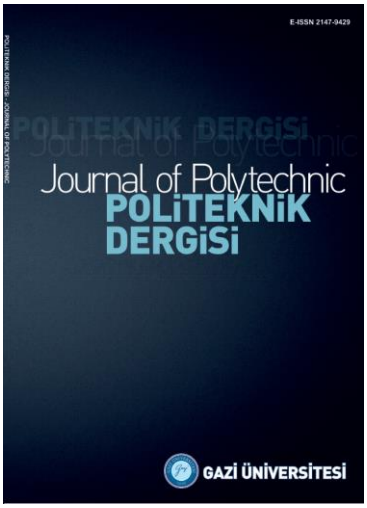

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Optimization and finite element modelling of tool wear in milling of Inconel 625 superalloy

Inconel 625 süper alaşımının frezelenmesinde takım aşınmasının sonlu elemanlar yöntemiyle modellenmesi ve optimizasyonu

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Optimization and Finite Element Modelling of Tool Wear in Milling of Inconel 625 Superalloy

Highlights

- *The flank wear in milling of Inconel 625 superalloy was analyzed using finite element and Taguchi methods.*
- *Analysis of signal-to-noise (S/N) ratio was used to evaluate optimum levels of the cutting parameters for minimum flank wear.*
- *Developing a mathematical model of tool wear using regression analysis.*

Graphical Abstract

In this study, machining experiments were performed on a CNC milling machine with different cutting parameters. Experimental results analyzed and a mathematical model was developed.

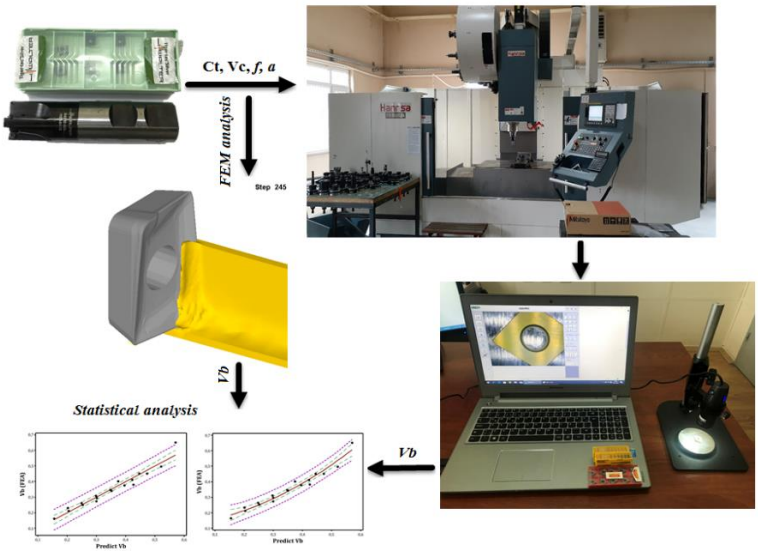

Figure. Experimental procedure

Aim

The aim of the study is to develop the mathematical model of the tool wear in milling of Inconel 625 superalloys using finite element and Taguchi methods.

Design & Methodology

The flank wear in milling of Inconel 625 superalloy was analyzed via Finite Element and Taguchi methods.

Originality

Unlike the literature, it is the development of the mathematical equation for flank wear in milling of Inconel 625 superalloy using finite element and Taguchi methods.

Findings

The mean deviation between experimental results and numerical results obtained with FEM was calculated as approximately 9.7%.

