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Research Article

Determination of the Tool Wear using Cutting Force in Face Milling of Ti-6Al-4V under High Pressurized Cooling Conditions

İnayet Burcu Toprak[1a], Oğuz Çolak[2b], Mustafa Bayhan[3c]
[1] Department of Control and Automation, Vocational School of Tech. Sciences, Akdeniz University, Antalya, Turkey
[2] Department of Mechanical Engineering, Faculty of Engineering, Eskişehir Technical University, Eskişehir, Turkey
[3] Department of Mechanical Engineering, Faculty of Engineering, Süleyman Demirel University, Isparta, Turkey

ibmutlu@akdeniz.edu.tr

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ORCID: [a]0000-0002-0894-5573; [b] 0000-0002-1777-9300. [c] 0000-0001-5793-5390.

Abstract : In this study, plain and profile cutting operations were carried out in Ti-6Al-4V material with sharp and worn tools. In the experiments, the cutting speed was 90 [m/min], the feed rate was 0.1 [mm/tooth], and the pressure of the applied coolant was changed to 6, 100, 200, 300 bar, respectively. Haar wavelet was applied to the Fx force signals recorded during the experiments and decomposition was made at Level 5. As a result of the analysis of the obtained CA5 wavelet coefficients with the receiver operating characteristic (ROC) curve analysis, the limit values were determined to separate the worn tool from the unworn tool. The threshold values are determined for plain cutting and profile cutting as 1150.26 and 899.59, respectively. In this way, it will be possible to stop the machine at the desired wear value.

Keywords : Ti-6Al-4V, Tool Wear, Cutting Force, Wavelet, ROC Analysis.

1 Introduction

The primary goal of the manufacturing industry is to improve product quality while decreasing the process costs. During metal cutting processes, the utmost affecting and indicating factor to provide manufacturing economy is the tool wear. During manufacturing, after a certain amount of tool wear, the surface quality of the workpiece starts to get deteriorated, energy consumption starts to increase and unwanted vibrations occur in the system [1]. Direct and indirect methods are used to measure the cutting tool wear. Direct methods are performed after stopping the cutting operation. Measurement is generally conducted using contact probes; optical, radioactive and proximity sensors and techniques like measuring the changes in electrical resistance. Online measurement of tool wear with contact sensors is impractical because of wear, breakage, vibration and chip removal problems. Instead of online techniques, indirect measurement techniques are used to monitor the tool wear which measures physical quantities such as shear force, acoustic emission, torque, temperature, vibration, motor current, and the strain on the tool holder and photographic images of the cutting tool.

Continuous monitoring of the tool condition is required to reduce machining cost and ensure sustained product quality. For this reason, a Tool Condition Monitoring (TCM) system which monitors tool condition, detects tool wear on time and alerts the operator or the control mechanism to have the tool get replaced, thus eliminates undesired consequences. Ideal automation system in cutting would be capable of recognizing process errors and eliminate them without any external input. In classical manufacturing processes, these tasks are performed by operators, on the other hand in intelligent manufacturing systems these tasks are performed by single/multiple sensors and devices which can make decisions by interpreting incoming signal information. A successful intelligent manufacturing system stands on the quality of the information received by the monitoring sensors and the techniques provide the decisions [2]. Li et al. [3] studied an effective algorithm that follows acoustic emission (AE) and analysis of the current signal based on the analysis of the discrete wavelet transform (DWT). The test results showed that the tool wear in the drilling process have 98.5% reliability and real-time monitoring was good. Al-Habaibeh and Gindy [4] performed research about tool wear in milling operations by using sound, force and vibration sensors in accordance with the tool state monitoring method. Using amplitude values of output signals, fuzzy logic and artificial neural network (ANN) models were generated. Li [5] reviewed the use of AE during tool wear monitoring in turning operations. The data of AE was processed using fast Fourier transform (FFT) and wavelet transform (WT) then both methods were compared. It is stated that WT produces better solutions in time and frequency. Çolak [6], used AI techniques in CNC hard milling process to monitor tool wear and to determine optimum cutting conditions. He has developed a fuzzy logic model by utilizing sound signals and vibration measurements. Milling dynamics was considered in the developed model, thus the model assured conducting the tool wear experiments without chattering. Multi-sensor-assisted test results used during monitoring the tool wear and characterization

