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Abrasion Wear Analysis of Commercial Cutting Inserts by Ball–On–Disc Method

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Today's machining requirements cannot be met without the right tool materials. An ideal universal tool material should combine the highest abrasive wear resistance and hardness with high strength and good toughness, while being chemically inert to the workpiece material. Despite the intensive development of materials sciences the fundamental contradiction between hardness, which guarantees resistance to abrasive wear, and toughness, which determines impact and fatigue strength, has not been satisfactorily resolved on a global scale. This paper presents the results of tribological wear testing of commercial cutting inserts of S20S, U10S and CC6090 grades. Chemical composition, density, hardness and tribological wear were determined using the ball on disk method. The analysis of the laboratory tests showed that the S20S, U10S and CC6090 cutting inserts have high resistance to abrasive wear, the loss of total volumetric mass did not exceed 1%.

Keywords: Carbides, Tool ceramics, Tribological testing, Machining

1 Introduction

The interaction between the tool and the material being cut causes the tool's cutting edge to wear with the time of cutting. Wear of the blade occurs on all its surfaces in contact with the workpiece material, nevertheless the intensity of wear is not the same everywhere.

Wear generally manifests itself in the form of loss of blade material, and therefore the basis for assessing the amount of blade wear is the size of the loss. [1,2]

The cutting process takes place under specific conditions of friction and abrasion. There are high unit pressures on the cutting surface, which are necessary for the mechanical separation of the material of the cut layer and the formation of a chip [3, 4]. As a result of the separation of the material of the cut layer by the blade, new surfaces of the workpiece (transition surface and work surface) and the chip are formed. The newly formed workpiece and chip surfaces interact with the blade in a frictional process at rapidly varying temperatures, reaching even the melting temperature of the cut material at individual contact points. [3,5,6].

In industrial production, the machining time is a crucial factor in productivity. By selecting appropriate values for the machining parameters, the main process time can be significantly reduced. It should be noted that excessively high values of the machining parameters may result in faster wear of the cutting blades and partial halting of the milling process in order to replace a worn cutting blade. [7,8] In order to select optimal cutting parameters, studies are conducted to optimize the wear of the cutting blades. Consequently, production efficiency is the product of the time available on machine tools, less the contribution of handling time, and the main values of machining parameters. The development of materials engineering has led cutting tool manufacturers to produce tools that have high quality requirements with possible long life. [9, 10,11]

In addition to the growing interest in advanced materials, there has been a notable increase in the use of ductile iron and vermicular graphite cast iron in mechanical engineering and engineering structures. These cast irons are distinguished by their favorable mechanical and tribological properties. However, machining them presents a significant technological challenge due to their unique microstructure and high ductility. Cutting tool manufacturers have developed tools with improved mechanical properties, including coated carbides, nitride ceramics, SIALON and CBN composites, which are suitable for machining cast iron. [11,12]

In their study, the authors in [13] analyzed the wear mechanisms of commercial cutting blades with TiCN and Al_2O_3 coatings deposited during the turning of bars of 34CrNiMo6 structural steel. Their findings indicated that the adopted cutting parameters had a significant impact on the wear of cutting blades, with the Al_2O_3 coating layer being the primary source of wear. For cutting blades of CNMG 120408-MP3 WPP10S, the presence of abrasive wear and growth on the cutting surface was observed. In contrast, cutting blades of CNMG 120408-MP3 WPP20S exhibited both abrasive and erosive wear.

In the paper [14], the authors conducted an analysis of the wear of cutting blades produced by laboratory Spark Plasma Sintering technology. The cutting blades were made of submicron and ultrafine carbide. Tests were conducted in the milling process of chipboard. Based on the observation of the cutting blades, it was revealed that, during the lapping period, splintering and chipping of the cutting edge dominated, which could be related to the mechanisms of erosion and fatigue resistance. In the zone of fixed wear, the presence of microcracks, furrows, scratches, cracks, and spalling of WC grains indicated the occurrence of abrasive wear mechanisms. These observations align with those reported in previous studies, including [15,16]. The resulting spalling on the cutting edge was attributed to the exceeding of the allowable tensile stress. The presence of numerous sand inclusions in the workpiece material may have contributed to this phenomenon.

2 Materials and Methods

The objective of this study was to determine the intensity of tribological wear of commercial cutting inserts of the S20S, U10S and CC6090 grades using the ball-on-disc method. The comprehensive study revealed the chemical composition, selected physical and mechanical properties of the cutting inserts.

The material used in the study was three commercially available cutting inserts of the P20, M10 and 6090 types. In accordance with ISO 513:2012, the cutting inserts utilized in the study are applicable to semi-finished machining for the following material groups [17]:

- P are intended for machining carbon steel: i.e. unalloyed, low-alloyed, high-alloyed,
- M are intended for machining stainless steels: i.e. ferritic-martensitic, austenitic, and duplex (austenitic-ferritic),
- K are designed for machining cast iron: gray, malleable, and ductile.

The chemical composition, physical and mechanical properties of the analyzed cutting inserts of the S20S and U10S grades are shown in Table 1 according to the manufacturer's catalog [18]. Information on the CC6090 grade cutting insert was not disclosed by the manufacturer. Figure 1 shows the geometry of the cutting inserts used in the tests.

