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Structure and cutting properties of WC-Co composites obtained by the SPS - Spark Plasma Sintering method

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Abstract: *Functional properties of WCCo composites obtained by the SPS – Spark Plasma Sintering method*. The rapid development of the furniture market results in the need to produce tools with increasingly better properties which make it possible to increase the efficiency of the production. One of the prospective paths of development for blades intended for cutting wood-based materials are carbides made using the Spark Plasma Sintering method. It makes it possible to produce sinters with submicron or even nanometric WC grain size in a very short time and without the need for using inhibitors. As a result of the specific heating conditions, this method makes it possible to obtain a material having high parameters in comparison with the material produced using conventional methods. This study aimed to determine the degree of wear of SPS tools compared to commercially available blades (of similar chemical composition). The results of research testing the basic properties (hardness, density, microstructure) of WCCo composites, obtained using the innovative SPS method, are included in the study. The quality of the produced tools and the intensity of wear of the blades made using the SPS method were evaluated. The results were compared to commercially available blades. The wear of individual blades was evaluated based on the machining of three-layer particleboard.

Keywords: Sintering; SPS (Spark Plasma Sintering); Tungsten Carbide (WCCo); Composite; Blade Durability, Wood-Based Materials

INTRODUCTION

The furniture industry is one of the dynamically developing branches of the economy. Because of the lower price and higher degree of homogeneity, solid wood is replaced by wood-based materials for the production of furniture. These materials consist of wood particles pressed in high temperature and/or other lignocellulosic material in the form of particles with a synthetic adhesive (Chapman 2006; Carvalho et al. 2012; Shalbafan et al. 2012; Lengowski et al. 2019). Three-layer particleboard is used for the production of furniture, the two outer layers are made of smaller wood particles, including microchips, which have a higher density and lower adhesive content than the inner layer made of larger particles (Nasser 2012; Ghalehno et al. 2011; Ntalos et al. 2002; Abdolzadeh et al. 2009; Taramian et al.2007).

In terms of machining, particleboard is a very demanding material. It is characterized by different density on the cross-section. The individual components of the boards differ in their machinability and density. Moreover, there are mineral impurities, which are the main material factor in the wear of cutting tools (Szwajka et al. 2016; Chladil et al. 2019; Wei et al. 2018). Additionally, it is a material with poor heat-conducting properties which cannot be machined with liquid coolant because of the hygroscopic properties of the lignocellulosic particles. The cutting edges of the blades working in the machining process are exposed to very high temperatures and thus to rapid wear.

Nowadays, the most popular are blades made of sintered carbides and synthetic diamond (PCD) (Astakhov et al. 2015; YU, Dongman, et al. 2010; Li, Guangxian et al. 2020; Philbin, Paul 2005). Among the solutions that have been recently developed, we can mention sintered carbides of submicron and nanometric grain size made using SPS - Spark Plasma Sintering methods, composites based on polycrystalline boron nitride (cBN) (Wachowicz et al. 2018; Yaman et al. 2009), ceramic composites using aluminium oxide Al_2O_3 (Klimczyk et al. 2008), diamond composite based on tungsten carbide matrix (Michalski et al. 2008) and many others.

Hard coatings applied to blades, e.g. titanium carbide (TiC) or nitride (TiN), are also used (Czarniak et al. 2020). Laser modifications of the top layer of the tool, ion implementation or plasma are becoming increasingly more popular (Wilkowski et al. 2019). These solutions are intended to increase tool durability and/or maximum cutting speed.

Tribological phenomena in the machining process of wood-based materials are difficult to research. Its conditions are constantly changing and the effects of machining are studied more than the actual process. The phenomena occurring during the machining process of wood-based materials are significantly different from the processes occurring when machining metals. During the machining of wood-based materials no adhesion wear, diffusion and direct oxidation occur. This is respectively the result of too low a temperature at the cutting edge, the above-mentioned differences in the physical and chemical properties of the workpiece and the blade material, as well as too low a pressure, causing no increase in the friction coefficient as the blade wears out. However, we can note other phenomena related to the moisture content of the workpiece and the aggressive chemicals present in it. These are high-temperature tribological phenomena, low-temperature tribological phenomena (low material humidity), electrostatic discharge (very low material humidity) (Wilkowski et al. 2019).