Table 1: Chemical composition and mechanical properties of Ti-6Al-4V material

	Chemical Composition							Mechanical properties		
Alloy Type	N	C	H	Fe	O	Al	V	Tensile Strength (N/mm2)	Yield Strength (N/mm2)	Elongation (%)
Ti-6Al-4V	0.05	0.08	0.015	0.40	0.20	5.50	3.50	900-1100	830	10

of the milling process dynamics were analyzed using AI techniques such as fuzzy logic and gene expression programming. Chen and Li [7] performed wavelet multi-resolution analysis on acoustic emission signals which are obtained from experiments performed using sharp and worn tools. 12th wavelet set of Daubechies was used as the main wavelet and the signals obtained from the experiments has been decomposed to 6 levels. For every cutting condition, the standard deviation, maximum, minimum, RSM and mean values of the coefficients were calculated. It was stated that the coefficients obtained from the sharp tool are more stable when compared with the worn tool. Alanso and Salgado [8] worked on the development of a reliable tool state monitoring system for industrial applications. The recommended tool condition monitoring system is based on the analysis of tool vibration signals. They explained that implementation of the single spectrum analysis and clustering analysis together increases the efficiency in signal processing. And it was indicated that the proposed system is fast and it is reliable for tool wear monitoring. Bhattacharyya et al. [9] used current and voltage signals of the spindle to predict the tool wear during face milling. They have introduced a system for prediction of the tool wear using multi-linear regression model. Gupta's [10] purpose in his research was to develop an empirical model in turning process for the prediction of surface roughness, tool wear and required power in terms of cutting speed, feed rate and cutting time. He used three different methods: RSM (Response Surface Methodology), ANN and SVR (Support Vector Regression). It was stated that the results of ANN and SVR were better than RSM. Zhang et al. [11] investigated the correlation between the cutting force and the tool wear during high-speed milling of Ti-6Al-4V alloy under dry cutting conditions. A positive correlation between Fy intercept of the cutting force and tool wear was observed. Zuperl et al. [12] introduced a TCM system that can detect the tool wear in real-time which uses both the ANFIS tool wear predictor and an error compensation module. Korenaga et al. [13] searched for the parameters which can help evaluation of the tool wear. They focused on the cutting force which is perpendicular to the cutting tool. They used Ti-6Al-4V alloy under various cutting conditions in milling to observe the effect of the cutting force on tool wear. They noticed that the lateral tool wear is decreased when the cutting force is decreased. Tiwari et al. [14] used the cutting force and surface images of the workpiece during milling of the Ti-6Al-4V alloy which was obtained under various cutting speed, feed rate and cutting depth to evaluate a model for prediction of tool wear. It was stated that the model which is developed using Kalman Filter Methodology provided good accuracy.

The aim of this study is to enhance the production process by monitoring the status of the metalworking machine and the tool wear using a single parameter. Ti-6Al-4V alloy was machined in plain milling and profile milling processes using sharp and worn tools. In the experiments, cutting speed and feed rate were selected as 90 [m/min] and 0.1 [mm/tooth] respectively, based on a review of the literature. And various values for the cooling fluid pressure was adjusted as 6, 100, 200, 300 bar. Wavelet transform was applied to the Fx force signals that were recorded during experiments. The obtained coefficients were examined through ROC analysis, and threshold values were determined to distinguish between sharp and worn-out tools. The machine can be stopped at the desired wear value with the limit value to be determined by conducting experiments in which tool wear is also measured. The proposed method offers a different solution from the literature in detecting tool wear.

2 Material and Method

2.1 Material

The Hartford VMC 1020 Vertical Machining Center located in the CAD/CAM Research and Application Center of Süleyman Demirel University shown in Figure 1 was used in the experiments.

Ti-6Al-4V alloy was used as a workpiece (dimensions: 100x130x50 mm) which is a popular alloy in electronics, computer, aerospace industries because of its high strength, density ratio, heat, and corrosion resistance. The chemical composition and mechanical properties of the workpiece are provided in Table 1.

When qualified according to cutting tool life, consumed energy and machined surface roughness after machining with any method, Titanium and its alloys are in the material group in which the materials can be processed very hardly using today's technology. Machinability can be managed by selecting proper processing parameters according to current conditions. Processing parameters are: cutting tool type, cutting speed, feeding speed, cutting depth and cooling [15]. During the processes of titanium alloys, using cutting coolant is recommended to reduce the temperature between the cutting tool and the workpiece, thus sticking of the titanium to the cutting tool would be avoided [15, 16, 17]. Water-miscible, semi-synthetic B-Cool 9665 machining coolant of Blaster Swisslube Company is used. B-Cool 9665 is preferred because it is suitable for light and heavy metal cutting and suitable for some grinding processes with titanium, stainless steel, and steel alloys. Palanisamy et al. [18] and Nandy et al. [19] machined Ti-6Al-4V under high-pressure cooling conditions and observed improvement in tool wear and tool life. When researches in the literature reviewed [20, 21, 22], it is seen that high-pressure cooling causes improvement of machinability and tool life when compared with regular cooling conditions [23]. A 7% concentration of high-pressure cutting fluid was injected through a 1.3 mm nozzle to the surface between the cutting tool and chip as shown in Figure 2.

