IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received July 1, 2019, accepted July 21, 2019, date of publication July 30, 2019, date of current version August 16, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2931976

Investigation of the Cutting Performance of Cutting Tools Coated With the Thermo-Reactive Diffusion (TRD) Technique

ŞENOL ERTÜRK[1] AND OĞUZ KAYABAŞI[2]
[1]Department of Mechanical Engineering, Faculty of Engineering, Duzce University, 81620 Duzce, Turkey
[2]Department of Biomedical Engineering, Faculty of Engineering, Duzce University, 81620 Duzce, Turkey

Corresponding author: Şenol Ertürk (senolerturk540@hotmail.com)

ABSTRACT The life of cutting tools used in metal cutting operations is limited due to wear. Therefore, increasing wear resistance is of great importance for minimizing economic losses. By using different coating techniques, tools may be coated with harder compounds for enhancing wear resistance. Tool hardness and toughness are also increased through coating. In this study, boron and titanium coatings were applied on round cutting tool surfaces made of AISI D2 and AISI M2 steels by the thermo-reactive diffusion technique. AISI D2 cutting tool surface was coated with boron at 950 °C for 1 hour, and AISI M2 cutting tool surface was coated with boron at 1000 °C for 1 hour. After boron coating, the surfaces of the samples were coated with titanium at 1050 °C for 1 hour. The coated samples were characterized by using SEM, X-ray diffraction, EDS analysis, and micro hardness tests. Machining tests were performed to observe the wear resistance of the samples and the roughness of the machined surface. Machining tests were carried out on DIN 1651 free-cutting steel. Cylindrical turning tests were run at three different cutting speeds, 38, 73, and 138 m/min. and at three different feeding values, 0.08, 0.12, and 0.16 mm/rev. The results showed that the boron- and titanium-coated tools performed 50% better than the just boron-coated tools. In terms of surface roughness, it was determined that there was no significant difference between the coated and uncoated tools. The cutting performance values of our coating method were compared to those of ISCAR brand RCMT (code of the insert used in turning and milling operations in the ISO norm) inserts coated with the PVD and CVD methods, and it was seen in the experimental results that the tool coated with the TRD method performed better.

INDEX TERMS Boron, coatings, chemicals, cutting tools, surface roughness, titanium.

I. INTRODUCTION

Surface roughness is quite important in terms of strength and providing the optimum operational conditions of machine parts. The factors affecting surface roughness are the quality of the cutting tool that is used, the type of coating, the hardness value, the chemical composition of the material removed and the rigidity of the lathe. Different coating methods have been developed for cutting tools to increase the life of the cutting tool and reduce surface roughness. A general classification of the surface coating methods included in this study are shown in Table 1. Chemical vapor deposition (CVD), physical vapor deposition (PVD) and thermo-reactive diffusion process (TRD) are used to increase the tool's lifetime in the manufacturing industry. A. Ginting et al. studied coated $TiN/Al_2O_3/TiCN$ by CVD and coated carbide TiCN by the PVD method in turning AISI 4340 steel.

It was reported that both coatings have a potential to increase tool life varying between 8.1 and 27.5 minutes for CVD and 4.8 and 40.3 minutes for PVD at 0.2 mm flank wear [1]. N. Michailidis investigated temperature-dependent coating properties associated with milling performance in Ti6Al4V at different cutting speeds in the cased of a PVD AlTiN-coated tool. A certain correlation is observed between the coating cutting performance at various cutting speeds by the temperature-dependent film mechanical properties [2]. Shuho Koseki *et al.* investigated the damage of cutting tools coated with the method of physical vapor deposition (PVD) during constant turning of a titanium alloy (Ti-6Al-4V). It was found that TiN coating on the cutting tool was worn faster than uncoated cemented carbide cutting tool [3]. Reza Soltani *et al.* studied depositing of NbC coatings on

The associate editor coordinating the review of this manuscript and approving it for publication was Ming Luo.

TABLE 1. A general classification of surface coating methods.

SURFACE COATING METHODS								
Gaseous state			Solution state			Molten or semi molten state		
CVD	PVD	IBAD	Chemical solution deposition	Electro chemical deposition	Sol gel	Laser	Thermal spraying	Welding

an AISI L2 steel substrate by thermo reactive diffusion and investigated its growth kinetics. The tribological characteristics of the coated and uncoated steel were evaluated by using a pin-on-disc set-up. It was found that significantly higher abrasion resistance and lower coefficient of friction for the coated metal were found in comparison to the bare metal [4]. Alejandro Orjuela G. *et al.* studied Niobium carbide coatings deposited on AISI 1045 low alloy steel by thermo reactive diffusion (TRD). The results showed that the thickness of the carbide coatings did not significantly change with an increasing amount of ferroalloy [5]. S. Tanaka *et al.* studied the effect of a dry micro-blasting treatment on the fracture resistance of (Al0.60Ti0.40) N coated cutting tool by PVD. The results indicated that the dry micro-blasting effect on fracture resistance was larger for the Low-σ coating than for the High-σ one [6]. Denis Boing *et al.* studied the limiting conditions for application of PVD and CVD coated cemented carbide tools in turning of three hardened steels, steel hardness and consideration of volume fraction in microstructure of carbides. It was found that suitable limitation conditions for application of coated cemented carbide grades in hard turning as a function of the steel microstructure and level of hardness [7]. G.K. Dosbaeva *et al.* compared the performance of CVD coated tungsten carbide tools with low Al_2O_3 layer to low-content PCBN tools for hard turning of D2 tool steel. It was found that the coated carbide tool could be better PCBN in machining the selected workpiece within a certain range of cutting speeds [8]. K. Bobzin *et al.* deposited nitride (Cr,Al)N, which is an oxynitride (Cr,Al)ON and CrN/AlN nanolaminate on steel AISI 420 by the PVD method. It was found that thermal effects induced during laser structuring lead to an increasing ratio of amorphous form on the crystalline domains of the PVD coating, causing a reduction in hardness [9]. R. Suresh et al. evaluated the performance of $TiC/TiCN/Al_2O_3$ coatings on a cemented carbide substrate by chemical vapor deposition (CVD) for metal cutting of hardened AISI 4340 steel. It was found that the optimum combination of low feed rate and low cutting depth with high cutting speedwas useful for reducing machining force. Higher feed rates are required to minimize the specific cutting force. Processing power and cutting tool wear increase almost linearly with the increase in cutting speed and feed speed. A combination of low feed rate and high cutting speed is required to minimize surface roughness [10]. F.E. Castillejo *et al.* deposited Niobium carbide, chromium carbide and niobium–chromium carbide coatings by the thermo reactive diffusion (TRD) method on AISID2 steel and tested wear and corrosion resistance. It was found that the Nb-Cr coating could perform well in applications where good mechanical properties are required, but not for parts that are exposed to corrosive environments [11].

CVD is usually carried out at high temperatures to ensure a significant accumulation on the coating material. CVD can be well below the tempering range of tool steels and requires expensive, complex equipment. Due to the limited diffusion generated during the process, it shows a weaker coating adhesion [12]–[14]. PVD coating is applied by the method of evaporating the material onto the surface of the cutting tool as a thin film by vaporizing or blasting high energy ions by the method called splashing [15], [16]. The TRD method is a relatively simple and economical coating method which allows obtaining coatings with high corrosion resistance on steels [17], [18]. With this method, the surface of the cutting tool may be coated with boron and titanium to increase the life of the cutting tool.

Boron coating is a surface hardening process realized by diffusion-based chemical reactions at high temperatures. When applied to steel-based materials, hard boride layers are formed on the material surface [19], [20]. In boron-coated surfaces, very good abrasive and adhesive wear resistance is obtained by forming compounds such as $FeB/F_{e2}B/TiB/CrB/Cr2B3$, which are characterized by high abrasion resistance and low friction resistance during their format6ion, providing very good abrasive and adhesive wear resistance [21]–[23]. Additionally, boron-coated surfaces can exhibit high corrosion/erosion resistance against diluted acidic and alkaline environments [24]. Heat treatment may be applied on steels after the boron coating process. With the TRD method, coatings consisting of borides, nitride, carbide, carbo-nitride and boron nitride compounds may be applied to metals capable of forming hard compounds such as titanium, vanadium, tantalum and molybdenum. As the hard ceramic layers obtained after the process are formed by reaction with the base material, a high-strength base material and coating interface are formed which are bonded to each other metallurgically [25].

Many researchers have studied the effects of coatings on surface roughness by using different coatings. Gupta *et al.* [26] developed three types of PVD cutting tools (TiN, AlCrN and TiAlN), and the cutting performance of these tools were investigated in turning of C45 steel. Staszuk *et al.* [27] determined the effects of the ALD +PVD hybrid coating material structure on coating properties. Zheng *et al.* [28] focused on the effect of cutting tool on wearing mechanism and surface roughness. Cutting parameters with the coated carbide tool were experimentally

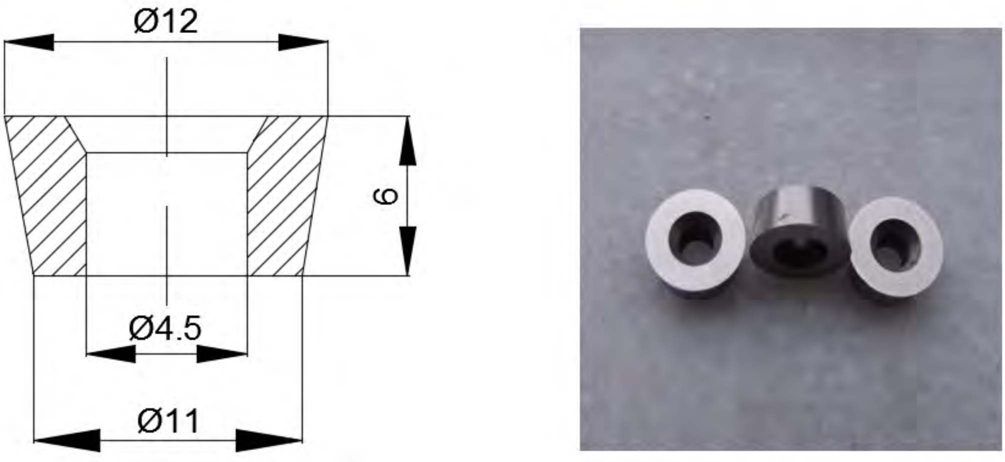

FIGURE 1. Geometric structures of cutting tools.

studied [29]–[31]. In the study, wear mechanism, adhesion, comminution, fatigue, diffusion, oxidation parameters of single or multilayer coated cutting tools were investigated.

