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Effect of noble gases ion implantation on the life time of WC-Co tools used in wood-based material machining

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Abstract: *Effect of noble gases ion implantation on the life time of WC-Co tools used in wood-based material machining*. The results of the investigations on the tool life of WC-Co tools, implanted with three noble gas ions, i.e. helium, neon and argon, are presented in the comparison with the virgin tools and tools implanted with nitrogen ions. The surface modification of the tools was preceded by the modelling of the depth profiles of the implanted elements. The implantation of the ions of noble gases resulted in an improvement in tool tool life, in the range from 5 to 49%.

Keywords: ion implantation, depth profiles, modelling, WC-Co tools, wood machining

INTRODUCTION

The tool life of the tools made of WC-Co material is still insufficient, especially during of the particleboard machining. The ion implantation method can be used to improve this tool life. It is the relatively cheap and a good process for the modification of the tools, because the modified region is not an additional layer, hence no adhesion problem occurs (no delamination) and a change of dimensions and of the surface finish of the implanted material is negligible (Barlak et al. 2016, Barlak et al. 2017).

In our previous papers (Morozow et al. 2021, Wilkowski et al. 2021, Wilkowski et al. 2022a) we presented the results obtained for the ion implantation of nitrogen, for the different tools, conditions and configurations.

In this paper, we would like to present the results obtained for WC-Co tools, implanted with three noble gases, i.e. helium, neon and argon, in the comparison with the virgin (non-treated, non-implanted) tools and tools implanted with mentioned above nitrogen.

The chemically neutral, noble gases are used as inert gases in many technological processes, both in the science and industry, but no papers in the literature about the ion implantation of noble gases to WC-Co material. The implanted helium ions are often used for example in the investigations of the reactors' materials (Hall 1976, Das et al. 2019), whereas neon and argon - in electronic devices (Węgierek and Billewicz 2011, Sanders et al. 1977).

MATERIALS AND METHODS

The Stopping and Range of Ions in Matter (SRIM-2013.00), freeware type code, based on Monte Carlo method, was used for the modelling (SRIM, Barlak et al. 2019a, Barlak et al. 2019b, Barlak et al. 2019c) before the ion implantation processes. The depth profiles of all ions implanted to W-C-Co material (modelling codes treat the sample as a set of atoms that do not form chemical compounds), the peak volume dopant concentrations (N_{max}), projected range R_p, range straggling ΔR_p, kurtosis and skewness were modelled using this code. The detailed description of these parameters was included in our previous paper (Barlak et al. 2023).

The modelling was performed for 100 000 implanted ions in the each case. The angle of the ion incidence was defined as 0° (perpendicular to the implanted surface). The simulations were performed for room temperature implantation.

The modelling did not account for the phenomenon of substrate sputtering by the implanted ions, substrate damages and the chemical reactions between the implanted ions and the substrate components, etc.

The theoretical values of the sputtering yield *Y*, defined as an average number of atoms sputtered (ejected) from the implanted substrate per one incident ion, were calculated with the use of the freeware type, quick ion implantation calculator SUSPRE, from the energy deposited in the surface region of the material using the Sigmund formula (SUSPRE). The calculated sputtering yield values were omitted at the modelling, for the simplicity.

W-C-Co implanted substrate material, including (at.%): 47.4% W, 47.4% C and 5.2% Co, i.e. in wt.%: 90.86% W, 5.94% C and 3.2% Co, with the density of 15.2 g/cm^3 was adopted as the substrate material to the modelling. This value of the density was declared by the supplier of the e.g. KCR08 type indexable knives (Ceratizit, Austria), commonly used in the furniture industry and presented at Fig. 1.

