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Experimental Vibration Analysis of Titanium Aluminum Nitride (TiAlN) Coated Milling Cutting Tool Effects on Surface Roughness of AISI 4140 Steel Products

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ABSTRACT

The vibration response of material removal process in milling has a significant effect on surface roughness of the product with respect to cutting tool coating. Recent requirements for improving of surface roughness have heightened the need for milling with coated cutting tools. The main objective of this study is to experimentally investigate the role of vibration behavior of cutting tool coated with titanium aluminum nitride (TiAlN) on an AISI 4140 alloy steel work piece surface roughness. The vibration data from work piece were recorded for three milling cutting tools with tool diameters of 10, 12, and 16 mm and for each diameter different coating thicknesses of 0.0, 2.0, 3.0, and 5.0 μ (microns) were used respectively. Vibration signals of work piece during milling process in two directions were collected and a roughness tester was used to measure the surface roughness of work piece. The results showed that vibration due to cutting tool coating thickness has a significant effect on surface roughness of work piece. It has been observed that the maximum average surface roughness was obtained for 16 mm tool diameters with coating thickness of 5.0 μ while the minimum average surface roughness was obtained for 10 mm tool diameters with coating thickness of 3.0 μ. Surface roughness can be improved by reduction sources of vibration by using appropriate cutting tool coating thickness.

Keywords: *AISI 4140, Milling, Coated cutting tool, TiAlN, Surface roughness, Vibration analysis.*

AISI 4140 Islah Çeliğinin TiAlN Kaplı Frezelerle İşlenmesi Sırasında Oluşan Yüzey Pürüzlülüğü ve Titreşiminin Deneysel Olarak İncelenmesi

ÖZET

Frezede talaş kaldırma işlemi sırasında oluşan titreşimlerin kesici takım kaplama kalınlığına bağlı olarak ürün yüzey pürüzlülüğü üzerinde önemli bir etkisi vardır. Son yıllarda yüzey pürüzlülüğünü iyileştirmek için kaplanmış

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kesici takımların kullanım ihtiyacı artmıştır. Bu çalışmanın amacı titanyum alüminyum nitrit (TiAlN) ile kaplanmış kesici takımın işlem sırasında kaplama kalınlığına bağlı olarak titreşim davranışlarının AISI 4140 alaşımlı çelikten yapılmış iş parçasının yüzey pürüzlülüğü üzerindeki etkisini deneysel olarak incelemektir. Çalışmada üç farklı çaptaki (10, 12 ve 16 mm) kesici takım ve her kesici takım için dört farklı kaplama kalınlığı (0.0, 2.0, 3.0 ve 5.0 mikron) kullanılmıştır. Frezeleme sırasında iş parçasında iki yönde titreşim sinyalleri toplanmış ve elde edilen yüzey pürüzlülüğü ölçülmüştür. Sonuçlardan 3.0 mikron kaplama kalınlığı olan 10 mm çapındaki kesici takımın diğer takımlara kıyasla daha iyi bir yüzey pürüzlülüğü elde ettiği görülmüştür. Yüzey pürüzlülüğün iyileştirilmesi, uygun kaplama kalınlığına sahip kesici takımın kullanılarak titreşimin azaltılması ile mümkün olduğu söylenebilir.

Anahtar Kelimeler: *AISI 4140, Freze, Kaplamalı kesici takım, TiAlN, Yüzey pürüzlülüğü, Titreşim analizi.*

