Annals of Warsaw University of Life Sciences - SGGW
Forestry and Wood Technology № 108, 2019: 45-52
(Ann. WULS - SGGW, For. and Wood Technol. 108, 2019)

Influence of the ion implantation of nitrogen and selected metals on the lifetime of WC-Co indexable knives during MDF machining

MAREK BARLAK[1], JACEK WILKOWSKI[2], KAROL SZYMANOWSKI[2], PAWEŁ CZARNIAK[2], PIOTR PODZIEWSKI[2], ZBIGNIEW WERNER[1], JERZY ZAGÓRSKI[1], BOGDAN STASZKIEWICZ[1]
[1] Plasma/Ion Beam Technology Division (FM2), National Centre for Nuclear Research Świerk - NCBJ
[2] Department of Mechanical Processing of Wood, Warsaw University of Life Sciences - SGGW

Abstract: *Influence of the ion implantation of nitrogen and selected metals on the lifetime of WC-Co indexable knives during MDF machining.* The paper presents the results of durability tests for WC-Co indexable knives during the machining of MDF. The knives were implanted with nitrogen, zirconium, molybdenum and tin, using MEVVA type implanter with non-mass separated beam. Additionally, the Monte Carlo simulation results of the main parameters of the depth profiles of the implanted elements are presented in this paper. A higher correlation of tool life with the project range and range straggling than with the parameter of the peak volume dopant concentration was demonstrated.

Keywords: WC-Co composites, ion implantation, modelling, MDF, milling

INTRODUCTION

Cemented tungsten carbides - a combination of hard and brittle carbides and a relatively soft and ductile metallic binder - provide an exceptional combination of favourable properties such as strength, hardness, fracture toughness, refractoriness, stiffness, resistance to compressive deformation and wear resistance at room temperature as well as at higher temperatures up to 400°C (Milman et al. 1997, Sheikh-Ahmad and Bailey 1999, Pirso et al. 2004, Bonny et al. 2004, Choi et al. 2010, Olovsjö et al. 2013). Unfortunately, the durability of tools made of this material is still insufficient. There are few methods to improve this property, ion implantation being one of them (Barlak et al. 2016, Barlak et al. 2017).

The present paper presents the influence of ion implantation of nitrogen and three metals, i.e. zirconium, molybdenum and tin, on the durability of WC-Co indexable knives, used for wood-based materials (in this case, for Medium Density Fiberboard - MDF) machining.

Nitrogen is a typical element used to improve the durability/tribological properties (Kamiński and Budzyński 2017). The ion implantation of this gas to WC-Co substrate leads to the formation of nitrides- and a carbon-rich layer. The presence of nitride precipitates and the "lubricating" effect of carbon improves tribological properties of the modified material (Sun et al. 1997).

Zirconium-based materials are used e.g. for sports technology (Khun et al. 2016), molybdenum oxides - in the system with aluminium bronze (Takeichi et al. 2009), and tin-based materials - in automotive industry or ocean tribology (Feyzullahoğlu et al. 2008, Wu et al. 2016).

MATERIAL AND METHODS

The ion implantation processes were preceded by Monte Carlo simulations of the main parameters of the depth profiles of the implanted elements (like peak volume dopant concentration N_{max}, projected range R_p and range straggling ΔR_p), using freeware type code SRIM-2013.00 (The Stopping and Range of Ions in Matter) (SRIM 2019). The simulation was performed for 100 000 implanted ions. The modelled substrate material W-C-Co (modelling codes treat the sample as a set of atoms that do not form chemical compounds) of a composition: 90.86% of tungsten, 5.94% of carbon and 3.2% of cobalt in weight percentages i.e. 47.4% of tungsten, 47.4% of carbon and 5.2% of cobalt in atomic percentages. The substrate material density, adopted for the simulation was 15.2 g/cm^3. This value was declared by the knives supplier.

