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Ion implantation of the tool's rake face for machining of the Ti-6Al-4V alloy

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A R T I C L E I N F O

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A B S T R A C T

In the paper, the results of experimental ion implantation of subsurfaces of NTP 25 multilayer coating on a carbide cutting tools inserts is presented. The implantation was performed with silicon ions, as well as with the mixture of silicon and nitrogen ions. After the implantation, the inserts characteristics were measured to determine the impact of implanted ions. It was found that the ion implantation led to the increase of the inserts hardness (up to 17.5%), decrease of the friction coefficient, and decrease of the cutting force magnitude during machining of the Ti-6Al-4 V alloy. Thus, it was proved that the ion implantation may be used as an effective method to improve the cutting tools characteristics for the machining of difficult-to-cut materials.

1. Introduction

Due to their extraordinary properties the titanium alloys are widely used in various branches of industry, e.g. in aeronautics and space industry [1] or in medicine, and the Ti-6Al-4 V alloy is the most widely used one [2]. Such a wide range of applications is a consequence of their unique mechanical properties and significant corrosion resistance they exhibit. On the other hand, due to their endurance and relative elongation (6–15%), as well as low heat transfer ability they are very difficult-to-cut materials. Those properties are responsible for generation of a large amount of heat in the machining region. As a consequence of low heat transfer conductivity of titanium alloys, the conventional cooling methods become ineffective [3] and a large amount of heat (not carried away with the chipped material) penetrates into the insert. Therefore the use of the specially prepared cutting tools and special cooling techniques becomes necessary during machining. For machining of the difficult-to-cut materials, the tool companies offer inserts with special coatings (typically multilayer compositions, where outer layers ensure low friction coefficient and inner layers constitute a barrier for the heat generated in the machining region). Above that, new synthetic cooling liquids and new cooling techniques of the machining region, e.g. high pressure cooling, pressured gas cooling [4], or cryogenic cooling [5], are used. These technologies are capable to carry away more heat from the machining region and to ensure higher durability of the cutting tool, compared to conventional cooling. Another approach is also the Thermally Assisted Machining (TAM), a technique that allows to decrease the cutting forces and to improve the machinability of the material [6].

The creation of hard layers using PVD methods (by the selection of the process, its parameters and components) enables to obtain layers with diverse physical and mechanical properties [7,8]. It is possible to obtain a specific microstructure, hardness and a residual stress in the subsurface layers of the coating [9,10]. Similar modifications of the structure are also possible using methods of surface engineering, e.g. using ion implantation techniques to modify the obtained layers or to facilitate the process of their deposition using IBAD, it is possible to induce changes in tribological properties [11], hardness or surface layer tensions [12,13]. All these techniques are aimed at reducing wear of the cutting tools. However, few studies can be found that assess the influence of ion implantation on the lifetime of carbide inserts at higher temperatures under real working conditions [14,15]. Thus, the influence of the silicon and nitrogen ion implantation into the subsurface layers of the rake face of carbide inserts on their properties is the subject of this work.

2. Surface integrity

Monitoring and control of process parameters and their variations during the machining are important for quality assurance, especially in case of in ultraprecision machining (UPM) processes. In order to achieve that, the experimental and theoretical investigations on surface integrity in material removal processes have been performed for years. To challenge complex dynamic phenomena and nonlinear and nonstationary processes, various approaches have been proposed. Many scholars presented experimental techniques for the measurement of various surface integrity parameters. Jawahir et al. [16] reported

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results of the study on surface integrity parameters such as residual stresses, hardness and roughness in turning, milling, grinding, and EDM.

Sealy et al. published the results of exploration of the process signature by examining the relationship between energy consumption and surface integrity in hard milling [17]. Their assumption was that every cutting process had a unique process signature correlating to surface integrity, critical to the functionality. The authors analyzed the energy consumption as one of the process signature metrics, using new characteristic parameters. They found that net cutting specific energy was an effective process signature for surface integrity and proposed some methods to optimize energy consumption and surface integrity. On the other hand, in aero engine manufacturing process, where increased reliability is required because of safety reasons, the surface integrity was treated as a complex quality measure regarding also the condition of the subsurface. It was emphasized that the integrity at the machined surface depends on the machined material properties, but also on the machining parameters and the condition of the cutting edge. Thus, Klocke et al. [18] used the temperature in the cutting zone as a measure to connect the cutting parameters and selected measures of the surface integrity.

Another investigations were conducted on the evolution of the residual stresses and re-hardened white layer during finish hard turning [19]. The authors found that the residual stress pattern was dominated by changes in cutting forces caused by the tool wear process. As the flank wear accelerated, the normal sliding force generated tensile residual stress at the surface of the machined detail and reduced the magnitude of compressive stress below the surface. The paper reports that the tool wear increased beyond a critical value, led to discontinuity between normal and tangential forces and proposes a new tool-life criterion for controlling surface integrity.

