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Araştırma Makalesi

AISI D2 Çeliğinin Yüzey Frezelemesinde Nano/Tabakalı Sert Kaplamaların Kesme Performansının İncelenmesi

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ÖZ

Kalıp döküm endüstrisinde, çeliklerin sertleştirilmiş durumda frezelenmesi yaygındır. Daha iyi bir yüzey kalitesi için bu işlem sırasında oluşan takım aşınması ve kesme kuvvetleri dikkate alınmalıdır. Bu çalışmada, nano katmanlı AlTiN/TiN kaplı karbür kesici takımların AISI D2 yüzey frezelemede kesme performansı incelenmiştir. Kesme performansı karşılaştırmak için tek katmanlı sert kaplamalı karbür kesici takımlar ve kaplamasız kesici takımlar kullanılmıştır. Tüm kesme hızlarında, nano katmanlı AlTiN/TiN kaplı karbür kesici takım, TiAlN ve TiN kaplı olanlardan ve kaplamasız takımdan daha uzun takım ömrü sergilemiştir. Tüm kesici takımlarda çentik aşınması ve yığma kenar oluşumu etkin aşınmaları olduğu görülmüştür. Tüm parametrelerde nano katmanlı AlTiN/TiN sert kaplamalar kullanılarak daha düşük kesme kuvveti değerleri ölçülmüştür.
Anahtar kelimeler: Takım Aşınması, Kesme Kuvveti, Sertleştirilmiş Çelik, Yüksek Hızda İşleme, nano-tabakalı kaplama.

Anahtar Kelimeler: *Tool wear, Cutting-force, Hardened steel, High-speed machining, nano-layer hard-coatings.*

Investigation of Cutting Performance of Nano/Layered Hard Coatings in Face Milling of AISI D2 Steel

ABSTRACT

In the die-molding industry, milling steels in a hardened condition is common. Tool wear and cutting-forces occurring during this process must be considered for better surface quality. The cutting performance of nano-layered AlTiN/TiN coated carbide cutting-tools in AISI D2 face-milling was evaluated in this work. Single-layer hard-coated carbide cutting-tools and uncoated cutting-tools were used to compare cutting performance testing. All cutting-speeds nano-layer AlTiN/TiN coated carbide cutting tool presented longer cutting-length than TiAlN and TiN coated ones and uncoated tool. Notch wear is an overriding wear mechanism, followed by build-up edge formation for all cutting-tools. Using a nano-layer AlTiN / TiN hard-coating, cutting-force values were lowered in all experiments.

Keywords: *Tool wear, Cutting-force, Hardened steel, High-speed machining, nano-layer hard-coatings.*

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I. INTRODUCTION

Due to environmental and economic concerns, sustainable material machining has become vital in today's society [1]–[6]. The economical and environmentally friendly manufacturing of materials may become possible by sustainable manufacturing. Machining of hardened steel (>45 HRc) [7], [8], called hard machining, can be regarded as sustainable manufacturing. In the hard machining operations, some steps of the process and coolant usage can be eliminated due to the negative impact on the environment and machining cost [9]–[14]. Because of its hardness, high toughness, and informal manufacture in complicated geometries, carbide cutting-tools are favoured for machining hard materials [15]–[16]. However, the extraordinary temperatures occurring in the cutting area during hard machining cause the cutting-tools to become unusable, and this situation restricts the usage of carbide cutting-tools in hard machining operations. Besides, the process cost also increases due to this rapid wear occurring in carbide cutting-tools. Various ways have been attempted to rise the wear resistance of carbide cutting-tools. Some of these methods are cryogenic heat treatment and thin hard-coatings. [17]–[20].

The first applications of hard-coatings were generally applied to the cutting tool materials as a single layer. The most commonly used of these coatings are TiN CrN TiAlN ceramic hard-coatings [21]–[23]. More durable TiAlN coatings have been developed because TiN coatings lose their properties at temperatures above 500 °C in dry machining [24]. Newly, multicomponent coatings have further improved the coating properties [25]. Thanks to the coating technology developed in recent years, hard-coatings can be applied as nano-layer [26] and nano-composite [27] instead of single-layer.