***Tab. 1** Chemical composition, physical and mechanical properties of S20S and U10S grade cutting insert [15]*

ISO 513:2012	Species	Chemical composition [%]			Average grain size [μm]	Density [g·cm^{-3}]	Flexural strength [MPa]	Hardness [HV]
		WC	TiC, TaC, NbC	Co				
P	S20S	58	31.5	10.5	2-4	10.6	1 700	1 550
M	U10S	84.8	9.7	5.5	1-2	13.2	1 700	1 600

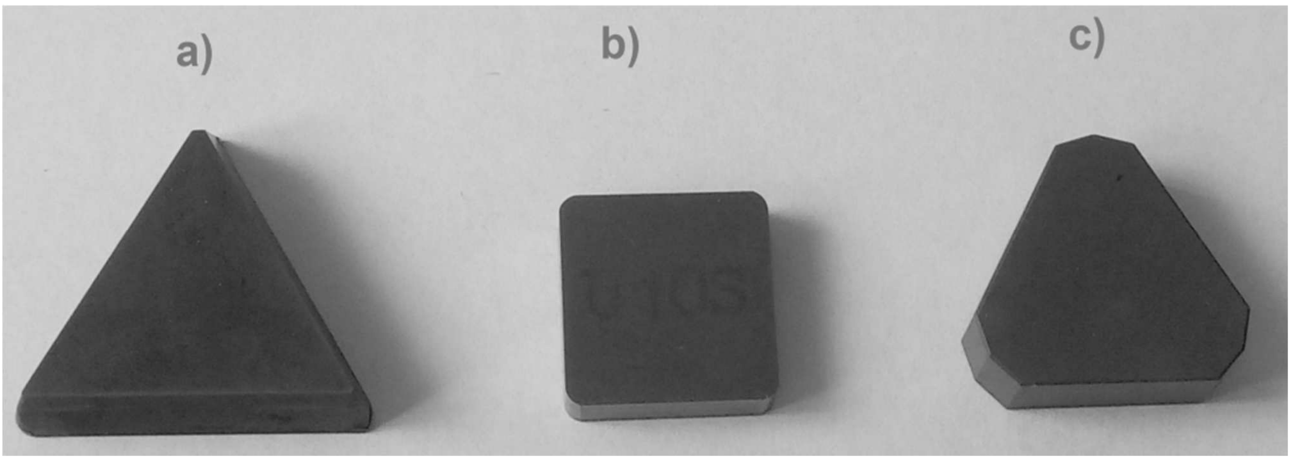


***Fig. 1** Cutting inserts of grades: (a) S20S, (b) U10S and (c) CC6090*

The samples were degreased in an ultrasonic cleaner in a C2H5OH ethanol solution for 15 minutes before testing. The chemical composition of S20S, U10S and CC6090 grade cutting inserts was analyzed using a TESCAN scanning electron microscope with an OXFORD Instruments EDS analyzer. The apparent density was measured by hydrostatic weighing using Archimedes' law. Measurements were carried out using a RADWAG AS 220.R2 PLUS laboratory balance. Hardness measurements were carried out by the Vickers method using an FV 700 type hardness tester with a diamond indenter load of 98.1 N, and a measurement time of 10 s, five hardness measurements were carried out for each cutting insert. Tests on the intesiveness of abrasive wear were carried out using a tribological tester type T 01M. The tests were carried out under dry friction conditions using the ball on disc method. A ZrO_2 ceramic ball with a diameter of 10 mm was used as a counterexample. At a load of 55 N. Twenty test cycles were carried out, the time of one test cycle was 300 seconds while the distance was 84.78 m. Tribological wear analysis was carried out using optical microscopy.

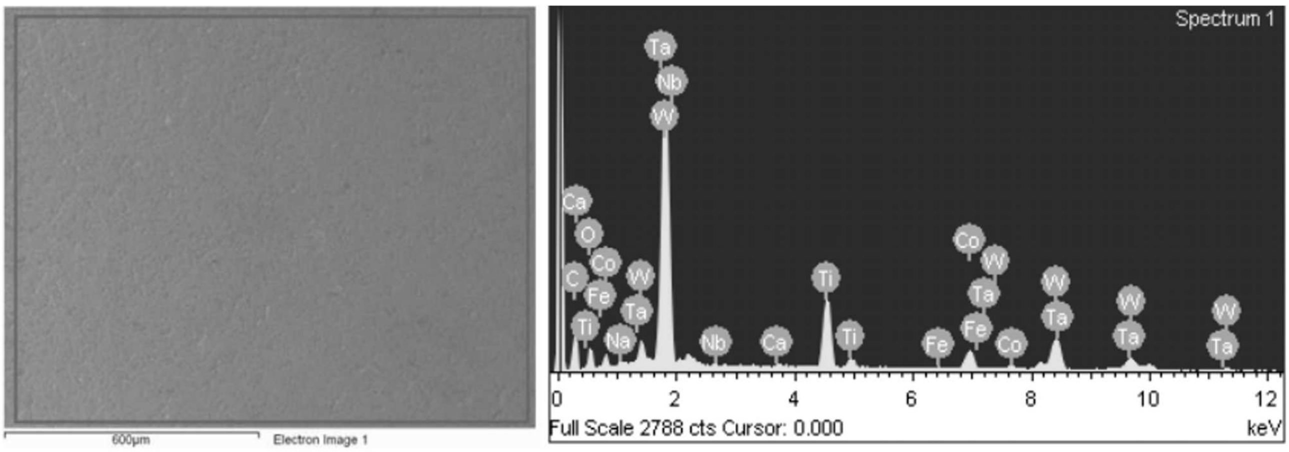
3 Results and Discussion

Figure 2-4 shows the peaks of chemical elements on EDS spectra occurring in cutting inserts of the S20S, U10S and CC6090 grades.

The chemical composition of the cutting insert of the S20S grade was analyzed, revealing the presence of Ti, Ta, and Nb in addition to the main components WC and Co. These elements, in combination with carbon, form inorganic chemical compounds, which, in turn, result in the formation of a composite of a group of carbides sintered by free sintering.