Conclusion

Taguchi method was a successful methodology to define the optimum cutting parameters in the milling of Inconel 625.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Optimization and Finite Element Modelling of Tool Wear in Milling of Inconel 625 Superalloy

Araştırma Makalesi / Research Article

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ABSTRACT

This study focuses on optimization of cutting conditions and numerical analysis of flank wear in milling of Inconel 625 superalloy using PVD AlTiN and CVD TiCN/Al_2O_3/TiN-coated carbide inserts. The milling experiments have been performed in CNC vertical machining centre according to Taguchi L18 orthogonal array. Finite element modelling of tool wear was performed using Deform 3D software. Analysis of variance was utilized to define the influences of the milling conditions on Vb. The results showed that the feed rate (with 41.5% contribution rate) is the most important parameter affecting Vb. The linear and quadratic regression analyses were used to estimate the results of the test. The regression analysis results showed that the estimated Vb values achieved by the quadratic regression model were more effective compared to the linear regression model. Statistical results revealed that the Taguchi method was successful to define optimum cutting parameters in the milling of Inconel 625.

Keywords: Inconel 625, milling, tool wear, taguchi, finite element analysis.

Inconel 625 Alaşımının Frezelenmesinde Takım Aşınmasının Sonlu Elemanlar Yöntemiyle Modellenmesi ve Optimizasyonu

ÖZ

Bu çalışma, PVD AlTiN ve CVD TiCN/Al_2O_3/TiN kaplı karbür uçlar kullanılarak Inconel 625 süper alaşımının frezelenmesinde kesme parametrelerinin optimizasyonuna ve yanak aşınmasının sayısal analizine odaklanmaktadır. Frezeleme deneyleri Taguchi L18 dikey dizinine göre CNC dikey işleme merkezinde gerçekleştirildi.Takım aşınmasının sonlu eleman yöntemiyle modellemesi Deform 3D yazılımı kullanılarak yapıldı. Takım aşınması üzerinde frezeleme şartlarının etkilerini tanımlamak için varyans analizi kullanılmıştır. Varyans analiz sonuçları, ilerleme miktarının (%41.5 katkı oranı ile) Vb'yi etkileyen en önemli parametre olduğunu göstermiştir. Test sonuçlarını tahmin etmek için lineer ve kuadratik regresyon analizleri kullanıldı. Regresyon analizi sonuçları, kuadratik regresyon modeli ile elde edilen tahmini Vb değerlerinin lineer regresyon modeline göre daha etkili olduğunu göstermektedir. İstatistiksel sonuçlar, Taguchi yönteminin Inconel 625 alaşımının frezelenmesinde optimum kesme parametrelerinin belirlenmesinde başarılı olduğunu göstermektedir.

Anahtar Kelimeler: Inconel 625, frezeleme, takım aşınması, taguchi, sonlu elemanlar analizi.

1. INTRODUCTION

Inconel 625, one of the nickel-based superalloys, has been used widely in aerospace engine and power generation turbine components, as well as in petrochemical, food processing, nuclear reactor, and pollution control equipment's. Some of the important properties of this material is high-temperature, creep resistance, excellent hot corrosion resistance, and thermal shock resistance. However, the nickel-based superalloys generally have poor machinability because of their high strength, and low thermal conductivity behavior. In addition, the existence of hard, abrasive intermetallic compounds and carbides in these alloys cause heavy abrasive wear on the tool tip [1-2].

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The cutting tool technologies are developing depending on the developments in engineering materials. This development is necessary for machining performance of materials with superior properties such as high tensile, creep, and rupture strength, outstanding fatigue and thermal-fatigue strength, excellent oxidation resistance at corrosive environments. Coating technology is one of the best significant ways of raising the wear resistance of tools inserts. Physical vapor deposition (PVD) and chemical vapor deposition (CVD) methods are used to coat the cutting tools. In recent years, researchers have focused on the comparison of PVD and CVD coatings in terms of machinability of difficult-to-cut materials. Jindal et al performed one of the first works related to this topic and they investigated the performance of different coated tools in turning [3]. The results showed that the best metal cutting performance has been obtained by TiAlN coated tools, followed by the TiCN and TiN coated tools. In another study, Sokovic et al [4]

investigated the cutting performance of the ceramic tools inserts with PVD and CVD coating. It has been observed that the application of hard coatings results in both longer tool life for cutting tools and improved machining surface quality. Kıvak investigated the machining performance of PVD and CVD coated inserts in milling Hadfield steel [5]. The analysis results showed that the feed rate was the most significant parameter affecting Ra whereas the cutting speed was the most important parameter affecting Vb. The machinability in hard turning of Hadfield steel using the mixed ceramic tool (Al_2O_3/TiC) evaluated by Horng et al [6]. The results showed that the cutting speed (Vc) and the nose radius of the cutting tool affected the flank wear.