In this study, cutting tools were manufactured from AISI D2 and AISI M2 steels. Two different coating materials were used by the TRD method to increase the cutting performance of the cutting tools. Boron coating and boron + titanium coated cutting tools were subjected to characterization and other coating methods, and cutting performances were compared. Then, a test setup was created in a universal lathe machine. The wearing behavior of the coated cutting tools using free cutting steel (9SMnPb28) and non-coated cutting tools were experimentally investigated. In order to investigate the performance of the most feasible base and coating materials which were determined by the experiments carried out by using two base and two coating materials, the wearing behavior of ISCAR brand RCMT type PVD and CVD coated cutting tools and the results of our study were examined. Tool wear and surface roughness measurements were performed during the cutting tests.

II. EXPERIMENTAL SETUP

In this study, boron and titanium coating processes were applied with the use of the TRD method on cold work steel and high-speed steel, which have been rapidly increasing in usage in recent years in the manufacturing industry. For this purpose, AISI (American Iron Steel Institute) D2 and AISI M2 steels were selected due to their superior properties like high strength based on thermal treatment, quite well wear resistance and thermal stability.

The ideal coating layer could not be obtained in coatings made on the surface of the AISI D2 cutting tool below the temperature of 950 °C and in less than 1 hour. Very thin and faint coating layers could be obtained in the coatings made on the surface of the AISI M2 cutting tool below a temperature of 1000 °C and in less than 1 hour. In the case of coatings over 1000 °C and a period of 1 hour, the coating layer was obtained as clear. As the coating temperature and coating duration increased, the thickness of the coating layer increased. However, the cost of coating also increased. Therefore, the ideal coating temperature was determined as 950 °C for boron coating of the AISI D2 surface, 1000 °C for boron coating of the AISI M2 surface, and the ideal coating time was determined as 1 hour. So, the materials were coated.

The boron coating process was applied on the AISI D2 steel at 950 °C for 1 hour and on the AISI M2 steel at 1000 °C for 1 hour. After the boron coating, titanium coating was applied to the surface of the specimens at 1050 °C for 1 hour due to its properties like high hardness, lubricity and preventing the heat transfer from chip to tool thanks to low thermal permeability, minimizing crater formation and free surface wearing. Therefore, cutting and feed speeds can be increased by up to 20%.

The properties of the layers formed on the surfaces of the coated samples were examined by scanning electron microscopy (SEM), X-ray diffraction analysis and microhardness measurements. The wear behavior of the boron-coated and titanium-coated samples were investigated by machining from the free cutting steel (9SMnPb28) in the test setup formed on the lathe. Additionally, the cutting forces, feed forces and surface roughness values that formed during the cutting tests were measured, and the performance values of only the heat-treated cutting tools and those coated with 2 different coating materials were compared to each other.

A. AISI D2 AND M2 CUTTING TOOL SAMPLES

The samples of the cutting tools used in the experiments were produced from AISI D2 and AISI M2 steel by using a material of Ø 15 mm diameter in the geometry and sizes as seen in Fig. 1. In order to obtain a homogeneous coating layer on the samples, the surfaces were polished with sandpaper after being ground.

TABLE 2. Chemical analysis of D2 and M2 steel.

	Chemical Composition (% by Weight)										
Steel Type	C	Si	Mn	P	S	Cr	Ni	Mo	W	V	Fe
AISI D2	1.7560	0.2710	0.2910	0.0353	0.0107	11.5600	0.2140	0.6090	0.0150	1.0000	84.1060
AISI M2	1.0100	0.3450	0.2820		0.0105	4.3600	0.0539	4.6400	6.0300	2.0800	80.7000

TABLE 3. Features of Ekabor products.

Type	Grain Size (μm)	Density, Compact, gr/cm^3	Property
EKabor 2	≤ 850	1.50	Perfect surface quality easy separation from the workpiece after the process
EKrit	≤ 420	1.55	Cover material, prevents oxygen leakage into powder boring products during boring

The spectral analyses of the steel samples used in the experiments were carried out by the Foundry Master spectral analyzer. The spectral analysis of AISI D2 and AISI M2 steels is given in Table 2.

B. BORON COATING PROCESS WITH TRD METHOD

Firstly, boron coating was applied to the cutting tools that were used in the experiments. This method was carried out in a PROTHERM electric oven with a processing accuracy of ± 1 °C which could reach 1200 °C. 3 mm thickness and Ø70×100 mm diameter closable mouth AISI 316L stainless steel cylindrical pots were used for the process. Boron coating was performed in a solid medium. Ekabor-2 as a boron source and Echite powder mixtures as a deoxidant were used. The properties of the Ekabor boronizing products are given in Table 3.

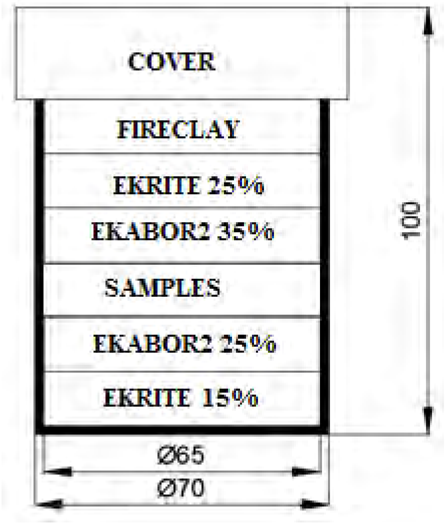

FIGURE 2. Preparation of boron coating pot.

TABLE 4. Chemical composition of ferro-titanium.

Material	Ti	Al	Si	P	S	N	C	Mn	Grain Size (mm)
Ferro Titanium	72.80	4.69	0.18	0.006	0.006	0.19	0.20	1.50	10-50

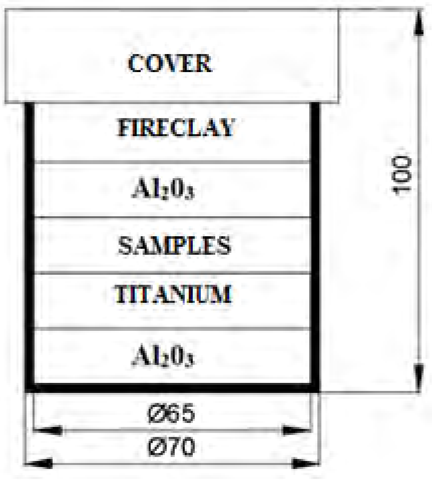

FIGURE 3. Preparation of titanium coating pot.

The boron coating process was carried out at 1000 °C for 1 hour. The samples of the inserts with the geometric characteristics are shown in Fig. 1. These were embedded in the pot filled with boron powder prepared as in Fig. 2 and the lid of the pot was closed tightly. New powder mixtures were used for each boring process. Inside the pot, the sample was placed between the sample and the edge of the pot with a minimum of 12 mm of boron powder and placed in the electric furnace which was raised to the process temperature. After boring, the samples were cooled in s pot to room temperature.

C. TITANIUM COATING PROCESS WITH TRD METHOD

In this process, the titanium coating process has been carried out on the surfaces of boron-coated cutting inserts as described above and for the comparison of coating types. The mixture of chemical powders used in titanium coating process consisted of 50% by weight ferro-titanium, 25% alumina, 15% ammonium chloride (NH_4Cl) and 10% naphthalene ($C_{10}H_8$). The results of the chemical analysis of the ferro titanium material are given in Table 4.

Alumina was placed on the base of the coating pot. The coating powder, sample, alumina and very little naphthalene were added, and sealing was provided by chamotte

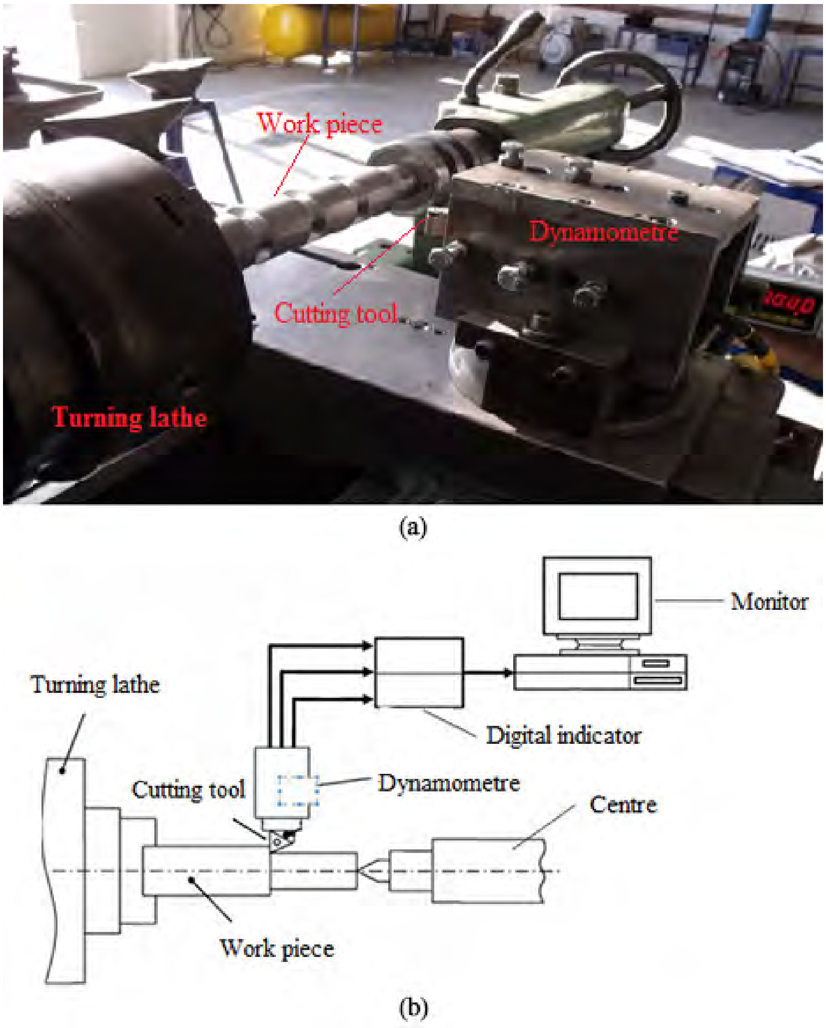

FIGURE 4. Experiment set measuring the forces during the machining process.