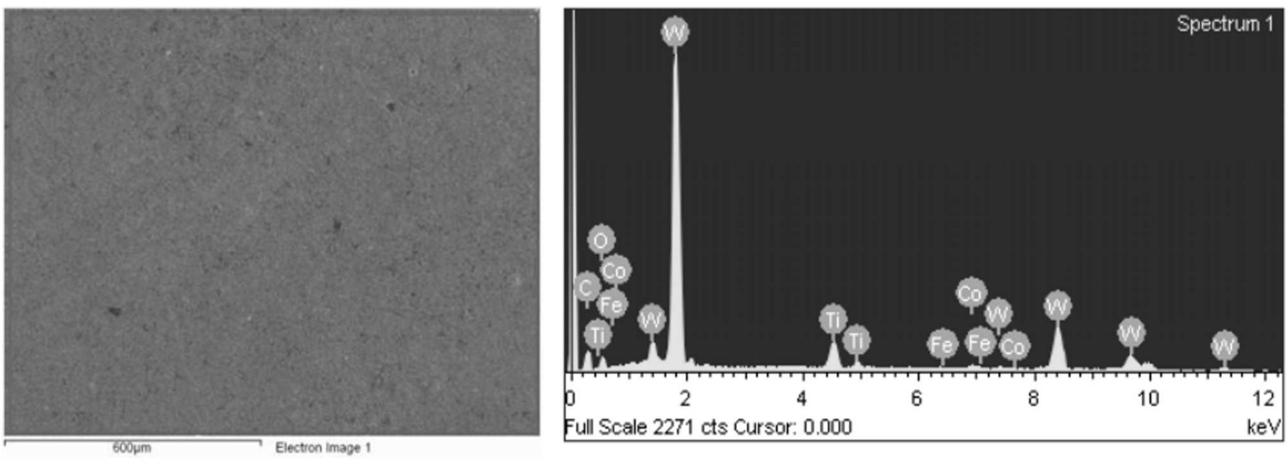
The EDS spectra for the U10S grade cutting insert revealed that in addition to the main components WC and Co, Ti was identified. This is in accordance with the chemical composition of titanium carbide (TiC), which forms when Ti is combined with carbon.

Based on the intensity of the peaks for the cutting insert of the CC6090 grade, it appears that the sinter produced is a two-phase material consisting of Si_3N_4 and Al_2O_3 phases. The composition of nitrides and oxides made it possible to produce cutting inserts from a group of tool ceramic materials.



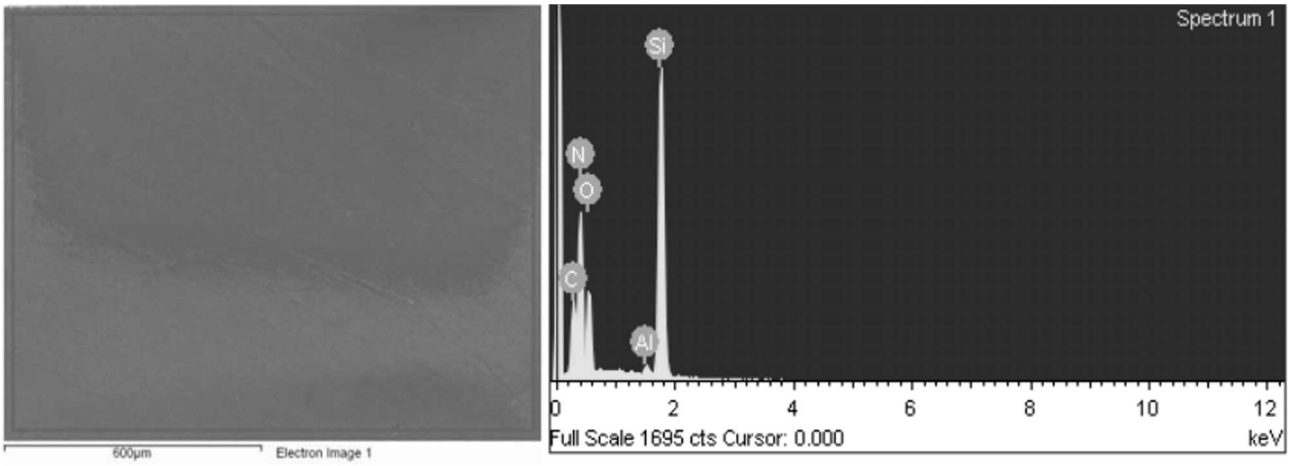
a) b)

Fig. 2 *Chemical element distribution of the S20S cutting insert: (a) the area was analyzed at 100x zoom, (b) EDS spectrum*



a) b)

Fig. 3 *Chemical element distribution of the U10S cutting insert: (a) the area was analyzed at 100x zoom, (b) EDS spectrum*



a) b)

Fig. 4 Chemical element distribution of the CC6090 cutting insert: (a) the area was analyzed at 100x zoom, (b) EDS spectrum

Based on the analysis of the chemical composition of commercial inserts, the chemical primes present in the cutting inserts were identified according to the estimated values given in Table 1.

The introduction of TiC, TaC, NbC in appropriate amounts in the chemical composition to the carbide group material is aimed at increasing the mechanical properties and improving the cutting properties when machining semi-finished unalloyed, low-alloyed, high-alloyed steel and steels such as, ferritic-martensitic, austenitic and duplex.

Identification of the chemical composition of the CC6090 grade cutting insert made it possible to classify the material into a group of tool ceramics dedicated to the machining of semi-finished broad, malleable and ductile cast iron.

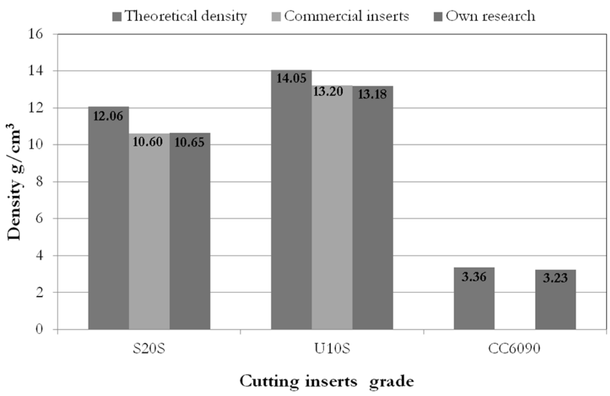


Fig. 5 Analysis of cutting insert density

The apparent density of a sinter is one of the most crucial parameters that define the material produced by powder metallurgy. The apparent density primarily determines the mechanical and functional properties. The apparent density of sinter can be optimized by modifying the parameters of the sintering process, including the heating speed, sintering temperature, sintering time, and protection atmosphere. Sinter with a low density relative to the theoretical density has pores in its structure, i.e. voids in the material, which reduce mechanical and functional properties. As part of the study, the apparent density was measured and compared with the density values provided by the cutting insert manufacturer. Figure 5 shows the results of the apparent density measurements of commercial inserts of the S20S, U10S and CC6090 grades.