Figure 1: Hartford VMC 1020 Vertical Machining Center

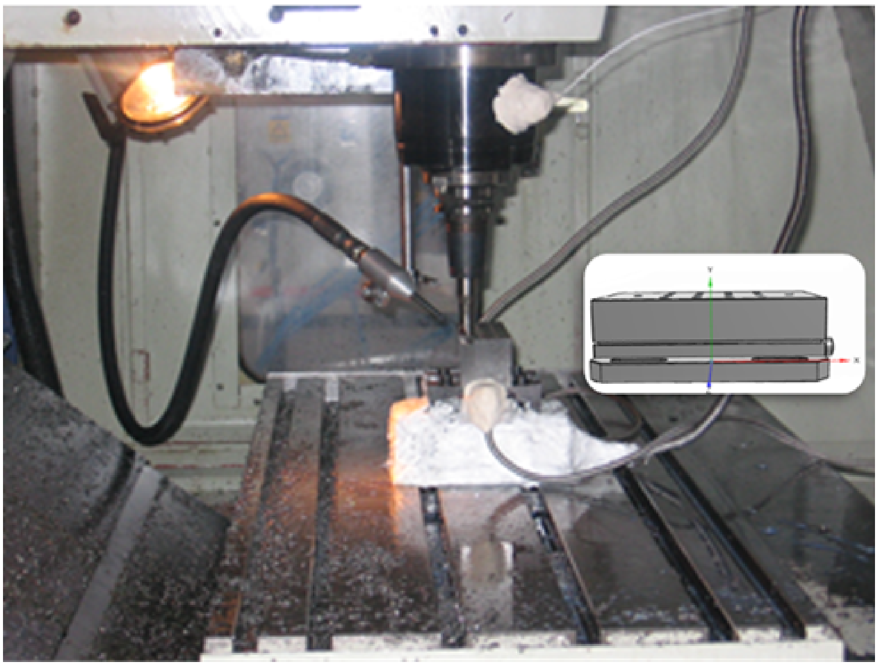


Figure 2: Injection of cutting fluid under high pressure to the cutting surface

The structure of the high-pressure jet cooling system with a compact design is shown in Figure 3. 6 Bar is selected as conventional coolant pressure; 100 Bar is selected for industrial machine high pressure coolant levels. 200 Bar and 300 Bar is selected for to see effect of ultra high pressure effects and experimental pump capacity is up to 450 bar. In this study, Kistler 9257-B dynamometer was used to obtain the shear force signals. The dynamometer was rigidly mounted on the milling machine table and covered with silicone for the isolation from the cutting fluid, then workpiece was mounted on top of it (Figure 4). Cutting force signals were passed through a signal conditioner and transferred to the computer through National Instruments DAQ 6062E type data acquisition card and the Kistler 5070 A type signal amplifier. Cutting force signals were measured for each three-dimensional axis. For this purpose, Cut-Pro software was used. Each force signals obtained at three axes were converted using FFT. It was observed that the signals obtained from a force signal on the x-axis are the same as the signals obtained from the FFT of a vibration signal [24]. For this reason, although measuring signals on all three axes, the cutting force signal on x-axis was used in the experiments.

