shank-type end mills and bore-type end mills; for graphite machining, shank-type end mills are employed. [8]

2.2 The objectives of the Experiment

Due to its low mechanical strength, graphite is generally considered easy to machine. However, certain difficulties arise during milling because of its layered crystalline structure. The predominant wear mechanism affecting cutting tools is abrasion, which is proportional to the cutting speed and the geometry of the tool employed. Graphite used for electrical discharge machining (EDM) is classified according to grain size. This parameter is considered a key criterion, since most of the other properties of graphite depend on the size and orientation of the grains. Currently, the market provides graphite grades with average grain sizes ranging from below 1 μm to approximately 20 μm . The choice of grain size mainly depends on the working conditions in which the material will be used—whether for roughing, semi-finishing, or finishing operations.[8]

This study aims to demonstrate that graphite milling in various geometries can be performed with ease when using the appropriate tools and cutting parameters. Different milling strategies for graphite will be tested in order to determine which approach performs best. Several tests were conducted to determine the duration for which a

milling cutter can be used before wear begins to occur.

The tools employed for graphite machining were tested by milling a predefined length, after which tool wear was assessed on that specific cutting distance. Two types of end mills were used in this experiment: one with a smaller diameter and another with a larger diameter. Tool wear measurements were taken after 4 m, 8 m, and 10 m of milling. Each milling test was repeated twice and when a significant discrepancy between the two results occurred, a third measurement was performed.

The smaller tool, with a diameter of 8 mm and a length of 63 mm was made of solid carbide and coated with TiAlN through the PVD process; this tool had two cutting edges. For higher cutting speeds, a second end mill with a diameter of 16 mm and four cutting edges was employed, also made of solid carbide with TiAlN coating. The feed per tooth (fz) was kept constant at 0.05 mm for both tools, in order to maintain consistent finishing characteristics throughout the experiment. After tool usage, several issues were observed, such as fractures, as well as chipped or broken edges and corners. The critical aspects requiring deeper analysis were identified based on these tests, in order to determine the most suitable tool geometry for machining this material.

The purpose of these tests was to investigate tool life by evaluating its performance under different cutting parameters.[8]

3. EQUIPMENT USED FOR CONDUCTING THE EXPERIMENT

3.1 PG-2000 Measuring Device

This device is used for measurement and inspection purposes. It allows for the measurement of angles, radii, and diameters of cutting tools.

3.2 Keyence VHX-5000

This equipment is a digital microscope that can be used for measuring and inspecting various tool angles or for assessing tool wear. It is also capable of providing a 3D view based on multiple captures of the respective tool.

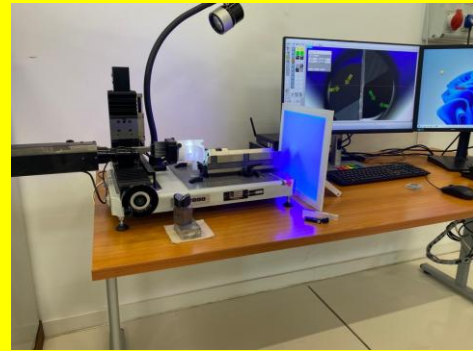


Fig. 3.1 PG-2000 Measuring Device.

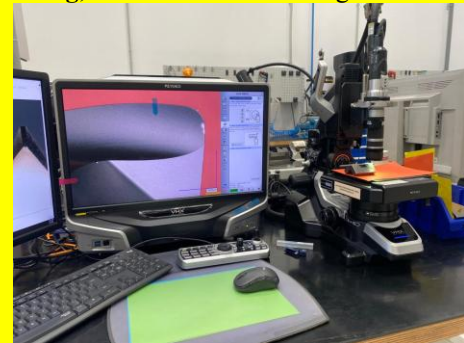


Fig. 3.2 Keyence VHX-5000.

3.3 Zeiss Sigma 300



Fig. 3.3. Zeiss Sigma 300.

The microscope (fig.3.3) is equipped with various analytical detectors, which are housed within the vacuum chamber containing the electron beam source, emitted by a filament. The vacuum is essential to prevent the filament from burning and to ensure that the atoms present in the air do not negatively affect the image quality.

3.4 Matsuura VX-1000 Vertical

The machining tests were conducted on a Matsuura VX-1000 machine.