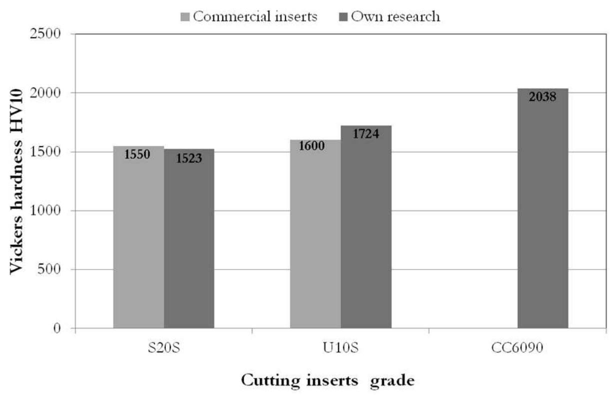


Fig. 6 Analysis of cutting inserts hardness

The apparent density of the test results was found to be in close proximity to the value declared by the manufacturer of the S20S and U10S grade cutting inserts (Table 1). The cutting insert of the S20S grade produced by free sintering reached 88.3% of the theoretical density, while the apparent density for the cutting insert of the U10S grade was 93.8% of the theoretical density. The cutting insert of the CC6090 grade has an apparent density of 96.1% of the theoretical density. The obtained results of density measurements indicate that the inserts are functional materials with application as cutting tools. The hardness of sinters depends mainly on the chemical composition and apparent density of sinters. The obtained results of hardness measurements of cutting inserts are shown in Figure 6.

The hardness measurements were found to be in close agreement with the values provided by the manufacturer. The S20S grade insert exhibited a hardness of 1523 HV, while the U10S grade insert demonstrated an increase in hardness of 11.6% compared to the S20S grade. Upon analysis of a wafer of the CC6090 grade, an increase in hardness was observed by a value of 15.4% compared to the U10S grade. The highest increase in hardness of 25.3% was observed between the CC6090 and S20S grades. The observed differences in hardness are attributed to the sinter consolidation parameters employed in powder metallurgy, the chemical composition, and the apparent density of the sinter. Each of the tested cutting inserts exhibits high hardness. It is noteworthy that the inserts have been developed for machining a range of material grades and have been successfully utilized in the machining industry.

A stabilized period of wear was observed in the cutting insert of the S20S grade, accompanied by a low intensity of wear. The total weight loss of the cutting insert after a distance of 1 695.6 m and a time of 6 000 seconds was 0.016%.

As illustrated in Figure 8, the observed wear phenomenon on the tested insert is abrasive wear. Based on the analysis of the surface topography presented in Figure 9, the roughnesses of Ra = 10.63 μm and Rz = 70.54 μm were determined.