During the machining process, the tools wear and it changes their dimensions, the shape of the cutting edge, weight of the tool, chemical and physical properties of the surface layer of the blade. This causes a decrease in the cutting properties of the blade and a change in physical and chemical processes. Loss of machining properties can be caused by several phenomena, such as wear, chipping, denting, breaking or cracking. They can also occur simultaneously. Individual effects that create the wear process of a tool are the mechanical, thermal, chemical and physical interaction between it and the material to be machined in an environment defined by the machine tool.

The wear of the tool depending on the machining distance is described by the Lorenz curve. There are three phases of the blade wear visible: intensive initial, stabilized and accelerated. In the process of machining wood-based boards using cemented carbides, the accelerated wear phase is difficult to notice. This results from the high resistance of this type of tools to deteriorating machining conditions with the wear of the blade (Chladil et al. 2019). When machining wood-based boards with WCCo blades, the tool undergoes the so-called "soft wear". Initially, a part of the binding phase is removed through plastic deformation and microabrasion, which means the removal of products of high-temperature binder corrosion and a certain amount of metallic cobalt by impacting the tool with mineral impurities of the smallest size. Wood-based materials have a heterogeneous structure and consist of wood particles or fibres, adhesive resin and mineral contamination in the case of particleboards. During machining, the cutting forces change depending on which part is being cut. These changing forces cause the carbide grains around which the binding is wiped out to move in their place of attachment in cobalt and eventually chip off (Sheikh-Ahmad et al. 1999). The point where the grains chip off, followed by the damage of the cutting edge, is ground as a result of friction between the tool and the material being cut (Wachowicz et al. 2019). Large particles of mineral contamination can cause catastrophic wear of the tool in the form of crushing or chipping, as a result of the immediate strength of the blade being exceeded (Porankiwicz et al. 2015; Sheikh-Ahmad el al. 1999).

Spark Plasma Sintering (SPS) is a pressurized sintering method that uses DC pulses to efficiently produce high-temperature discharges between sintered material particles. It's a quick sintering method. Thanks to the self-heating mechanism of the sintering powder and the release of heat exactly where it is needed for sintering, the whole process can be significantly reduced. During the flow of electric current, the temperature of the material increases to a high level and after the current vanishes it rapidly decreases to the sintering temperature. Thanks to this way of delivering energy the process is very effective thermally. The powder is heated through the

Joule heat and the spark discharges ignited in the pores between the individual powder particles. The advantages over conventional sintering methods, such as HP (Hot Press) or HIP (Hot Isostatic Press), are the ease of use, accuracy of sintering energy control, speed of sintering, speed of heating and cooling of the sintered material, reduction of energy consumption, which is combined with low costs, high repeatability, safety and reliability. This method makes it possible to sinter a wide range of materials including difficult to sinter, nanocrystalline, gradient, fibre-reinforced ceramic, advanced composite materials and biomaterials, which are very difficult to achieve with conventional methods (Cha et al. 2003; Jiang et al. 2007; Srivastava et al. 2018; Michalski et al. 2007; Chmielewski et al. 2015).

MATERIALS AND METHODS

The material of the blade was made using the pulse-plasma sintering method with a prototype SPS device. The sintering process had two stages: degassing and proper sintering. The first stage lasted 5 minutes and was carried out at a pressure of 30 MPa, at 600°C. The second one lasted 10 minutes at a pressure of 50 MPa and, depending on the sample, was performed at temperatures of 1100°C and 1170°C. WCCo sinters were made as part of the study.

Next, the blades with four cutting edges, 12x12x1.5 mm in size and a blade angle of 55° were formed from the material obtained. Two groups of WCCo tools manufactured using the SPS method and commercial tools of similar composition and properties were used in the tests. In commercial tools, the binding phase consists of cobalt (as the main binder) and additives in the form of nickel and chromium. Nickel is designed to protect the material from corrosion, and chromium prevents the powder grains from growing during sintering. The basic properties of the blades used for testing are listed in Tables 1 and 2.