Innovative nano-composite and nano-layer coatings have been used frequently to machining hard materials. They are preferred due to their unique superior properties, for example, excellent adhesion to substrate materials, high hardness, and oxidation resistance [28]–[33]. However, the hard-coatings are expected to be compatible with chemical content and structure concerning the machined workpiece material. Yao et al. [30] used nano-layer CrN/Ag coating in the turning process of S45C steel in their work and achieved an increase in wear resistance compared to cutting-tools coated with single-layer CrN. In another study, Caliskan et al. [34] used nano-layer coated carbide cutting-tools to machining AISI O2 steel material and observed an increase in cutting performance.

In this work, innovative nano-layer AlTiN / TiN, TiN, and TiAlN coatings were dumped on carbide cutting-tools supplied uncoated. Then, cutting-performance in AISI D2 work-piece face-milling was then examined at determined high cutting-speeds.

II. MATERIALS AND METHODS

Experiments were realised on AISI D2 cold-work steel, which is commonly used in mill rolls, hunting knives, punches, blanking dies, shear blades, and spinning tools. The work-piece material has sizes of 150x100x50 mm and a hardness of 55 HRC as annealed. The heat-treatment includes: (1) slowly heating to 650°C-850°C in 45 min, individually, (2) keeping 30 min for austenitizing at 1040 °C, (3) quickly cooling in a furnace under 3 bar nitrogen atmosphere, (4) tempering for 150 min at 525 °C and 545°C. The AISI D2 steel chemical composition is seen in Tab. 1.

Table 1. *AISI D2 chemical-composition [36].*

C	Mn	Si	P	Cr	S	V	Mo	Fe
1.55	0.22	0.34	0.018	11.68	0.001	0.95	0.73	Remaining

R390-11T308M-KMH13A coded cutting-tools provided by Sandvick were used in cutting tests. The diameter of the tool holder is 25 mm, and two cutting-tools can be attached to the holder. During the tests, a cutting tool was attached to only one mouth of the tool holder because the cutting tool's cutting behaviour can be determined more accurately. A 3-axis CNC machine was used to do surface-milling operations. The work-piece was mounted on a piezoelectric dynamometer (Kistler 9257-B) to measure milling operations' cutting-forces.

A PVD system was used to deposit single-layer TiAlN and TiN and nano-layer AlTiN/TiN hard-coatings. AlTiN/TiN nano-layer coating was deposited using one Ti target and three segmental TiAl targets. The tools were 2-fold rotated during the deposition process. A 50 N load was used to test the coatings' hardness in a nano-indentation instrument. The calotest technique measured coating thicknesses.

The cutting parameters are given Table 2. Three different cutting-speeds were used, while radial and axial depths of cut feed rate were kept continuous. The amount of wear was measured using a stereo zoom microscope with software assistance. Afterward, each cutting-length of 450 mm, the cutting tool was taken from the CNC and attached on the stereo-zoom-microscope, and the quantity of wear was measured from its flank face. According to the images obtained from the cutting-tools' flank faces, the dominant wear types are flank wear and notch wear. When the flank-wear amount of the cutting-tool reaches 0.35 mm and the notch wear amount reaches 0.8 mm, the face-milling standard (TSISO8688-1) assumes the cutting tool is worn.

