MODIFICATION OF CUTTING TOOL SURFACES WITH ION IMPLANTATION

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Abstract. The paper presents some recent achievements on ion implantation enhancement of tool materials. Due to high mechanical, chemical, and thermal loads, materials for cutting tools must exhibit very differentiated properties. Implementation of the ion implantation technique for the tool surface engineering seems to be increasing in the last decades. This way not only the surface of the core material of carbides or ceramics is modified, but also the additional hard surface layers (TiN, TiC, Al_2O_3) undergo ion implantation. In the presented research, ions of rhenium (Re^+), and yttrium (Y^+) were used in the ion implantation process of the Si_3N_4 ceramic cutting tools. After the modification, both the structure and chemical composition of the surface layer are changed. Formation of the defected and amorphous layers is possible, which ensures completely different characteristics than that of a substrate. Among them, enhanced hardness and wear resistance can be named, which resulted with reduced friction forces during the cutting tests, and respectively longer time before the critical wear threshold was reached. In the paper, the results of the tribological tests and the cutting tests are presented together with wear analysis after cutting. From this perspective, the tested ceramic implanted with higher dose 2×10^{17} ions per cm^2 of yttrium exhibited better performance than those of other tested materials. It should be noted that the wear resistance of the cutting tool resulted with better quality of the machined surface. The results presented and discussed in the paper demonstrate feasibility of the ion implantation process for cutting tool surface modification, which is more effective in the case of the hard-to-machine materials and finishing cutting operations. Prolonged service time of the cutting tools and improved machined surface integrity contribute to greener and sustainable manufacturing.

Keywords: cutting; machining; surface engineering; sustainability.

Introduction

Apart from quality management and risk assessment [1; 2], fabrication of any machine or mechanism needs an accurate and high quality machining process. Modern, high-performance cutting tools for high speed cutting, able to exploit all the advantages of CNC machining centres, are of fundamental importance. Among others, tool ceramics is a promising material for a cutting edge [3-5]. In turn, the efficiency of machining processes is closely dependent on wear resistance of the working edges of a cutting insert [6; 7]. This applies primarily to the flank and rake surfaces, since they are in direct contact with the workpiece and the resulting chip.

One of the well-known techniques for increasing tool durability is ion implantation [8; 9]. This process involves introducing ions of various elements into the surface layer of the substrate material [10]. This is possible due to the high kinetic energy of ions, which ensures their permanent penetration into the solid body. The distinguishing advantages of the method include the lack of measurable dimensional changes of the implanted elements due to an atom-thick additional layer, cleanliness of the process performed in vacuum, ability to introduce various elements into various substrates, low temperature of the process, and also coating with substantial material savings. As a result of ion implantation, atoms create a near-surface layer of a thickness of 0.01÷1 μm with different physical and chemical properties than that of the starting material [11]. The depth of ion penetration depends on their energy and is usually 0.2÷0.3 μm, up to a maximum of 1 μm [12]. The implanted ions pose important changes on the structure and chemical composition of the surface layer of the implanted material [13-16]. This allows for obtaining highly defective or even amorphous layers with properties significantly different from the ones of the substrate material [17; 18]. Through adjustment of parameters of the process and with different ions used, this technique makes it possible to obtain desired properties of the surface layer, including tribological properties, increased wear resistance, fatigue resistance, or corrosion resistance [19-21]. Due to the small depth of ion penetration, the process affects the material only within its surface layer, without causing changes to the structure throughout its volume. For this reason, the use of ion implantation to modify tools seems very advantageous.

It is very important to keep in mind the sustainability issues. In particular, the true effect on sustainability can be achieved only when the workpiece, tool, and the process could be modified accordingly [22]. Since the development of cost-effective methods of cutting tool pretreatment contributes to the overall sustainability [23], the effort was undertaken using the ion implantation procedure.

Ion implantation procedure

Ion implantation can be classified as a physical method of shaping the properties of the surface layer of materials. The atoms of the selected element are ionized and then move in the magnetic field, passing through a separator. It separates the ions to be implanted from those that entered the beam accidentally. The next stage is to accelerate the ions to a specific speed at which they reach the assumed kinetic energy, form a stream, and finally hit directly the surface of the processed element covering it with foreign ions. This way a thin coating can be made using a wide range of materials, both metal alloys and non-metal materials, including ceramics, and also polymers, due to the low process temperature of 150 or 200 °C.