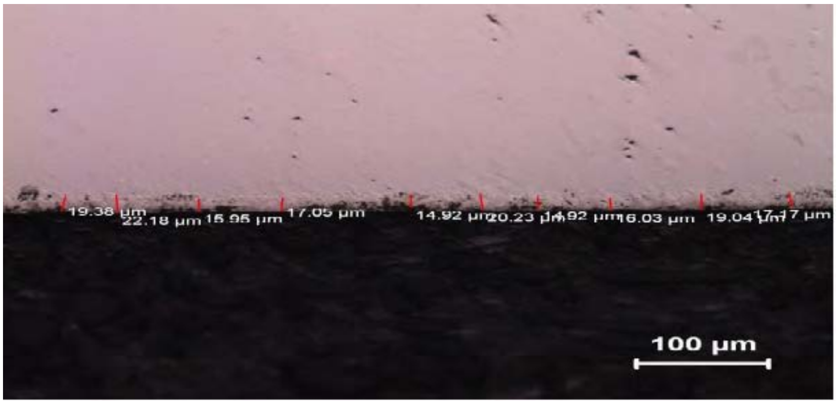

FIGURE 5. Microstructure of boron coated AISI D2 cutting tool.

mud (Fig. 3). The previously prepared pots were placed into the oven in which the temperature had been raised. The powder mixture was prepared for each experiment. The TRD process was performed at 1050 °C for 1 hour for the AISI D2 and AISI M2 steels. After coating, the samples were cooled to room temperature in open air.

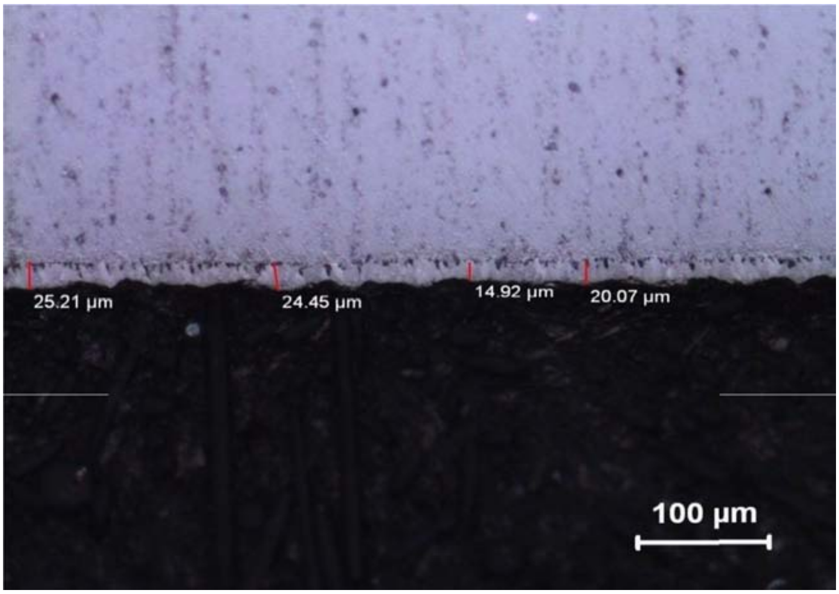

FIGURE 6. Microstructure of boron coated AISI M2 cutting tool.

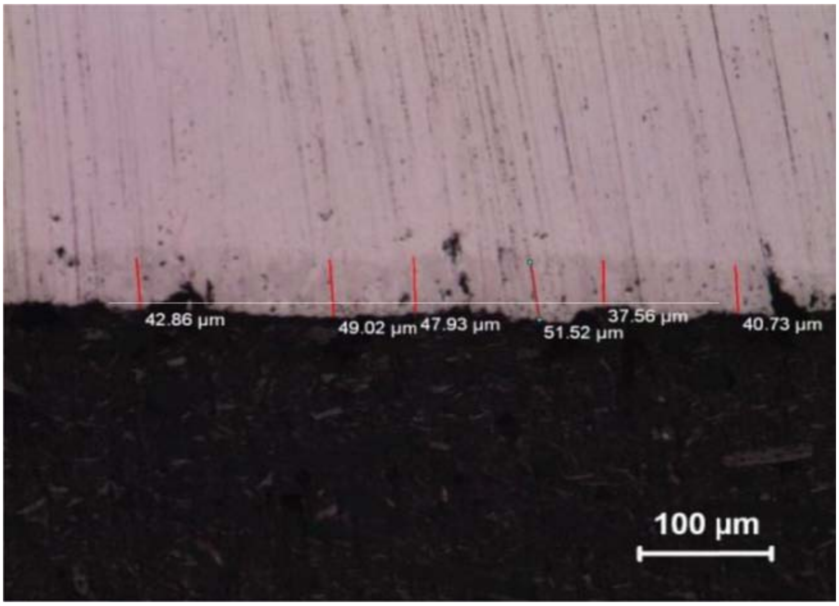

FIGURE 7. Microstructure of Boron + titanium coated AISI D2 cutting tool.

D. HEAT TREATMENT

Uncoated cutting tools were hardened by the heat treatment method to compare the cutting performance of coating types to each other. In the heat treatment method, the AISI D2 and AISI M2 steel samples were preheated until they reached 550 °C in the oven, and they were kept at this temperature for 30 minutes. The samples were then immersed in a salt bath of Barium Chloride and Barium Cyanide, and the furnace was allowed to rise to 1000 °C. The samples were cooled down in the ambient atmosphere after they were kept for 30 min. in this temperature.

E. MICROSTRUCTURE INVESTIGATIONS

After cutting the cutting tool samples that were exposed to TRD boron and titanium coating for bakalite, a sanding process was performed with 400–600–800–1000–1200 mesh sandpapers. After the sanding process with 1200 grid sandpaper, polishing was applied with 0.3 μm alumina solution. The samples were then etched with 3% Nital, and the microstructures were revealed. The samples that were metallographically prepared were examined by SEM.

X-ray diffraction (XRD) analysis was used to determine the phases and their properties. SEM and element analysis

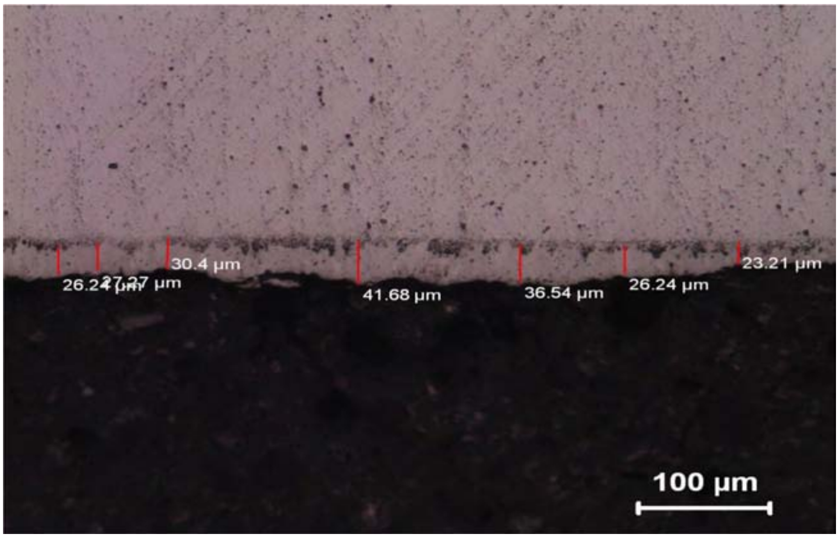

FIGURE 8. Microstructure of Boron + titanium coated AISI M2 cutting tool.

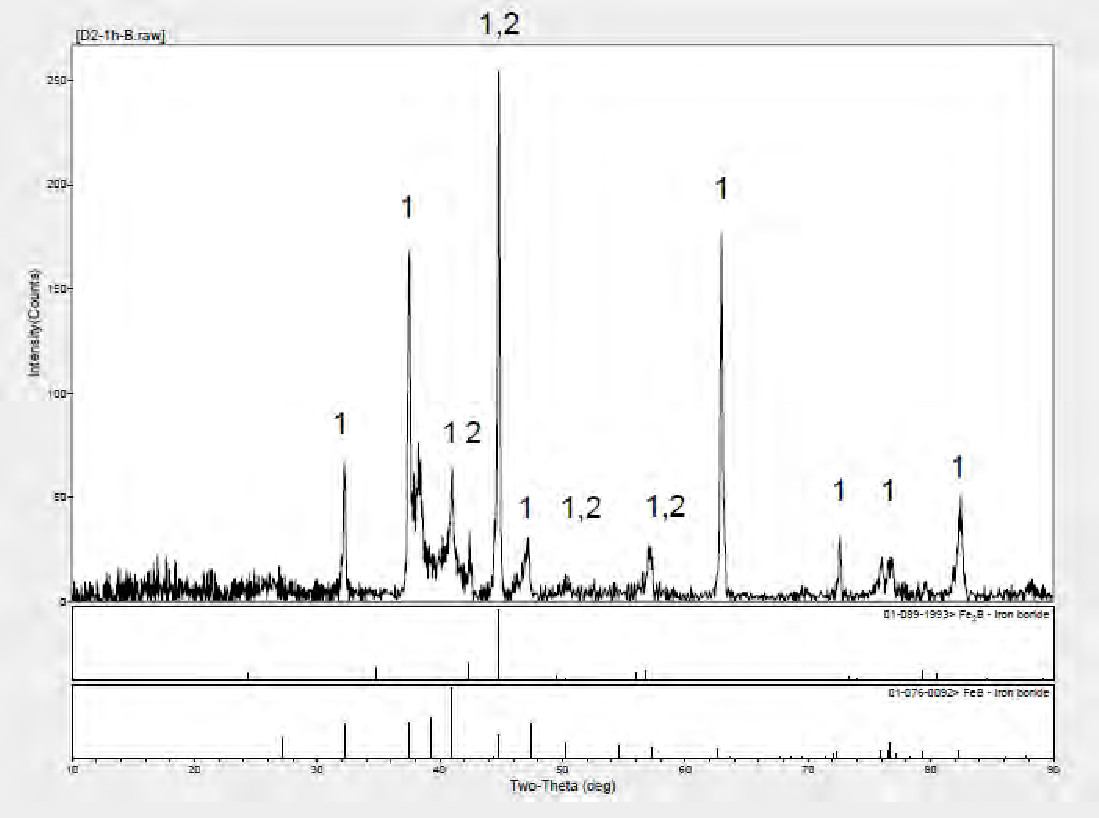

FIGURE 9. X-ray analysis of boron coated AISI D2 steel (FeB = 1, Fe_2B = 2).