In all cases, the simulations were performed for room temperature and for the total implanted fluence of 2e17 cm^{-2} and the acceleration voltage of 60 kV, including percentage charge state distribution data from Table 1.

During the ion implantation processes using implanters with non-mass separated beam (with direct beam), the nitrogen beam includes two kinds of ions, i.e. N^++N_2^+, in the ratio ~1:1, so there are two elementary charges per three atoms. In the case of the molecule N_2 implanted with the acceleration voltage of 60 kV, each atom carries the energy of 30 keV, according to the law of energy conservation. Likewise, the average charge state is at the level of 0.67.

The beam of metallic ions usually includes ions with a different degree of the ionization. Additionally, the percentage shares of individual ion types are also different. In this case, the average charge state can be determined by the addition of the values of multiplication of the percentage shares and the ionization degree. For example, for molybdenum it will be:

$$0.07 \cdot 1 + 0.3 \cdot 2 + 0.4 \cdot 3 + 0.2 \cdot 4 + 0.03 \cdot 5 = 2.82 \approx 2.8 \tag{1}$$

Two ion charge states were used for the modelling, and then for the ion implantation of N and Sn, four for Zr and five for the Mo beam.

The atomic radii of the implanted elements, determined from minimal-basis-set SCF functions are, in angstroms: 0.56 Å for N, 2.06 Å for Zr, 1.9 Å for Mo and 1.45 Å for Sn (Clementi et al. 1967).

The modelling did not account for the phenomenon of substrate sputtering by the implanted ions.

Table 1. The percentage charge state distribution and average charge state of the ions implanted to WC-Co knives (Krivonosienko et al. 2001)

Implanted ions	Ion energy for acceleration voltage of 60 kV (keV)						Average charge state
	30	60	120	180	240	300	
	Percentage charge state distribution (%)						
	1+		2+	3+	4+	5+	
$N_2^+ + N^+$	67	33	-	-	-	-	0.67
$Zr^+ + Zr^{2+} + Zr^{3+} + Zr^{4+}$	-	1	47	45	7	-	2.6
$Mo^+ + Mo^{2+} + Mo^{3+} + Mo^{4+} + Mo^{5+}$	-	7	30	40	20	3	2.8
$Sn^+ + Sn^{2+}$	-	47	53	-	-	-	1.5

The commercially available, WC-Co indexable knives, produced by Ceratizit company (KCR08), with dimensions 29.5×12×1.5 mm^3 and presented in Fig. 1, were used in the investigations.

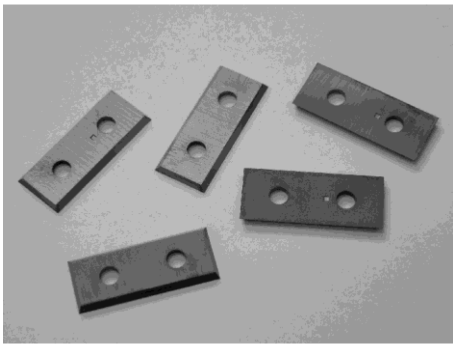

Figure 1. WC-Co indexable knives

Before processing, the knives were washed in high purity acetone under ultrasonic agitation. Next, the flank surfaces of the knives were implanted with nitrogen, zirconium, molybdenum and tin, using MEVVA (Metal Vapor Vacuum Arc) type implanter with non-mass separated beam, described in detail elsewhere (Bugaev et al. 1994). Nitrogen of 99.999% purity was used as the source of the implanted gaseous ions and as a working gas in the case of the implantation of metallic ions.

The implanted fluence was at a level of 2e17 cm^{-2} and the acceleration voltage was 60 kV for all cases. The ion current densities were about 50 $\mu A/cm^2$ and therefore, the estimated value of temperature of the implanted samples was about 300°C. The base pressure in the vacuum chamber was at a level from 2 to 5e-4 Pa.