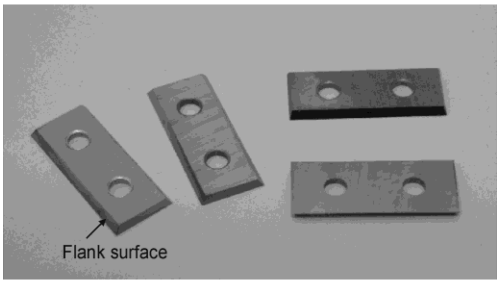

Figure 1. WC-Co composite indexable knives

Three noble gases, i.e. helium, neon and argon were used in the modelling processes, as implanted elements. Additionally, two kinds of nitrogen ion implantation were added for the comparison of the obtained results.

The modelling was performed for the implanted fluence of 5e17 cm^{-2}. The acceleration voltage was 50 kV. Due to single ionisation of He^+, Ne^+, Ar^+ and N^+ ions, their value of the ion kinetic energy is numerically identical with the value of the accelerating voltage, e.g. 50 keV and 50 kV. The different situation is in the case of the implantation of nitrogen ions, without mass separation. In this case, the implanted nitrogen was delivered as two kinds of ions, i.e. N^++N_2^+, in the ratio ~1:1; so, there were two elementary charges per three atoms. For example, in the case of N_2 molecule implanted with the acceleration voltage of 50 kV, each atom carries the energy of 25 keV, according to the law of energy conservation. It means that, for example, for a total fluence of 5e17 cm^{-2}, the fluence of 1.65e17 cm^{-2} is implanted with the energy of 50 keV and the fluence of 3.35e17 cm^{-2} is implanted with the energy of 25 keV. The average charge state (ACS) in this case is at the level of 0.67 (Wilkowski et al. 2022b).

The ion implantation processes were performed using two kind of ion implanters, i.e. the implanter without mass separation (with direct beam), exploited in National Centre for Nuclear Research Świerk (NCBJ) in Otwock, Poland (implantation of He^+, Ne^+, Ar^+ and N^++N_2^+ ions) and the implanter with mass separation (without direct beam) in Helmholtz-Zentrum Dresden-Rossendorf (HZDR) in Dresden, Germany (implantation of N^+ ions).

The commercially available, popular and commonly used in the furniture industry, mentioned earlier and presented in Fig. 1, KCR08 WC-Co indexable knives (WC grain size of 0.5÷0.8 μm, Co content of 3.2 wt.%, mentioned above density of 15.2 g/cm^3, hardness HV30 of 1885 and transverse rupture strength of 2300 MPa), with a dimension of 29.5×12×1.5 mm^3, produced by Ceratizit company (Reutte, Austria), were used for the investigations. The flank surfaces of these indexable knives, were implanted with all described above ions.

5N purity gases were used as a sources of the implanted ions. The implanted fluence was 5e17 cm^{-2} and the acceleration voltage was 50 kV, in all cases. The estimated value of the temperature of the implanted tools did not exceed 200°C.

The tool life tests were carried out for virgin and all ion implanted WC-Co indexable knives. During the tests, the knives were placed in one edge milling head Faba FTS.07L4043.01 (Faba S. A. Baboszewo, Poland), with a diameter of 40 mm.

The three-layer particleboard, produced by Pfleiderer Company, with a thickness of 18 mm and a density of 649 kg/m^3 was used in these tests. Other, selected mechanical and physical properties of the tested particleboard were following: tensile strength of 0.41 MPa, swelling after 24 h of 20.5%, flexural strength MOR of 8.68 MPa and modulus of elasticity MOE of 2212 MPa. All panels for the examination came from the same batch. These panels are a standard construction material, commonly used in the furniture industry.

The workpieces of the three-layer particleboard with dimensions 1000×400×18 mm^3 were milled on CNC Busellato Jet 130 working center. The grooves (with the width equal to the tool diameter, i.e. 40 mm) were made in the particleboard panels on the depth of 6 mm. During the machining, constant cutting parameters (the feed speed of 2.7 m/s, the spindle speed of 18000 rpm and the feed per tooth of 0.15 mm) were maintained. Ten repetitions were made on each workpiece.