spectrometry (EDS) were performed to investigate the distribution and morphology of the elements in the coating layer. Microstructure images were obtained for different boronizing and titaniumizing temperatures and the duration of each material.

The hardness measurements of the coating layers and the matrix were performed using a Knoop hardness tip under a 50 g load in the microhardness device. The measurements were carried out on the outer surface of the coating layer.

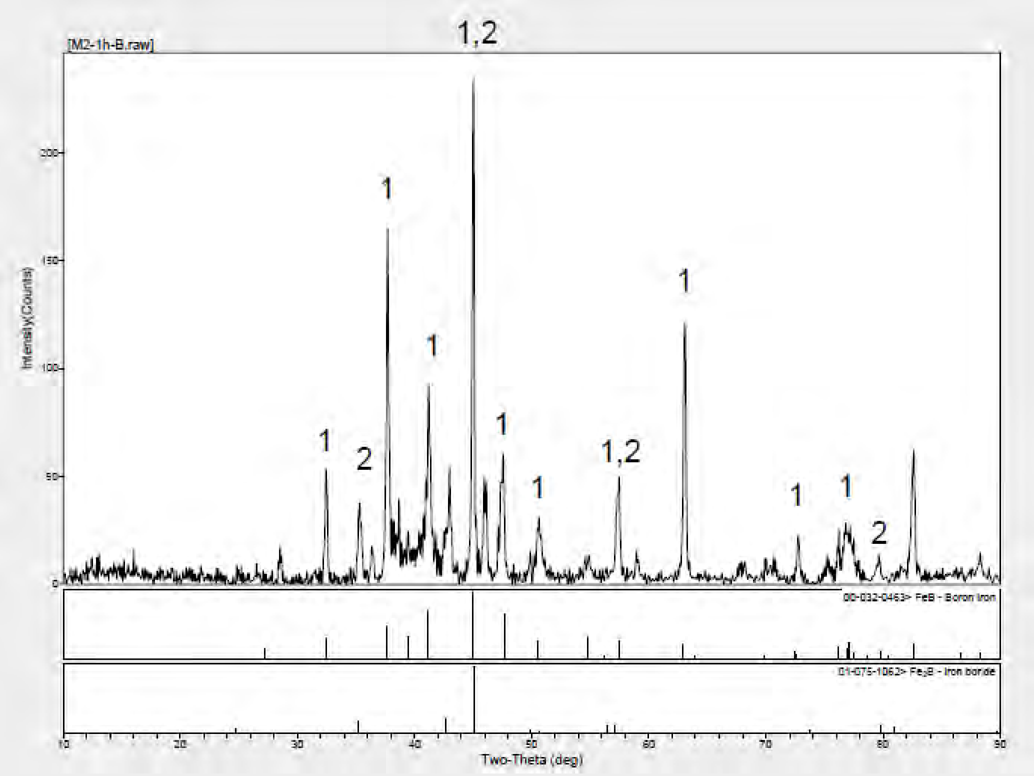

FIGURE 10. X-ray analysis of boron coated AISI M2 steel (FeB = 1, Fe_2B = 2).

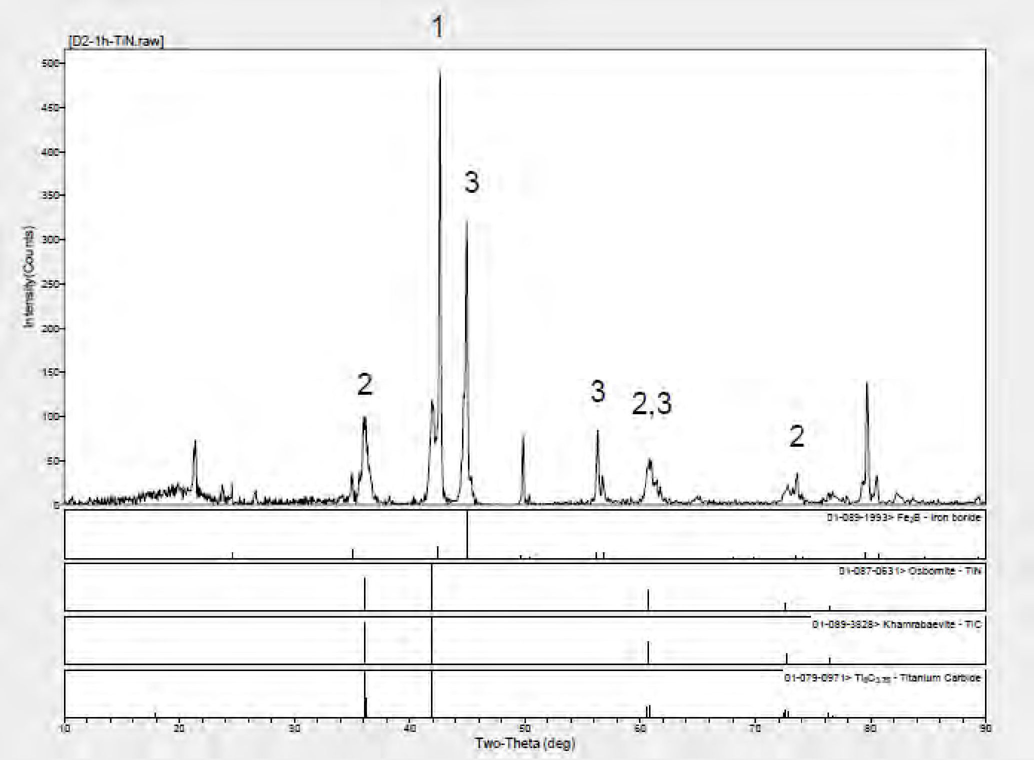

FIGURE 11. X-ray analysis of boron + titanium coated AISI D2 steel (TiN = 1, TiC = 2, TiB_2 = 3).

F. MACHINING TESTS

A machining test was carried out via free cutting steel with a diameter of 50 mm to investigate the performance of the coating process with the samples coated in the prepared test set. The chemical composition of the free cutting steel used as the work piece in the experiment is given in Table 5.

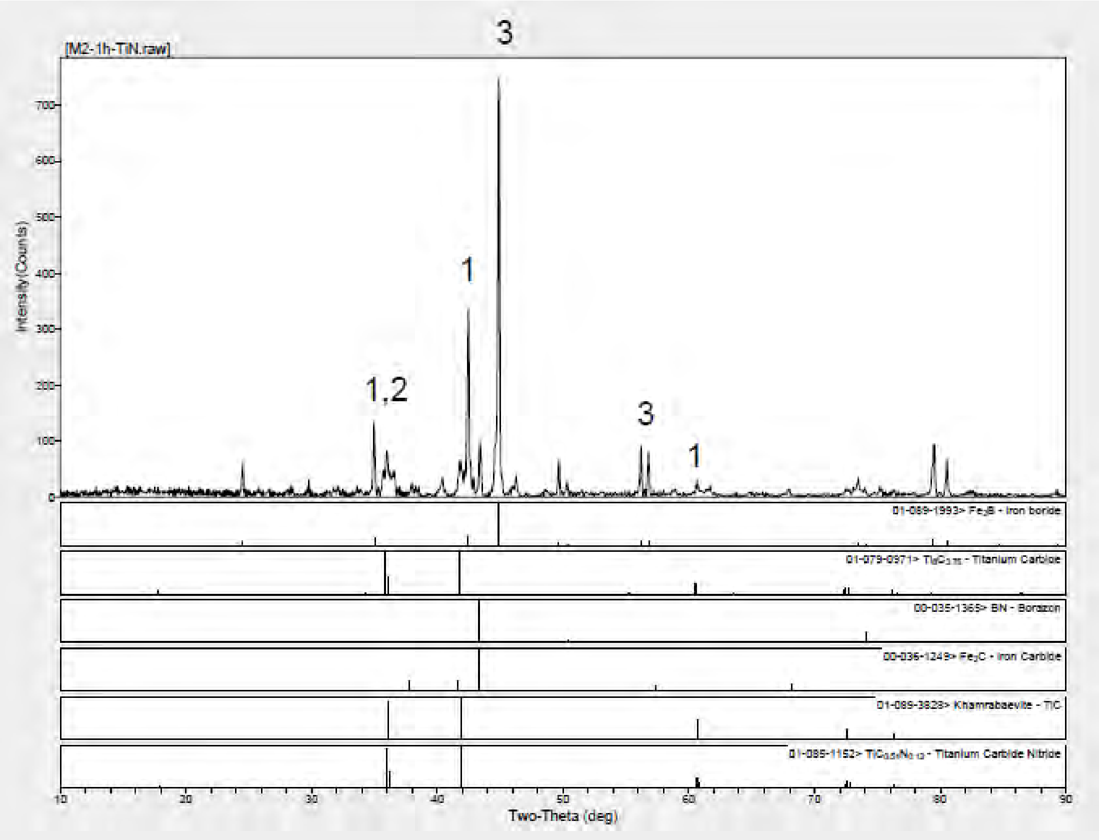

FIGURE 12. X-ray analysis of boron + titanium coated AISI M2 steel (TiN = 1, TiC = 2, TiB_2 = 3).