Table 2. *Cutting Parameters*

Cutting Parameter	**1**	**2**	**3**
Cutting-speed, *Vc* [m/min]	50	100	150
Feed Rate, *fz* [mm/tooth]	0.05		
Axial depth of cut, a_p [mm]	0.1		
Radial depth of cut, a_e [mm]	15		

III. RESULTS AND DISCUSSION

A- MICRO-HARDNESS OF HARD-COATINGS

The maximum load of 50 mN for the coatings and the maximum load of 1000 mN for the substrate were used to measure the microhardness. The measurements in the load-displacement graph that considerably deviated from the overall trend were removed to improve the dependability of the results. The hardness of the coatings was calculated as the mean of the remaining values, which were frequently around twenty. The measurements in the load-displacement graph that considerably deviated from the overall trend were removed to improve the dependability of the results. The hardness of the coatings was calculated as the mean of the remaining values, which were frequently around twenty.Tab. 3. shows the micro-hardness and thickness measurements of single-layer TiAlN and TiN and nano-layer AlTiN/TiN coatings. As realized from the table, TiAlN single layer coating has the highest micro-hardness, followed by nano-layer AlTiN/TiN and TiN coatings.

Table 3*. Hardness and thickness of the hard-coatings*

Coating	**Hardness [HV]**	**Thickness [µm]**
nanolayer AlTiN/TiN	3417	4.2
TiAlN	4969	5.7
TiN	3044	3.3

B- TOOL LIFETIME

To finish the life of the cutting tool, two separate values were employed as criterion. The amount of flank wear is 0.35 mm, while the amount of notch wear is 0.80 mm. The cutting-tools are considered worn when they reach these wear amounts. Figure 2 shows the tool-life at 50 m/min cutting-speed based on the cutting-length.