The measurement of tool wear was carried out after each passage (1 m of the feed distance), using a workshop microscope. The maximum width of wear observed in flank surface (direct, geometrical indicator VB_{max}) was estimated (Wilkowski and Górski 2011). The machining was stopped when the wear width was equal to or higher than 0.2 mm. This value (VB_{max} = 0.2 mm) was assumed as the tool wear criterion. The cutting length up to achieve the tool wear criterion was its durability indicator. Eight cutting edges was investigated for each modification type and the virgin tools.

RESULTS AND DISCUSSION

Fig. 2 shows the results, obtained during the modelling, i.e. the modelled depth profiles of the implantation of nitrogen and three noble gases, i.e. helium, neon and argon. All profiles were obtained for the fluence of 5e17 cm^{-2} and the acceleration voltage of 50 kV.

It is seen, that the height and the width of the depth profiles strongly depends on the mass of the implanted ions. The depth profile is the lowest and widest for lightest helium, with an atomic mass of 4.0026 u. These profiles are higher and narrower for the elements with the higher atomic mass, like nitrogen (14.0067 u) and neon (20.1797 u). The narrowest and highest profile was obtained for heaviest argon (39.948 u).

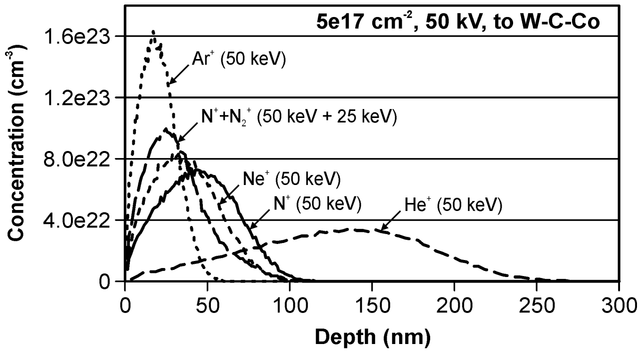

Figure 2. The modelled depth profiles of the implanted ions of nitrogen, helium, neon and argon

All detailed data, i.e., the values of peak volume dopant concentrations, projected range, range straggling, kurtosis and skewness, characterizing the modelled depth profiles for all kinds of the implanted elements, have been presented in Table 1. Additionally, the sputtering yield values were added for the information.

Worth noting that, the skewness is negative for helium and positive for all other elements. Additionally, the skewness value for N^++N_2^+ case is more than 4-fold higher in the comparison with N^+ case. This is, of course, related to the non-homogeneity of the ion beam.

The difference of the sputtering yield is more than 100-fold between the extreme cases, i.e. between helium and argon. This value is similar for both cases of nitrogen ion implantation. Sputtering yield is not the same for the elements with similar atomic mass, i.e. nitrogen and neon. It is about 2-fold higher for the second element.

Table 1. The modelled values of the peak volume dopant concentrations, projected range, range straggling, kurtosis, skewness and sputtering for all kinds of the implanted elements

Ions	Acceleration voltage (kV) / Ion energy (keV)	Peak volume dopant concentration, N_{max} (cm^{-3})	Projected range, R_p (nm)	Range straggling, ΔR_p (nm)	Kurtosis	Skewness	Sputtering yield, Y (atoms/ion)
N^+	50 / 50	7.32e22	44.5	43.8	2.44	0.19	0.43
N^++ N_2^+	50 / 50+25	9.97e22	31.7	38	3.61	0.85	0.49
He^+	50 / 50	3.44e22	125.1	104	2.47	-0.09	0.02
Ne^+	50 / 50	8.33e22	36.6	38.8	2.67	0.39	0.81
Ar^+	50 / 50	1.63e23	20.1	21.4	2.75	0.42	2.03