It should be noted that modification by ion implantation should not be understood as a coating process. In fact, the obtained surface layer is not a coating, but a significantly modified layer of the original material. There is no phenomenon of building an additional layer.

Despite the small depth of penetration of the substrate with the bombarding ions, the properties of the surface layer of the implanted material change noticeably. This change is caused by the deformation of the crystal structure of the substrate material and increased number of defects in the lattice. This way, the strong compressive stresses are being introduced to the surface layer of the substrate, resulting in increased strength, hardness and abrasion resistance, and other characteristics of the surface layer [24]. Moreover, application of doping ions of elements other than those that form the structure of the substrate material causes local phase changes, formation of new particles, and even transformations leading to amorphization [25; 26]. The lattice defects, including precipitates, grain boundaries, and dislocations in the surface layer of ca. 10 nm thick, contribute to the improvement of the mechanical properties of the material [27; 28].

Materials and methods

In the experiments, multi-edge ceramic cutting inserts made out of Si_3N_4 underwent the ion implantation procedure. During the process usually referred to as MEVVA (Metal Vapour Vacuum Arc), the substrate surfaces were bombarded with ions of yttrium (Y^+) and rhenium (Re^+). The experiments were repeated with the implantation doses of both elements of 1×10^{17} and 2×10^{17} ions per cm^2. The ion beam energy was 65 keV.

To assess the altered tribological characteristics, the tests were carried out using a ‘roller-block’ type tribotester device [29; 30]. The device is useful in assessment of wear resistance during friction of metals and plastics, and in tests of the resistance against seizing of low-friction coatings of highly loaded machine elements, as well as in determination of the properties of technical lubricants. In the test, the ion-implanted surface worked against ŁH15 steel (Polish nomenclature, corresponding with 100Cr6 or 1.3505).

It was found important to perform also cutting tests of the ion-implanted inserts. For that purpose, the inserts were fixed in a typical holder MTJNL 2020K-16W-M, and a typical difficult-to-cut titanium alloy Ti-6Al-4V was cut. Its hardness was 34 HRC. Figures 1 and 2 present the insert used for ion implantation and the cutting test rig.

Fig. 1. **IS9 Si_3N_4–based cutting insert before ion implantation**

Fig. 2. C**utting test rig**

For the tests, the machine tool centre DMG NEF400 CNC was used. In the experiments, the cutting depth was a_p = 0.5 mm at the cutting speed v_c = 50 m·min^{-1} and the feed rate f = 0.15 mm·rev^{-1}. During the cutting tests, no lubricating fluids or coolants were used. The force load was analyzed in its three components, distinguishing the cutting force F_c, passive force F_p, and the feed force F_f. The sampling period was 0.1 s.

Results and discussion

Figure 3 shows diagrams of the friction force *Ft* obtained from the 'roller-block' type tribotester. The curve denoted IS9 represents the results for the non-implanted cutting insert, while the others correspond with the surfaces treated with respective elements (Re^+ and Y^+) and doses (1×10^{17} and 2×10^{17} ions per cm^2). From the analysis, the following trends can be noted:

