CIRP Annals - Manufacturing Technology xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Bias voltage optimum adjustment considering coatings' strength and adhesion requirements when cutting various steels

G. Skordaris (2)[a,b,*], K.-D. Bouzakis (1)[a,b], T. Kotsanis [a,b], P. Charalampous [a,b], E. Bouzakis [c], R. Bejjani [d]

[a] Laboratory for Machine Tools and Manufacturing Engineering (LMTME), Mechanical Engineering Department, Aristotle University of Thessaloniki, Greece
[b] Fraunhofer Project Centre Coatings in Manufacturing, in LMTME and in Fraunhofer Institute for Production Technology in Aachen, Germany
[c] German University of Technology in Oman, Department of Engineering, Oman
[d] Sandvik Coromant, Sweden

ARTICLE INFO

Keywords:
PVD-coating
Wear
Adhesion

ABSTRACT

PVD coatings were deposited at various bias voltages on cemented carbide inserts. The coating's mechanical properties, fatigue and adhesion were determined via FEM-supported evaluation of nanoindentation, perpendicular and inclined impact test results. The coated inserts were applied in milling hardened and normalized steel. For explaining the wear evolution based on the cutting loads and stress fields developed in the coating and its substrate, FEM calculations were performed considering among others the films' strength and adhesion. According to the workpiece properties, certain coating's parameters become prevailing for the tool life. These depend on the bias voltage and facilitate its optimum adjustment.

1. Introduction

Various PVD coating properties significantly affecting the coated tool life can be attained by applying different deposition methods and parameters [1–4]. Recent research revealed the crucial effect of the bias voltage on the coating strength data and herewith on the cutting performance of coated tools [5,6]. A bias voltage augmentation increases the mechanical properties of PVD coatings due to the consequent formation of dislocations in their crystalline structure. However, the coating adhesion may be deteriorated [6]. The latter becomes prevailing for the tool life at elevated workpiece material strength associated with high cutting loads. Hence, the bias voltage has to be adjusted considering both coating mechanical properties and adhesion. For highlighting this issue, tools coated at different bias voltages were used in milling steels of diverse mechanical strength. The wear evolution on the coated tools was explained with the aid of the developed stresses in the PVD films during milling. These were calculated by means of FEM supported procedures, taking into account among others the film mechanical properties and adhesion occurred at the applied bias voltages.

2. Experimental and computational details

The geometry and further data of the used cutting inserts are presented in Fig. 1. PVD TiAlN films were deposited by Sandvik on cemented carbide inserts with R245-12 T3 specifications. Hereupon, three individual PVD processes were carried out by varying the substrate bias voltage. More specifically, three groups of coated inserts were prepared at a low (−30 V), medium (−50 V) and multi (−30 V and −90 V) bias voltage. In the first two cases, the bias voltage was kept constant throughout the PVD process resulting in the formation of film structures with almost uniform properties. In the third case, the bias voltage was changed few times from −30 V up to −90 V during the coating deposition. Main workpiece material properties used in the conducted milling experiments are also displayed in Fig. 1. A hardened steel (42CrMo4 QT) and a low carbon normalized one (15CrNi6 N) of diverse strength were applied for obtaining different cutting loads and herewith coating stresses in the performed milling investigations.

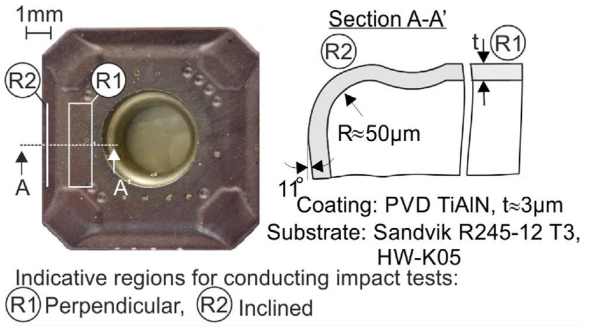
For determining the mechanical properties of the coatings deposited at various bias voltages, nanoindentations were carried out by a FISCHERSCOPE H100 device. The load–displacement diagrams for the investigated film cases are presented in Fig. 2. According to the achieved results, a bias voltage augmentation during the film deposition reduces the maximum indentation depth. This hardening effect is explained considering the residual stress growth imposed by the formation of dislocations in the coating crystalline structure when the bias voltage increases [6].

---

* Corresponding author at: Laboratory for Machine Tools and Manufacturing Engineering (LMTME), Mechanical Engineering Department, Aristotle University of Thessaloniki, Greece.
E-mail address: gskor@eng.auth.gr (G. Skordaris).

https://doi.org/10.1016/j.cirp.2018.03.023
0007-8506/© 2018 CIRP.

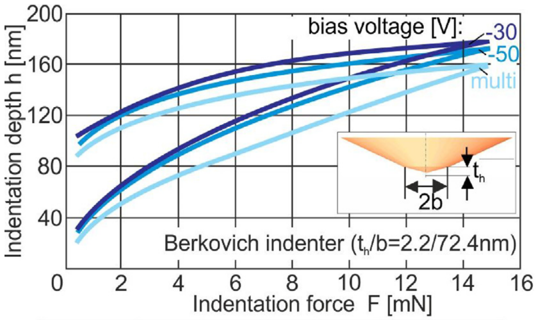
Please cite this article in press as: Skordaris G, et al. Bias voltage optimum adjustment considering coatings' strength and adhesion requirements when cutting various steels. CIRP Annals - Manufacturing Technology (2018), https://doi.org/10.1016/j.cirp.2018.03.023



Workpiece Material	42CrMo4 QT	15CrNi6 N
Hardness HV	300	180
Mechanical properties $E/S_Y/S_M$ [GPa]	210/0.7/1	210/0.4/0.7
Chemical composition C/Cr/Si/Mn [%]	0.43/1.1/0.2/0.7	0.15/1.5/0.2/0.5

E : Elasticity modulus S_Y/S_M : Yield/Rupture stress

Fig. 1. Main data of the applied coated cutting inserts and workpieces.