I. INTRODUCTION

Milling process results in different kind of vibrations from the machine structure, cutting tool, and work piece. Vibration generated from interaction between cutting tool and work piece causes tool wear and reduces work piece surface quality. Vibration between the cutting tool and work piece deteriorates surface roughness. Surface roughness is one of the most important issues for evaluating surface quality in milling process. Controlling vibration is very important for improving work piece surface roughness quality. Milling a work piece is a complex process in which many parameters can affect the desired results. Vibration exists throughout the cutting process while influenced by many parameters such as diameter of cutting tool, tool coating thickness, cutting speed etc. A number of studies have been conducted to monitor vibration during the milling process. The final surface quality of product is connected with vibration in machining process [1-3]. Tool life is also influenced by vibration [3, 4]. Integrated vibration avoidance has experimentally shown to improve the damping on workbench table [5]. Vibration due to cutting force in milling was studied by [6]. Regression model using vibration signals of cutting force was presented by [7]. Control of cutting tool vibration using a damping pad was studied by [8]. Chatter stability prediction was studied to understand machine tool dynamics under operational conditions [9]. Vibration and tool wear relationship was investigated during end milling by [10, 11]. In general, the coated cutting tools experience lesser wear and decreases the effects of vibration compared to uncoated tools [12]. Surface roughness and vibration in turning of AISI 4140 steel was optimized using Taguchi method [13]. So, the main objective of this study is to experimentally investigate the effect of vibration behavior of cutting tool with different diameters and coating thickness on AISI 4140 steel alloy work piece surface roughness.

II. EXPERIMENTAL SETUP

The experiments were carried out under dry milling conditions in a vertical type milling lathe referenced Falco VTM-3HS. Cutting tools with three different diameters of 10, 12, and 16 mm were coated with titanium aluminum nitride (TiAlN) which is suitable for high speed milling and high temperature without use of coolant. Three different coating thicknesses of 2.0, 3.0, and 5.0 μ (microns) were employed for each of cutting tools using Physical Vapor Deposition (PVD) coating process. One uncoated cutting tool is also employed for comparison. The cutting tools have four teeth. AISI 4140 steel is used as a work piece for test sample because it is one of the most commonly used materials in industry. Technical drawing and picture of work piece before and after milling process are given in Figure1. AISI 4140 steel has distinct chemical and mechanical characteristics which make it valuable for different industrial applications. The properties of AISI 4140 steel are given in Table 1. The work piece hardness is measured about 42 HRC using a device branded Teskon TH320. The work piece was clamped to the milling table which moved in the x direction.