TABLE 5. Chemical composition of free-cutting steel used in experimental study.

Free Cutting Steel (9SMnPb28) Composition					
Material	Amount	Material	Amount	Material	Amount
Fe	97.9000	Ni	0.0740	Pb	0.2950
C	0.0420	Al	0.0010	Sn	0.0137
Si	<0.0500	Co	0.0096	B	0.0105
Mn	1.1930	Cu	0.0762	Ca	0.0001
P	0.0620	Nb	<0.0020	Zr	0.0023
S	>0.1700	Ti	<0.0020	As	0.0142
Cr	0.0940	V	<0.0020		
Mo	0.0100	W	<0.0100		

200 mm long cylindrical turning was performed for each test by using a fixed chip depth of 0.25 mm in the machining process. Surface roughness measurements were performed in the region close to the last part of the work length. Tool wear at the cutting tool free surface at the end of the process was measured by an optical microscope. The tests were carried out at the cutting speeds of 38, 73, 138 m/min in a universal lathe with a power of 7kW and at 0.08, 0.12, 0.16 mm/rev. There was no cooling liquid used in the experiments.

A two-component dynamometer, capable of measuring forces between 0 and 5 kN, was used to measure the cutting and progression forces during the turning of the three-different cutting tools including the heat treated (not coated), boron-coated and boron + titanium-coated samples.

Surface roughness measurements were performed on the first 40 mm and final 40 mm sections on a workpiece of 200 mm length for each test. Thus, it was possible to determine the effect of tool wear on surface roughness. The test set-up used in the chip removal tests is shown in Fig. 4 a and b.

III. FINDINGS

In the material surface, it is highly advantageous to form a boride layer of non-oxide ceramics by practical and economic thermochemical processes. As a result of boronizing which is a thermochemical surface treatment, surface hardness, abrasion, oxidation and corrosion resistance of metallic materials rise to quite high levels. For this purpose, first, boron coating was performed by using Ekabor 2 on the cutting tools which were made of AISI D2 and AISI M2 steel materials. In order to investigate the distribution and morphology of the elements in the coating layer, a JEOL-JSM-6060 LV brand scanning electron microscope (SEM) was used. As a result of the research, 15-25 μm coating thickness in AISI D2 cutting tool samples and 25-35 μm coating thickness in AISI M2 cutting tool samples were obtained as seen in Figs. 5 and 6. The coating layer, the coating-matrix interface and the matrix are clearly seen in the figures. The coating layers showed a flat, dense and homogeneous distribution. It is seen that the

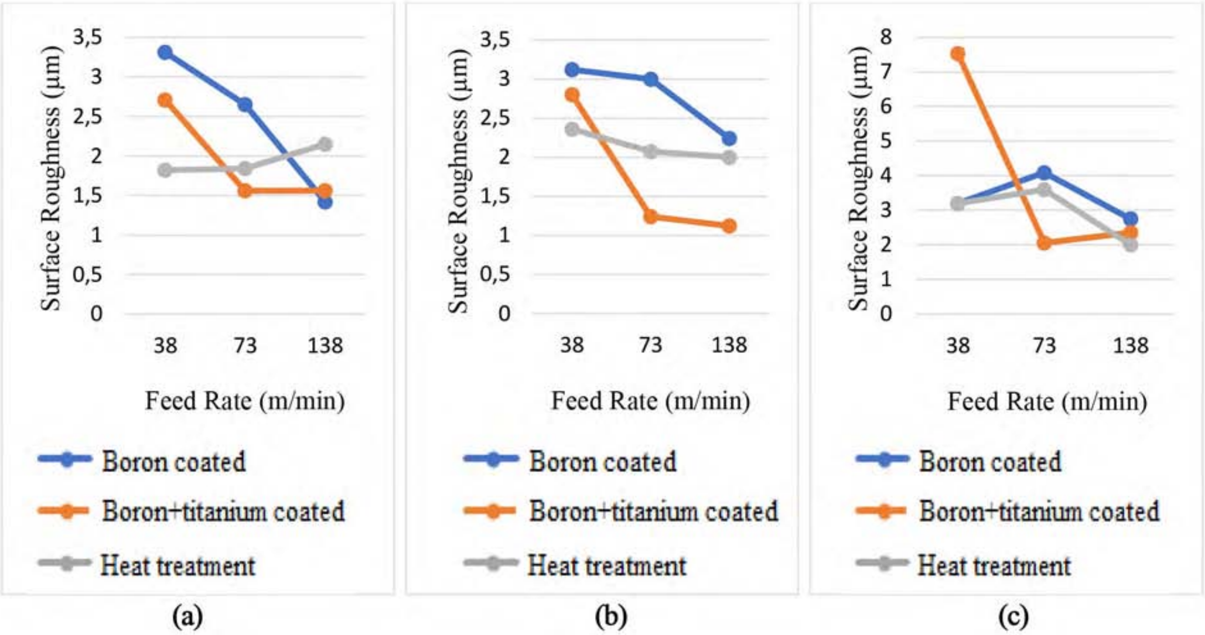

FIGURE 13. Effect of different AISI D2 cutting tools on surface roughness. a: f=0.08 mm/rev; b: f=0.12 mm/rev; c: f=0.16 mm/rev.

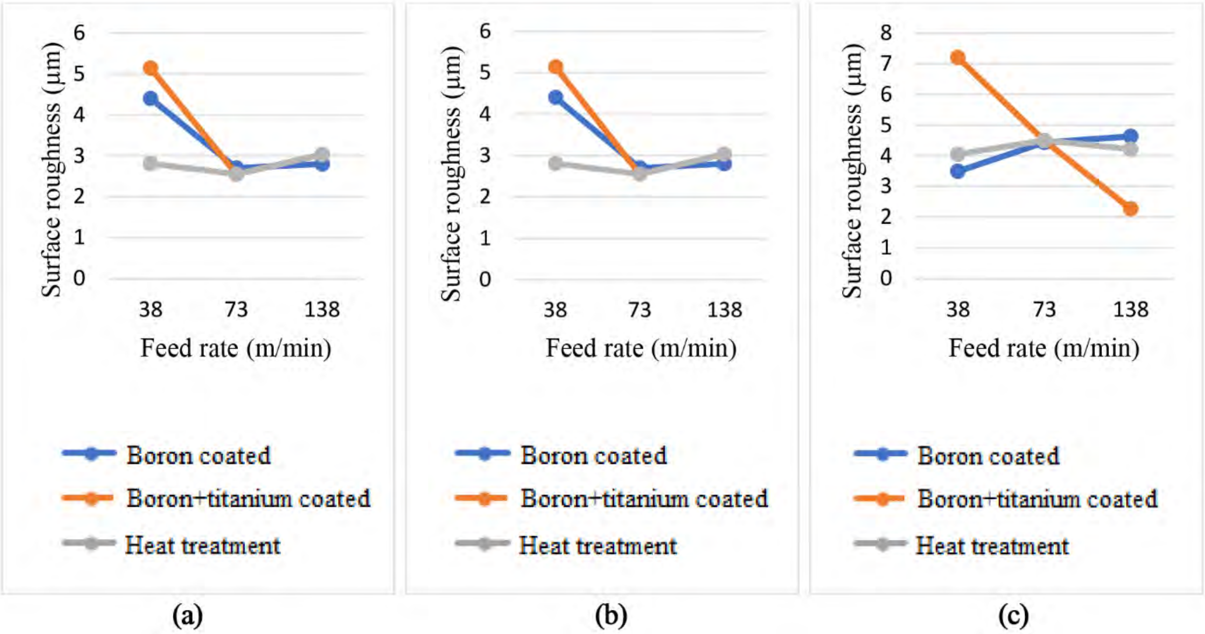

FIGURE 14. Effect of different AISI M2 cutting tools on surface roughness. a: f=0.08 mm/rev; b: f=0.12 mm/rev; c: f=0.16 mm/rev.

covering layer consisted of a boron-coated region, transition zone and base as three regions, respectively.

At the second phase of our study, we coated boron-coated cutting tool samples with titanium. The purpose of titanium coating was that the high hardness, low thermal conductivity and low friction coefficient of titanium would be effective in reducing the cutting forces. As a result of this, the coating chipping would not occur, and the surface roughness value would be at the desired range since the chemical reaction would not occur. The boron-coated D2 and M2 were coated on the surface of the samples by reacting with titanium at 1050 °C for 1 hour. In the SEM study, a 1-2 μm titanium coated layer was observed. The results that were obtained in the experiments are shown in Figs. 7 and 8.