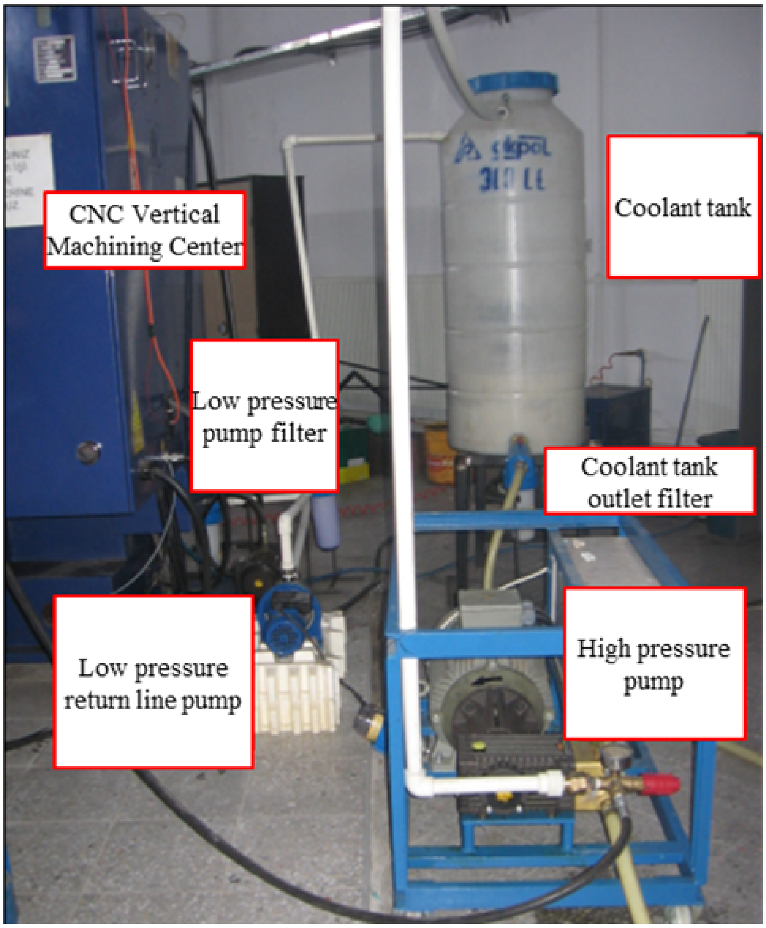


Figure 3: Structure of the high-pressure jet cooling system

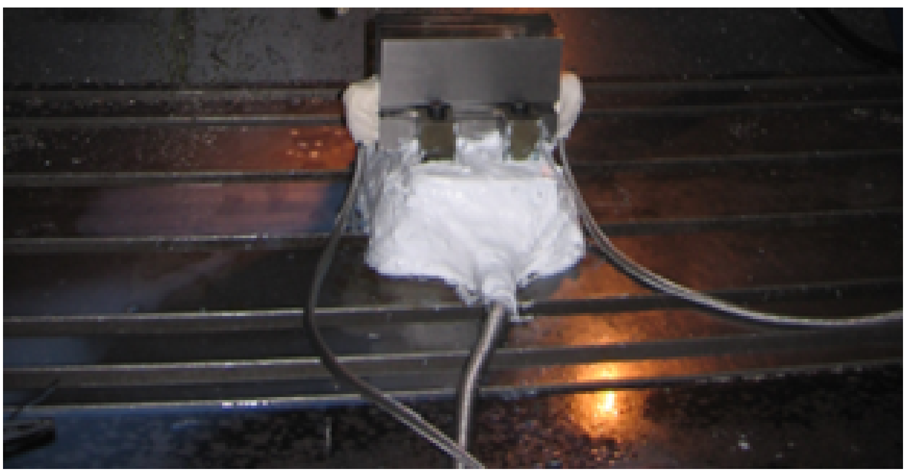
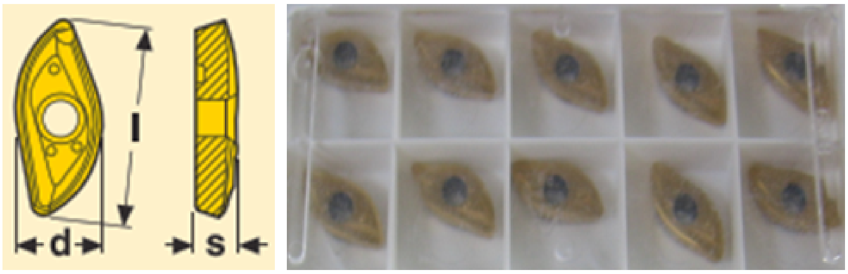
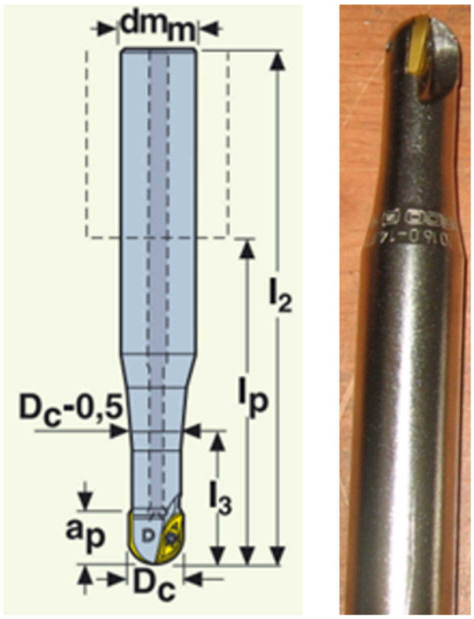


Figure 4: Dynamometer assembly



l [mm]	s [mm]	d [mm]
15,64	3,21	6,88

Figure 5: The cutting tool inserts and their dimensions used in the experiments



D_c	dm_m	l_2	l_p	l_3	a_p
16	20	120	70	36	14

Figure 6: Copy milling cutter and its dimensions

Experiments were performed with Seco F40M ((Ti, Al) N-TiN) coated 218.20-0.80ER-ME04 tool insert (Figure 5) and Seco R218.20-2016.0-14.070 copy milling cutter (Figure 6). You can access detailed information about the cutting tool from the company's website. The copy milling cutter is connected to the tool holder using the Seco Easy Shrink 15 device (Figure 7).