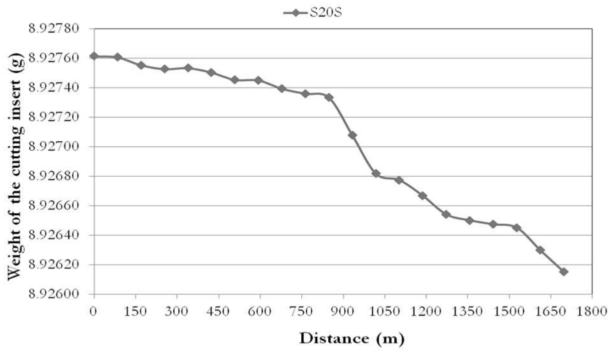


Fig. 7 *Weight loss of cutting insert of S20S grade during tribological tests*

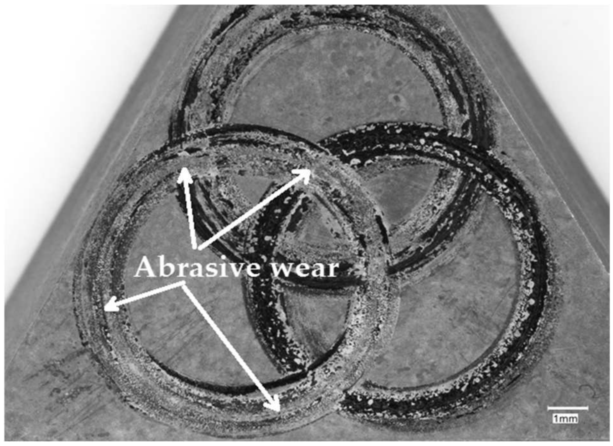


Fig. 8 *Analysis of tribological wear phenomena*

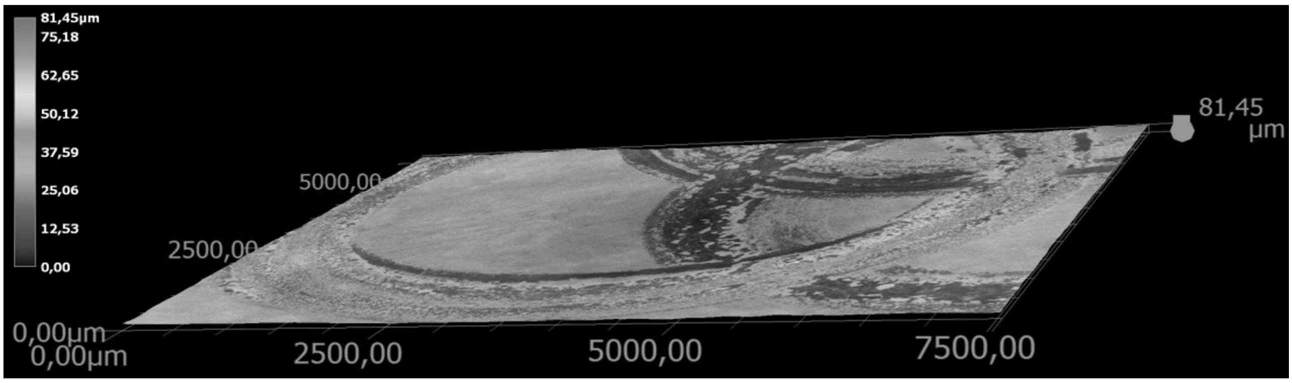


Fig. 9 *Surface roughness analysis of a cutting insert of S20S grade*

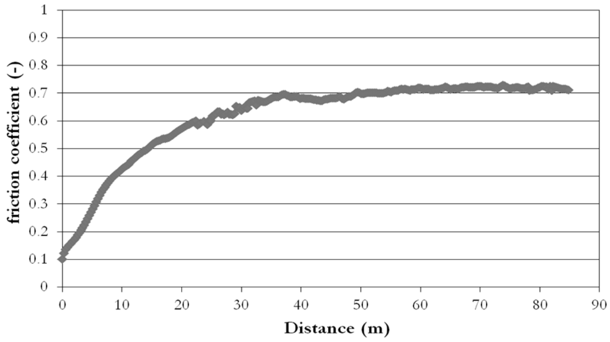


Fig. 10 *Coefficient of friction after the twentieth test cycle for a cutting insert of S20S grade*

The analysis of the friction coefficient, as illustrated in Figure 10, revealed a stabilized course of the friction coefficient, which was corroborated by the kinetics of the wear intensity of the cutting insert. The average value of the friction coefficient was $\mu = 0.707$.

The kinetics of the wear intensity of the U10S grade cutting insert, as illustrated in Figure 11, revealed a period of initial lapping of the cutting insert surface after a distance of 169.5 m, followed by a period of normal operation accompanied by low wear intensity. The total weight loss of the cutting insert after a distance of 1 695.6 m and a time of 6 000 seconds was 0.023%. The wear phenomenon observed in

Figure 12 was abrasive wear. The surface topography of the cutting insert, as shown in Figure 13, revealed a roughness of Ra = 12.54 μm and Rz = 125.11 μm.

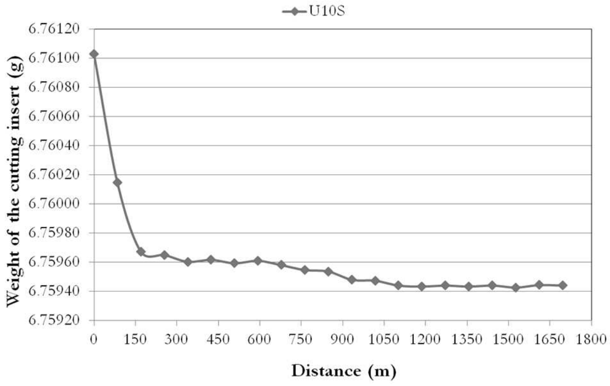


***Fig. 11** Weight loss of cutting insert of U10S grade during tribological tests*

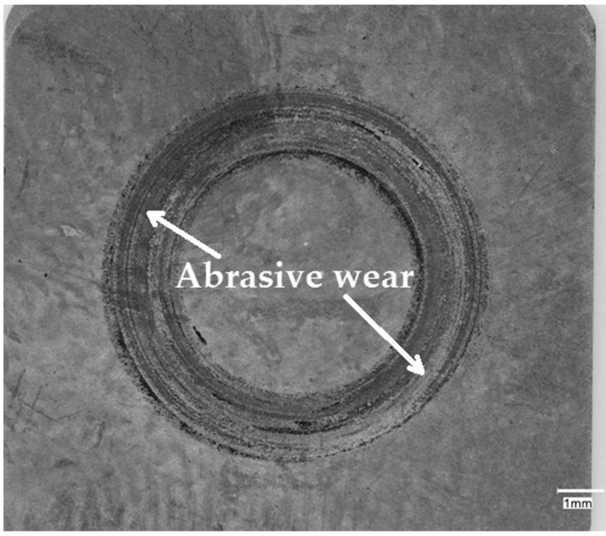


***Fig. 12** Analysis of tribological wear phenomena*

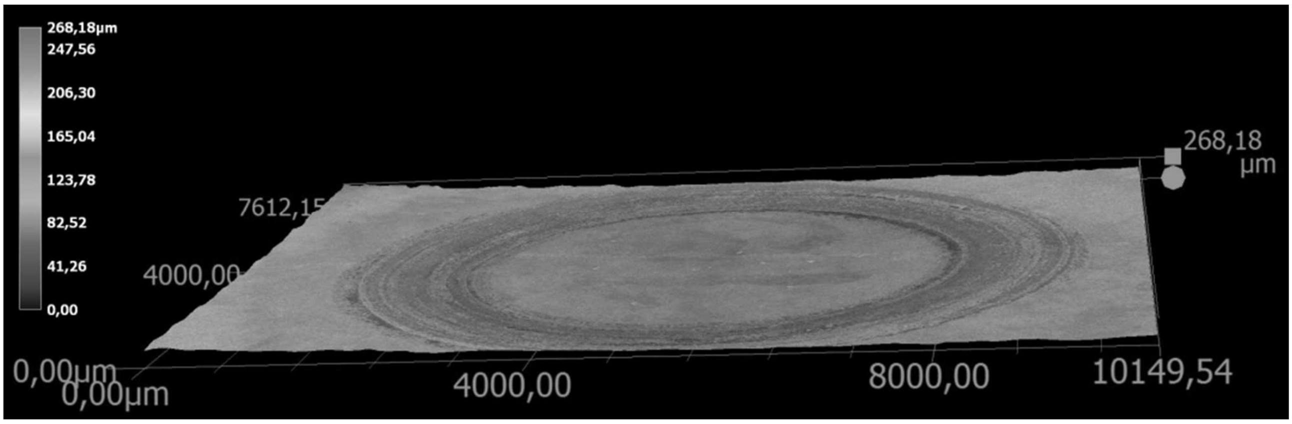


***Fig. 13** Surface roughness analysis of a cutting insert of U10Sgrade*

The analysis of the coefficient of friction for the U10S grade cutting insert (Fig. 14) revealed that after a distance of 21.195 m, the friction force stabilizes, which is indicative of the low intensity of wear observed on the cutting insert. The mean coefficient of friction after a distance of more than 1 695.6 m and a time of 6 000 s was μ=0.569.