Fig. 3.4 Matsuura VX-1000 Vertical.

The machine has a maximum spindle speed of 20,000 rpm and is equipped with a cooling system to reduce temperatures during the machining process. Considering the dust generated during graphite machining, the machine is also fitted with a vacuum extraction system.

3.5 Kistler Dynamometer

This equipment is a piezoelectric dynamometer that enables the measurement of forces along each machining axis. The force ranges on the X and Y axes are up to 30 kN, while on the Z axis the range is from -10 to 60 kN. The measurement plate has dimensions of 260 × 260 mm. Its high resolution allows for detecting even the smallest dynamic variations under high force conditions.



Fig. 3.5 Kistler Dynamometer.

3.6 Alicona Infinite Focus G5

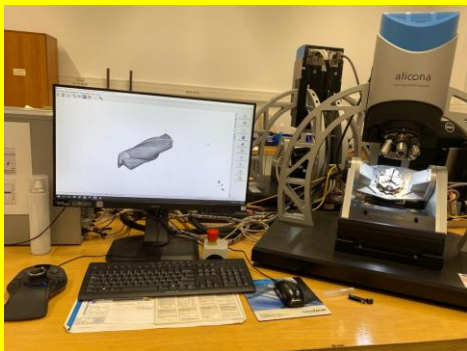


Fig. 3.6 Alicona Infinite Focus G5.

The equipment is used for surface measurements or for measuring surface

roughness, from which the wear of the respective tool can be inferred. Measurements can be repeatedly performed using a vertical device with a resolution of up to 10 nm. Its measurement principle is based on vibration-isolation hardware capable of accurately assessing tool roughness. The device axes are equipped with precise encoders that ensure accurate incremental movement.

4. PRESENTATION OF THE END MILLS USED IN THE EXPERIMENT

Several types of 6 mm diameter diamond-coated end mills were tested to evaluate their durability when milling ELLOR+25 graphite. These tests were also conducted to improve the geometry of the end mills used. For confidentiality reasons, the specific names of the tested tools cannot be disclosed. In total, 15 end mills with different geometries and numbers of cutting edges were employed, although each tool had a similar diamond coating.

Table 4.1

Data Regarding the Tools Used During Machining

No.	Name	Unit of Measure	Tool Diameter	Number of Cutting Edges	Tip Radius	Overall Length
1.	Competitor 1	[mm]	Ø6	2	0.3	100
2.	Competitor 2	[mm]	Ø6	2	0.5	100
3.	Competitor 3	[mm]	Ø6	3	0.5	100
4.	Competitor 4	[mm]	Ø6	2	1.0	100
5.	Competitor 5	[mm]	Ø6	2	0.5	100
6.	Competitor 6	[mm]	Ø6	2	0.5	100
7.	Competitor 7	[mm]	Ø6	2	0.5	100
8.	Competitor 7.1	[mm]	Ø6	2	0.5	100
9.	Competitor 8	[mm]	Ø6	2	0.5	100
10.	Competitor 8.1	[mm]	Ø6	4	0.5	100
11.	Competitor 8.2	[mm]	Ø6	2	0.5	100
12.	Competitor 8.3	[mm]	Ø6	3	0.5	100
13.	Competitor 8.4	[mm]	Ø6	2	0.5	100
14.	Competitor 8.5	[mm]	Ø6	2	0.5	100
15.	Competitor 9	[mm]	Ø6	2	0.5	100

In Table 4.1 it can be observed that all the end mills used have a diameter of 6 mm and most of the tools have two cutting edges with a total length of 100 mm. However, there are differences among these end mills, such as tip radii and the number of cutting edges, which will have significant implications during the experiment. Due to the large volume of information, the following tools will be presented: from Competitor 1, Competitor 2, Competitor 3, Competitor 8.1 and Competitor 9.

Table 4.2

Data Regarding the presented Tools Used During Machining

Name	Unit of Measure	Tool Diameter	Number of Cutting Edges	Tip Radius	Overall Length
Competitor 1	[mm]	Ø6	2	0.3	100
Competitor 2	[mm]	Ø6	2	0.5	100
Competitor 3	[mm]	Ø6	3	0.5	100
Competitor 8.1	[mm]	Ø6	4	0.5	100
Competitor 9	[mm]	Ø6	2	0.5	100



Fig. 4.1 End Mill from Competitor 1.