2.2 Method

Plain and profile cutting processes were performed with sharp and worn tools with Ti-6Al-4V and the force signals were recorded. During the experiments, the coolant pressure was adjusted to various values (6, 100, 200, 300 bar) while the cutting speed (90 [m / min]) and the feed rate (0.1 [mm / tooth]) were kept constant. Haar wavelet was used and the recorded Fx signals were decomposed to level 5. Since ADD is applied to discrete data, the decomposition process can be applied until 1 approximation and 1 detail coefficient remain at the final decomposition level. In practice, this choice is up to the analyst's judgment. The factors that may affect this decision can be said to be the characteristics of the time series and the purpose of the analysis. In this study, CA5, the last approximation component, offers a good approximation by showing the general features of the initial signal in a much more simplified form. For this reason, level 5 separation is made. CA5 coefficients were analyzed

Figure 7: Seco Easy Shrink 15 device and a tool in the holder

by ROC analysis, and the threshold value showing the difference between a sharp tool and a worn tool was determined. Figure 8 shows the model of the performed profile cut and Figure 9 shows the dimensions of the profile model.

2.2.1 Wavelet Transform

The Fourier analysis converts a signal from the time domain to the frequency domain, thus time domain disappears after frequency domain takes its place. In the spectral analysis, the time may be important for a component and in this situation the Fourier analysis may be inefficient.

Wavelet Transform (WT) is the most effective method for time-frequency analysis of transient signals. The most important advantage of WT is its narrow window size in high frequency and wide window size in low frequency. In this way, optimum time-frequency representation can be achieved in the whole frequency range.

There are two types of WT: Continuous wavelet transform (CWT) and Discrete Wavelet Transform (DWT). In continuous wavelet transform, scaling and transformation parameters are changed continuously so it is difficult and time-consuming to calculate wavelet coefficients. Therefore, in such calculations, DWT is used. With WT, a signal is decomposed in a specified number of products. This process is called multiresolution analysis and it is shown in Figure 10 for the x (n) sign. In the figure, the first outputs of the products of the high-pass filter (g [.]) and the low-pass filter h [.] are detailed and approximate lower bands: D1 and A1, respectively. The A1 band resolves again and the process continues as shown in the figure.

Haar wavelet is applied to the Fx signals recorded in plain and profile cutting made with sharp and worn tools, and decomposition is made at Level 5. There is no specific algorithm for detecting wavelets. For this reason, other wavelets in the wavelet family should be tried on the signal until the highest efficiency is obtained. The Haar wavelet used in the analyzes was chosen in line with the literature [3].

In order to exemplify the decomposition tree of Discrete Wavelet Transform into lower frequency bands on our provided data, while the coolant pressure was at 6 bar, the Fx signal recorded during profile cutting with a worn tool, and the lower bands obtained through wavelet transform, are shown in Figure 11.

In wavelet transform, approximations represent the original of the signal and are obtained with high scale. Details are low-scale information and high-frequency components of the signal.

The decomposition process continues until a meaningful signal solution is produced. Each time, the remaining approximate series can be decomposed into repetition, approximation, and detail. The approximation coefficients cA5 contain less noise than the original signal and show high scale low frequency components.

Descriptive statistics of the CA5 wavelet coefficients obtained from the Fx signal in plain and profile cutting with worn and sharp tools are given in Table 2.