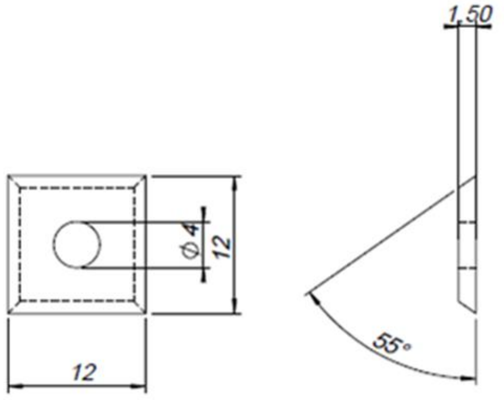

Figure 1. Geometry of the test tool used.

Table 1. Characteristics of WCCo tools produced by SPS method

Name	SPS 1100°C	SPS 1170°C
Powder grain size as specified by the manufacturer [µm]	<1	<1
Cobalt content [%]	6	6
Density [g/cm^3]	14.70	14.74
Relative density [%]	98.99	99.26
Hardness [HV]	1958	1942

Table 2. Characteristics of commercial tools

Name	Commercial 1	Commercial 1
Powder grain size as specified by the manufacturer [µm]	0.5 – 0.8	1.0 – 1.4
Cobalt content [%]	4.2	4.5
Density [g/cm^3]	15.20	Trade data
Relative density [%]	100	Trade data
Hardness [HV]	1920	1800

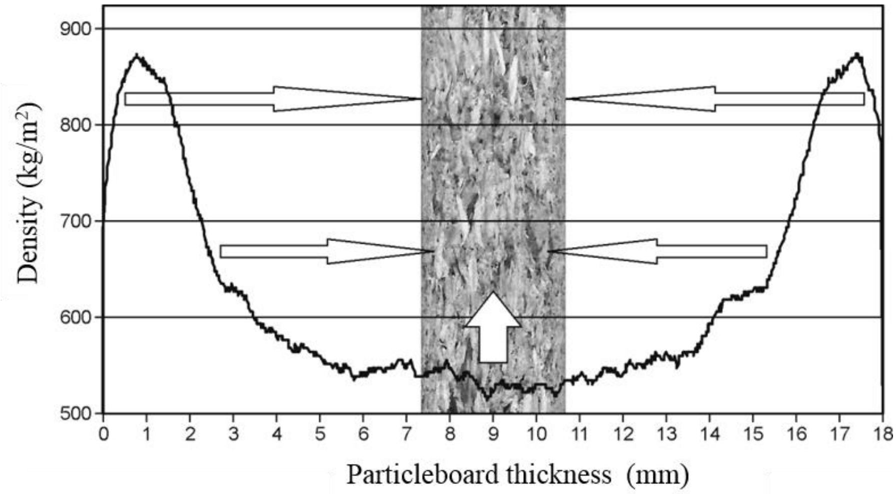

Figure 2. Density profile of the particleboard used for machining (Wilkowski et al. 2019).

Raw, 18 mm thick, three-layer particleboard was used for the tests. The density profile is presented in Figure 2. The blade durability tests were carried out on the Busellato Jet 130 machining centre, the blades were placed in a double-edged shank cutter (Figure 3). Machining was made to a depth of 6mm at a spindle speed of 15000 rpm, the feed per tooth was 0.15 mm and the feed rate was 4.5m/min. The machined particleboard was raw and had three layers, the measurement of the frictional wear of the application surface was made every 1m of the feed path with a workshop microscope until the critical value VB_{max} = 0.2 mm was reached. On each sample, the depth of abrasion of the application surface was tested for two blades.

Figure 3. Geometry of the test tool used.

The hardness of the materials tested was measured using the Vickers hardness test. To determine the hardness of the materials tested, the HV5 method was chosen, which means that the force was 49.03 N. Eight imprints were made on each specimen along its diameter. The microstructure of the materials tested and the abrasion of the blade application surface were pictured using a scanning electron microscope (SEM) type FEI Quanta 200.To determine the wear of the application surface, a PZO workshop microscope of the MWD model was used, equipped with a digital reading of the table shift. The phase composition of the obtained sinters was determined by means of Philips PW 1140 diffractometer with PW 1050 goniometer using Co Kα radiation.