Fig. 4.2 End Mill from Competitor 2.



Figure 4.3 End Mill from Competitor 3



Figure 4.4 End Mill from Competitor 8.1



Fig. 4.5 Reference Too (Competitor 9).

5. EXPERIMENTAL RESULTS

5.1 Tool Wear Evolution During the Milling Process

Using the Keyence VHX-5000, Alicona, and Zeiss SEM Sigma 300 devices, the geometry of the end mills was measured and analyzed. After the end mills were used over various cutting distances, these measurements were repeated.

Analyses were initially performed on new, unused tools, and subsequently, the same measurements were carried out on the used tools, with results varying from one end mill to another.

During the experiment, both primary faces of the end mills were analyzed and measured, alongside each cutting edge individually with their tip radii. The tip radius was measured after usage and images were captured for each cutting edge, including the rake face and the flank face.

With the ZEISS SEM Sigma 300 electron microscope, the extent of coating wear on the end mills could be observed after a certain cutting distance. Using the Kistler dynamometer, the cutting forces along each axis were recorded and analyzed.

5.2 Results Obtained with the End Mill from Competitor 1

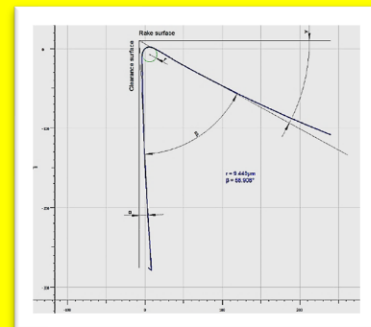


Fig. 5.1 Flank Wear Radius Before Machining.

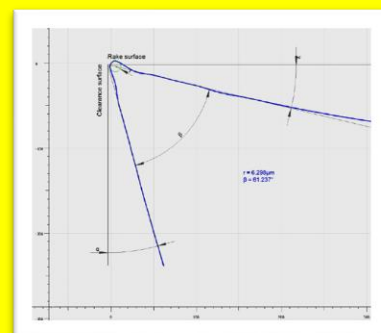


Fig. 5.2 Flank Wear Radius After Machining.

The initial flank wear radius was $9\text{ }\mu\text{m}$, while after machining (138.14 m) it measured $8\text{ }\mu\text{m}$.

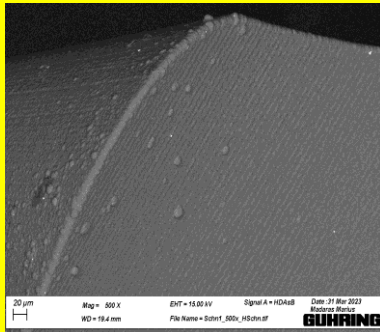


Fig. 5.3 Cutting Edge Before Machining.

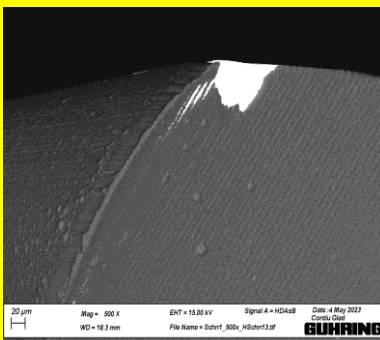


Fig. 5.4 Cutting Edge After Machining.

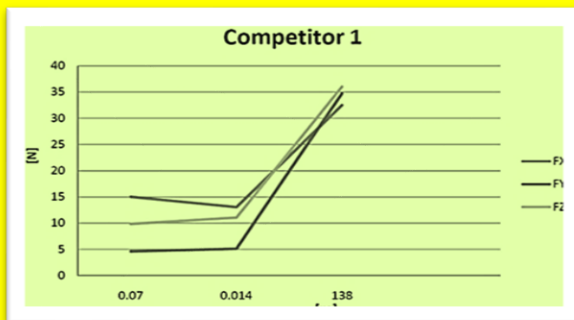


Fig. 5.5 Forces Present During Machining along the Three Axes.

The first end mill used for graphite machining in this experiment was from Competitor 1. It had 2 cutting edges, a total length of 100 mm, a tip radius of 0.3 mm, and a diameter of 6 mm. The tool was made of carbide and was coated with diamond.