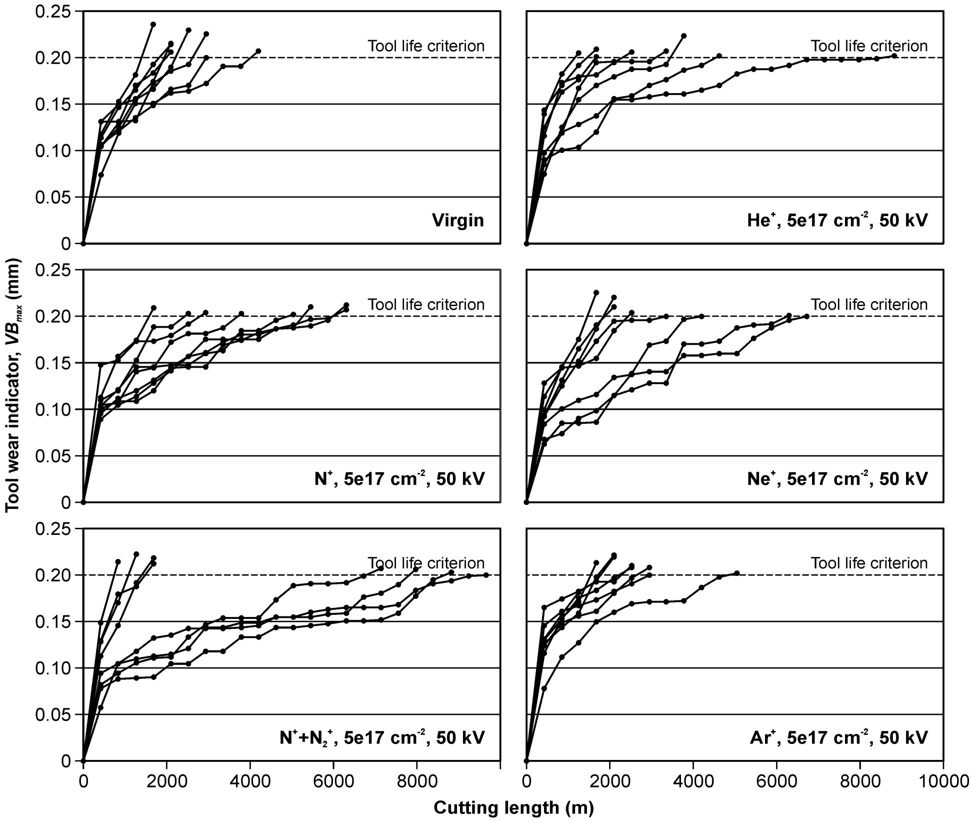

Figure 3. The wear curves of the tested WC-Co indexable knives

The wear curves of the tested WC-Co indexable knives, i.e. the dependence of tool wear on the cutting length, are shown in Fig. 3. These are curves for virgin tools, tools implanted with nitrogen and all noble gases. All wear curves obtained in the experiment are in accord with the classic Lorenz wear curve, with a difference that due to the tool withdrawal from the service, with the wear criterion specified for the direct wear indicator VBmax equal to 0.2 mm, the third curve period (Failure region) was not achieved. This level of the criterion is justified by the practical and industrial.