Virgin (non-modified, non-implanted) and implanted knives were tested for the lifetime. Four blades were tested in each modification group. Medium Density Fiberboard (MDF), produced by Pfleiderer company, with the thickness of 16 mm and the density of 743 kg/m^3 was used for the experiments. The above-mentioned panels are a standard construction material, commonly used in furniture industry. Chosen properties of the cutting material are presented in Table 2.

Table 2. Selected mechanical and physical properties of the tested MDF

Material	Density (kg/m^3)	Tensile strength (MPa)	Swelling after 24h (%)	Flexural strength MOR (MPa)	Modulus of elasticity MOE (MPa)
MDF 16 mm thickness	743	0.76	13.5	34.4	3367

Workpieces with dimensions of 2800×400×16 mm^3 were milled on a CNC machining center Busellato Jet 130, equipped with a Faba FTS.07L4043.01 single-cutting milling head with a diameter of 40 mm. Grooves were made in the particleboard (with a width equal to the tool diameter, i.e. 40 mm) at a depth of 6 mm. During machining, constant cutting parameters were maintained (feed speed of 2.7 m/s, spindle speed of 18000 rpm and feed per tooth of 0.15 mm). The tool wear measurement was carried out after each pass (feed distance of 2.8 m), using a workshop microscope. The maximum wear width on the flank face of the VB_{max} blade was estimated. Machining stopped when the VB_{max} was equal to or greater than 0.2 mm. The cutting length was an indicator of the tool's durability to achieve the tool's wear criterion.

RESULTS AND DISCUSSION

Fig. 2 and Table 3 present the results of the computer simulations of the main parameters and the depth profiles of ions implanted without mass separation to W-C-Co material. Additionally, a graphical definition of the main parameters of the depth profiles of the implanted elements is presented in the upper right-hand corner of Fig. 2.

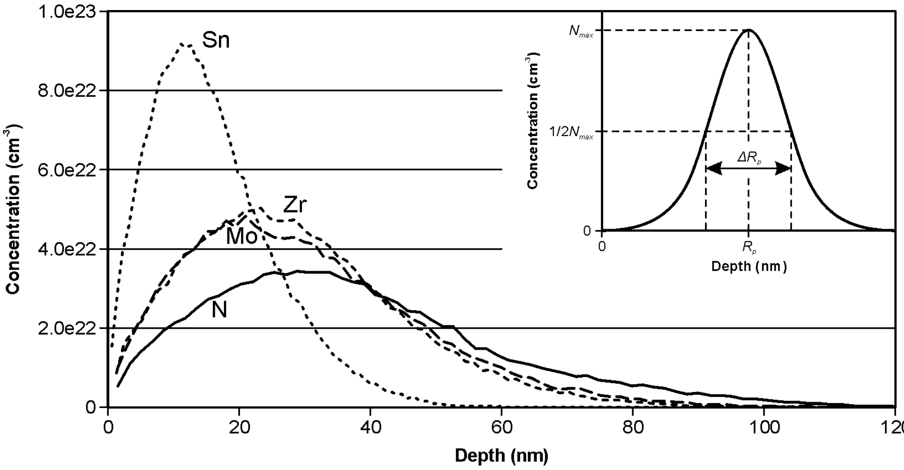

Figure 2. The depth profiles of N, Zr, Mo and Sn ions implanted to W-C-Co material

The maximum value of the peak volume dopant concentration is observed for tin ions, and the minimum - for nitrogen. The difference is about threefold. These values are similar for two others elements, i.e. for zirconium and molybdenum and they are about 5e22 cm^{-3}.

The maximum values of the projected range and the range straggling are obtained for nitrogen ions and the minimum ones- for tin. In this case, the difference is more than twofold. These values are also very similar to zirconium and molybdenum (the depth profiles for both elements are very similar).