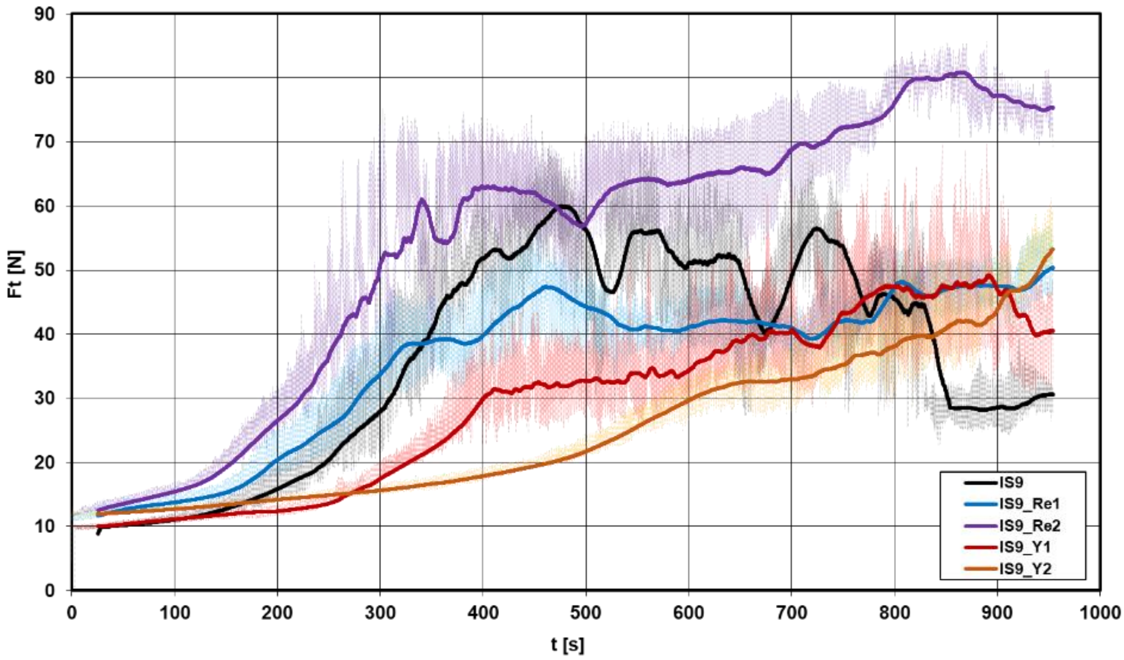

Fig. 3. **Friction force F_t between ceramics IS9 and steel ŁH15 with no lubrication:** Re1 – 1×10^{17} ions per cm^2; Re2 – 2×10^{17} ions per cm^2; Y1 – 1×10^{17} ions per cm^2; Y2 – 2×10^{17} ions per cm^2

- The lowest and the most stable friction was exhibited by the yttrium-implanted insert at dose 2×10^{17} ions per cm^2;
- Other inserts exhibited increase of the friction force during the first 300-400 s, which stabilized afterwards;
- The highest friction force on the entire time span was exhibited by the rhenium-implanted insert at dose 2×10^{17} ions per cm^2;
- The standard, non-implanted IS9 cutting tools exhibited the largest fluctuations of the curve.

Figure 4 presents the diagrams of the cutting force component F_c as results of the cutting tests. From the comparative analysis of the cutting force diagrams, registered during 200 seconds of the cutting test, it can be concluded as follows:

- The lowest and the most stable cutting force took place in the case of the yttrium-implanted insert at dose 2×10^{17} ions per cm^2. In fact, the force *Fc* was almost unchanged during 180 s, jumping by ca. 20% afterwards;
- Other inserts exhibited substantial increase of the cutting force before 50 s, with gradual increase afterwards;
- In the case of the inserts implanted with 1×10^{17} Y^+ per cm^2, the starting point was the lowest, ca. 170 N, but after 100 s the force F_c started to increase rapidly reaching 450 N by the end of the test;

- The rhenium-implanted inserts exhibited uniform increase at the cutting force with rather small fluctuations;
- The standard, non-implanted IS9 cutting tools exhibited the largest fluctuations of the respective curve.

