TECHNICAL NOTE: LIFETIME IMPROVEMENT AND THE CUTTING FORCES IN NITROGEN-IMPLANTED DRILLS DURING WOOD-BASED MATERIAL MACHINING

*Jacek Wilkowski**†

Assistant Professor
Department of Mechanical Processing of Wood
Warsaw University of Life Sciences – SGGW
Nowoursynowska Str. 159
Warsaw 02-787, Poland
E-mail: jacek_wilkowski@sggw.pl

Marek Barlak

Assistant Professor
E-mail: marek.barlak@ncbj.gov.pl

Zbigniew Werner

Professor
E-mail: zbigniew.werner@ncbj.gov.pl

Jerzy Zagórski

Technologist
Plasma and Ion Technology Division (FM2)
National Centre for Nuclear Research Świerk - NCBJ
7Andrzeja Sołtana Str.
Otwock 05-400, Poland
E-mail: jerzy.zagorski@ncbj.gov.pl

Paweł Czarniak

Assistant Professor
E-mail: pawel_czarniak@sggw.pl

Piotr Podziewski

Assistant Professor
E-mail: piotr_podziewski@sggw.pl

Karol Szymanowski

Assistant Professor
Department of Mechanical Processing of Wood
Warsaw University of Life Sciences – SGGW
Nowoursynowska Str. 159
Warsaw 02-787, Poland
E-mail: karol_szymanowski@sggw.pl

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* Corresponding author.
† SWST member

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Abstract. This study explored the effects of nitrogen (N) ion implantation of drills for wood-based materials. Modification of a tool's surface is a common process of prolonging its lifetime. For the purpose of this study, ion implantation was used for modification of drills commonly used in the furniture industry. The rake face of high-speed steel drills was implanted with different doses of nitrogen ions. Durability tests were conducted with the use of a computerized numerical control woodworking machine used for drilling laminated particleboards. The cutting force and drilling torque were measured. The obtained results were presented as wear curves of the examined drill bits. Based on the results, tools implanted with nitrogen ions at different doses had a longer tool life.

Keywords: Nitrogen ion implantation, drill durability, wood-based materials, CNC woodworking machine, cutting forces.

INTRODUCTION

High-speed stainless steel (HSS) is still a popular material in wood-based material mechanics, especially as it applies to drills, despite the introduction of new tool materials such as WC-Co composites, polycrystalline diamonds, and others. The continued use of HSS can be attributed to lower cost, reduction of breakage in older spindles and hand routers, sharper edges allowing for easier hand feeding, and different geometries (Bai et al 2004; Kusiak et al 2005; Philbin and Gordon 2005; Eblagon et al 2007; Nouveau et al 2007; Aknouche et al 2009; Benlatreche et al 2009; Gogolewski et al 2009).

Tools are often surface modified to prolong their lifetime. There are three ways to extend the lifetime of tools (Labidi et al 2005): modification of the surface region, deposition of an additional layer, and duplex treatment, ie modification of the surface region and the deposition of an additional layer.

In the case of steel tools for wood and wood-based materials, modification of the surface layer by doping was realized mainly by using an ion nitriding method (Rudnicki et al 1998; Beer et al 2005) and plasma immersion ion implantation (Raebel et al 1990).

The deposition of additional layers usually means the application of hard coatings, produced by different alternatives of physical vapor deposition or chemical vapor deposition methods (Beer et al 1999a, 1999b, 2003; Faga and Settineri 2006). In addition, vacuum-arc, magnetron sputtering, and galvanochemical methods were used for layer deposition (Djouadi et al 1999).

In the first stage of the duplex treatment, the tool material is ion nitrided. The hard coating can be deposited in the second stage, such as the magnetron sputtering or arc evaporation process (Beer et al 2003; Labidi et al 2005). The hard coating has better adhesion properties when it is deposited on the pretreated (nitrided) substrate. This method of increasing the layer adhesion is common (Barlak et al 2007a; Narojczyk et al 2009).