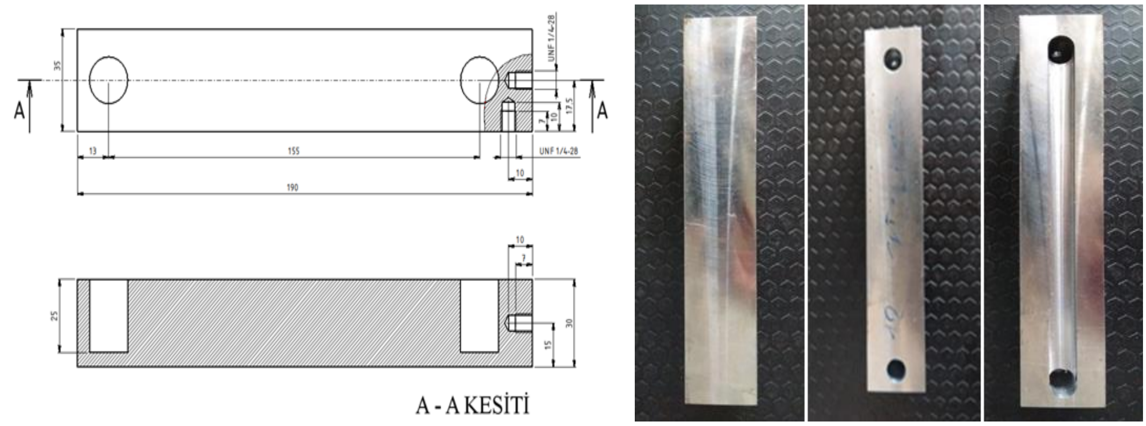

Figure 1. *Technical drawing of work piece*

Table 1. *Chemical composition of AISI 4140 steel*

Element	C	Si	Mn	P	S	Cr	Mo	Al
(%)	0.39	0.27	0.74	0.008	0.01	1.06	0.2	0.03

Two accelerometers (608A11 type) sensor were used to collect vibration signals of work piece and identify the dynamic characteristics of the cutting tool during milling process in x and y direction on the work piece holder. The accelerometers were set as Ch1 and Ch2 for x and y directions respectively. The captured vibration signals have been analyzed in frequency spectrum which is a plot of the amplitude of the vibration response versus frequency. The specifications of the accelerometer are as follows; sensitivity 10.2 mV (m/s^2) and frequency range 0.5 to 10 kHz. Data acquisition (DAQ) unit from SpectraQuest was used to record vibration signals. Five parameters were considered in the experiments: cutting tool diameter, cutting tool coating thickness, spindle rotating speed, cutting depth, and feed rate. The cutting data used in the experiment are given in Table 2. Since the cutting tool coating thickness, cutting speed, and cutting feed play a very important role influencing surface roughness, the vibration signals data were recorded for twelve cutting tools having different coating thickness, cutting speed, and cutting feed parameters.

Table 2. The details of the experimental conditions

	Test Number											
	1	2	3	4	5	6	7	8	9	10	11	12
	Cutting Tool Diameter *(mm)*											
	10				12				16			
	Coating Thickness *(μ)*											
	0.0	2.0	3.0	5.0	0.0	2.0	3.0	5.0	0.0	2.0	3.0	5.0
Spindle Speed *(rev./min.)*	2388	2388	2388	2388	1990	1990	1990	1990	1492	1492	1492	1492
Feed Rate *(mm/min.)*	192	192	192	192	318	318	318	318	358	358	358	358

In order to fix the cutting speed to 75 m/min the spindle speed was chosen 2388 rev/min. (revolution per minute) for cutting diameter of 10 mm, 1990 rev/min. for diameter of 12 mm, and 1492 rev/min. for diameter of 16 mm. Each of experimental tests is carried out at cutting depth of 0.5 mm for each cutting layer and continued ten times to reach a total of cutting depth up to 5.0 mm in order to see the effect of cutting tool wear on final surface roughness of work piece. So, a total of 120 tests were carried out. Test work piece with final level surface were measured for average surface roughness, Ra, by a device branded ALPA-SM RT-60.

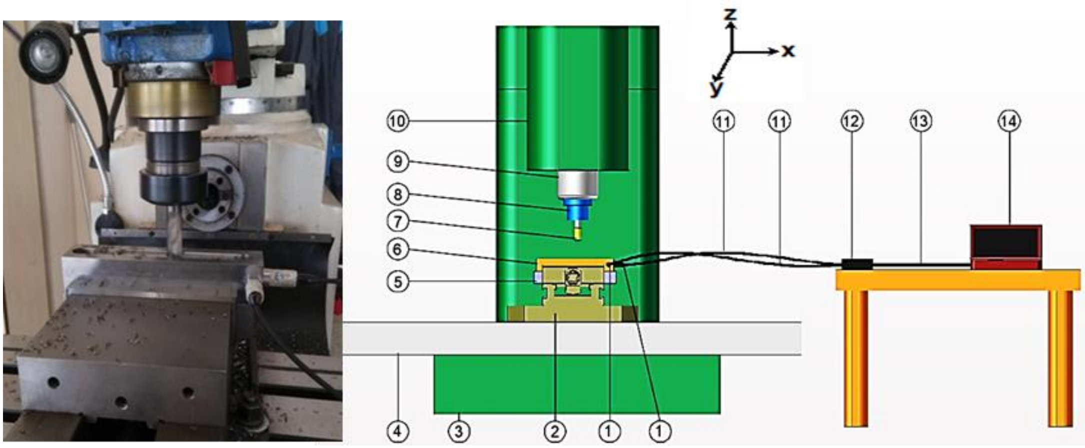

Figure 2. *Experimental setup: 1-Accelerometer; 2- Vice; 3-Workbench Base; 4- Workbench Table; 5-Mount; 6-Workpiece; 7-Cutting Tool; 8-Tool Holder; 9-Spindle; 10-Bench Column; 11-Accelerometer Cable; 12-Data Acquisition Unit; 13-Connection Cable; 14-Computer*