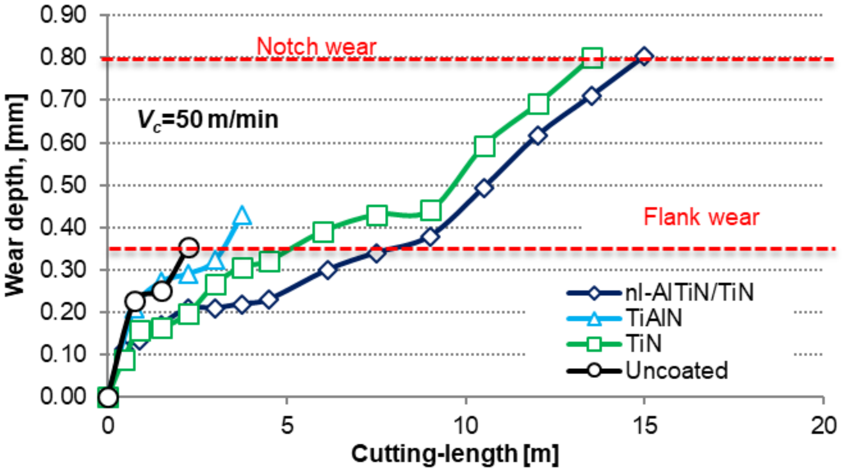

Figure 2. *Tool-life at 50 m/min cutting-speed depending on cutting-length*

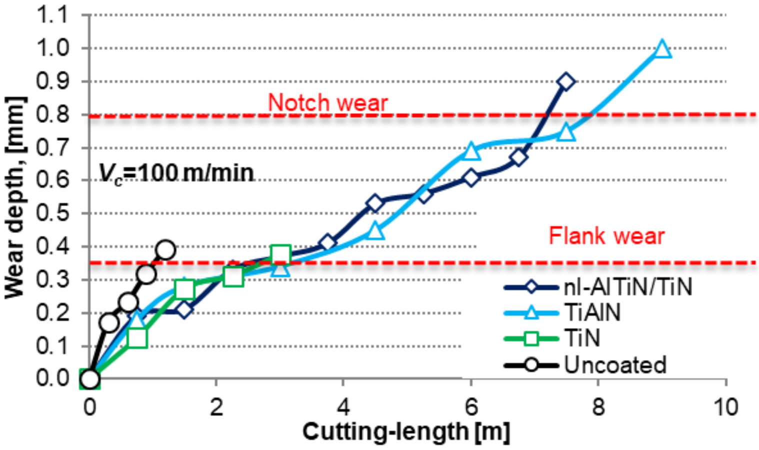

Figure 3. Tool-life at 100 m/min cutting-speed depending on cutting-length

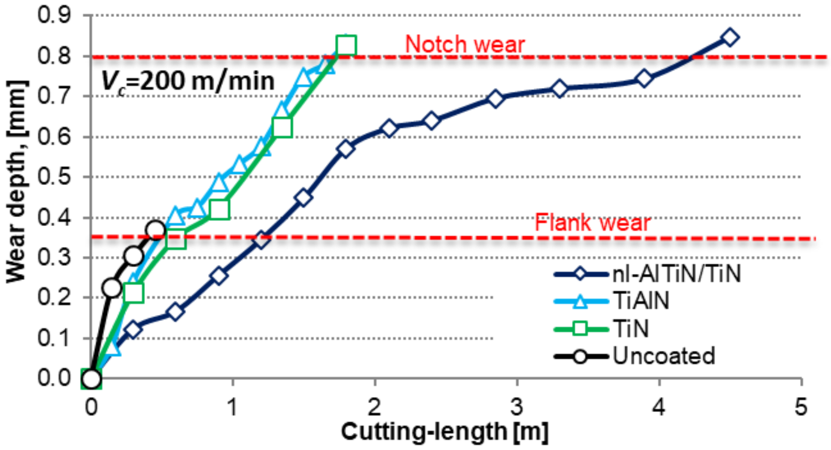

Figure 4. *Tool-life at 200 m/min cutting-speed depending on cutting-length*

All coated cutting-tools showed more tool-life than uncoated ones. The cutting tool-life of a nl-AlTiN/TiN coated tool was created to be seven times longer than that of an uncoated tool and TiAlN and TiN-coated tools with 15 m cutting-length. At first cutting parameter, TiAlN coated, and uncoated tools were worn predominately by flank wear and the others by notch wear. As a result of the lifetime criterion of 0.35 mm flank wear, the TiAlN coated tool was approved to finish its lifespan early.

Figure 3 shows the tool-life for several coated cutting-tools at second cutting parameter, depending on the cutting-length. In this case, flank wear criteria were applied to uncoated and TiN coated tools. The nano-layer AlTiN/TiN and TiAlN coated tool showed notch wear as tool failure. Nanolayer AlTiN/TiN and TiAlN coated tool presented almost the same tool wear progress, while TiAlN outperformed around notch wear criteria with a cutting-length of ~8 m.

Figure 4 shows the tool-life for various coated cutting-tools, allied with the cutting-length, at third cutting parameter. All the coated tools had notch wear at third cutting parameter, except the uncoated tool. With a cutting-length of 4.5 m, the nano-layer AlTiN/TiN coated tool had a longer tool-life than the other tools, with a cutting-length of 10 times that of the uncoated one. TiAlN and TiN coated cutting-tools showed a similar cutting-length of ~1.8 m. It is seen that cutting-tools coated with nano-layer hard-coating have higher tool-life at high cutting-speeds than single-layer coated cutting-tools.

C- ANALYSIS OF TOOL WEAR

The worn cutting-tools with different hard-coatings and uncoated ones are given in Figure 5. Wear types and mechanisms on the worn tools were summarized in Table 4 and ordered according to their dominance on the tool. As seen from the figure, uncoated tools demonstrated flank wear at all parameters. Flank wear was detected with the TiN coated tool at second cutting parameter, while notch wear was the leading wear type at the first and third cutting parameters. TiAlN coated tool demonstrated flank wear at first cutting parameter, notch wear becomes dominant wear type at higher cutting-speeds. In the nano-layer, AlTiN/TiN coated tools, notch wear was leading tool disappointment at all cutting-speeds.