Ion implantation is the method of modification of the near-surface area (Barlak et al 2016, 2017). The modified region is not a layer; therefore, no problem occurs with adhesion and a change in the dimensions (Straede 1996; Mikkelsen et al 2002; Rodrìguez et al 2002). This process can be conducted at temperatures <500°C (Werner et al 2007), and even <200°C (Straede and Mikkelsen 1996) and <100°C (García and Rodríguez 2011).

Ion implantation is a relatively cheap method of tool improvement and gives spectacular results for tools used for a "mild wear" processing of soft materials, such as paper, rubber, and meat. There is little information regarding the application of classical ion implantation for the modification of tools (especially drills) for wood machining. This method is only briefly mentioned in some references (Raebel et al 1990; Ko 1998; Dearnaley and Arps 2006). Ion implantation is a very popular method for the modification of other materials (Jagielski 2005; Jagielski et al 2006), such as metals and alloys (Barlak et al 2014), ceramics (Piekoszewski et al 2004; Olesińska et al 2006; Barlak et al 2007b), composites (Sheikh-Ahmad and Bailey 1999), and semiconductors (Werner et al 2013).

Nitrogen ion implantation is the most widely used method for the modification of steels (Byeli et al 1995; Bull et al 1996; Jones and Bull 1996; Narojczyk et al 2001; Narojczyk et al 2005). Ion implantation with carbon (C) is also quite popular (Yan et al 1998; Sánchez et al 2002). The transition metal elements, such as titanium (Ti), chromium (Cr), manganese (Mn), nickel (Ni), and molybdenum (Mo), and rare-earth elements, such as lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), dysprosium (Dy), erbium (Er), and ytterbium (Yb), can be occasionally implanted (Rodriguez et al 1996; Jin et al 1997; Jin et al 2006).

The mechanisms of wear reduction and the prolongation of tool life of ion-implanted materials are fairly well known. Increased microhardness is predominately due to the formation of hard nitrides for nitrogen implantation, and the reduction of friction is due to carbon precipitation for ion implantation of this element (Uglov et al 2002; Chou and Liu 2004). In other cases, the formation of new phases is observed.

In the current literature, there is little information about ion implantation of drills (only one reference [Mändl et al 1998] was found by the authors), especially drills for wood and wood-based materials. In this article, the authors will try to provide more insight into the subject.

Figure 1. Leitz HSS 033467 drills.

MATERIALS AND METHODS

HSS Leitz drills (Leitz GmbH and Co. KG, Stuttgart, Germany) with a diameter of 10 mm and total length of 68 mm (dowel drills with 10-mm shanks), commonly used in the furniture industry and presented in Fig 1, were used for the investigations.

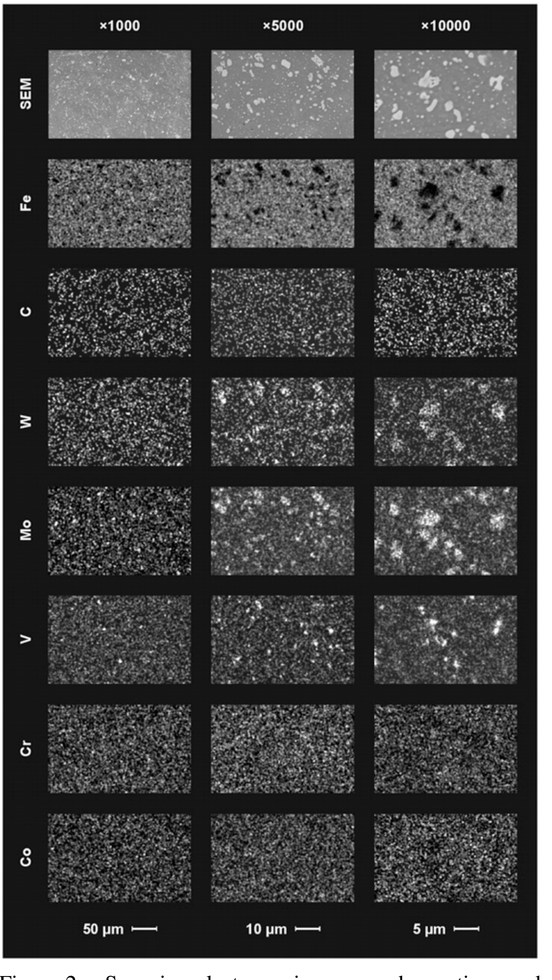

Figure 2. Scanning electron microscope observations and energy-dispersive spectroscopy measurement results for the drill material.