RESULTS AND DISCUSSION

Samples made by the SPS method - SPS 1100°C - 1958 HV and SPS 1170°C - 1942 HV had hardness similar to the tools available on the market, respectively 1920 HV for Commercial 1 and 1800 HV for Commercial 2 (Figure 4). However, the samples obtained at 1100°C are characterized by a small spread of results in hardness over the entire cross-section of the sample, which indicates high uniformity of this material. In the case of samples sintered at 1170°C, significant differences between the hardness results were noticed. The hardness measurement results are shown in Table 3.

Table 3. Hardness measurement of the of the sinters

	Measurement No.	Hardness [HV5]	Diagonal mean [mm]	Diagonal 1 [mm]	Diagonal 2 [mm]
HF6 1100°C	1	1971	0.0686	0.0686	0.0686
	2	1940	0.0691	0.0695	0.0687
	3	1977	0.0685	0.0680	0.0690
	4	1937	0.0692	0.0693	0.0691
	5	1938	0.0692	0.0696	0.0688
	6	1962	0.0687	0.0685	0.0690
	7	1974	0.0685	0.0688	0.0683
	8	1962	0.0687	0.0687	0.0687
	mean	1958			
HF6 1170°C	1	1877	0.0703	0.0698	0.0708
	2	2007	0.0680	0.0677	0.0682
	3	1938	0.0692	0.0693	0.0690
	4	1970	0.0686	0.0685	0.0687
	5	1962	0.0687	0.0680	0.0695
	6	1877	0.0703	0.0700	0.0705
	7	1970	0.0686	0.0685	0.0687
	8	1933	0.0693	0.0695	0.0690
	mean	1942			

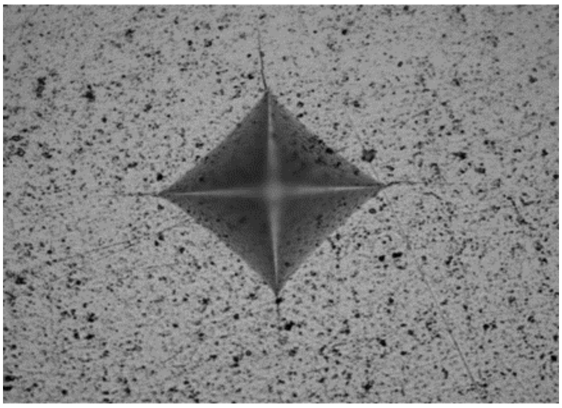

Figure 4. Picture of the imprint produced during the hardness test

Fig. 5 is an X-ray diffraction pattern analysis image of cemented carbides with different Co contents. According to XRD pattern, the cemented carbides were composed of WC and Co. There were no carbon-deficient (W_2C) phase and η phase (W_3Co_3C or W_6Co_6C) in the cemented carbide with the addition of binder phase compared to the traditional sintering method. These two substances have poor wettability with WC and often cause the performance of the cemented carbides to deteriorate. This shows that the SPS technology can make the cemented carbide has better chemical compatibility among the various components (Liu et al. 2018).

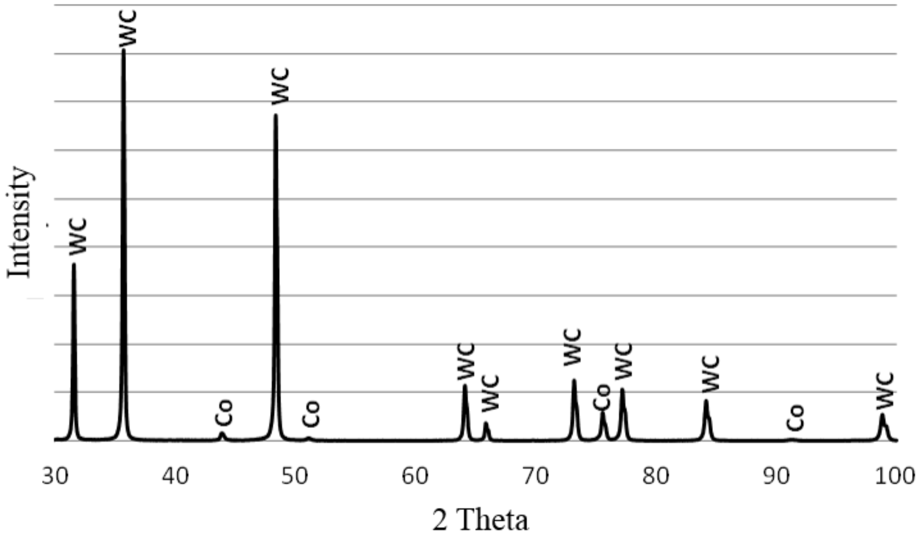

Figure 5. Diffraction analysis WCCo composite by SPS method.