5.3 Results Obtained with the End Mill from Competitor 2

The initial flank wear radius was $11\text{ }\mu\text{m}$, while after machining (138.14 m) it measured $6\text{ }\mu\text{m}$.

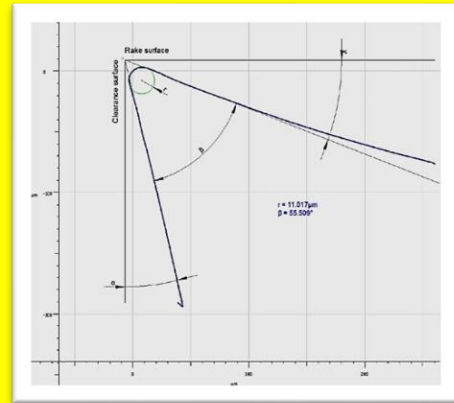


Fig. 5.6 Flank Wear Radius Before Machining.

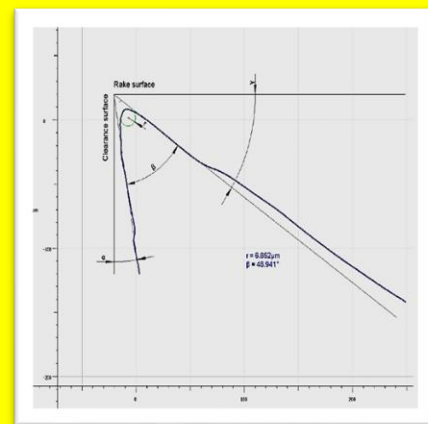


Fig. 5.7 Flank Wear Radius After Machining.

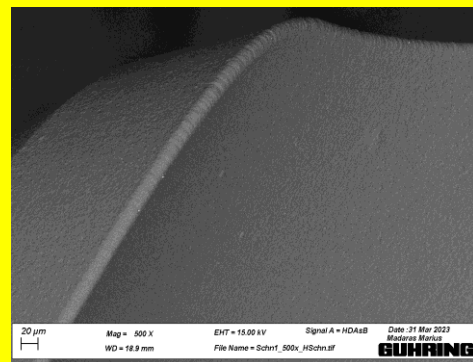


Fig. 5.8. Cutting Edge Before Machining.



Fig. 5.9. Cutting Edge After Machining.

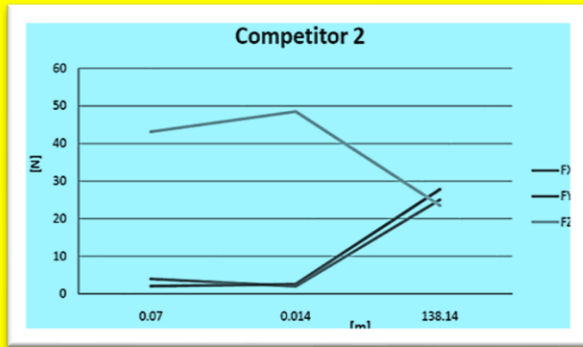


Fig. 5.10. Forces Present During Machining along the Three Axes.

The second end mill used for graphite machining in this experiment was from Competitor 2. It had 2 cutting edges, a total length of 100 mm, a tip radius of 0.5 mm and a diameter of 6 mm. The tool was made of carbide and was coated with diamond.

5.4 Results Obtained with the End Mill from Competitor 3

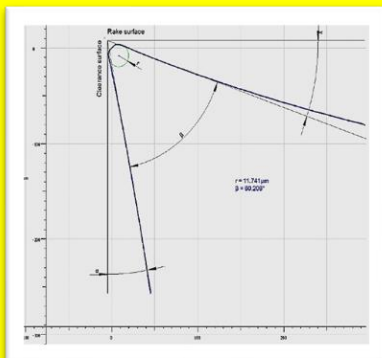


Fig. 5.11. Flank Wear Radius Before Machining.

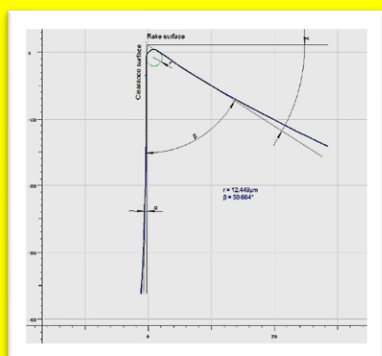


Fig. 5.12. Flank Wear Radius After Machining.