Table 3. Detailed parameters of N, Zr, Mo and Sn ion implantation to W-C-Co material

Implanted ions	Peak volume dopant concentration N_{max} (cm^{-3})	Projected range R_p (nm)	Range straggling ΔR_p (nm)
$N_2^+ + N^+$	3.44e22	36.8	21.8
$Zr^+ + Zr^{2+} + Zr^{3+} + Zr^{4+}$	5.02e22	28.3	16.2
$Mo^+ + Mo^{2+} + Mo^{3+} + Mo^{4+} + Mo^{5+}$	4.81e22	29.3	17.6
$Sn^+ + Sn^{2+}$	9.17e22	15.6	9.3

The results of durability tests for the virgin samples and for the samples implanted with nitrogen, zirconium, molybdenum and tin are presented in Figs 3 and 4.

Fig. 3 presents the values of the cutting length for all types of modification. Additionally, the standard deviation values are marked by error bars.

The average values of the cutting length were: 51, 99, 81, 81 and 86 km for virgin samples and samples implanted with N, Zr, Mo and Sn, respectively. As we can see, the ion implantation resulted in an increased durability of the modified knives in each case. This effect was greatest in the case of nitrogen implantation (nearly 100% increase). The values of the cutting length for the implantation of metal ions increased by over 50% and, interestingly, were very similar in all cases.

Unfortunately, it was worse in the case of uniformity of results. The value of standard deviation amounted to only 1 km for virgin knives, while for knives implanted with N, Zr, Mo and Sn these values were: 40, 25, 14 and 31, respectively. The most homogeneous values were obtained for Mo implantation.

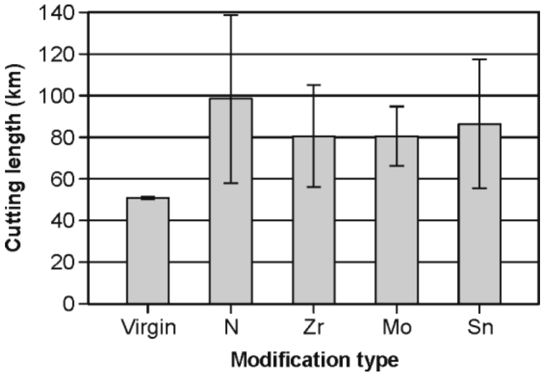

Figure 3. The cutting length with standard error bars for virgin indexable knives and knives implanted with nitrogen, zirconium, molybdenum and tin

The maximum, average and minimum values of the relative tool life index for the indexable knives implanted with nitrogen, zirconium, molybdenum and tin are shown on Fig. 4.

The best result of the maximum, i.e. nearly threefold increase in durability, was obtained for nitrogen implantation. The ion implantation of metallic ions increased the tool durability at the level of 100%. The worst result was observed for Zr implantation, but the worst results for tin and nitrogen implantation were similar to it.

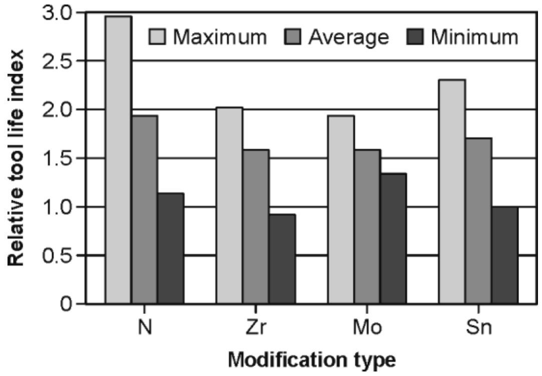

Figure 4. The relative tool life index for indexable knives implanted with nitrogen, zirconium, molybdenum and tin

The correlation between the values of the main parameters of the depth implanted profiles and the cutting length (tool life) was also analysed (Fig. 5). The analysis revealed a greater correlation with the projected range R_p ($R^2 \approx 0.75$) and the range straggling ΔR_p ($R^2 \approx 0.76$), than with the peak volume dopant concentration N_{max} ($R^2 \approx 0.37$). So, from the point of view of quality of the ion implantation process affecting the tools' life, it is better to perform modification taking into account the projected range and the range straggling, than to obtain a higher peak volume dopant concentration.