In the manufacturing industry, it is desired to improve the manufacturing quality while reducing the production costs. There are many factors that have an influence upon product cost and quality; for example, rigidity of machine tool, the workpiece and tool materials, machining parameters, cooling etc. Therefore, numerous researchers recommend that the cutting simulation and optimization of input parameters is necessary to reduce the production cost and machining time [7-15]. Yaşar [16] investigated the thrust force modelling by using Advantedge software and optimization of Ra in drilling of AA-7075. The results showed that there is approximately 4.9% difference between the test and the simulation thrust force values. In addition, it was observed, in both experimental and numerical analysis results, that the thrust force increases with increase in feed rate. Korkmaz and Günay [17] studied the modelling of cutting forces and the power consumption by using Advantedge software based on finite element method in turning of AISI 420 martensitic stainless steel. Consequently, it was determined that there was an average 7% difference between experimental and simulated cutting forces. They also referred that the finite element modelling of Fc and power consumption is appropriate with the tests results, and it can be made with high correctness without extreme machining tests of difficult-to-cut materials.

Literature survey shows that there are not much studies related to finite element modelling of the tool wear in milling Inconel 625 alloys using cutting tools coated with different coatings. Apart from that the comparison of PVD and CVD coatings, in terms of machining performance of this material, has not been done. For this reason, in this work, experimental and numerical analyzes were performed to determine Vb in milling of Inconel 625 depending on the milling parameters and also cutting tools coating (AlTiN-PVD and TiCN/Al_2O_3/TiN-CVD).

2. MATERIAL and METHOD

2.1 Material and Equipment

The purpose of this work is to research the effects of tool insert coating and cutting parameters on the tool wear in milling of Inconel 625 alloy. Therefore, the machining tests were performed without a coolant in CNC vertical machining. Inconel 625, nickel-based superalloy, was used for the machinability testing. The chemical composition of Inconel 625 is given in Table 1. Figure 2 shows experimental setup used for milling.

Table 1. Chemical compositions of Inconel 625 alloy used in this research

Ni+Co	C	S	Mn	P
58	0.1	0.015	0.46	0.002
Si	**Cr**	**Mo**	**Ti**	**Al**
<0.5	20-23	8-10	<0.4	<0.4

The milling experiments were performed using two different cutting tools, three different cutting speeds (60, 80, and 100 m/min) and three feed rates (0.07, 0.1 and 0.13 mm/tooth), while the depth of cut (0.6 mm). The milling conditions is given in Table 2. The milling experiments were conducted using two types of cemented carbide tool inserts: PVD-coated and CVD-multi-layer coated tools. The geomatics of the cutting tools are ADKT1035PDERLC and their quality produced by kennametal is KC522M and KCPK30, respectively [18].

Table 2. Milling parameters

Milling Parameters	Symbol	I	II	III
Cutting speed (m/min)	*Vc*	60	80	100
Feed rate (mm/tooth)	*f*	0.07	0.10	0.13
Depth of cut (mm)	*a*	0.6	-	-

2.2 Tool Wear Measurement

The flank wear (Vb) of the worn cutting tools were measured using ISM-PM200SA brand Insize that is a professional digital microscope having 2M (resolution: 1600x1200) pixel and high magnification capabilities (up to 200×). The Vb measurements were created by examining the worn cutting tools using the ISM-PRO software supplied with the microscope after 150 mm milling on Inconel 625 with different cutting parameters.