The initial flank wear radius was 11,56 μm , whereas after machining (220,39 m) it measured 11,20 μm .

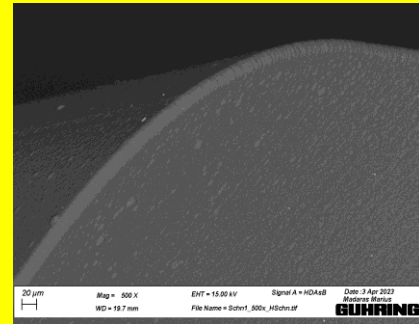


Fig. 5.13. Cutting Edge Before Machining.

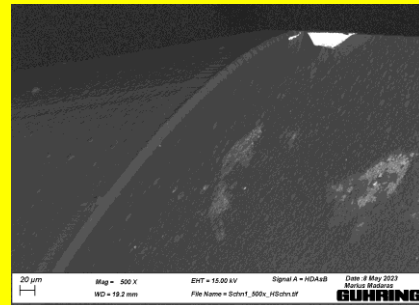


Fig. 5.14. Cutting Edge After Machining.

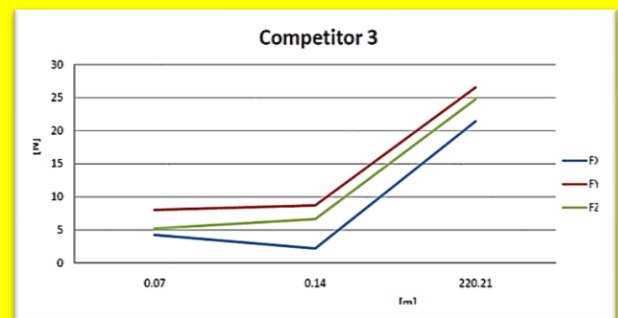


Fig. 5.15. Forces Present During Machining along the Three Axes.

5.5 Results Obtained with the End Mill from Competitor 8.1

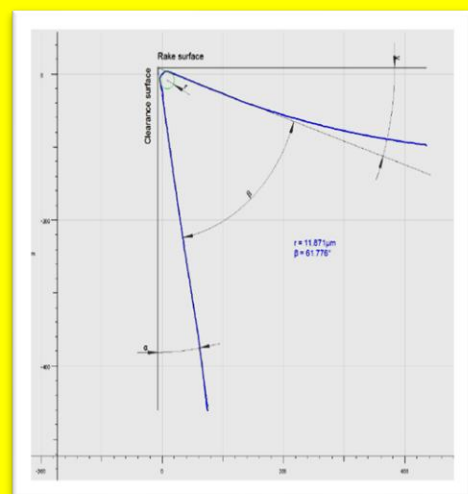


Fig. 5.16 Flank Wear Radius Before Machining.

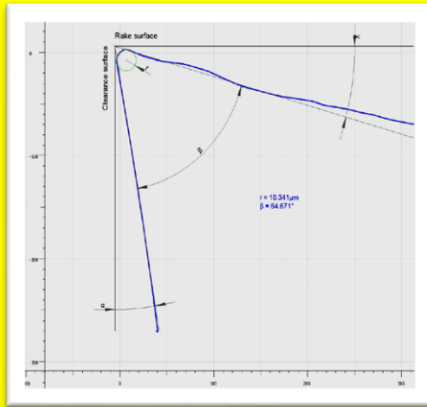


Fig.e 5.17. Flank Wear Radius After Machining.

The initial flank wear radius was 11 μm , whereas after machining it measured 10 μm .

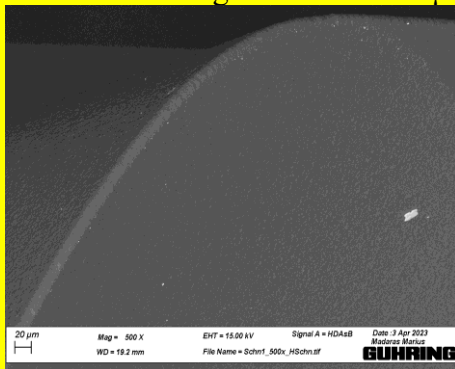


Fig. 5.18 Cutting Edge Before Machining.