III. Findings

Table 3 gives average surface roughness, Ra, value of final level cut surface of work pieces for three milling cutting tools with tool diameters of 10, 12, and 16 mm and for each diameter different coating thicknesses of 0.0, 2.0, 3.0, and 5.0 μ were used respectively. For milling process using cutting tool with diameter of 10 mm, the lower Ra value measured is 0.72 μm for coating thickness of 3.0 μ while for cutting tool with diameter of 12 mm, the highest Ra value measured is 1.87 μm. It can be seen from Table 3 that smaller coated cutting diameter results better average surface roughness compared to larger coated cutting tool diameter for all coating thicknesses of 2.0, 3.0, and 5.0 μ with exception of 12 mm diameter subject to coating thickness of 5.0 μ. The minimal surface roughness was obtained with combination of cutting tool diameter of 10 mm, cutting tool speed of 2388 rpm (~ 40 Hz), feed rate of 192 mm/min., and cutting tool coating thickness of 3.0 μ.

Table 3. *Average surface roughness, Ra, value of final level cut surface of work pieces*

Work piece Number	Cutting Tool Diameter *(mm)*	Coating Thickness *(μ)*	Ra *(μm)*
1	10	0.0	1.72
2	10	2.0	0.91
3	10	3.0	0.72
4	10	5.0	1.06
5	12	0.0	1.87
6	12	2.0	1.17
7	12	3.0	0.85
8	12	5.0	0.96
9	16	0.0	1.29
10	16	2.0	1.24
11	16	3.0	1.07
12	16	5.0	1.43

The coated cutting tool decreases the effects of vibration. From Figure 3 it can be seen that different coating thicknesses have different internal damping characteristics to damp the vibration during milling process. Among three different coated and one uncoated conditions, the cutting tool with coating of 3.0 μ produces the superior surface quality. It can be seen from Figure 3 that no significant changes are observed for all cutting tools with coating thickness of 3.0 μ although a small difference in vibration amplitude level may be noticed. It can be said that the amplitude of vibration increases with advancement of cutting tool wear caused from friction between the tool and work piece. Plots in Figure 4 give the vibration spectrums for different condition of cutting tool and the spectra of vibration acceleration of the last milling process during the advancement of cutting tool wear. Comparing the amplitudes shown in Figure 4, it can be found that the dominant vibration spectrum peaks in y directions (Ch2) are larger than those in the x directions (Ch1). Cutting tool exhibits a characteristics vibration signatures that is uniquely its own. From spectrum plot it can be seen that the dominant frequency components are around the spindle rotating frequency, Tooth Pass Frequency (TPF), and their harmonics. TPF is equal to spindle rotating frequency multiplied by cutting tool teeth [14]. It can be seen from spectrum plot along with Tooth Pass Frequency (TPF) and its harmonic (1x, 2x, 3x, 4x, etc.) are presented. 52th for Ch1 and 54th for Ch2 multiple of TPF (160 Hz) show the dominancy among all other harmonics for uncoated cutting diameter of 10 mm. 5th for Ch1 and 59th for Ch2 multiple of TPF (160 Hz) for cutting diameter of 10 mm with coating thickness of 3.0 μ show the dominancy among all other harmonic. 72th for Ch1 and 74th for Ch2 multiple of TPF (133 Hz) show the dominancy among all other harmonics for uncoated cutting diameter of 12 mm. 6th for Ch1 and 54th for Ch2 multiple of TPF (133 Hz) show the dominancy among all other harmonics for cutting diameter of 12 mm with coating thickness of 3.0 μ. 73th for Ch1 and 66th for Ch2 multiple of TPF (100 Hz) show the dominancy among all other harmonics for uncoated cutting diameter of 16 mm. 11th for Ch1 and 71th for Ch2 multiple of TPF (100 Hz) show the dominancy among all other harmonics for cutting diameter of 16 mm with coating thickness of 3.0 μ.