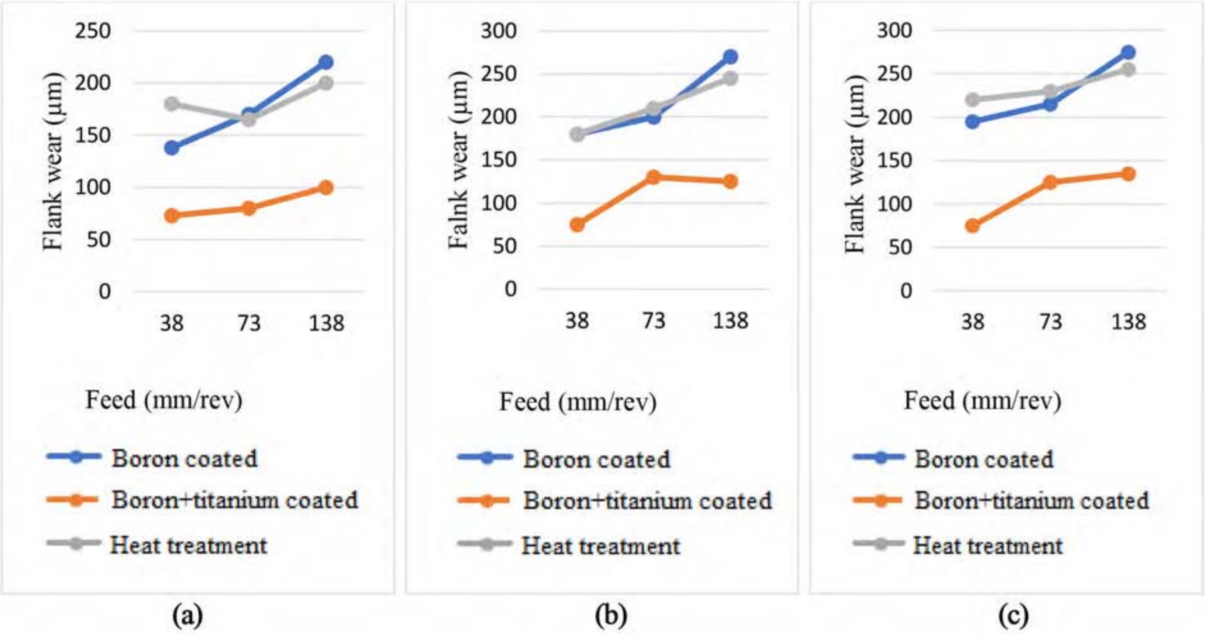

FIGURE 15. Flank wear of different AISI D2 cutting tools. a: f=0.08 mm/rev; b: f=0.12 mm/rev; c: f=0.16 mm/rev.

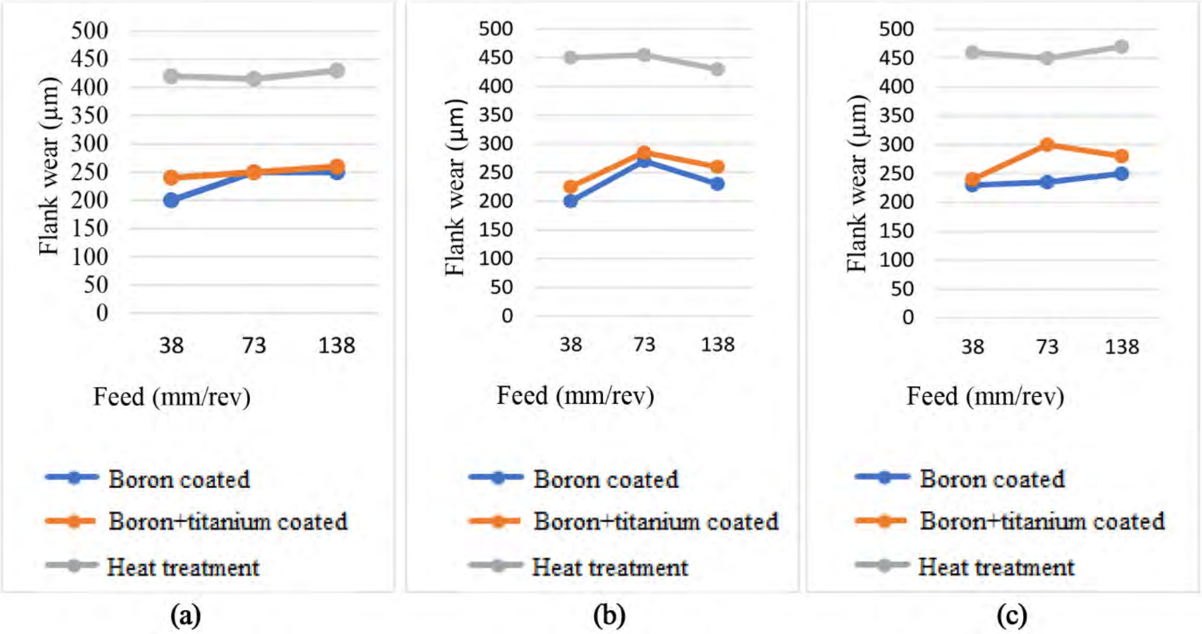

FIGURE 16. Flank wear of different AISI M2 cutting tools. a: f=0.08 mm/rev; b: f=0.12 mm/rev; c: f=0.16 mm/rev.

In the coating process, it is necessary to look at the phase values of the coating layer to determine if the coating layer is formed at the optimum level. The purpose of examining phase values is to determine whether the coating time and temperature are at the optimum values. The effect of coating time and temperature on production cost is quite high. An increase in the thickness of the coating layer has the disadvantage of the adhesion of the coating to the surface. In this process, the X-ray diffraction analysis method was used to examine the phases of the coating layer. In the X-ray diffraction analysis method, the K characteristic x-ray beam, which is usually derived from a target element such as Cu or Co, is sent on the sample to be analyzed. The sample-specific diffraction pattern is obtained by scattering the beam from the

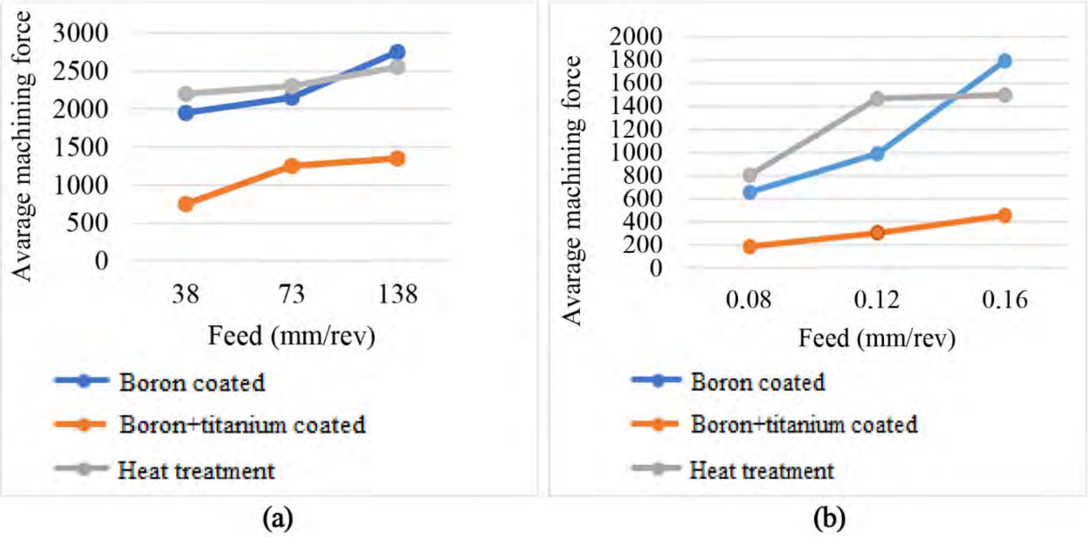

FIGURE 17. Average machining forces of AISI D2 and AISI M2 cutting tools. a: AISI D2, V=38 m/min; b: AISI M2, V=38 m/min.

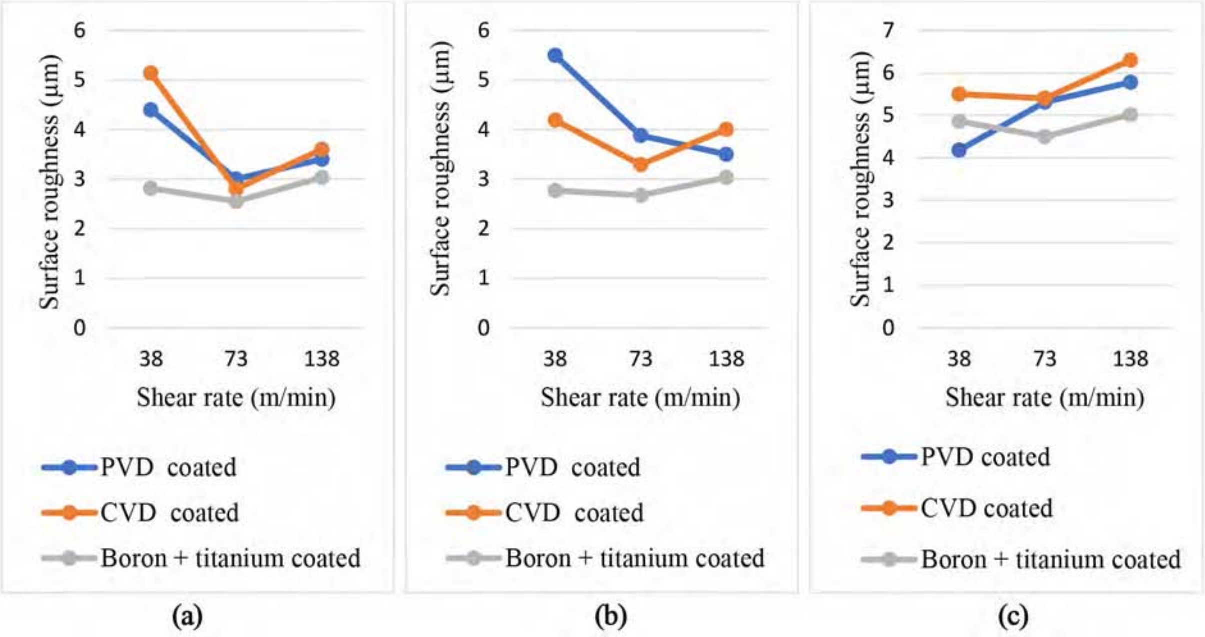

FIGURE 18. Effect of different AISI M2 cutting tools on surface roughness. a: f=0.08 mm/rev; b: f=0.12 mm/rev; c: f=0.16 mm/rev.

three-dimensional crystal lattices of the sample with specific wavelengths. These patterns are examined by comparing them to certain standard materials that have known compositions. As a result of the X-ray analysis, FeB and F_2B borides were formed on the boron-coated cutting surfaces. The resulting phases are shown in Figs. 9 and10.

The presence of the TiN, TiC and TiB2 compounds on titanium-coated D2 and M2 steels on boron coating was determined by X-ray diffraction analysis. The resulting phases are shown in Figs. 11 and 12.