The SPS 1100°C sample is the only one where slightly rounded grain edges were noticed, which indicates insufficient sintering of the material. Several pores are visible on the pictures of fractures. The grain size in sinter was estimated as 0.6 μm. In the SEM images, the paths of the binding phase - cobalt along the WC grain boundaries can be noticed. The pictures of the SPS 1170°C samples show well-sintered grains with sharp edges. Some of them are visibly larger than others. Single cavities (pores) at the fracture of the sample are noticeable.

Cobalt is clearly visible. In commercial blades, WC grains are well sintered, their sharp edges are clearly visible. In the sample Commercial 1, the grain size was estimated as 0.6 µm, and the Commercial 2 grain size was estimated as 1.0 µm, both of which contain single larger grains. The binding phase is visible at the WC grain boundaries. Figure 7 shows SEM images of samples made with the SPS method, and Figure 8 shows commercial samples.

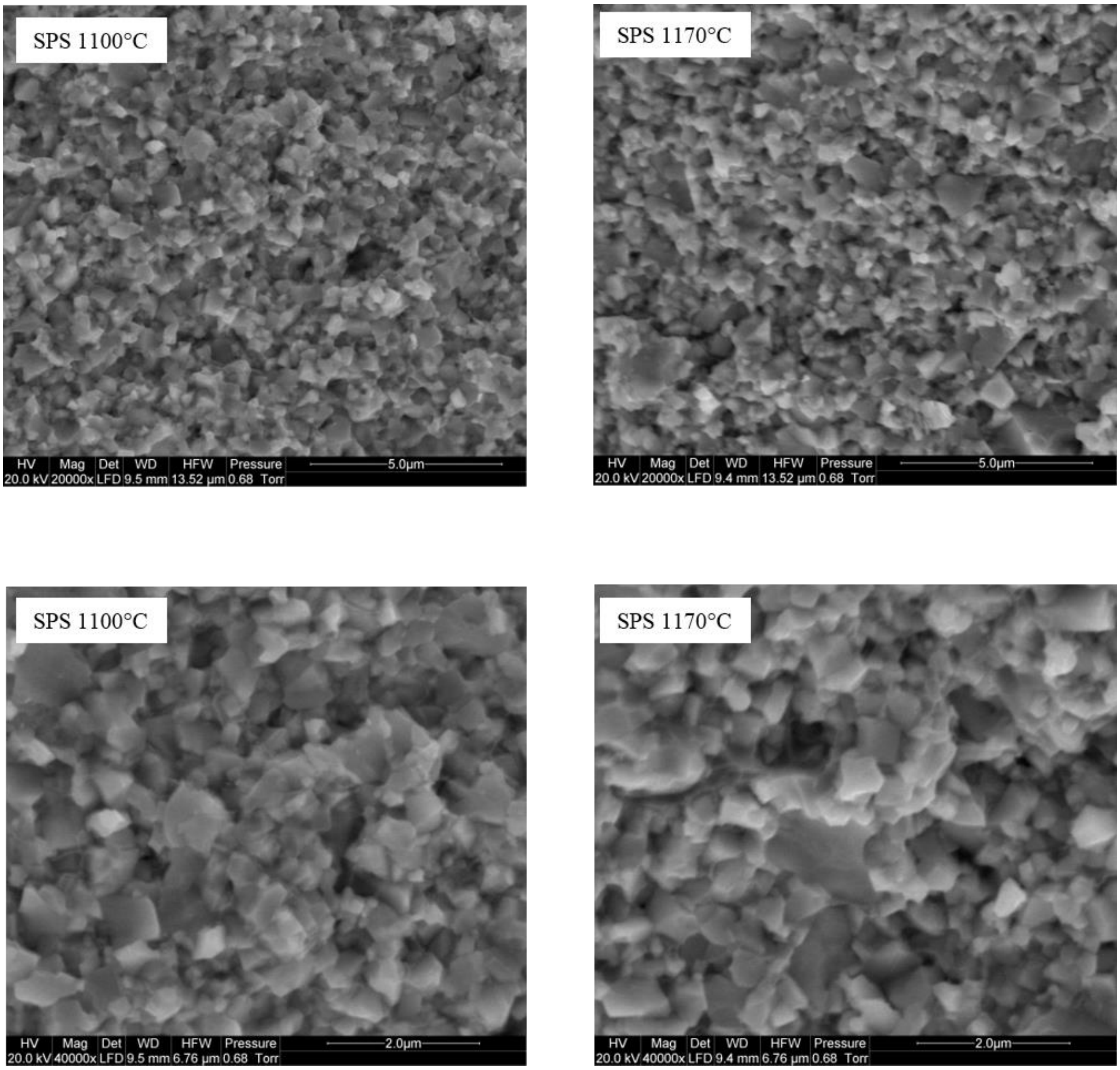

Figure 7. Comparison of microstructure of SPS 1100 °C and SPS 1170 °C samples.