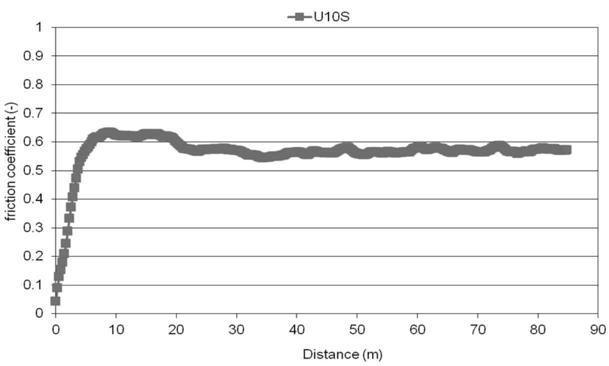


***Fig. 14** Coefficient of friction after the twentieth test cycle for a cutting insert of U10S grade*

Figure 15 illustrates the wear intensity kinetics of the CC6090 grade cutting insert. It can be observed that the cutting insert surface exhibited stabilized wear. The total weight loss of the cutting insert after a distance of 1 695.6 m and a time of 6 000 seconds was 0.76%. The wear phenomenon observed in Figure 16 was abrasive wear and plastic deformation. The surface topography of the cutting insert, as illustrated in Figure 17, exhibited a roughness of Ra = 45.21 μm and Rz = 227.37 μm.