Table 1. Main parameters of ion implantation processes.

Modification type	Implanted ions	Implanted dose (cm^{-2})	Acceleration voltage (kV)	Beam current density ($mA\ cm^{-2}$)
1	$N_2^+ + N^+$	2e17	60	~0.3
2	(~1:1)	2e17		~1
3		3e17		~0.3
4		3e17		~1
5		5e17		
6		6e17		

The microstructure of the drill material; shape of the cutting edge; quality of the surfaces of the rake face of the nonmodified, implanted, and durability-tested drills; the distribution of the HSS elements; and the presence of the implanted ions were examined with the use of a Zeiss EVO MA10 (Carl Zeiss, Jena, Germany) scanning electron microscope (SEM) with an EDX Bruker Quantax 200 (Bruker Corporation, Billerica, MA) energy-dispersive spectroscopy (EDS) system.

The microstructure of the drill material and the distribution of the main elements included in the composition are presented in Fig 2, for magnifications 1000×, 5000×, and 10,000×.

The SEM photographs show (especially for magnifications 5000× and 10,000×) the clear regions on a dark background and the corresponding clusters on EDS maps mainly containing tungsten (W), molybdenum (Mo), and vanadium (V).

Besides iron (Fe) and carbon, the chemical composition in weight percentages is 5% of tungsten, 3.6% of molybdenum, 1.6% of vanadium, 3.8% of chromium, and 0.9% of cobalt (Co). In the aforementioned clusters, approximately 18.8% of C, 25.7% of W, 19.8% of Mo, 3.8% of V, 3.6% of Cr, and 0.3% of Co were detected.

The aforementioned content values were determined using the EDS method. The investigation was conducted for the cross-sectional microstructure of the drill material, for magnifications 1000× (all material) and 10,000× (clusters), and for the accelerating voltage of 20 kV. The projected range of 20 keV electrons (Starodubtsev and Romanov 1962) in Fe, the main component of steel, is approximately 1.3 μm. This was determined by the Suspre code (SUSPRE 2001), commonly used for particle range determination.

In the next step, before processing, the drills were washed in high-purity acetone under ultrasonic agitation.

Ion Implantation

The rake faces of high-speed steel drills were implanted with nitrogen ions with a nonmass separated beam in a homemade semi-industrial implanter (beam current density at a level of 0.3 mA cm^{-2}) and with a MEVVA-type implanter (Institute of High Current Electronics, Siberian Branch of the Russian Academy of Sciences, Tomsk, Russia) with a direct beam (beam current at a level of 1 mA cm^{-2}), described in detail by Bugaev et al (1994). Nitrogen of 99.9% purity was used as the source of the implanted ions. The implanted doses were in the range from 2e17 cm^{-2} to 6e17 cm^{-2}. The implanted nitrogen is delivered as two kinds of ions, ie $N_2^+ + N^+$. Ions were implanted at 60 kV acceleration voltage. The modeled value of the projected range and the range straggling of nitrogen ions implanted with energy of 60 keV to iron (main component of steel) using the SUSPRE code are about 72 nm and 102 nm, respectively. The theoretical thickness of the modified region can be assumed to be approximately 200 nm. In practice, this value can be higher because of, eg, the diffusion of the dopant element.

The temperature of the implanted drills was approximately 200°C for 0.3 mA cm^{-2} beam current density and in the range 300-400°C for 1 mA cm^{-2}. The details of the ion implantation parameters are presented in Table 1. In addition,

Table 2. Selected mechanical and physical properties of the applied laminated particleboard.