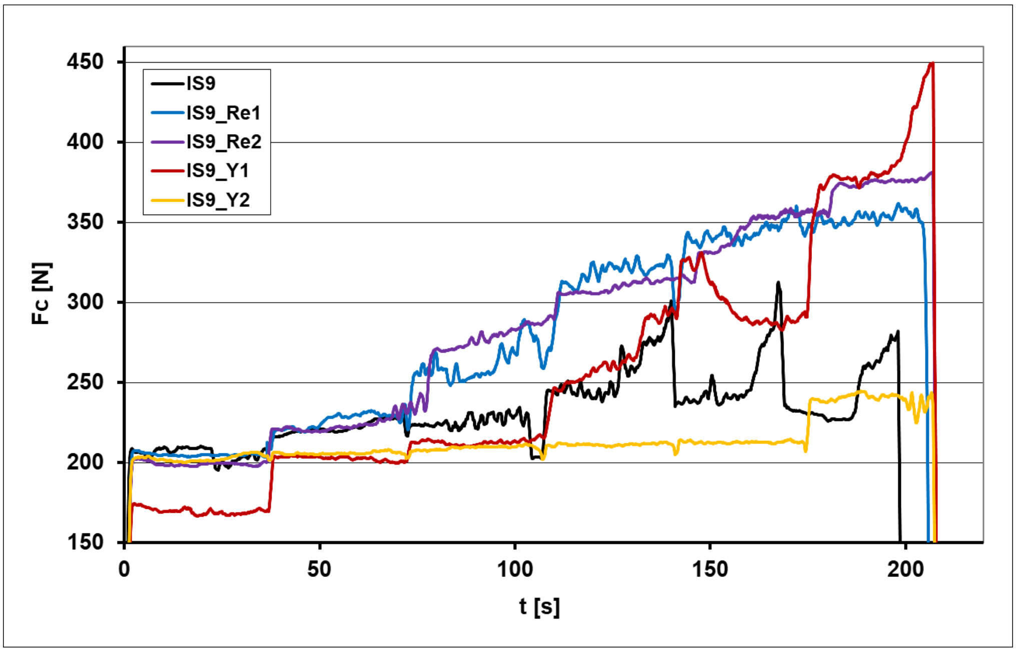

Fig. 4. **Cutting force component F_c during the cutting tests:** Re1 – 1×10 ^{17} ions per cm^2; Re2 – 2×10 ^{17} ions per cm^2; Y1 – 1×10 ^{17} ions per cm^2; Y2 – 2×10 ^{17} ions per cm^2

Figures 5 and 6 present the examples of the worn rake surfaces after the cutting tests of non-implanted and rhenium-implanted inserts.

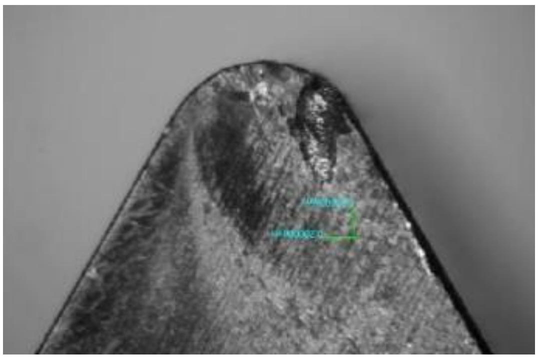

Fig. 5. **Non-implanted IS9 Si_3N_4–based cutting insert after the cutting test**

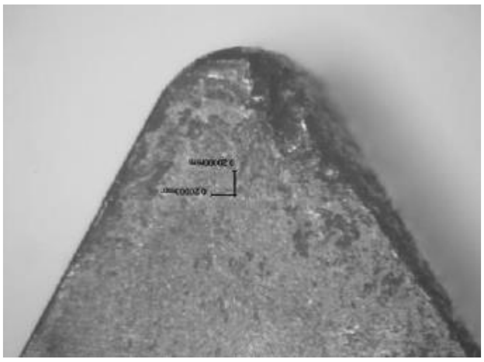

Fig. 6. W**orn cutting insert (Re $^+$ 1×10 ^{17} ions per cm^2)**

Notably, the wear resistance of the ion-implanted was reduced in terms of VBc wear, while no significant difference was found in the case of the notch wear VBn. It should be noted, however, that the wear resistance of the cutting tool resulted with better quality of the machined surface. The results demonstrate feasibility of the ion implantation process for the cutting tool surface modification, which resulted in reduction of the cutting forces, friction forces and wear. Improved quality and machined surface integrity, as well as prolonged service time of the cutting tools contribute to greener and sustainable manufacturing.

Conclusions

1. Ion implantation of Si_3N_4–based ceramic cutting tools improved their tribological properties and the cutting performance.

2. Among the tested variants, implantation with Re^+ at dose of 1×10^{17} ions per cm^2 was the least effective.
3. In turn, ion implantation of Si_3N_4–based ceramic with Y^+ at dose of 2×10^{17} ions per cm^2 provided the smallest cutting forces and friction forces.
4. No substantial differences between the wear resistance of the tested ion-implanted cutting inserts were found.

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