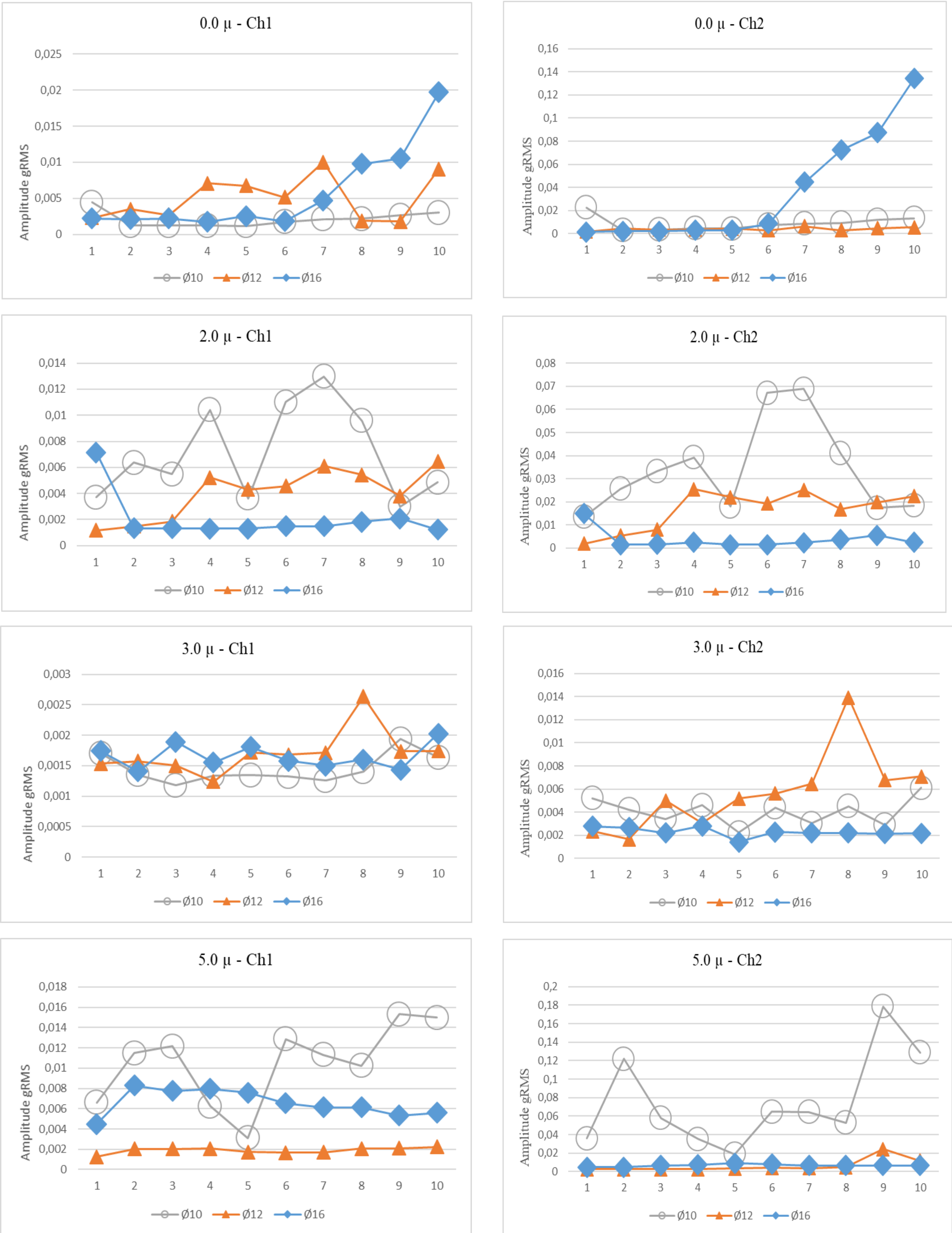

Figure 3. *The maximum amplitude values of cutting tools with advancement of cutting tool wear*