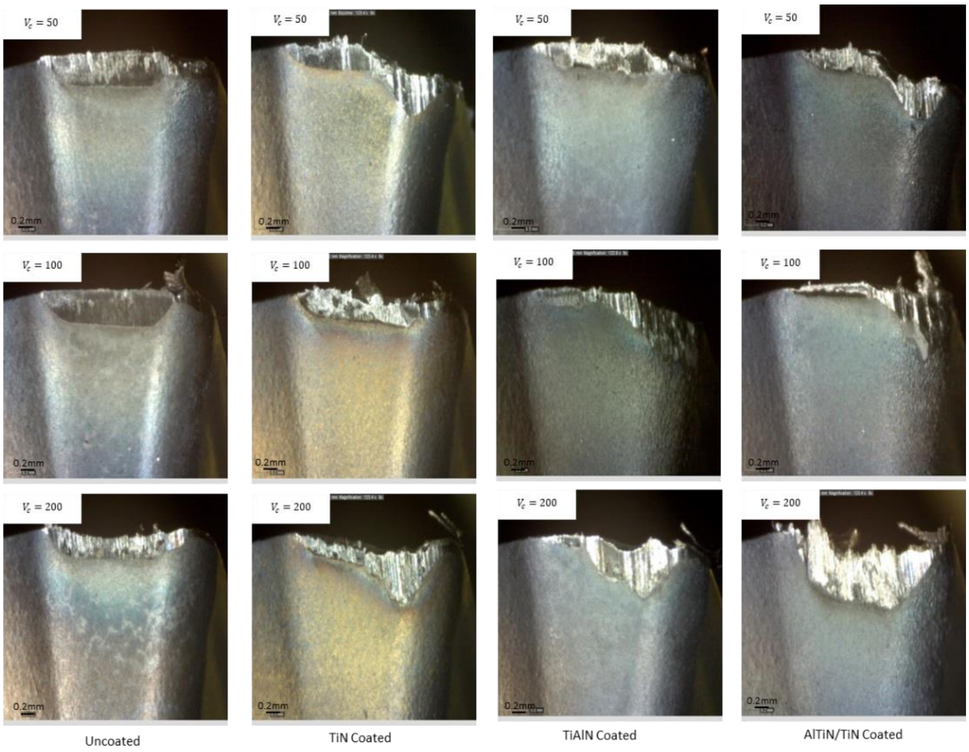

Figure 5. *Worn cutting-tools*

Table 4. *A summary of wear type and mechanism on the worn cutting-tools*

Coating	**Cutting-speed** *(m/min)*	**Wear Type**	**Wear mechanism**
Uncoated	50	Flank wear, Chipping, Build-up-edge, Seizure	Abrasion, Adhesion, Oxidation
Uncoated	100	Flank wear, Chipping, Seizure	Abrasion, Adhesion, Oxidation
Uncoated	200	Flank wear, Chipping, Seizure	Abrasion, Adhesion, Oxidation
TiN	50	Build-up-edge, Notch wear, Flank wear, Chipping, Seizure	Abrasion, Adhesion, Oxidation
TiN	100	Build-up-edge, Chipping, Flank wear, Seizure	Abrasion, Adhesion, Oxidation
TiN	200	Notch wear, Chipping, Build-up-edge, Seizure	Abrasion, Adhesion, Oxidation
TiAlN	50	Flank wear, Chipping, Seizure	Abrasion, Adhesion, Oxidation
TiAlN	100	Notch wear, Flank wear, Chipping, Breakage, Seizure	Abrasion, Adhesion, Oxidation
TiAlN	200	Notch wear, Chipping, Flank wear, Seizure	Abrasion, Adhesion, Oxidation
AlTiN/TiN	50	Notch wear, Chipping, Flank wear, Seizure	Abrasion, Adhesion, Oxidation
AlTiN/TiN	100	Notch wear, Chipping, Build-up-edge, Flank wear, Seizure	Abrasion, Adhesion, Oxidation
AlTiN/TiN	200	Notch wear, Chipping, Build-up-edge, Seizure	Abrasion, Adhesion, Oxidation