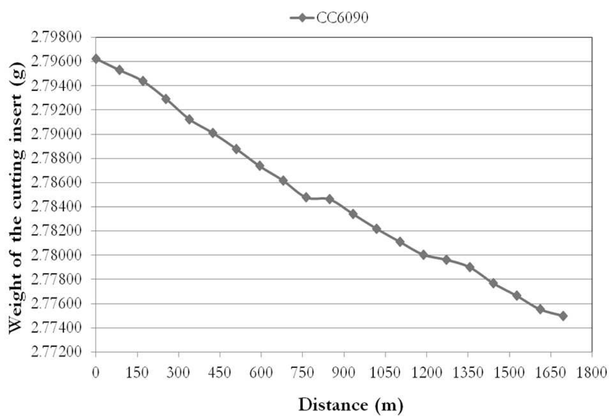


***Fig. 15** Weight loss of cutting insert of CC6090 grade during tribological tests*

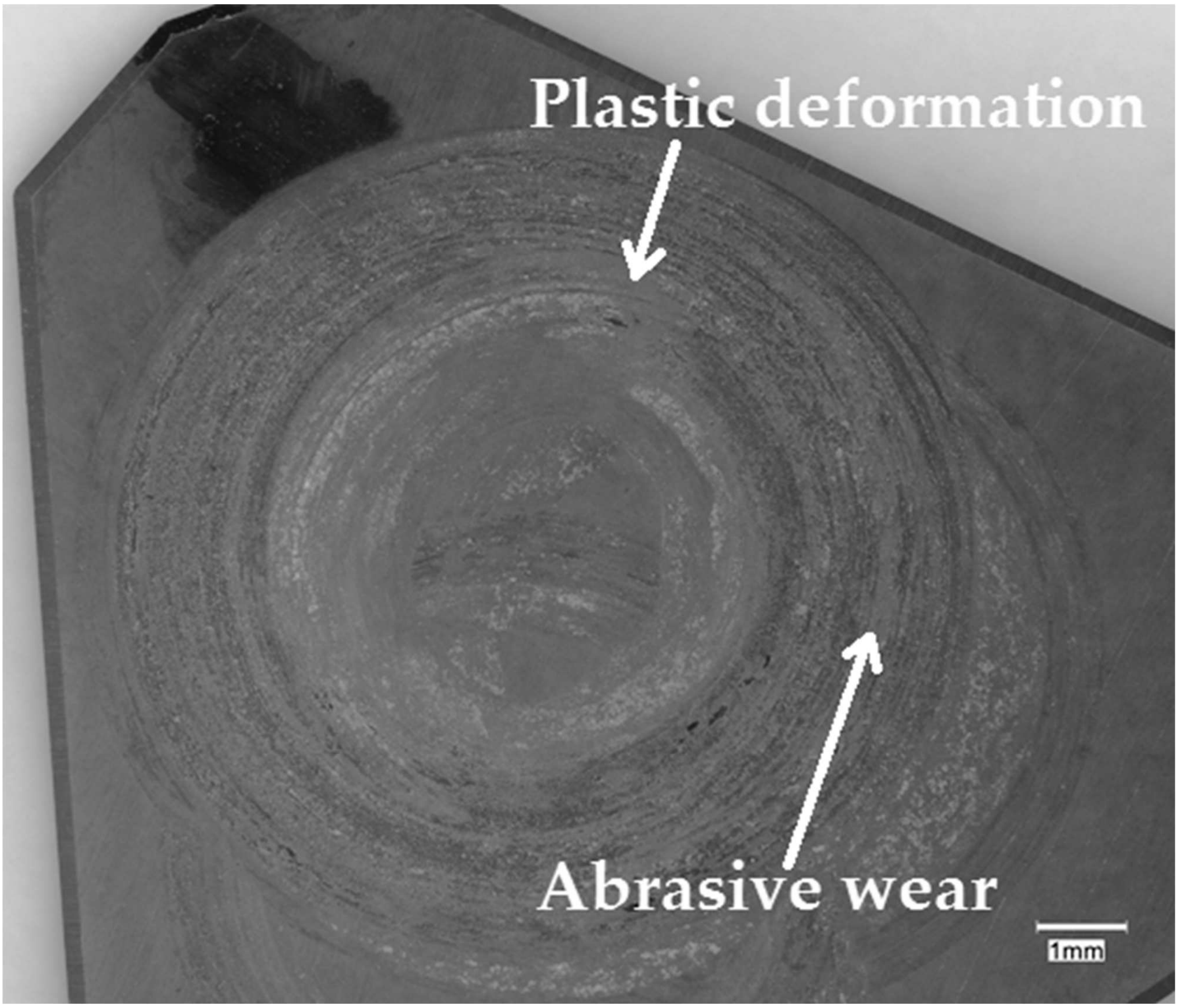


Fig. 16 *Analysis of tribological wear phenomena*

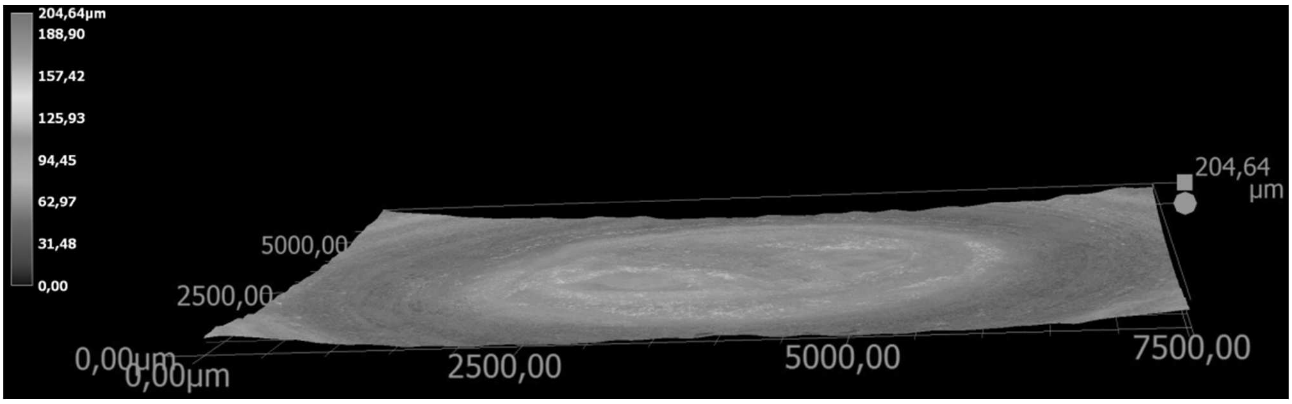


Fig. 17 *Surface roughness analysis of a cutting insert of CC6090 grade*

A charmonic, unstable friction coefficient curve was observed based on the analysis of the CC6090 grade cutting insert (Fig. 18). The average coefficient of friction was $\mu = 0.738$.

A tribological wear analysis of the tested cutting inserts of S20S, U10S, and CC6090 grades revealed that all inserts exhibited excellent abrasive wear properties. The volumetric loss in weight was below 1%, indicating optimal chemical composition, high mechanical properties, and low tribological wear. It is important to note that each commercial insert is designed for specific materials. The implementation of optimal machining parameters will result in an increased service life for cutting inserts within the enterprise.

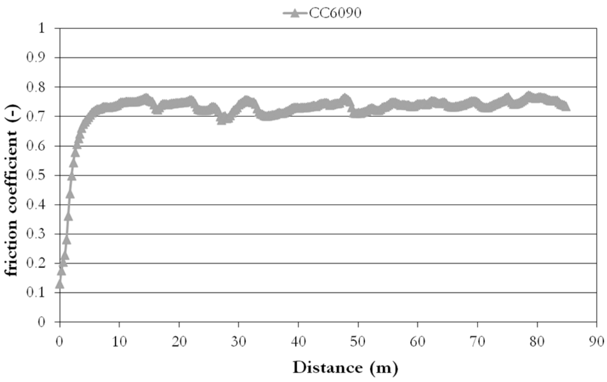


Fig. 18 *Coefficient of friction after the twentieth test cycle for a cutting insert of CC6090 grade*

4 Summary and Conclusions

Three grades of commercial cutting inserts manufactured under industrial conditions by the free sintering method were used for the study. Performed tribological wear tests deepened by analyzing the surface topography, using optical microscopy, revealed the degree of abrasive wear of the cutting inserts. The obtained results of physical and mechanical properties were confronted with the manufacturer's results. As a result, the following conclusions were formulated:

- The results of the measurements of apparent density for the S20S and U10S grades of cutting blades were found to be within the static error of 1%.
- The S20S grade insert, following the sintering process, achieved 88.3% theoretical density, the U10S grade insert achieved 93.8% theoretical density, while the CC6090 grade insert achieved 96.1% theoretical density. The observed differences in the theoretical density of the tested cutting inserts are primarily attributed to the chemical composition.
- The measurement of hardness demonstrated a correlation between the apparent density of the sinter and its hardness. The highest hardness was observed for the CC6090 grade insert, with a value of 2038 HV, followed by the U10S grade insert, with a value of 1724 HV, and the S20S grade insert, with a value of 1523 HV. The hardness measurements of the S20S and U10S grade cutting inserts are in close agreement with the values provided by the manufacturer.
- After a distance of 1 695.6 m and a time of 100 minutes, the lowest weight loss was observed for the S20S grade cutting insert, which was 0.016%. The total weight loss for the U10S grade insert was 0.023%, while the total weight loss for the CC6090 grade insert was 0.761%. The observed wear phenomena for the carbide cutting inserts were abrasive wear and scratches, while for the ceramic cutting insert were abrasive wear and plastic deformation. The cutting inserts subjected to tribological tests under laboratory conditions exhibited very good resistance to abrasive wear, with the total weight loss not exceeding 1%.
- Future research will be conducted by the authors to analyze the wear of cutting inserts of the S20S, U10S, and CC6090 grades under industrial conditions for semi-finished products dedicated to cutting inserts at different machining parameters.