Material	Density (kg m^{-3})	Tensile strength (MPa)	Swelling after 24 h (%)	Flexural strength (MPa)	Modulus of elasticity (MPa)
Laminated particleboard	670	0.39	61.8	15.35	2950

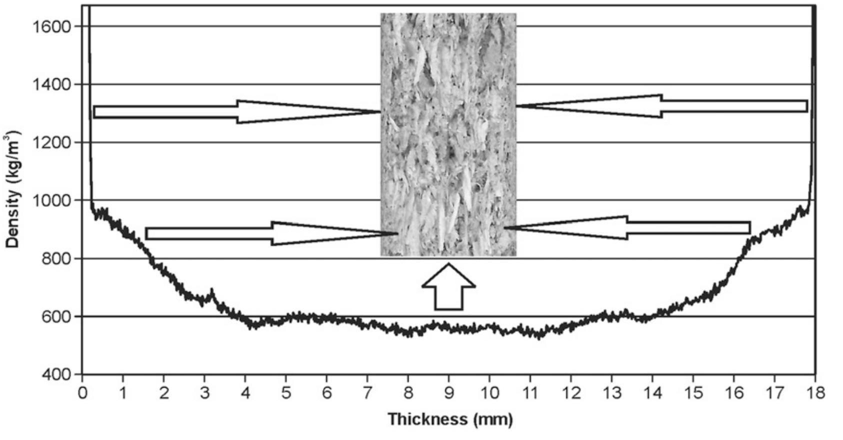

Figure 3. Density profile of a laminated particleboard.

in the authors' investigations, nonmodified drills were used for comparison.

Cutting Tests

Durability tests were performed during the process of drilling a laminated particleboard. The characteristics of this material are presented in Table 2 and in Fig 3.

The study was conducted with the use of a computerized numerical code machine tool Busellato Jet 130 (Casadei-Busellato, Thiene, Italy). The conducted tests consisted of drilling blind holes in a laminated particleboard with six modified and one nonmodified (control) drills. Fourteen corners were examined in series.

During the study, each of the tools was analyzed for wear after each blunting cycle using a workshop microscope (Mitutoyo, Kawasaki, Japan) with a digital readout and accuracy of 0.001 mm. The value of the W indicator, the maximum size of the corner wear, was measured as shown in Fig 4.

The average values of the W indicator of the drill were calculated from Eq 1,

$$W = (W_1 + W_2)/2, \quad (1)$$

where W_1 is the corner wear of the first edge of the drill (mm) and W_2 is that of the second edge of the drill (mm).

Drilling was carried out for the cutting parameters recommended by the tool manufacturer, ie feed

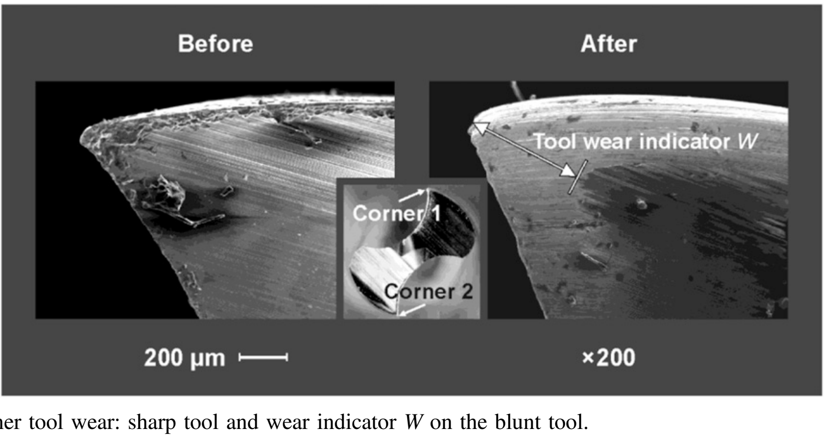

Figure 4. Corner tool wear: sharp tool and wear indicator W on the blunt tool.

Table 3. Number of holes drilled in successive blunting cycles.

Cycle no.	1	2	3	4	5	6
Holes count	15	30	60	90	120	120
Total	15	45	105	195	315	465

speed 2 m min^{-1} and a spindle speed of 6000 rpm.

The blunting process was conducted in the form of cycles. The number of holes for particular cycles of wearing and the overall amount of holes are given in Table 3. The tool life criterion W was pre-established as 0.25 mm. This is the value recommended by the tool manufacturer. In addition, deterioration of the drilling quality (edge chipping of the hole) has been observed from this value.