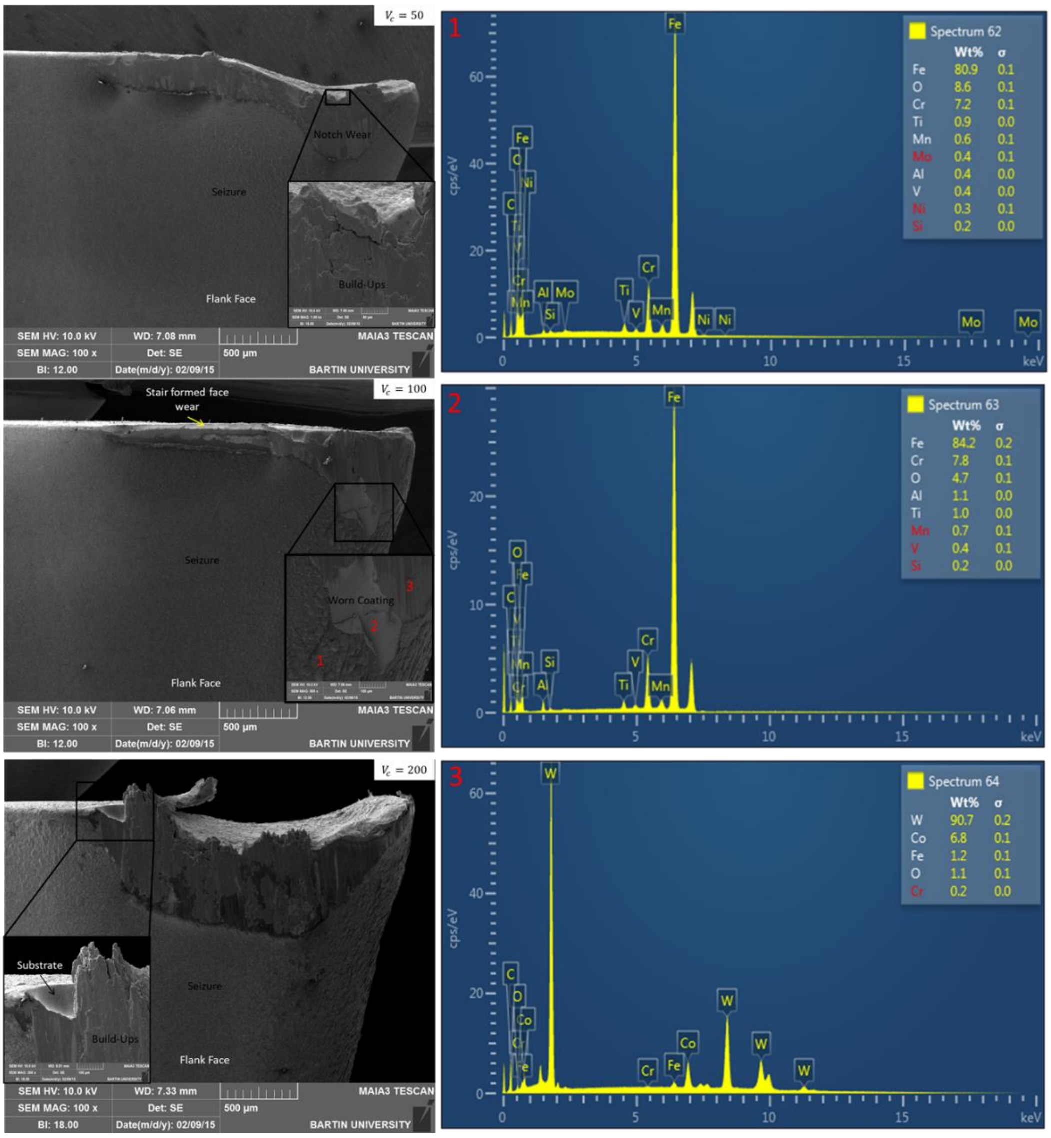

Figure 6. *EDS analysis and SEM images of AlTiN/TiN Coated worn tools*

Abrasion, work-piece adhesion, and oxidation were dominant tool wear mechanisms on all the tools with different amounts. Scanning Electron Microscopy pictures of the worn nano-layer AlTiN/TiN coated tools obtained at cutting-speeds 50, 100, and 200 m/min are given in Fig. 6. Seizure zone, built-up-edge, exposed substrate material, and worn coating were recognized on the cutting-tools by SEM pictures and EDS analysis. As the cutting-length increases, the wear of the hard-coatings deposited on the cutting-tools rises, and the substrate material of the cutting tool is further damaged. When the area of the substrate material got larger, the cutting temperature of the cutting edge increased. The cutting-edge temperature reached approximately 1100o C at this temperature; the coating lost its defensive ability, and so Seizure at the flank face could be observed. The worn substrate zone was shaped by sliding and rubbing by chips. Worn substrate zone EDS was analysis seen in Fig. 6, the point of 2. Seizure zones have occurred due to the work-piece obeying the cutting tool. Seizure zones EDS analysis was presented in Fig. 6, the point of 3. BUE formation is seen on the cutting tool's flank face, the hard-coating zone, and the substrate material of the cutting tool. Because of the high temperature in the cutting-zone, the welding of the work-piece material to the cutting tool causes BUE production. BUE zone EDS analysis was presented in Fig. 6, the point of 2. [36–39]. Wear