After the coating processes, hardness measurements were performed on the surface of the coated and heat treated but uncoated cutting tools to reveal the effect of the coating layer on mechanical properties such as surface hardness, fracture toughness and wear. The hardness measurements were carried out in a direction perpendicular to the surface of the coated samples. The results are given in Table 6. When the table is examined, its seen that the highest hardness values were obtained as titanium coated, just boron coated and heat treated materials, respectively.

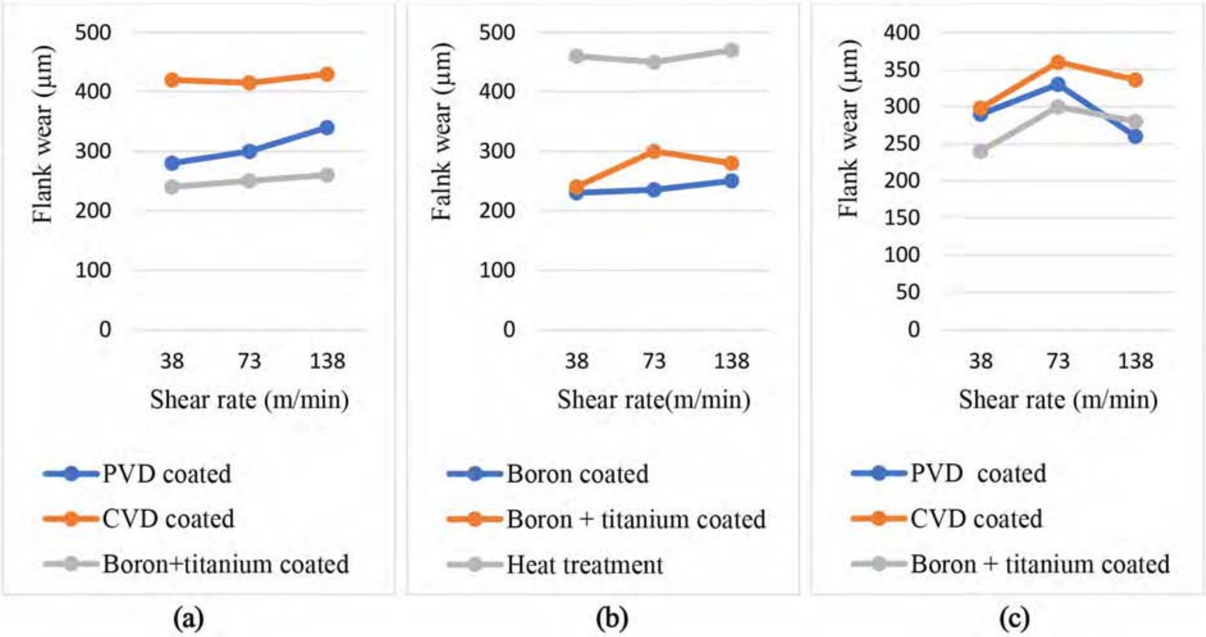

FIGURE 19. Flank wear of different AISI M2 cutting tool. a: f=0.08 mm/rev; b: f=0.12 mm/rev; c: f=0.16 mm/rev.

TABLE 6. Hardness measurement values.

Name of Steel	Coating Material	Applied Load (g)	Hardness of plate (HV)
M2	Boron coating	50	2000
	Boron + titanium coating	10	2900
	Heat treated	100	710
	Untreated	100	365
D2	Boron coating	50	2000
	Boron + titanium coating	50	2800
	Heat treated	100	690
	Untreated	100	350

In order to investigate the performance values of the base material and the coating process and to compare the performance values of the uncoated cutting tool, surface roughness and tool wear were examined by means of chip removal test on the free cutting steel. Figs. 13 and 14 show that the surface roughness value increased as the feed rate increased. It is thought that this was due to the geometric effect on the surface caused by the amount of progress and the increased chip load on the surface. The increase in the cutting speed generally resulted in a reduction in surface roughness. The results were comparable to this expectation. This is especially clearly seen at the low feed rate. In some high cutting speeds and feed conditions, the reduction in surface quality may have been caused by excessive tool wear. As the results were variable, there was no clear or general result that could be concluded regarding the effect of tool type on surface quality.

The tool wear results are given in Figs. 15 and 16 according to the different tool material and process parameters. The wear rate of the "free" surface was considered as the tool wear criteria. The width of the wear zone on the free surface was measured perpendicularly to the cutting edge, and the value that was obtained was considered as the amount of wear. In the tests that were performed, it was determined that the least wearing tool was the boron-coated and titanium-coated tool, and the most wearing tool was the heat treated tool. When all the results were taken into consideration, it was determined that there was no significant difference in wear resistance between the heat-treated tool and only the boron coated tool. If we look at the plot, the boron and titanium coated tool could be said to have worn by about 50% less than the others.

Fig. 16 shows the feed rate-average cutting force occurred in the cutting tool during the machining process of free cutting steel at the same cutting speed (V = 38 m/min.) and three different feed rates (F = 0.08-0.12-0.16 mm/rev.). As a result of the cutting tests, the average amount of cutting force on the cutting tool increased as the feed rate increased. The reason was thought to be the increase in the chip removal force onto the cutter tool. This was because the cutting tool had to remove more amount of chips in one revolution with the increasing feed rate. The results are shown in Fig. 17.

At the last stage of our study, the performance values of the AISI M2 cutting tool used in the experiments, which were the best in terms of coating and machining ability, were investigated for the performance of the tools coated with the PVD and CVD techniques. At this stage, under the same conditions, the chip removing process was performed on the free cutting steel with both the tools that we coated and the ISCAR brand RCMT 06 02 M0 2025 tool coated by the PVD and CVD methods. The surface roughness and wear values that were obtained are given comparatively in Figs. 18 and 19.

IV. RESULTS AND DISCUSSIONS

In this study, boron coating and boron + titanium coating processes were carried out by the thermo-reactive diffusion method on cutting tools made from AISI D2 and AISI M2 steel. The cutting performance of the TRD method against the other methods like PVD and CVD was investigated.

- It was determined in the metallographic examinations that a 15-25 μm thick layer consisting of the FeB and Fe_2B phases was formed on boronized AISI D2 samples and connected to the matrix with a transition zone.
- It was seen that 2-4 μm thick TiB_2, TiN and TiC compounds were formed on the boron + titanium coated samples.
- It was seen that the boron-coated surfaces have an average of 2000 HV hardness while the boron + titanium coated samples had a 2800 HV hardness. These values were approximately 3 and 4 times higher than those of the uncoated hardened sample.
- As a result of the chip removal tests, the boron + titanium-coated samples were worn by about 50% less than the others.
- The surface roughness and tool wear results obtained with the AISI M2 cutting tool were compared to the cutting test results of commercially available ISCAR brand RCMT cutting tools which were carried out on the free cutting steel under the same conditions. The boron + titanium coated AISI M2 tool is seen to exhibit a better performance.
- In general, the roughness of the treated surface was determined to be inversely proportional to the cutting speed and directly proportional to the feed rate. However, in some high cutting and feed rate conditions, it was determined that the roughness value increased, and this was caused by excessive tool wear. In terms of the effect on surface roughness, all tools showed similar behavior, no significant difference was observed between the tools, and the tools showed better results than the PVD- and CVD-coated tools.
- Surface roughness varied depending on the cutting speed, which affected the amount of time the tool was used. It was observed that the surface roughness was reduced when the cutting speed was high and the feed rate was low, but it increased when the cutting speed was low and the feed rate was high. Roughness was also increased due to the increased amount of chips that the cutter had to take in one cycle if the feed rate was high.
- The structure of the material in the chip removing process, the cutting speed and feed rate significantly affected the machinability. The most important factors affecting the surface roughness in chip removal were the cutting speed and feed rate. Many studies have been carried out on how to select the ideal cutting speed or how the cutting speed affects the surface roughness. Reduction in the surface roughness with increasing cutting speed was observed. The surface roughness varied depending on the feed rate. It was determined that the surface roughness value increased with the increasing feed rate.

REFERENCES

[1] A. A. Ginting, R. Skein, D. Cuaca, Herdianto, Pieter, and Z. Masyithah, "The characteristics of CVD-and PVD-coated carbide tools in hard turning of AISI 4340," *Measurement*, vol. 129, pp. 548–557, Dec. 2018. doi: 10.1016/j.measurement.2018.07.072.

[2] N. Michailidis, "Variations in the cutting performance of PVD-coated tools in milling Ti6Al4V, explained through temperature-dependent coating properties," *Surf. Coat. Technol.*, vol. 304, pp. 325–329, Oct. 2016. doi: 10.1016/j.surfcoat.2016.07.022.

[3] S. Koseki, K. Inoue, K. Sekiya, S. Morito, T. Ohba, and H. Usuki, "Wear mechanisms of PVD-coated cutting tools during continuous turning of Ti-6Al-4V alloy," *Precis. Eng.*, vol. 47, pp. 434–444, Jan. 2017. doi: 10.1016/j.precisioneng.2016.09.018.

[4] R. Soltani, M. H. Sohi, M. Ansari, A. Haghighi, H. M. Ghasemi, and F. Haftlang, "Evaluation of niobium carbide coatings produced on AISI L2 steel via thermo-reactive diffusion technique," *Vacuum*, vol. 146, pp. 44–51, Dec. 2017. doi: 10.1016/j.vacuum.2017.09.023.

[5] A. OrjuelaG, R. Rincón, and J. J. Olaya, "Corrosion resistance of niobium carbide coatings produced on AISI 1045 steel via thermo-reactive diffusion deposition," *Surf. Coat. Technol.*, vol. 259, pp. 667–675, Nov. 2014. doi: 10.1016/j.surfcoat.2014.10.012.

[6] S. Tanaka, T. Shirochi, H. Nishizawa, K. Metoki, H. Miura, H. Hara, and T. Takahashi, "Micro-blasting effect on fracture resistance of PVD-AlTiN coated cemented carbide cutting tools," *Surf. Coat. Technol.*, vol. 308, pp. 337–340, Dec. 2016. doi: 10.1016/j.surfcoat.2016.07.094.