At the moment when the drill achieved or exceeded a value of 0.25 mm in a given cycle, the process of blunting was terminated, recognizing this tool as not suitable for further exploitation. As soon as this value was reached, the number of holes made by this tool was interpolated to make the result (up to the tool wear criterion) more reliable. The overall number of holes made with the use of the examined drill in all cycles of wearing up to $W = 0.25$ was considered as its tool wear durability.

After each cycle of wearing, measurement of axial force and torque with the use of the measurement circuit described in Fig 5 was recorded. The first part of the equipment was a two-component piezoelectric Kistler 9345A transducer (Kistler Group, Winterthur, Switzerland). A Kistler 5073A preamplifier transducer (Kistler Group) was the next element included in the measurement circuit. The supplier, Bayonet Neill–Concelman connector box, and acquisition card National Instruments (NI) PCI-6034E sampling signal with frequencies of 50 kHz were the next elements of the measurement stand. The signals were processed and analyzed by means of special software developed in the NI LabVIEW 2015 environment (National Instruments, Austin, TX). The cutting resistance was measured during 10 successive holes, and the mean values for each cycle were calculated.

RESULTS AND DISCUSSION

The widening of the blunted cutting edge zones was clearly visible and became more evident with an increase in the curve radius (10 times), deep cracks, and damages of the blunted edge. Moreover, wide bands of wear on the flank wear zone were clearly visible in SEM images. This observation indicates a dominant role of abrasive character in tool wear (Klamecki 1976; Porankiewicz et al 2005). High-temperature corrosion and the abrasion process create visible deep cracks on the cutting edge and are due to

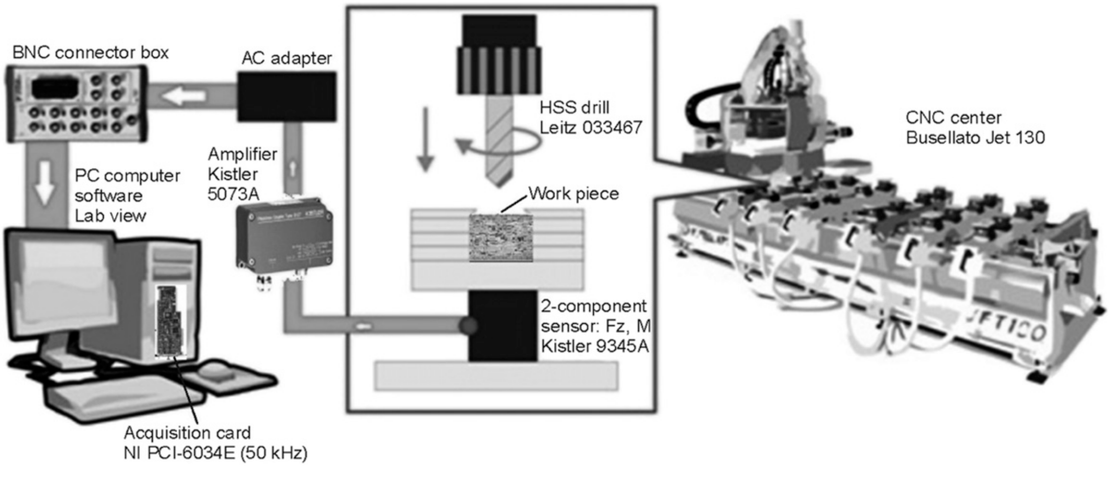

Figure 5. Measurement chain of cutting forces.

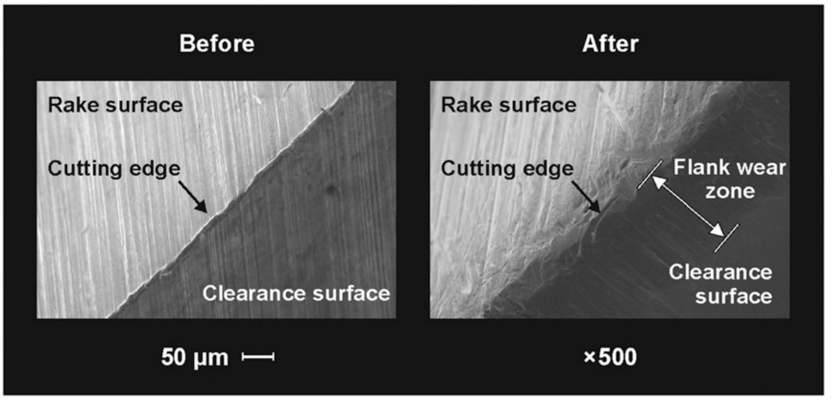

Figure 6. Scanning electron microscope analysis of cutting edge.