zones had different wear mechanisms. Abrasion appears to be the effective wear mechanism in all worn tools. Submitted substrate material started widening with increased cutting-length, and the temperature at the cutting area became higher; for this reason, diffusion wear mechanism became leading, and then creating craters on the flank face. Seizure and adhesion, abrasion, and diffusion wear mechanisms were caused by the zones of built-up edges.

D- CUTTING FORCES

This section gives the graphs obtained with the cutting-forces measured in the first 150 mm cutting-length with all cutting-tools. The values after a specific progress value (30 mm cutting-length) were used for the calculations to compare the measured values accurately with each other. This section only compares the values of the cutting-forces obtained by milling tests with nlAlTiN/TiN coated cutting-tools and uncoated cutting-tools. Compared to uncoated and single-layer coated tools, lower cutting-force values were measured with nano-layer coated cutting-tools.

The comparison of the cutting-forces measured in milling tests at first cutting parameter with uncoated and nano-layered nlAlTiN/TiN coated cutting-tools are seen in Fig. 7 a. Accordingly, the values of the cutting-forces measured with nano-layered nlAlTiN / TiN cutting-tools in all cutting-force components were lower than those measured with uncoated cutting-tools. Furthermore, it is seen that in all cutting-force mechanisms, the cutting-forces gained with the uncoated cutting tool are received with more fluctuations than those with the coated one.