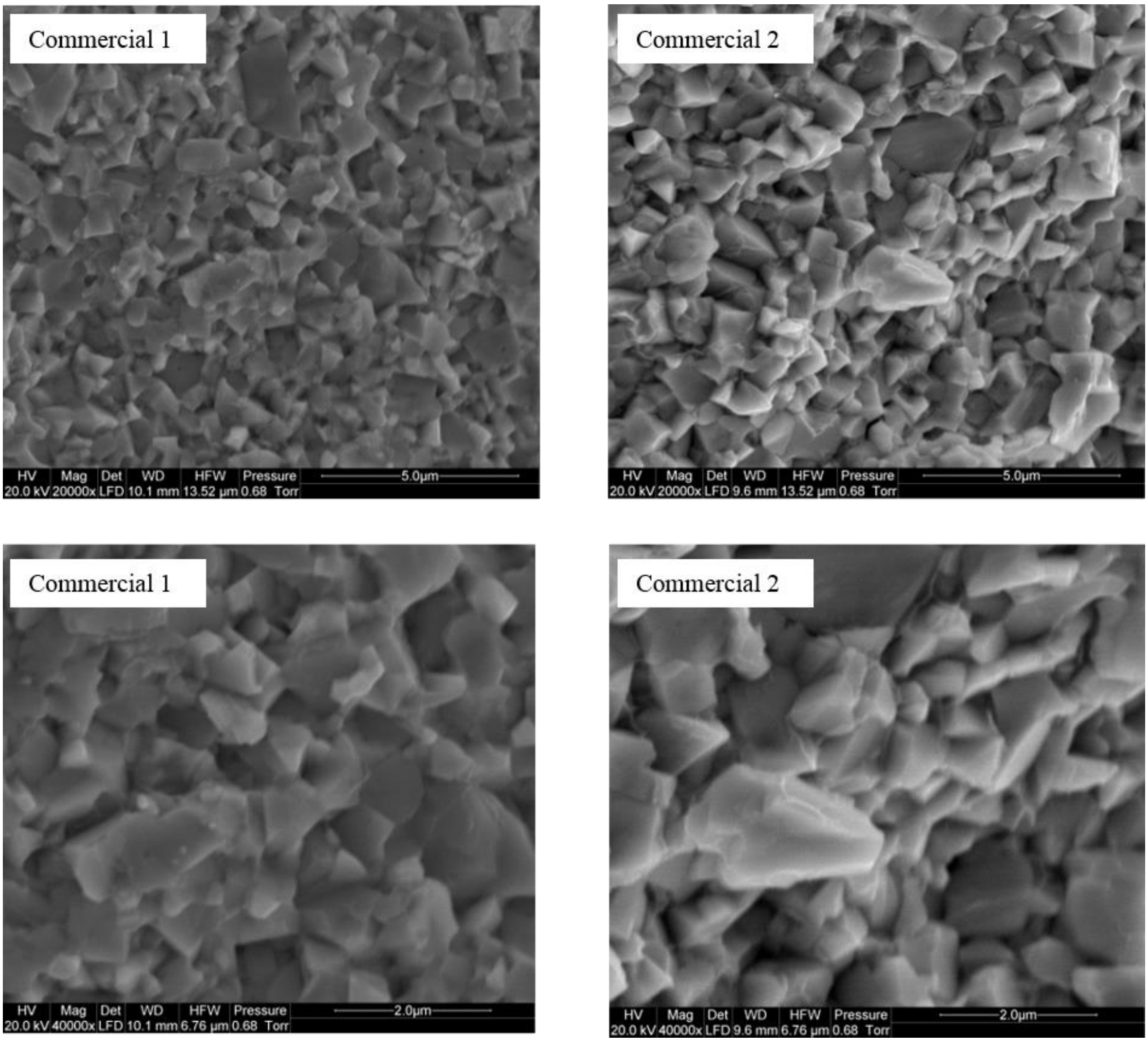

Figure 8. Comparison of the microstructure of Commercial 1 and Commercial 2 samples

Figure 9 shows the machining paths of each group of blades. The differences between the results were significant, the most durable was the commercial tool marked as Commercial 1, which covered a distance of 5024 m, equivalent to 16 m of feed path to achieve the edge wear of