destructive influences on hard mineral contaminations in the machined material (Porankiewicz 2003; Porankiewicz et al 2006, 2008, 2016, 2018). Figure 6 presents the virgin cutting edge before testing and after abrasive wear at the end of tool life. A similar wear behavior was observed on the clearance face and the cutting edge (rounding) in two cutting edges of the same drill bit. The most significant wear (abrasive wear) occurred on the clearance faces. The wear on the rake faces was only a small part of the total wear area.

Figure 7 presents the curves of tool wear assumed as a function of tool life, in other words a relationship between the indirect tool wear indicator and the number of holes made in the experiment. The wear on the drills was proportional to the number of drilled holes.

The lowest number (154 holes) executed to achieve the tool wear criterion (W = 0.25 mm) was obtained for the drill modified with the implanted dose 2e17 cm^{-2} and beam current density of approximately 0.3 mA cm^{-2}, which stands for the lowest level of modification parameters applied in this experiment. A slightly higher tool life was achieved for unmodified tools (211 holes). The highest number of holes was produced by the drills modified with the implanted dose 5e17 cm^{-2} and a beam current density of 1.0 mA cm^{-2} (472 holes).

The durability tests of the examined tools were expressed with the relative tool life index (Table 4 and Fig 8) in comparison with the reference drill (nonmodified). Indices were calculated from Eq 2:

$$\text{Relative index} = H_1 \big/ H_{\text{Nonmodified}}, \qquad (2)$$

where H_1 is the number of holes obtained with the use of a modified drill denoted as 1 and $H_{\text{Nonmodified}}$ is the number of holes made with the unmodified tool. A higher relative index above 1 meant a longer tool life than the reference tool (nonmodified). Thus, the modification in mode 5 caused more than 2-fold prolongation of tool life with respect to the reference tool (relative index = 2.24).

Clear influence of the implanted dose on the relative tool life index was observed. Simultaneously,

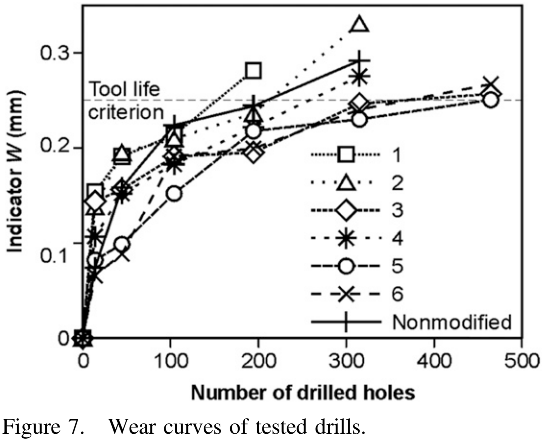

Figure 7. Wear curves of tested drills.

Table 4. Number of holes drilled to obtain wear $W = 0.25$ mm.

Modification type	1	2	3	4	5	6	Nonmodified
Holes count	154	213	382	258	472	376	211
Relative index	0.73	1.01	1.81	1.22	2.24	1.78	1.00

when the implanted dose increased from 2e17 cm^{-2} to 3e17 cm^{-2} and finally up to 5e17 cm^{-2}, the tool life was noticeably increased (Fig 8). For the implanted dose of 6e17 cm^{-2}, the tool life negligibly decreased in comparison with the implanted dose of 5e17 cm^{-2}; however, the relative indicator maintained a high level of 1.78. Unambiguous influence of the beam current density on the relative tool life index was not observed. Maybe, it can result from a moderate range of beam current density.