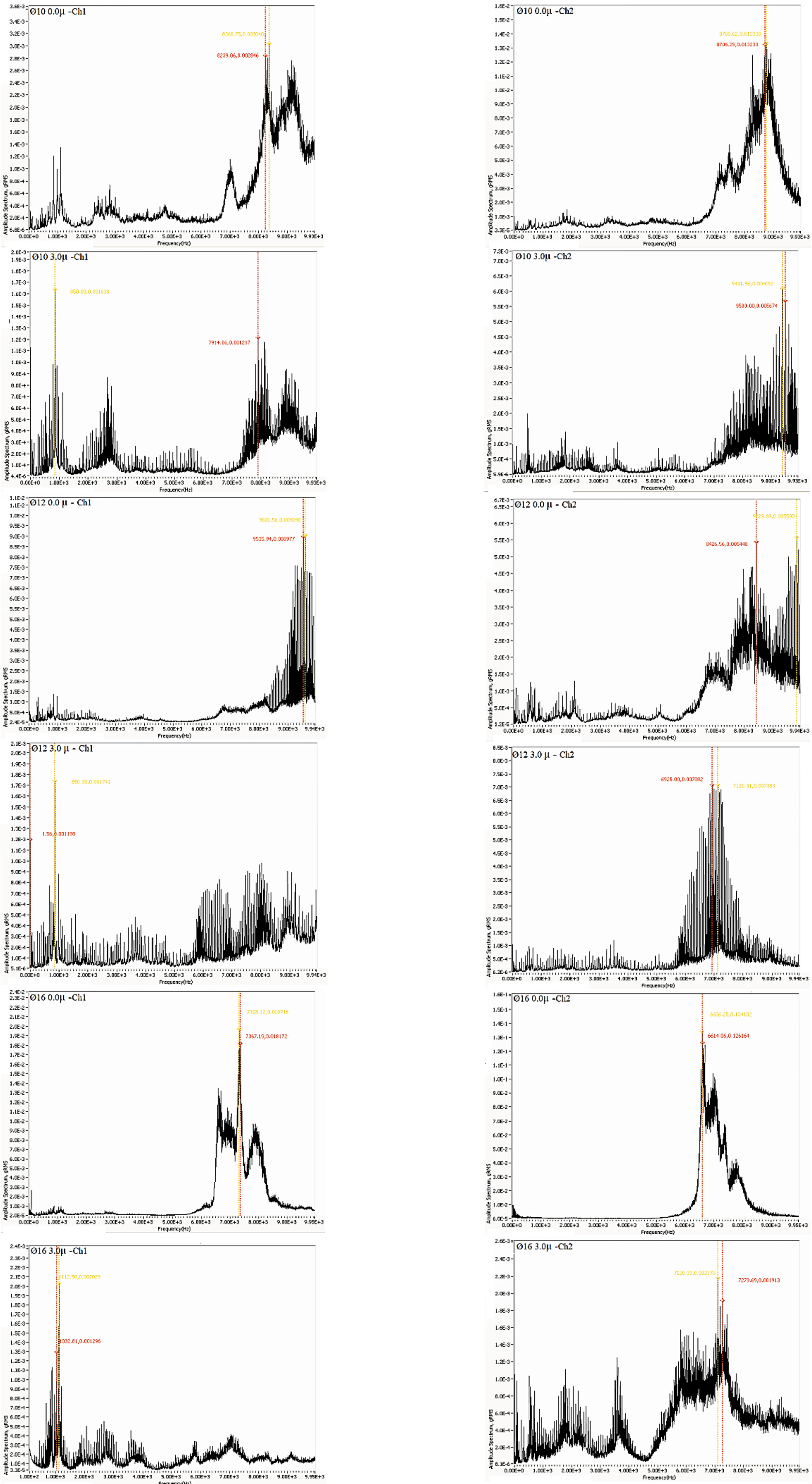

Figure 4. *The spectra of vibration acceleration of the last milling process during the advancement of cutting tool wear*

IV. Conclusion and Discussion

The objective of this study was to experimentally investigate the effects of coated milling cutting tool vibration on the resulting surface roughness in the dry milling process of AISI 4140 steel widely used in the industry. The results have shown that the coating thicknesses have to be chosen with care in order to maintain low vibration during milling process. Low vibration prevents generation of micro cracks on the cutting tool edge and work piece surface. It has been seen from results that the maximum average surface roughness was obtained for 16 mm tool diameters with coating thickness of 5.0 μ while the minimum average surface roughness was obtained for 10 mm tool diameters with coating thickness of 3.0 μ. The minimal surface roughness was observed with the combination of low feed rate and high spindle rotating speed. It can be concluded that surface roughness can be improved reduction of vibration using appropriate cutting tool coating thickness.

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