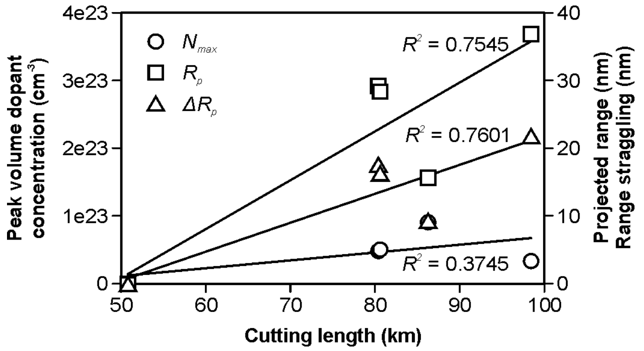

Figure 5. The relationship between the projected range R_p, the range straggling ΔR_p and the peak volume dopant concentration N_{max} and the cutting length

CONCLUSION

The average durability values of WC-Co indexable knives after ion implantation increased in all cases. The largest, on average almost two-fold increase was observed for tools implanted with nitrogen, while for the other elements it was at the level of 50%. The best results among metallic ions were achieved for tin. Zirconium and molybdenum are very comparable, both in terms of the implanted depth profiles and their influence on the durability of the modified knives; only the molybdenum effect is more homogeneous, i.e. the value range, from minimum, through average to maximum was the smallest for knives modified with this element.

As one can easily see, there is no direct impact of the atomic radius of the implanted element on the durability of the tools into which it is introduced. However, despite the fact that durability depends on more factors, a higher correlation was demonstrated between the tool life and the depth parameters of the projected range and the range straggling than the parameter of peak volume dopant concentration.

The large inhomogeneity of obtained results is a problem at this stage of investigations. There is a chance to further increase the average durability of modified tools after overcoming this problem.

REFERENCES

1. BARLAK M., WILKOWSKI J., WERNER Z., 2016: Ion implantation changes of tribological and corrosion resistance properties of materials used in wood industry, *Annals of Warsaw University of Life Science - SGGW, Forestry and Wood Technology* 94, 19-27.
2. BARLAK M., WILKOWSKI J., BORUSZEWSKI P., WERNER Z., PAŁUBICKI B., 2017: Changes of functional properties of materials used in wood industry after ion implantation processes, *Annals of Warsaw University of Life Science - SGGW, Forestry and Wood Technology* 97, 133-139.
3. BONNY K., DE BAETS P., PEREZ Y., VLEUGELS J., LAUWERS B., 2010: Friction and wear characteristics of WC-Co cemented carbides in dry reciprocating sliding contact, *Wear* 268, 1504-1517.
4. BUGAEV S.P., NIKOLAEV A.G., OKS E.M., SCHANIN P.M., YUSHKOV G.YU., 1994: The “TITAN” ion source, *Review of Scientific Instruments* 65, 3119-3125.
5. CHOI S.-H., KANG S.-D., KWON Y.S., LIM S.G., CHO K.K., AHN I.-S., 2010: The effect of sintering conditions on the properties of WC-10wt%Co PIM compacts, *Research on Chemical Intermediates* 36, 743-748.