Nitrogen diffusion in iron and steels depends very strongly on temperature. A change in temperature by 100°C causes a change in the diffusion coefficient by an order of magnitude. For example, the diffusion coefficient of nitrogen in iron is about 5e−10, 3e−9, and 3e−8 cm^{-2} s^{-1} for 200, 300, and 400°C, respectively (Verein Deutscher Eisenhüttenleute 1984). Also, Bobadilla and Tschiptschin (2015) show that the value of the theoretic diffusion coefficient of nitrogen in the austenite phase is 2.4701e−15 cm^{-2} s^{-1} for 350°C and 1.9704e−14 cm^{-2} s^{-1} for 400°C, and that in the ferrite phase is 1.78601e−9 cm^{-2} s^{-1} and 5.35635e−9 cm^{-2} s^{-1}, respectively.

The higher value of the diffusion coefficient leads to a greater range of implanted ions. Because the value of the sputtering yield is constant for the same energy of the implanted ions, the quantity of the introduced element is higher for higher value of the temperature. The higher thickness of the modified region and higher quantity of the dopant can cause a change of the properties of the implanted material.

After each cycle of blunting, the axial force and torque measurements were recorded. At the beginning of tool life, for the brand new tools subjected to modification, a decrease of the aforementioned values was noticed. The decrease of cutting resistance grew with the level of the implanted dose for 2e17 cm^{-2}, 3e17 cm^{-2}, and, finally, for 5e17 cm^{-2} (Figs 9 and 10). Thus, for the modification variant 5 (implanted dose 5e17 cm^{-2} and beam current density of 1.0 mA cm^{-2}), the lowest level of cutting forces during machining with respect to the brand new tool was obtained. The noticed relationships were not confirmed for further levels of tool wear.

A decrease of the axial force and torque for brand new tools probably coincides with a decrease of the friction coefficient in the contact area between the edge material caused by the process of nitrogen ion implantation. However, until now, this problem has not been explored and described in a comprehensive way. The influence of implanted ions on a decrease of the friction coefficient was demonstrated (Uglov et al 2002; Chou and Liu 2004; Budzynski 2015). However, for wood-based materials, machined with tools made of steel, scientific reviews are missing. Simultaneously with the tool wear process, the positive effect of modification disappeared (Figs 11 and 12). This effect was explained by the presence of clear interactions between the character of the tool wear process and the cutting forces interfering the beneficial result of modification.

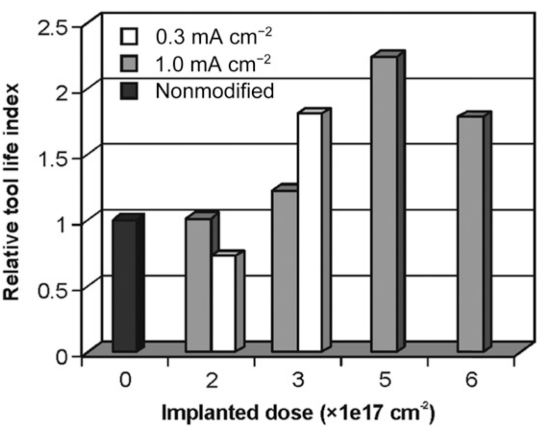

Figure 8. Cumulated results of the tool lifetime tests.

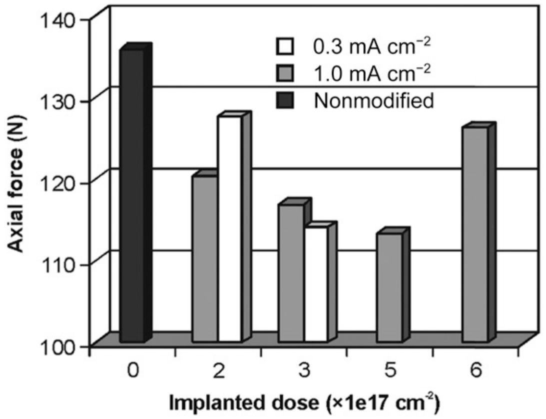

Figure 9. Cumulated results of the axial force tests for the new tool.