the application surface. The SPS 1100°C tool had the least durability, with a distance of 2512 m / 8 m feed path. Commercial 2 tool had a slightly higher value, with 2826 m distance / 9m feed path. The SPS 1170°C covered the distance of 3454 m / the feed path of 11 m.

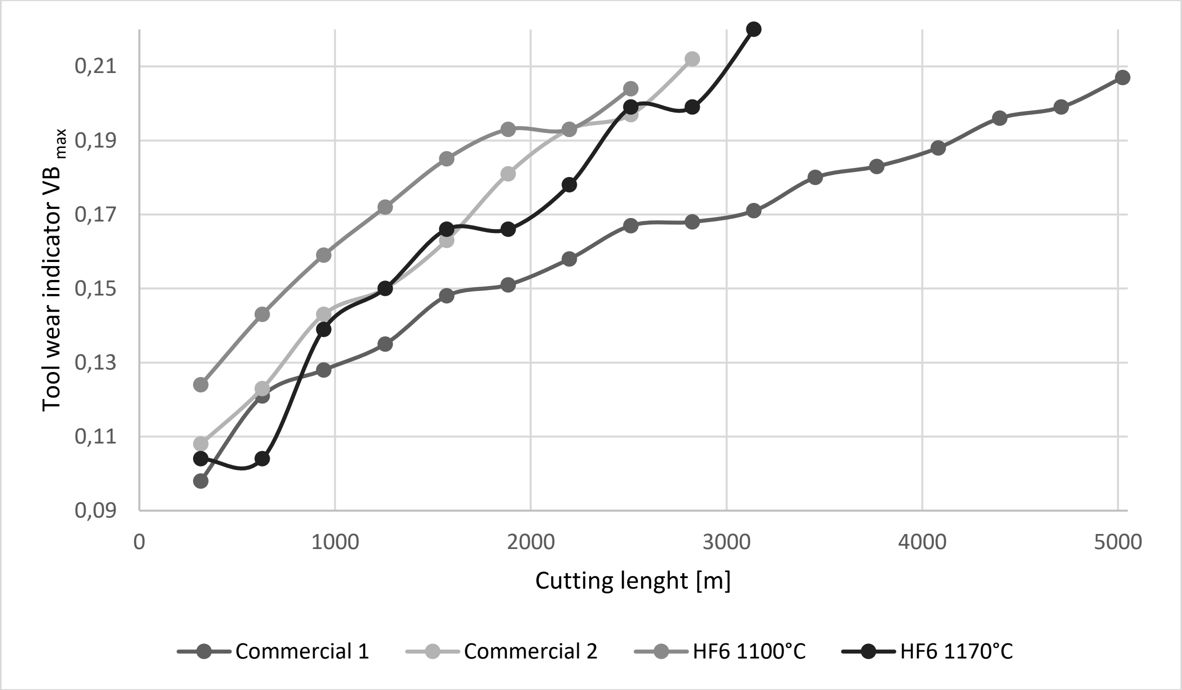

Figure 9. Graph of the relation between the wear indicator [mm] and the cutting lenght [m]