[GPa] / [V]	E	S_Y	S_M	S_Y/S_M [-]	S_D	CSR [-]
-30	600	3.9	5.4	0.72	2.1	0.05
-50	600	4.3	5.9	0.73	2.2	0.02
multi	600	5.2	7	0.74	2.4	0.005

S_D :Fatigue endurance stress CSR :Contact Stiffness Ratio

Fig. 2. Nanoindentation results on the investigated coatings deposited at various bias voltages and the determined mechanical and adhesion data.

Via an appropriate FEM supported evaluation of the obtained nanoindentation results [1], the coating mechanical properties such as of the elasticity modulus, yield and rupture stress were determined. These are captured in the table of Fig. 2. The accuracy of the previously mentioned experimental-analytical procedures was verified by determining the elasticity modulus of reference materials. The attained data were within properties deviations of the tested materials amounting to roughly ±1.2% [7]. According to the attained results the yield and rupture stress as well as their corresponding ratios grow when increasing the bias voltage from −30 V up to −50 V and from −30 V up to −90 V repetitively for few times. The elasticity modulus remains practically stable in all cases whereas the small enlargement of the yield to rupture stress ratios is not sufficient to cause a film brittleness [6].

Furthermore, perpendicular and inclined impact tests were carried out on the coated cutting inserts in the regions R1 and R2 respectively, as shown in Fig. 1. These aimed at determining the coatings' fatigue endurance stress and their adhesion with the aid of appropriate FEM supported evaluation methods described in Refs. [1,8]. The coating adhesion was characterized by the contact stiffness ratio (CSR) introduced in Ref. [8]. CSR is defined as the ratio of the tangential to the normal stiffness of the employed contact elements for simulating the coating–substrate interface adhesion. The fatigue endurance stresses S_D of the investigated coatings are also illustrated in the table of Fig. 2. Based on these data, on the one hand, it can be concluded that the coating's strength and fatigue endurance grow when applying a higher bias voltage. On the other hand, the contact stiffness ratio CSR diminishes and thus, the adhesion deteriorates as the bias voltage increases.

3. Theoretical and experimental investigations in milling using tools coated at various bias voltage

3.1. FEM supported determination of the thermal and mechanical loads on the coated cutting edge during milling

For facilitating a targeted optimization of the bias voltage when coated tools are used in milling materials of different strengths, it is necessary to know which film property, a high mechanical strength or adhesion is more dominant for the wear evolution. In the present paper, the effect of these film properties on the coated inserts cutting performance was investigated in milling at various mechanical loads, but at almost equal thermal ones in the most endangered cutting edge transient position ① from the flank to the tool rake (see Fig. 3). Therefore, the cutting speed in the case of low carbon normalized steel had to be adjusted for attaining a similar cutting temperature course versus the cutting length l_c in the mentioned position ① as in milling hardened steel. The related temperature's fields in milling these steels were calculated by the DEFORM-2D software employing the workpiece material data available in its library. In Fig. 3, the course of the developed cutting temperatures versus the cutting length l_c is presented at the indicated positions ① and ② of the coated cutting edge. The wear evolution in position ① is at most intensive, as further explained. For attaining almost equal thermal loads in this position when milling 42CrMo4 QT and 15CrNi6 N, the cutting speed in the latter material case had to be increased from 200 m/min to 400 m/min (see Fig. 3). The cutting temperature evolution on the position ② is also demonstrated. At this position, an intense coating wear develops when milling hardened steel with coated inserts of poor adhesion, as further in the following described.

Further FEM calculations were performed using the ANSYS software for determining the stress fields developed in the tool cutting wedge. In these calculations, the geometry of the cutting

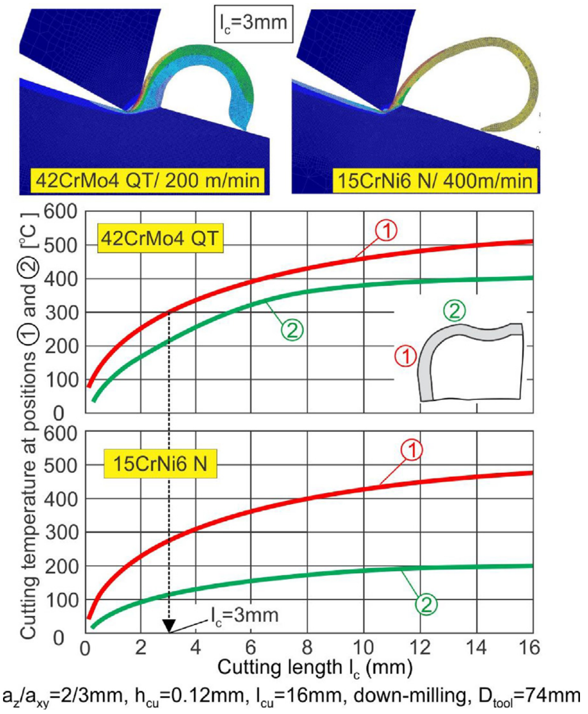


Fig. 3. Developed temperatures at the coated tool wedge positions ① and ② versus the cutting length in milling various steels.

Please cite this article in press as: Skordaris G, et al. Bias voltage optimum adjustment considering coatings' strength and adhesion requirements when cutting various steels. CIRP Annals - Manufacturing Technology (2018), https://doi.org/10.1016/j.cirp.2018.03.023