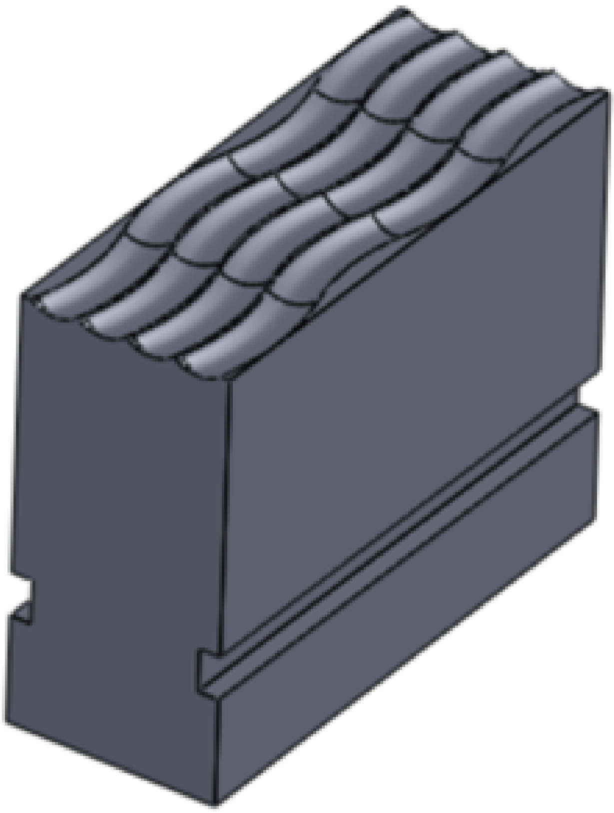


Figure 8: Model of the profile cut

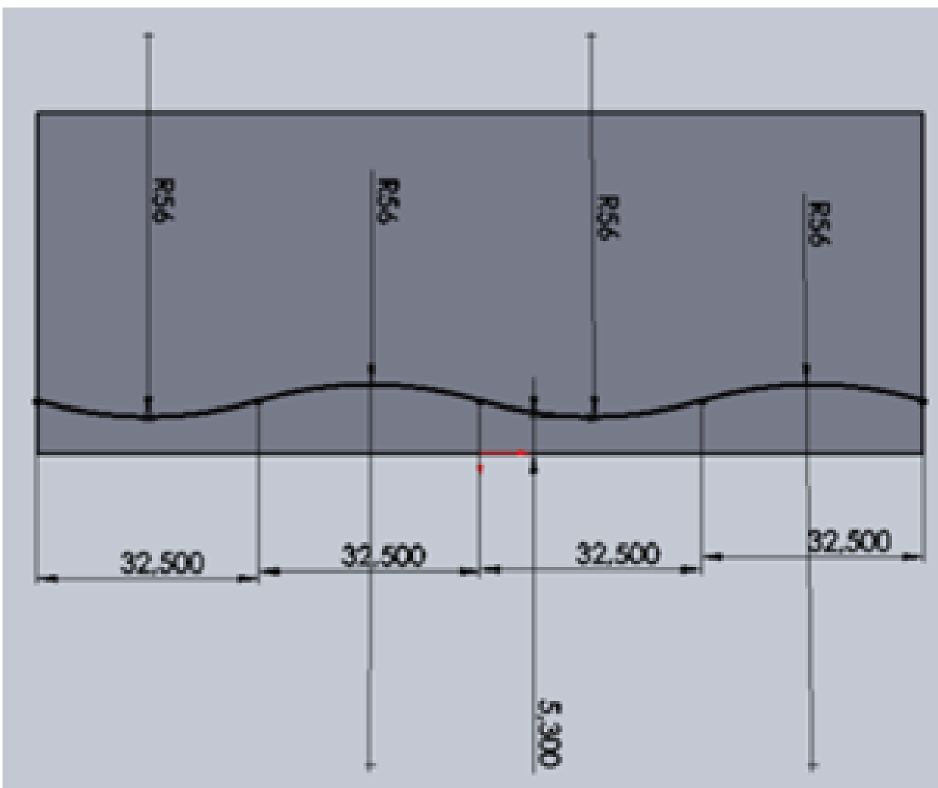


Figure 9: Dimensions of the profile model

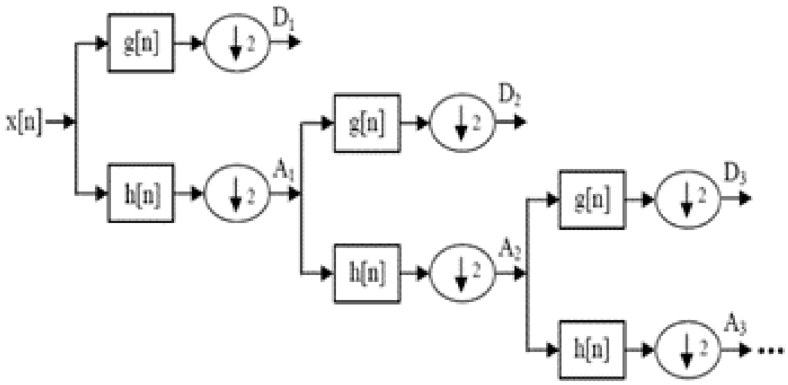


Figure 10: The decomposition tree of Discrete Wavelet Transform to lower frequency bands [24]