[7] D. Boing, A. J. de Oliveira, and R. B. Schroeter, "Limiting conditions for application of PVD (TiAlN) and CVD ($TiCN/Al_2O_3/TiN$) coated cemented carbide grades in the turning of hardened steels," *Wear*, vols. 416–417, pp. 54–61, Dec. 2018. doi: 10.1016/j.wear.2018.10.007.

[8] G. K. Dosbaeva, M. A. El Hakim, M. A. Shalaby, J. E. Krzanowski, and S. C. Veldhuis, "Cutting temperature effect on PCBN and CVD coated carbide tools in hard turning of D2 tool steel," *Int. J. Refractory Metals Hard Mater.*, vol. 50, pp. 1–8, May 2015. doi: 10.1016/j.ijrmhm.2014.11.001.

[9] K. Bobzin, T. Brögelmann, A. Gillner, N. C. Kruppe, C. He, and M. Naderi, "Laser-structured high performance PVD coatings," *Surf. Coat. Technol.*, vol. 352, pp. 302–312, Oct. 2018. doi: 10.1016/j.surfcoat.2018.07.094.

[10] R. Suresh, S. Basavarajappa, and G. L. Samuel, "Some studies on hard turning of AISI 4340 steel using multilayer coated carbide tool," *Measurement*, vol. 45, no. 7, pp. 1872–1884, 2012. doi: 10.1016/j.measurement.2012.03.024.

[11] F. E. Castillejo, D. M. Marulanda, J. J. Olaya, and J. E. Alfonso, "Wear and corrosion resistance of niobium–chromium carbide coatings on AISI D2 produced through TRD," *Surf. Coat. Technol.*, vol. 254, pp. 104–111, Sep. 2014. doi: 10.1016/j.surfcoat.2014.05.069.

[12] A. Gaydaychuk, S. Zenkin, and S. Linnik, "Influence of Al-Si-N interlayer on residual stress of CVD diamond coatings," *Surf. Coat. Technol.*, vol. 357, pp. 348–352, Jan. 2019. doi: 10.1016/j.surfcoat.2018.10.030.

[13] M. Arabloo, A. Shokrollahi, F. Gharagheizi, and A. H. Mohammadi, "Toward a predictive model for estimating dew point pressure in gas condensate systems," *Fuel Process. Technol.*, vol. 116, pp. 317–324, Dec. 2013. doi: 10.1016/j.fuproc.2013.07.005.

[14] A. Najafi-Marghmaleki, A. Tatar, A. Barati-Harooni, M. Arabloo, S. Rafiee-Taghanaki, and A. H. Mohammadi, "Reliable modeling of constant volume depletion (CVD) behaviors in gas condensate reservoirs," *Fuel*, vol. 231, pp. 146–156, Nov. 2018. doi: 10.1016/j.fuel.2018.04.130.

[15] K. S. Selivanov, A. M. Smyslov, Y. M. Dyblenko, and I. P. Semenova, "Erosive wear behavior of Ti/Ti(V,Zr)N multilayered PVD coatings for Ti-6Al-4V alloy," *Wear*, vols. 418–419, pp. 160–166, Jan. 2019. doi: 10.1016/j.wear.2018.11.016.

[16] F. Pougoum, J. Qian, L. Martinu, J. Klemberg-Sapieha, Z. Zhou, K. Y. Li, S. Savoie, R. Lacasse, E. Potvin, and R. Schulz, "Study of corrosion and tribocorrosion of Fe_3Al-based duplex PVD/HVOF coatings against alumina in NaCl solution," *Surf. Coat. Technol.*, vol. 357, pp. 774–783, Jan. 2019. doi: 10.1016/j.surfcoat.2018.10.060.

[17] C. Sun, Q. Xue, J. Zhang, S. Wan, A. K. Tieu, and B. H. Tran, "Growth behavior and mechanical properties of Cr-V composite surface layer on AISI D3 steel by thermal reactive deposition," *Vacuum*, vol. 148, pp. 158–167, Feb. 2018. doi: 10.1016/j.vacuum.2017.11.015.

[18] M. Biesuz and V. M. Sglavo, "Chromium and vanadium carbide and nitride coatings obtained by TRD techniques on UNI 42CrMoS4 (AISI 4140) steel," *Surf. Coat. Technol.*, vol. 286, pp. 319–326, Jan. 2016. doi: 10.1016/j.surfcoat.2015.12.063.

[19] A. Meneses-Amador, D. Sandoval-Juárez, G. A. Rodríguez-Castro, D. Fernández-Valdés, I. Campos-Silva, R. C. Vega-Morón, and J. L. Arciniega-Martínez, "Contact fatigue performance of cobalt boride coatings," *Surf. Coat. Technol.*, vol. 353, pp. 346–354, Nov. 2018. doi: 10.1016/j.surfcoat.2018.07.104.

[20] J. Di, S.-S. Wang, L. Zhang, L.-X. Cai, and Y.-H. Xie, "Study on the erosion characteristics of boride coatings by finite element analysis," *Surf. Coat. Technol.*, vol. 333, pp. 115–124, Jan. 2018. doi: 10.1016/j.surfcoat.2017.10.042.

[21] I. Campos-Silva, M. Palomar-Pardavé, R. P. Pastén-Borja, O. K. Feridun, D. Bravo-Bárcenas, C. López-García, and R. Reyes-Helguera, "Tribocorrosion and cytotoxicity of FeB-Fe_2B layers on AISI 316 L steel," *Surf. Coat. Technol.*, vol. 349, pp. 986–997, Sep. 2018. doi: 10.1016/j.surfcoat.2018.05.085.

[22] Y. Jian, Z. Huang, J. Xing, L. Sun, Y. Gao, and Q. Zheng, "Investigations on the mechanical properties and three-body wear behavior of pure Fe_2B intermetallic with different chromium additions," *Wear*, vols. 418–419, pp. 273–280, Jan. 2019. doi: 10.1016/j.wear.2018.10.011.

[23] A. Ebrahimi, H. Esfahani, A. Fattah-alhosseini, and O. Imantalab, "*In-vitro* electrochemical study of TiB/TiB_2 composite coating on titanium in Ringer's solution," *J. Alloys Compounds*, vol. 765, pp. 826–834, Oct. 2018. doi: 10.1016/j.jallcom.2018.06.312.

[24] X.-R. Lu, M.-H. Ding, C. Zhang, and W.-Z. Tang, "Comparative study on stability of boron doped diamond coated titanium and niobium electrodes," *Diamond Relat. Mater.*, vol. 93, pp. 26–33, Mar. 2019. doi: 10.1016/j.diamond.2019.01.010.

[25] H. Pouraliakbar, G. Khalaj, L. Gomidželović, M.-J. Khalaj, and M. Nazerfakhari, "Duplex ceramic coating produced by low temperature thermo-reactive deposition and diffusion on the cold work tool steel substrate: Thermodynamics, kinetics and modeling," *Ceramics Int.*, vol. 41, no. 8, pp. 9350–9360, 2015. doi: 10.1016/j.ceramint.2015.03.306.

[26] K. M. Gupta, K. Ramdev, S. Dharmateja, and S. Sivarajan, "Cutting characteristics of PVD coated cutting tools," *Mater. Today, Proc.*, vol. 5, no. 5, pp. 11260–11267, 2018. doi: 10.1016/j.matpr.2018.02.092.

[27] M. Staszuk, D. Pakuła, G. Chladek, M. Pawlyta, M. Pancielejko, and P. Czaja, "Investigation of the structure and properties of PVD coatings and ALD + PVD hybrid coatings deposited on sialon tool ceramics," *Vacuum*, vol. 154, pp. 272–284, Aug. 2018. doi: 10.1016/j.vacuum.2018.04.032.

[28] G. Zheng, R. Xu, X. Cheng, G. Zhao, L. Li, and J. Zhao, "Effect of cutting parameters on wear behavior of coated tool and surface roughness in high-speed turning of 300M," *Measurement*, vol. 125, pp. 99–108, Sep. 2018. doi: 10.1016/j.measurement.2018.04.078.

[29] S. Chinchanikar and S. K. Choudhury, "Wear behaviors of single-layer and multi-layer coated carbide inserts in high speed machining of hardened AISI 4340 steel," *J. Mech. Sci. Technol.*, vol. 27, no. 5, pp. 1451–1459, 2013. doi: 10.1007/s12206-013-0325-2.

[30] A. K. Sahoo and B. Sahoo, "Experimental investigations on machinability aspects in finish hard turning of AISI 4340 steel using uncoated and multi-layer coated carbide inserts," *Measurement*, vol. 45, no. 8, pp. 2153–2165, 2012. doi: 10.1016/j.measurement.2012.05.015.

[31] Q. An, C. Wang, J. Xu, P. Liu, and M. Chen, "Experimental investigation on hard milling of high strength steel using PVD-AlTiN coated cemented carbide tool," *Int. J. Refractory Met. Hard Mater.*, vol. 43, pp. 94–101, Mar. 2014. doi: 10.1016/j.ijrmhm.2013.11.007.

ŞENOL ERTÜRK was born in Geyve, Sakarya, Turkey, in 1977. He received the bachelor's degree from the Department of Mechanical Education, Faculty of Technical Education, Marmara University, Istanbul, in 2001, and the master's degree from the Department of Mechanical Education, Faculty of Technical Education, Sakarya University, in 2010. He is currently pursuing the Ph.D. degree with the Department of Mechanical Engineering, Faculty of Engineering, Düzce University.

OĞUZ KAYABAŞI received the bachelor's degree from the Department of Mechanical Education, Faculty of Technical Education, Marmara University, Turkey, in 2000, the master's degree from the Gebze Advanced Technology Institute, Turkey, and the Ph.D. degree in mechanical engineering from the Faculty of Engineering, Marmara University, Turkey. He currently serves as an Assistant Professor with the Department of Biomedical Engineering, Faculty of Engineering, Düzce University. He has many publications, including the national and international publications.

• • •