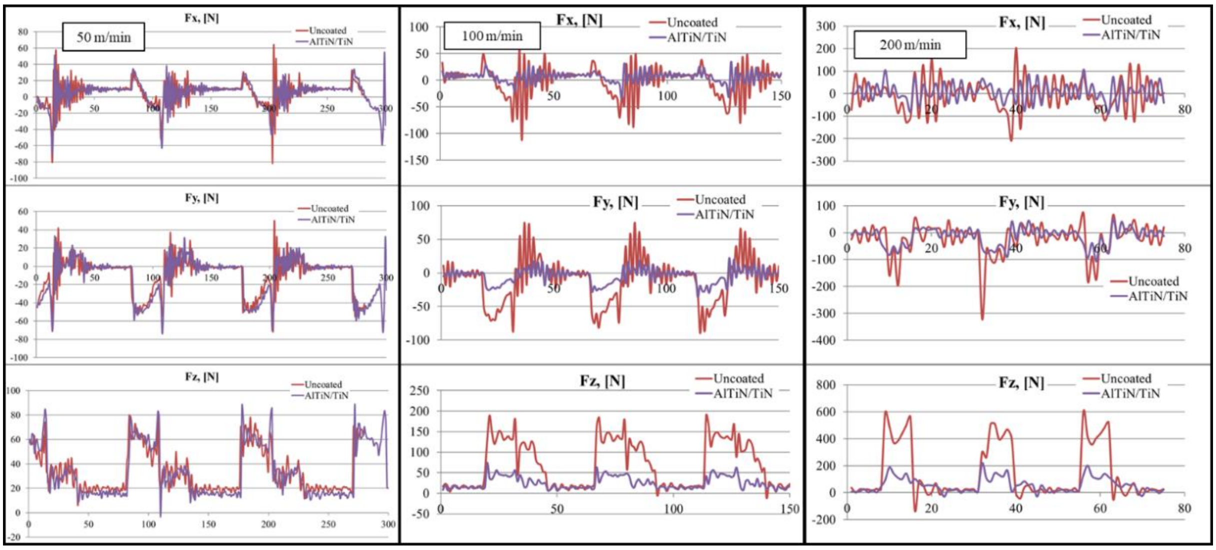

Figure 7. Cutting-forces comparison measured at a cutting-speed of 50, 100, 200 m/min

The comparison of the cutting-forces (F_x, F_y, F_z components) measured in milling tests at a cutting-speed of 100 m/min with uncoated and nano-layered nlAlTiN/TiN coated cutting-tools n are seen in Fig. 7. In all components of the cutting-force, the nano-layer coated carbide cutting tool showed higher cutting performance than the uncoated one. The most significant improvement in the F_z cutting-force component, which has the most significant impact on the cutting tool material wear behavior, has been achieved in the face-milling operations. The milling process with innovative nano-layer hard-coated cutting-tools deposited on the cutting tool material is thought to advance cutting performance because of the low friction coefficient provided by the hard-coating.

Comparing the cutting-forces (F_x, F_y, F_z components) measured in milling tests at a 200 m/min cutting-speed with uncoated and nano-layered nlAlTiN/TiN coated cutting-tools are seen in Fig. 7. As with the previous cutting-speeds, lower cutting-force values were obtained in milling operations with nano-layer cutting-tools than milling tests with uncoated cutting-tools.

IV. CONCLUSIONS

In this work, the effect of nano-layer hard-coated carbide cutting-tools on cutting tool-life and cutting-forces in the processing of AISI D2 steel was investigated. In addition, the wear behavior of the worn carbide cutting-tools was investigated. All the results obtained after all applied tests are as follows.

- An increase in the cutting-tools' tool-life has been observed at all cutting-speeds thanks to the coating material.
- 15 m cutting-length has been reached with a nano-layer cutting tool at 50 m / min cutting-speed. Compared to the test results with uncoated cutting-tools, approximately seven times more tool-life has been achieved.
- At cutting parameter nano-layer, AlTiN/TiN and TiAlN coated tool presented almost the same tool wear progress, while TiAlN outperformed around notch wear criteria with cutting-length of ~8 m.
- At 200 m/min cutting-speed nano-layer, AlTiN/TiN coated tool showed longer cutting-length than the other cutting-tools, foremost to ~ ten times longer tool-life than the uncoated one.
- After the tool-life tests applied at a cutting-speed of 100 m/min, the worn TiN coated cutting tool observed flank wear; at first and third cutting parameters, notch wear was observed.
- TiAlN coated tool demonstrated flank wear at low cutting-speed; notch wear becomes the leading wear type at advanced cutting-speeds.
- In nano-layer coated tools, notch wear led to tool disappointment at all cutting-speeds.
- Abrasion, adhesion of work-piece, and oxidation were dominant tool wear mechanisms on all the
- Built-up-edge, seizure zone was identified on both cutting-tools.
- The milling process with innovative nano-layer hard-coated cutting-tools deposited on the cutting tool material improves cutting performance because of the hard-coating's low friction coefficient compared to the uncoated one.

It is planned to examine the performance of the same hard-coating in the machining of other hard work-piece materials in future investigations.

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