The longest average machining distance was achieved by Commercial tools 1. They had high hardness (1920 HV), which was due to the small WC grain size (~0.7 µm) and the lowest content of binding phase (4.2 %). All these factors had a positive impact on the durability of the blade. The higher the hardness, the higher the tool durability. The small size of the carbide grains makes the wear depth of the application surface increase slightly when they chip off. The small amount of cobalt slows down the process of wearing the binding phase from between the WC grains, which makes it possible for them to chip off easily. The grains with sharp edges visible in the SEM images indicate good sintering of the powder. Evenly distributed cobalt is visible at their edges, this is caused by sintering at high temperature with the liquid phase of cobalt. No empty spaces were noticed in the material that could reduce its properties.

The least durable samples turned out to be Commercial 2, from the beginning it was indicated by hardness much lower (1800 HV) than other samples. Despite the relatively low content of cobalt (4.5 %), the large size of the grains (~1 µm) caused the formation of large spaces between them filled with a binding phase exposed to easy abrasion during machining. As a result of the size of the WC grains, when they chipped off during the tool's operation, the increase in the depth of abrasion of the application surface progressed rapidly. The shape of the grains indicates good sintering of the material.

Tools made with the SPS method were characterized by the highest hardness (1958 HV and 1942 HV) and the smallest size of powder grains (~0.6 µm). These are some of the factors improving durability. The features reducing their durability are a high proportion of the binding phase (6 %) and the occurrence of pores. Despite the hardness of the SPS 1100°C sample was higher than the SPS 1700°C, it had a shorter machining distance, most likely resulting from insufficient burning of the material, as evidenced by the shape of the powder grains visible in the sample fracture images, their edges are rounded and this could have caused the carbide grains to chip off more easily. In the SPS 1170°C samples, cases of catastrophic tool wear in the form of chipping were noticed, the hardness measurement of this sample was characterized by a large amplitude of values, which indicates material heterogeneity. It may have been caused by several factors, such as the formation of local cobalt clusters or porosity resulting in the creation of an area of low hardness. The transition of cobalt to the liquid phase caused by the high temperature during the sintering process and the leakage of the binding phase from the sinter resulting in a material with high hardness but also fragility. The distinctly higher roughness proves that carbide grains chip off as early as during the sinter processing stage to shape the blade. It is also possible that the blade was exposed to large amounts of mineral contamination during operation, which resulted in exceeding its immediate strength and chipping.

CONCLUSION

It is possible to obtain a sinter using the SPS method for the production of tools used for machining wood-based boards.

An increase in the WC grain size results in a reduction of the durability of WCCo tools. The SPS method makes it possible to produce a material of high hardness, without any visible growth of WC grains created during sintering without the addition of inhibitors such as chromium.

Despite the relatively high content of cobalt (6 % by weight) in blades sintered using the SPS method, they were characterized by high durability. It is therefore advisable to continue research on the WCCo sintering technology using the SPS method to optimise sintering conditions and obtain tools with the best possible characteristics.

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Streszczenie: *Struktura i własności skrawne kompozytów narzędziowych WC-Co, otrzymywanych metodą SPS – Spark Plasma Sintering*. Szybki rozwój przemysłu meblarskiego powoduje konieczność wytwarzania narzędzi o coraz lepszych właściwościach, które pozwalają na zwiększenie efektywności produkcji. Jedną z perspektywicznych ścieżek rozwoju ostrzy, przeznaczonych do obróbki materiałów drewnopochodnych są węgliki WCCo, wytwarzane metodą Spark Plasma Sintering. Metoda ta umożliwia wytwarzanie spieków o submikronowej i nanometrycznej wielkości ziarna WC w bardzo krótkim czasie oraz bez konieczności stosowania inhibitorów.

Celem pracy było określenie stopnia zużycia narzędzi otrzymywanych techniką SPS w porównaniu z dostępnymi na rynku ostrzami (o podobnym składzie chemicznym). W pracy przedstawiono wyniki badań podstawowe właściwości (twardość, gęstość, mikrostrukturę) kompozytów WCCo, uzyskanych metodą SPS. Oceniono intensywność zużycia ostrzy wykonanych metodą SPS. Wyniki porównano z dostępnymi na rynku ostrzami.

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