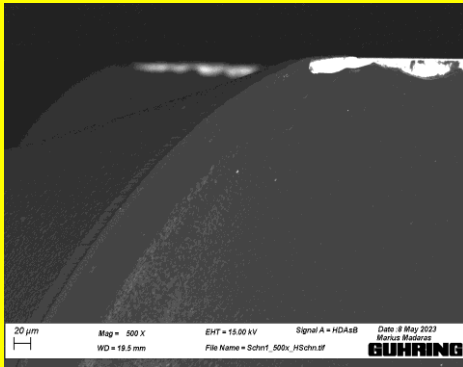


Fig. 5.19 Cutting Edge After Machining.

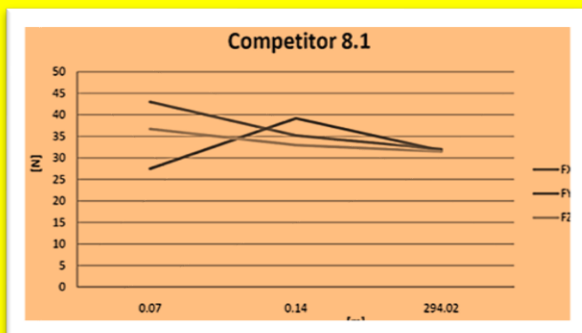


Fig. 5.20 Forces Present During Machining along the Three Axes.

5.6 Results Obtained with the Reference Tool

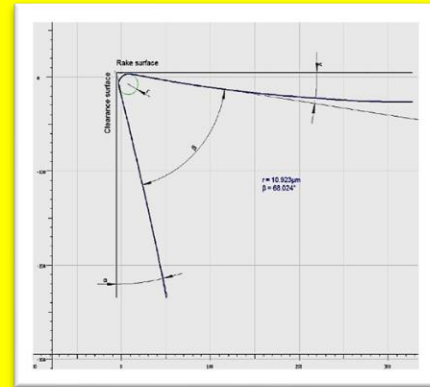


Fig. 5.21. Flank Wear Radius Before Machining.

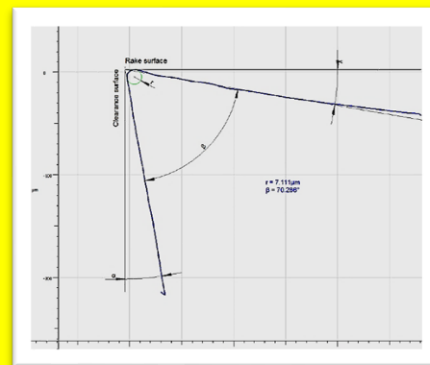


Fig. 5.22. Flank Wear Radius After Machining.

The initial flank wear radius was 10 μm , whereas after machining it measured 7 μm .

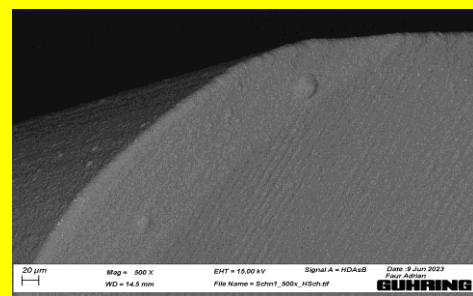


Fig. 5.23 Cutting Edge Before Machining.

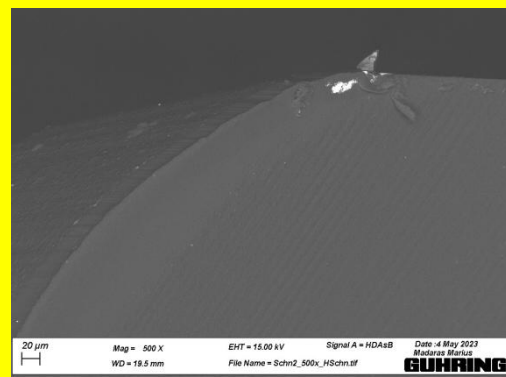


Fig. 5.24 Cutting Edge After Machining.