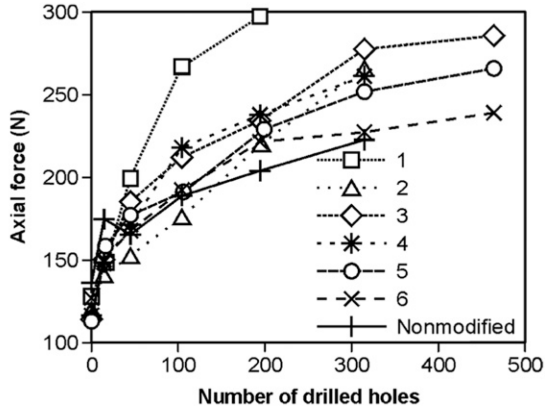

Figure 11. Measured axial cutting force growth after each blunting cycle.

With drills' wear, the modified layer was subject to abrasion and the geometry of the edges began to differentiate. The geometry differences between the two cutting edges of a drill bit could affect the actual cutting forces. The resulting differences in the cutting forces can create additional torsion moment, which can change the linear direction of drill bit penetration and additionally change the cutting forces (Sharapov et al 2018). This may be the reason for such a behavior of the modified tools.

Relationships between the tool wear and axial force were obvious (Fig 11); however, for torque, this phenomena was not clear (Fig 12).

The abovementioned influence of tool wear on axial force and torque was confirmed with the Pearson correlation coefficient (Table 5). This coefficient is a measure of the linear correlation between two variables. It has a value between +1 and −1, where 1 is total positive linear correlation, 0 is no linear correlation, and −1 is total negative linear correlation.

The Pearson correlation coefficient achieved high values (from 0.88 up to 0.98) and indicated strong relationships between axial force and tool wear. For the torque for some tools, these values were lower (from 0.12 up to 0.97), and for the unmodified tool, this value was even negative (−0.49).

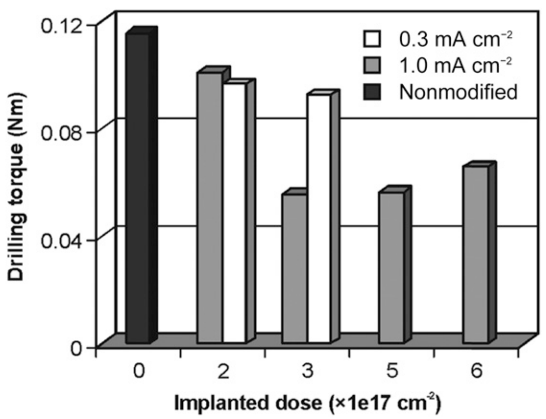

Figure 10. Cumulated results of the drilling torque tests for the new tool.

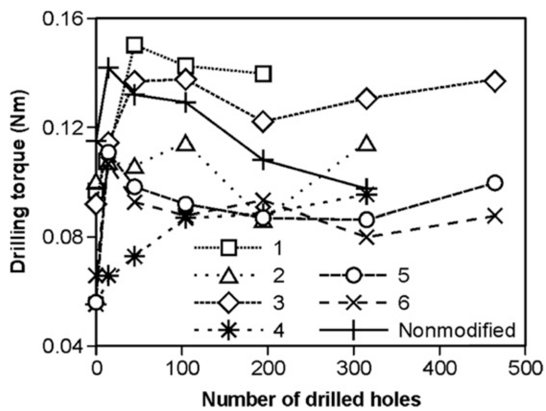

Figure 12. Measured drilling torque after each blunting cycle.

Table 5. Summary of the Pearson correlation coefficient for the tool wear indicator W and cutting forces.

Modification type	1	2	3	4	5	6	Nonmodified
Axial force	0.88	0.90	0.93	0.97	0.99	0.98	0.93
Drilling torque	0.81	0.22	0.85	0.97	0.39	0.12	−0.49

CONCLUSIONS

1. Nitrogen ion implantation improved drill bit wear resistance and prolonged their tool life in most cases. Better results were achieved by the tools treated with higher nitrogen doses and a higher beam current density.
2. A decreased axial force and torque were proven for brand new tools modified with ion implantation. A decrease in the cutting resistance with an increased implanted dose and beam current density was observed.
3. Cutting edge wear resulted in proportional changes in axial force values. Lower correlation relationships were obtained for the torque.
4. The presented results provide the basis for extending the research. Tools implanted with nitrogen ions at different doses were shown to have a longer tool life.

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