Development of sensing and communication technologies enabled to work out the sensor-based monitoring approaches for detection of variations in the machining process. For example, Kan et al. [20] proposed a new heterogeneous recurrence monitoring approach to detect dynamic transients in ultraprecision machining processes. It consisted of four stages: first, a high-dimensional state space was reconstructed from in situ sensing signals. Second, a Dirichlet Process (DP) driven clustering procedure segmented the state space into local recurrence regions. Third, a fractal representation was used to describe state transitions among recurrence regions and to extract subsequent measures to quantify heterogeneous recurrence patterns. And fourth, a multivariate control chart with heterogeneous recurrence features was integrated. It was able to perform both in situ monitoring and predictive control of the UPM process. Authors reported that experimental results proved the ability of the proposed approach to detect effectively transitions with a small magnitude, and to identify the shift from stable cutting (Ra = 35 nm) to unstable cutting (Ra = 82 nm) in UPM processes [20].

In order to assess the influence of the rake angle on the surface integrity and fatigue performance of hard machined surfaces, Choi applied the crack propagation rate integrated from the initial crack size to the final crack size [21]. He found that when the loading is increased, the calculated crack propagation life decreases more significantly than the calculated crack initiation life. The effect of the rake angle on the crack propagation life increases significantly under lower loading conditions.

3. Experimental research

3.1. State of art

The first attempts to modify characteristics of materials by ion beams were reported in the early 1960 s, mostly in the frames of nuclear science. In the natural way, the first objective of ion implantation was to improve the desired electrical properties of materials, especially semiconductors, by the implantation of active dopants such as boron into silicon [22]. Soon it was found, however, that the mechanical characteristics of the ion implanted surface were altered in significant way, too, and the experiments on the cutting tools gave very good results. Vesnovsky described different wear mechanisms of metal cutting tools and proved that almost all physicomechanical properties of the tool material responsible for its wear resistance can be changed with the ion beam irradiation [23]. Poletika et al. reported results of the study of the ion implantation effects on surface contour, microhardness, micro-, and submicrostructures, as well as chemical composition of surface layers of cermet hard alloy tools and high-speed steel tools. They found that a thin crystalline structure of carbide grains was formed in this layer and the residual compressive strains increased the fatigue resistance of the tools. Formation of high-strength compounds such as borides, oxides, nitrides, etc. in the surface layer was recorded. The authors performed also the wear resistance tests for the implanted tools and revealed that the effect of the cutting tool implantation depends also on the type of material being machined, as well as on the machining process conditions [24].

García and Rodríguez [25] described the on implantation techniques for non-electronic applications. They pointed out that tribology, as well as corrosion and wear resistance are the topics most studied in research on ion implantation of metals and alloys. The researchers focused also on the control of friction coefficient. Out of the reported investigations, nitrogen implantation performed excellent results in terms of hardness, and wear resistance improvement, with hardness increasing with the implanted dose. In fact, more than 90% of ion implantations in non-electric applications are nitrogen implantations.

3.2. Apparatus

The purpose of this work was to investigate the influence of ion implantation into the subsurface layers of the rake face of carbide inserts on the change of their properties. The SPUN 120304 (ISO standard) inserts with NTP 25 multilayer coating (TiN + Al_2O_3 + TiCN + TiC) implanted with silicon ions (i) and with the mixture of silicon and nitrogen ions (ii). The parameters of implantation process were collected in the Table 1. The choice of the donor ions was made based on papers by Wang et al. [26] and by Shtansky et al. [27] where it was shown that TiN layers oxidize relatively quickly with respect to TiO_2 in 550 °C. They also showed that the addition of silicon or aluminium significantly increases the high temperature corrosion resistance.

In order to further understand the inf ulation of complex shaped coated c luence of modifications of NTP 25 coating on the tribological properties the friction coefficient measurements were performed on implanted and unimplanted inserts, as well as the EDS analysis of the tested surfaces. The measurements were performed on a standard T01 tribometer, in the pin-on-disc setup, where the pin was made from Ti-6Al-4 V alloy and the studied insert constituted the disc. The force transducer was of HBM-S2/100 N type, of nominal force value 100 N with maximal loadability 150%. Its nominal sensitivity was 2 mV/V with non-linearity δ_{nl} = 0.05%. The shape and size of the pin ensured nominal contact pressure during the friction tests. The measurement setup is schematically illustrated on the Fig. 1, where the arrows indicate rotation direction, velocity v and the force F on the pin.

Both implanted and unimplanted inserts underwent the turning

Table 1
Ion implantation parameters.

Ion type	Ion dose [Ion/cm^{-2}]	Beam energy [keV]
(Si^+)	2×10^{17}	65
($Si^+ + N^+$)	$(1 + 1)\times10^{17}$	65