6. CLEMENTI E., RAIMONDI D.L., REINHARDT W.P., 1967: Atomic screening constants from SCF functions. II. Atoms with 37 to 86 electrons, *The Journal of Chemical Physics* 47, 1300-1307.
7. FEYZULLAHOĞLU E., ZEREN A., ZEREN M., 2008: Tribological behaviour of tin-based materials and brass in oil lubricated conditions, *Materials and Design* 29, 714-720.
8. KAMIŃSKI M., BUDZYŃSKI P., 2016: Tribological properties of Stellite 6 cobalt alloy implanted with nitrogen ions determined in the tests conducted in engine fuel atmosphere, *Advances in Science and Technology. Research Journal* 11, 215-219.
9. KHUN N.W., YU H., CHONG Z.Z., TIAN P., TIAN Y., TOR S.B., LIU E., 2016: Mechanical and tribological properties of Zr-based bulk metallic glass for sports applications, *Materials and Design* 92, 667-673.
10. KRIVONOSIENKO A.W., NIKOLAEV A.G., LI S., 2001: Технические описание и инструкция по эксплуатаци ионного источника "Титан-3" (Technical descriptions and operating instructions of the ion source "Titan-3"), *Российская Академия Наук - Институт Сильноточной Электроники*, Tomsk, in Russian.
11. MILMAN. YU.V., CHUGUNOVA S., GONCHARUCK V., LUYCKX S., NORTHROP I.T., 1997: Low and high temperature hardness of WC-6 wt% Co alloys. *International Journal of Refractory Metals and Hard Materials* 15, 97-101.
12. OLOVSJÖ S., JOHANSON R., FALSAFI F., BEXELL U., OLSSON M., 2013: Surface failure and wear of cemented carbide rock drill buttons - The importance of sample preparation and optimized microscopy settings, *Wear* 302, 1546-1554.
13. PIRSO J., LETUNOVITŠ S., VILJUS M., 2004: Friction and wear behaviour of cemented carbides, *Wear* 257, 257-265.
14. SHEIKH-AHMAD J.Y., BAILEY J.A., 1999: High-temperature wear of cemented tungsten carbide tools while machining particleboard and fiberboard. *Journal of Wood Science* 45, 445-455.
15. SRIM. Interactions of ions with matter, http://www.srim.org/
16. SUN J.S., YAN P., SUN X.B., LU G., LIU F., YE W., YANG J.Q., 1997: Tribological properties of nitrogen ion implanted WC-Co, *Wear* 213, 131-134.
17. WU H., ZHU S., CHENG J., QIAO Z., YANG J., 2016: Tribological Behavior of Tin-Based Babbitt Alloy Lubricated by Seawater, *Tribology Transactions* 59, 838-844
18. TAKEICHI Y., CHUJO T., OKAMOTO N., UEMURA M., 2009: Effects of molybdenum trioxide on the tribological properties of aluminium bronze under high temperature conditions, *Tribology online* 4, 135-139

Streszczenie: *Wpływ implantacji jonów azotu i jonów wybranych metali na trwałość wymiennych noży WC-Co podczas obróbki płyt MDF.* W artykule przedstawiono wyniki testów trwałościowych wymiennych noży WC-Co podczas obróbki płyt MDF. Noże były implantowane jonami azotu, cyrkonu, molibdenu i cyny, przy użyciu implantatora typu MEVVA bez separacji masowej. Ponadto, w artykule zamieszczono wyniki modelowania profili głębokościowych implantowanych pierwiastków, uzyskanych przy pomocy programu opartego o metodę Monte Carlo. Wykazano wyższe zależności korelacyjne trwałości ostrza z wartościami zasięgu rzutowanego i rozrzutu zasięgu niż z wartościami maksymalnej koncentracji objętościowej domieszki.

Corresponding author:

Marek Barlak
e-mail: marek.barlak@ncbj.gov.pl
National Centre for Nuclear Research Świerk - NCBJ
Plasma/Ion Beam Technology Division (FM2)
7 Andrzeja Sołtana St.
05-400 Otwock, Poland

ORCID ID:

Barlak Marek:	0000-0003-1416-7461
Wilkowski Jacek	0000-0001-5798-6761
Szymanowski Karol	0000-0003-0383-0897
Czarniak Paweł	0000-0001-8759-7679
Podziewski Piotr	0000-0002-2628-5062
Werner Zbigniew	0000-0003-1172-0268
Zagórski Jerzy	0000-0001-6311-947X
Staszkiewicz Bogdan	0000-0002-7741-4362