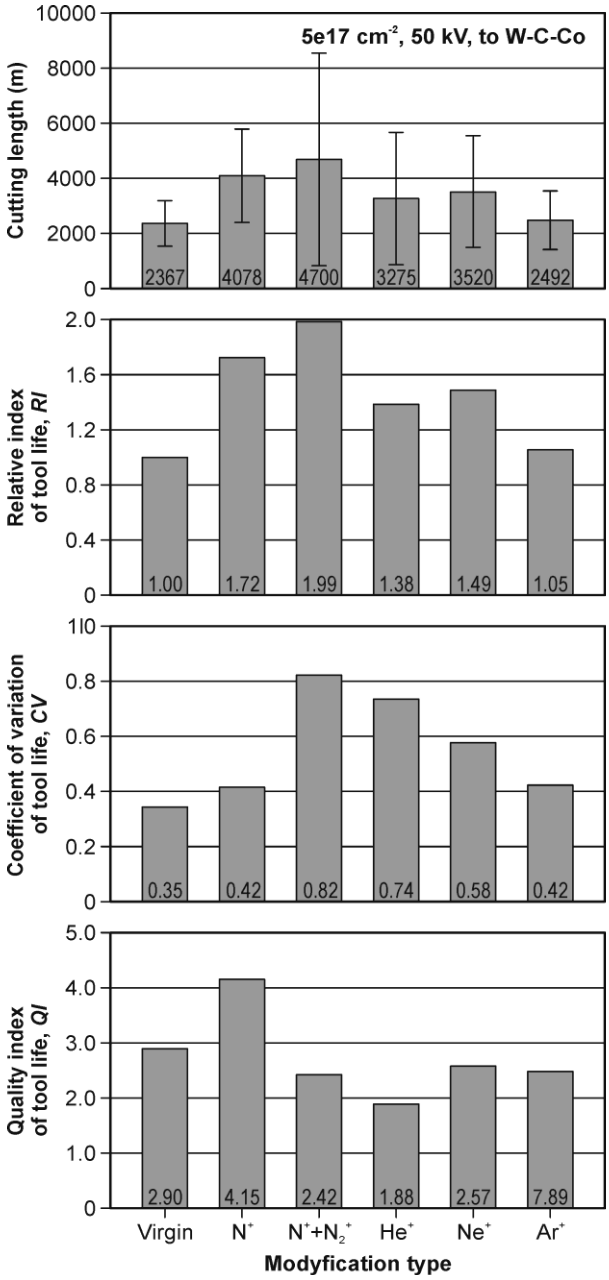

Figure 4. The statistical values of tool life

Fig. 4 presents the statistical values of the tool life, described in details in (Barlak et al. 2020). The ranges on the chart indicate the mean ± standard deviation. It is seen on the cutting length and relative index of tool life RI, that the tool life increased in all cases of the implanted tools, but the standard deviation values are high. The mentioned increase is greatest with both nitrogen implantations and it is more than 70% for N+ ions and about 100% for N++N2+ ions. This increase is less spectacular for noble gases and it is 38% for helium, 49%

for neon and only 5% for argon. Perhaps, the higher tool life increase of WC-Co knives implanted with nitrogen is caused by the relatively shallow depth profile and relatively low value of the sputtering yield. Although, the profile for argon is shallower, but the calculated sputtering yield for this element is more than 4-fold higher.
Unfortunately, the coefficient of variation of tool life CV is the smallest for non-implanted tools, slightly higher for N+ ions and the highest for N++N2+ ions. This value is in the range from 0.42 to 0.74 for noble gases, inversely proportional to their atomic mass.
Finally, the quality index of tool life QI is the best for N+ ions. This value is worse than non-implanted tools in all other cases.

CONCLUSIONS

Based on the results of the research, the following conclusions can be drawn:
- the modelled shape and the position of the depth profiles of all implanted elements are different,
- the results of tool life tests are not very spectacular for more expensive noble gases in the comparison with cheap nitrogen, moreover, the variability of the implanted tools is greater than the virgin ones,
- no correlation was observed between the position of the depth profiles and the life time of the implanted tools,

Perhaps, the ion implantation of different elements with ion energy, which results in generating a similar depth profiles, described in Barlak et al. 2023, will result in greater correlation. Such investigation are currently realized in the frame of HZDR Project No 23003338-ST.

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Streszczenie: *Wpływ implantacji jonów gazów szlachetnych na trwałość narzędzi WC-Co stosowanych w obróbce materiałów drewnopochodnych*. Przedstawiono wyniki badań trwałości narzędzi WC-Co, implantowanych jonami trzech gazów szlachetnych, tj. helu, neonu i argonu, w odniesieniu do narzędzi wyjściowych i implantowanych jonami azotu. Modyfikację powierzchni narzędzi poprzedzono modelowaniem głębokościowych profili implantowanych pierwiastków. Implantacja jonów gazów szlachetnych spowodowała poprawę trwałości narzędzi w zakresie od 5 do 49%.

Słowa kluczowe: implantacja jonowa, głębokość, profile, modelowanie, narzędzia WC-Co, obróbka drewna

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