References

[1] DUDIK, K., GÓRSKI, E. (2016). *Poradnik Tokarza*. Wydawnictwa Naukowo Techniczne. Poland. ISBN 978-83-01-18547-3.

[2] GÓRSKI, E. (2016). *Poradnik Frezera.* Wydawnictwo Naukowo Techniczne. Poland. ISBN 978-83-01-18593-0

[3] PASIEKA, D., DEMBICZAK, T., FIK, J., KRUZEL, R. (2023). Opracowanie procesu technologicznego obróbki skrawaniem na przykładzie półfabrykatu z żeliwa szarego. In: *Stal Metale&Nowe Technologie*, No. 5-6, pp. 66-71. ELAMED. Poland. ISSN 1895-6408

[4] MAJERÍK, J., MAJERSKÝ, J., BARÉNYI, I., CHOCHLÍKOVÁ, H., ESCHEROVÁ, J., KUBASÁKOVÁ, M. Surface Roughness, Topography, Accuracy, Chip Formation Analysis & Investigation of M390 and M398 Steels after Hard Machining. In: *Manufacturing Technology,* Vol. 23, No. 1, pp. 67-72. J. E. Purkyně University in Ústí nad Labem. Czech Republic. ISSN 2787-9402

[5] SIVAIAH, P., CHAKRADHAR, D. (2019). Modeling and optimization of sustainable manufacturing process in machining of 17-4 PH stainless steel. In: *Measurement*, Vol. 134, pp. 142-152. Elsevier. ISSN 1873-412X

[6] KUNDRÁK, J., PÁLMAI, Z., KARPUSCHEWSKI, B., FELHŐ, C., MAKKAI, T., BORYSENKO, D. Force and Temperature Conditions of Face Milling with

Varying Chip Quotient as a Function of Angle of Rotation. In: *Manufacturing Technology*, Vol. 21, No. 2, pp. 214-222. J. E. Purkyně University in Ústí nad Labem. Czech Republic. ISSN 2787-9402

[7] FIGURSKI, J. (2020) *Przygotowanie obrabiarek sterowanych numerycznie do obróbki*. Wydawnictwo Szkolne i Pedagogiczne. Poland. ISBN 978-83-02-15618-2

[8] FIGURSKI, J. (2016). *Wykonywanie obróbki na obrabiarkach sterowanych numerycznie*. Wydawnictwo Szkolne i Pedagogiczne. Poland. ISBN 978-83-02-15619-9

[9] PAPROCKI, M., WYGODA, M., WYCZESANY, P., BAZAN. P. Symptoms of wear HSS cutting tools in different wear stages. In: In: *Manufacturing Technology*, Vol. 21, No. 3, pp. 387-397. J. E. Purkyně University in Ústí nad Labem. Czech Republic. ISSN 2787-9402

[10] MAŁECKA, J., WIT, G., KOWALCZYK, D., KISZKA, P. (2011). Image Based Analisys Of Wear Stage Of Ceramic Nitride Cutting Tools After Machining Of Nodular Cast Iron. In: *Tribologia*, Vol. 236, No. 2, pp 71-84. Stowarzyszenie Inzynierów i techników mechaników polskich. Poland. ISSN: 0208-7774

[11] HOMLBERG, K., MATTHEWS, A. (1994). Coating Tribology. Properties, Techniques and Applications in Surface Engineering. Tribology. Elsevier. ISBN 978-0080-875-92-7

[12] FELDSHTEIN, E., LABER, A., DEVOJNO, O., YATSKIEVICZ, O. (2010). Badania tribologiczne powłok ceramicznych natryskiwanych plazmowo. In: *Tribologia*, Vol. 230, No. 2, pp. 23-34. Stowarzyszenie Inzynierów i techników mechaników polskich. Poland. ISSN 0208-7774

[13] NÁPRSTKOVÁ, N., ŠRAMHAUSER, K., HREN, I., NOVOTNÝ, J., SVIANTEK, J. (2023). Microscopic Wear Analysis of Indexable Inserts after Machining of 34CrNiMo6 Steel. In*: Manufacturing Technology*, Vol. 23, No. 10, pp. 676-684. J. E. Purkyně University in Ústí nad Labem. Czech Republic. ISSN 2787-9402

[14] WACHOWICZ, J., DEMBICZAK, T., STRADMOSKI, G., BAŁAGA, Z., DYNER, M., WILKOWSKI, J. (2021). Properties of WCCo Composites Produced by the SPS Method Intended for Cutting Tools for Machining of Wood-Based Materials. In: *Materials*. Vol. 14, No. 10. MDPI. eISSN 1996-1944

[15] WILKOWSKI, J., BARLAK, M., BÖTTGER, R., WERNER, Z., KONARSKI, P., PISAREK, M., WACHOWICZ, J., VON BORANYC, J., AURIGA, A. (2022). Effect of nitrogen ion implantation on the life time of WC-Co tools used in particleboard milling. In: *Wood Material Science & Engineering*, Vol. 17, No. 6, pp. 21-532. Taylor & Francis. ISSN: 1748-0280

[16] BARLAK, M., WILKOWSKI, J., SZKARŁAT, F., WERNER, Z., ZAGÓRSKI, J., STASZKIEWICZ, B., OSIPIUK, J. (2018). The influence of edge defects on the lifetime of wood machining tools. In: *Annals of WULS - SGGW. Forestry and Wood Technology*, Vol. 104, pp. 533-539. WULS. ISSN 1898-5912

[17] ISO 513:2012 Classification and application of hard cutting materials for metal removal.

[18] Katalog firmy Węgliki Spiekane Baildonit (2020). Płytki z węglików spiekanych do narzędzi lutowanych.