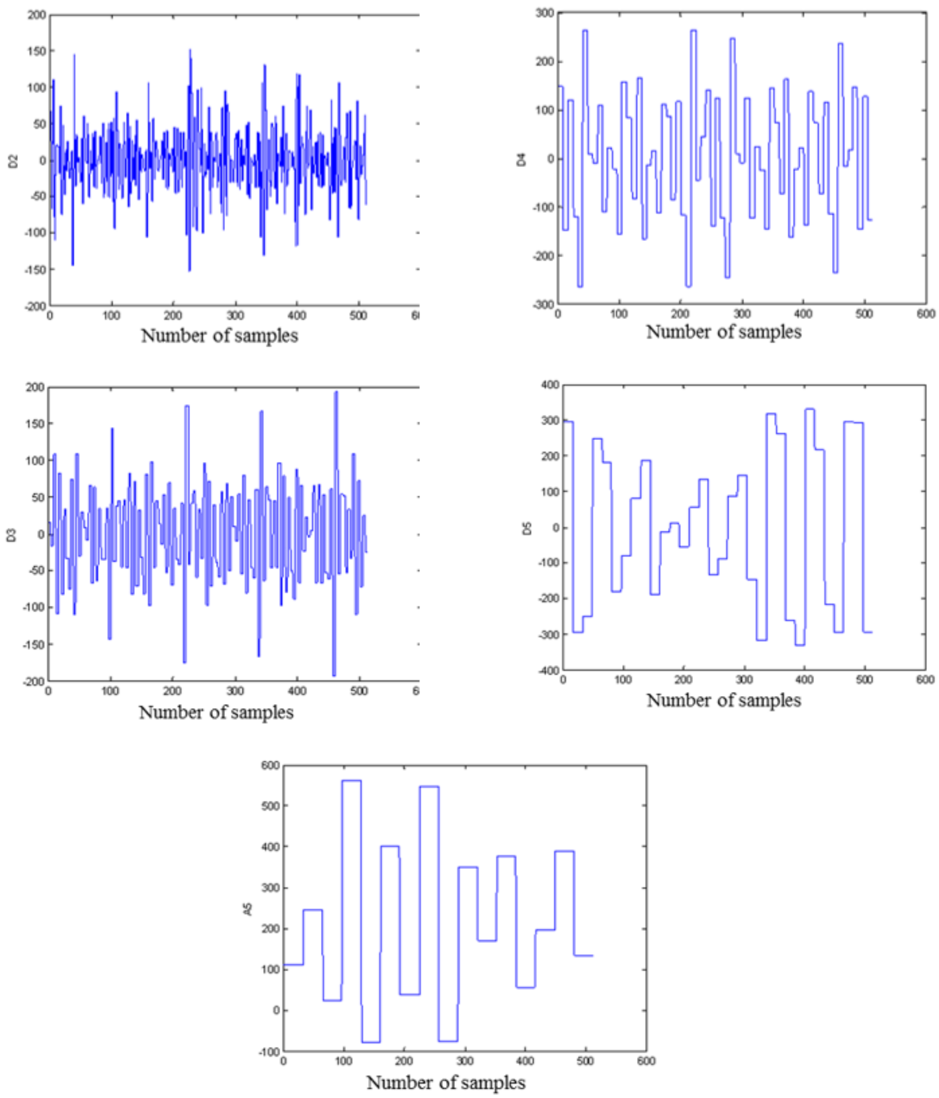


Figure 11: Decomposition of the Fx signal to the lower bands at the 5th level with the Haar wavelength (P = 6 bar, working with the worn tool)

Table 2: Descriptive statistics

Tool condition	Milling type	Minimum	Maximum	Average	Std deviation
Sharp	Plain cutting	545.66	952.53	737.50	97.102
	Profile cutting	206.62	830.34	492.93	149.866
Worn	Plain cutting	1348	1834.07	1574.35	109.765
	Profile cutting	968.85	1868.38	1362.24	198.961

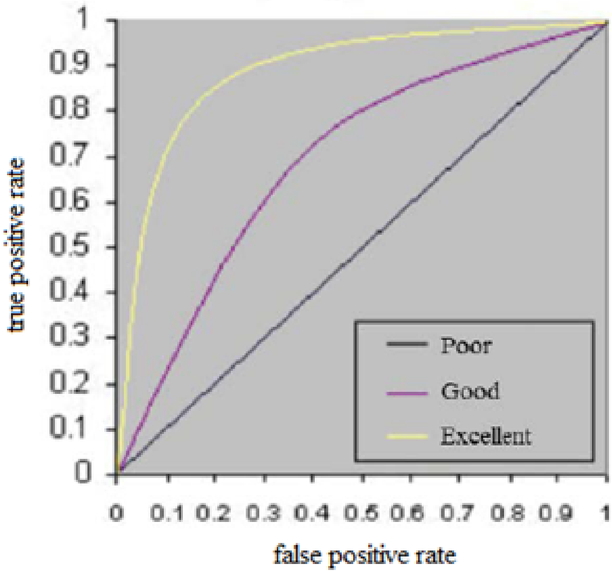


Figure 12: ROC curves according to their performances [26]

2.2.2 ROC Curve Analysis

ROC analysis is a method to determine the performance of diagnostic tests and to evaluate the precision of statistical models like logistics models and linear classification analysis. It is used to evaluate the precision of diagnostic tests and predictive models, to present the precision with analytical methods, and to compare the precision of the predictions.

In measurement tests where continuous numbers are used, decomposition of the features leads a complicate analysis and increases the possibility of errors. The ROC analysis determines the optimal threshold and the values which will be eliminated (located between sensitivity and specificity). Thus, the ROC curve analysis facilitates to understand the relation between the sensitivity and specificity of the measurements.

ROC curve is obtained by calculating the sensitivity values using every possible value of a variable in the alteration range, used to classify different subjects and marking the sensitivity values with the false positive rates (1-specificity) of the test.

In the coordinate system where the ROC curve will be generated, in y-axis true positive values (sensitivity) of the diagnostic test, in x-axis false positive values (1-specificity) are located [25]. On each point that corresponds to true positive and false positive points are combined together to form the ROC curve.

ROC curves belong to ideal and poor performance tests are given in Figure 12.

In an ideal test, ROC curve that doesn't have false values goes through the points (0.0), (0.1) and (1.1). The ROC curve that belongs to the poor test is a diagonal line with an angle of 45^{o} between the points (0.0) and (1.1). Generally, the ROC curve is altered between these two curves.