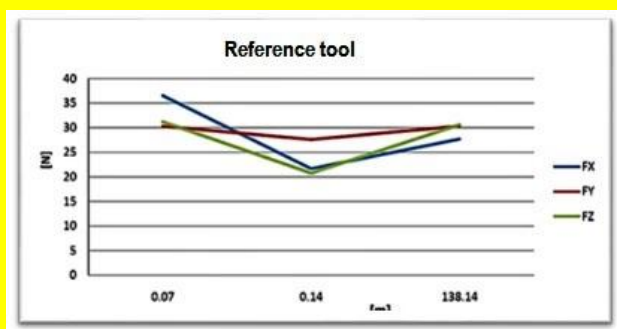


Fig. 5.25 Forces Present During Machining along the Three Axes.

6. CONCLUSIONS AND PERSONAL CONTRIBUTIONS

After all the measurements and analyses carried out within this project, it was observed that all five presented end mills (Competitor 1, Competitor 2, Competitor 3, Competitor 8.1, and Competitor 9) exhibited wear marks on each cutting edge, depending on the cutting parameters that were used and the distance machined with the respective tool.

The purpose of this study was to implement a new technology for graphite end mills, as the company did not previously possess this capability. This goal was achieved because the final end mill was designed by the company based on the results obtained and the tests conducted with the end mills from Competitor 1, Competitor 2, Competitor 3 and Competitor 8.1. Additionally, other tools not explicitly presented, which showed similar results, were also taken into account.

All end mills used had a diameter of 6 mm and a total length of 100 mm. The base material for all tools was carbide, and each end mill was coated with diamond. The role of the diamond coating is to protect the tool surfaces and increase tool life by reducing wear.

The tests were performed using the following cutting parameters: a cutting speed of 358 m/min, a feed rate of 2584 mm/min, a cutting depth of 2 mm, and a feed per tooth that varied depending on the number of cutting edges. For two-flute end mills, the feed per tooth was 0.136 mm/rev; for three-flute end mills, it was 0.204 mm/rev; and for four-flute end mills, it was 0.272 mm/rev.

In all cases, analyses were performed on the cutting edges, the rake and flank faces of the tools, the tip radius and the forces present during machining. To better observe wear development during cutting, different microscopes were used.

Initially, images of the unused tools were captured and subsequently, images of the worn tools were taken after varying machining distances.

For the two-flute end mills (Competitor 1 and 2), significant wear was observed on the cutting edges and rake faces, resulting in deterioration of the diamond coating and thinning of the cutting edges. For the three-flute end mill from Competitor 3, wear became noticeable later, after a cutting distance of 220.39 m. For the four-flute end mill from Competitor 8.1, wear was less pronounced since it was distributed across all four cutting edges.

The end mill designed by Gühring, with two flutes, a diameter of 6 mm, and a total length of 100 mm, showed the following results after 138.21 m of machining: the diamond coating remained almost intact, minor wear appeared on the rake face of both cutting edges, and the tip radius exhibited no significant wear.

In conclusion, based on all measurements and analyses conducted during this study, it was established that two-flute end mills demonstrate acceptable wear and, therefore, represent a durable tool option. However, it was also observed that many factors influence wear during the machining process, with tool geometry being the most significant.

The smallest wear on the flank radius was measured for the end mill from Competitor 3, while the highest flank wear was observed on the tool from Competitor 2. Measurements of the forces present during cutting indicated that the best performance was achieved with the reference tool.

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Cercetări privind evaluarea uzurii sculelor la frezarea grafitului

Lucrarea a fost elaborată ca parte a unei colaborări între Universitatea Tehnică din Cluj-Napoca – Facultatea de Inginerie Industrială, Robotică şi Managementul Producţiei – şi Compania Guhring SRL. Scopul acestui studiu a fost de a implementa o tehnologie de frezare pentru prelucrarea grafitului, deoarece Guhring nu deţinea anterior această capacitate. Obiectivele cercetării au inclus dezvoltarea unei geometrii îmbunătăţite a sculelor şi a unui strat de acoperire pentru frezarea grafitului, concentrându-se pe optimizarea designului frezei, îmbunătăţirea performanţei stratului de acoperire şi minimizarea uzurii sculelor în timpul procesului de prelucrare

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