The size of the area under the ROC curve indicates the statistical importance of the classification capability of the diagnostic test. When the diagnostic test has no classification capability then the area under the ROC curve is equal to 0.50. In a perfect test, due to zero wrong positive and zero wrong negative values, the area will be 1.00. An area of the ROC curve of any diagnostic test should be between these two values. In Figure 13, ROC curves generated with SPSS 19 for plain and profile cutting are shown.

The area under each curve is calculated and given in Table 3.

For each predicted value, the area under the curve is significantly different from the diagnostic insignificant values of 0.500 ($p < 0.05$). Accordingly, it can be noticed that all predicted values are statistically true for determining the cut-off value.

Table 3: Area under curve

Milling type	Area	Standard error	p	Lower limit	Upper limit
Plain milling	1.000	0.000	0.000	0.000	0.000
Profile milling	1.000	0.000	0.000	0.000	0.000

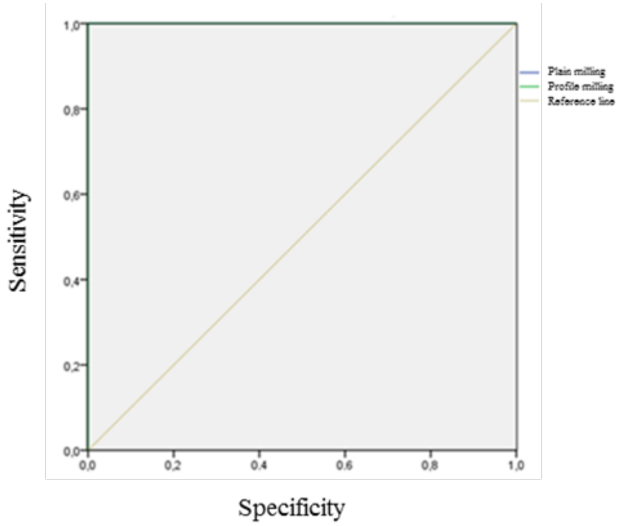


Figure 13: ROC curves

Table 4: Threshold values

Milling type	Threshold	Sensitivity	Selectivity
Plain milling	1150.26	1.000	1.000
Profile milling	899.59	1.000	1.000

In the prediction of the threshold, it was aimed to determine the optimum values for sensitivity and selectivity. Area of the predicted values was 1 which indicates that there is an open cut-off point. Therefore, the cut-off value for each predicted value was determined by 100% sensitivity and 100% selectivity. The threshold for determined sensitivity and selectivity values is given in Table 4.

3 Conclusion and Suggestions

In the process of chip removal, unnoticed tool wear not only increases part defects but also leads to tool breakage and high damages in expensive CNC machine tools. The accurate determination of tool wear compensation values based on the wear rate highlights the necessity of an automated monitoring system that tracks the chip removal process. This system identifies the moment when the wear on the tool reaches an unacceptable limit in terms of the dimensions and surface quality of the workpiece, prompting a replacement with a new tool before any breakage occurs. Therefore, monitoring tool wear and establishing a precise automation tracking system are crucial for enhancing the quality of workpieces and reducing the risk of damage in CNC machines [27, 28, 29].

The Ti-6Al-4V alloy, primarily used as a biomaterial or in aerospace applications, belongs to a group of materials that are difficult to machine using conventional methods due to its high electrical resistance and low heat conductivity [30]. In this study, it was processed through plain milling and profile milling operations using both sharp and worn tools. For the first time in the literature, a control value has been found for the detection of tool wear in plain and profile cutting. Haar wavelet was used and Fx signals recorded in the experiments were decomposed to 5 levels. After examining the CA5 coefficients through ROC analysis, the threshold values were determined which distinguish the worn tool and sharp tool. The threshold values are determined for plain cutting and profile cutting as 1150.26 and 899.59, respectively. It will be possible to stop the machine at the desired wear value with the limit value to be determined by carrying out experiments in which the wear on the tool is also measured. The implementation of this method is possible in places where chip removal machining is performed using a dynamometer.

In future studies, it is planned to investigate whether the limit values will be reached in machining operations other than milling, how the results will change in work materials other than titanium, and whether it will be possible to determine threshold values from signals other than the Force signal. The Haar wavelet used in the analyzes was chosen in line with the literature. The Haar wavelet is actually a differential operator. The daubechies1, symlet1, coiflet1 and biorspline1.1 wavelets are the same as the Haar wavelet. In future studies, different wavelets will be tried.

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Authors' Contributions

IBT (Inayet Burcu Toprak, Dr.) and MB (Mustafa Bayhan, Prof. Dr.) conducted the planning of the study. IBT conducted the experimental studies and analyses in collaboration with OC (Oguz Colak, Prof. Dr.) and wrote the article. MB is the overall supervisor of the study. All three authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

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