2.3 Finite Element Simulations

The Deform 3D software was used to determinant the tool wear. The advantage of the FEM software is that it has an ability to save data for each solution range by automatically re-creating the finite element network during solutions. In addition, generating a very dense grid of nodes near the tool-tip provides the possibility to see more changes in parameters such as deformation, deformation rate, and temperature occurring in the cutting area.

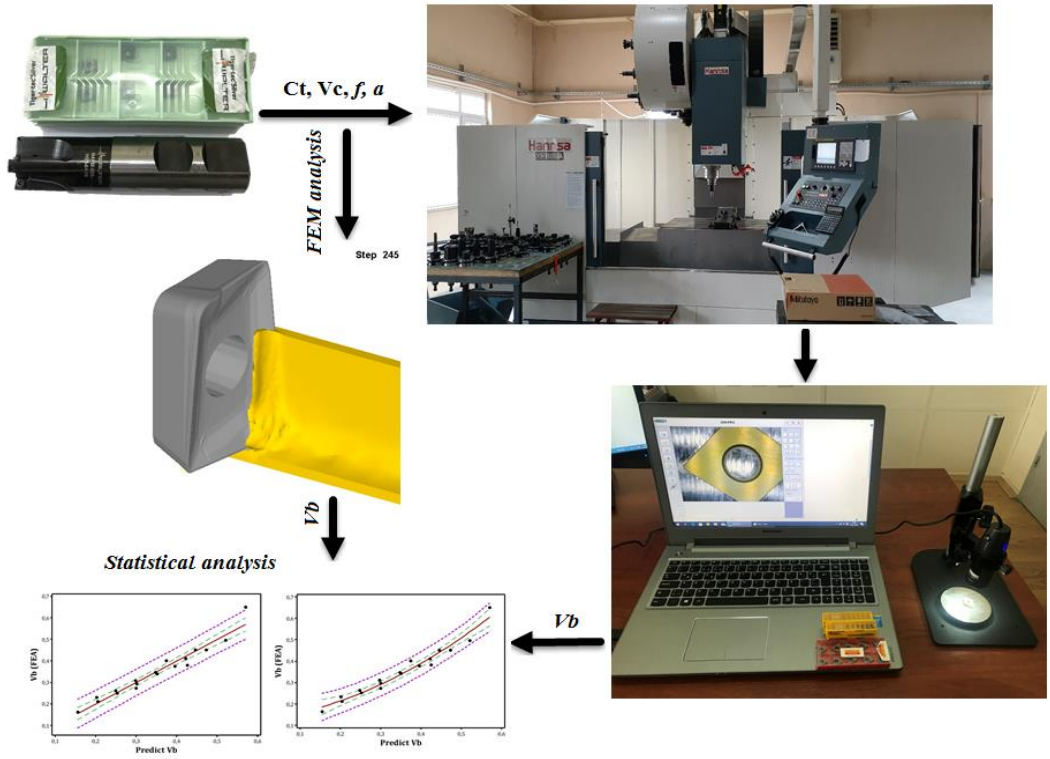


Figure 1. Experimental setup used for milling

Table 3. Tool wear rate models

Tool wear rate models	
$\frac{dW}{dt} = G(V,f) + Dexp\left(-\frac{E}{RT}\right)$	Takeyama's wear model [22]
$\frac{dW}{dt} = A\sigma_n \vartheta_s e^{(-B/T)}$	Usui's wear model [23]
$\frac{dL}{dt} = 9 \times 10^8 \frac{A}{Pt}$	The equation presented by Wong et al [24].
$\frac{dW}{dt} = C_1 exp\left(-\frac{c_2}{\theta}\right)$	The equation presented by Trigger and Chao [25]
$L = Tool\ life\ \sigma_{n=}Normal\ stress\ T = Cutting\ temperature\ V = Cutting\ speed$ $f = Feed\ rate\ E = Activation\ energy\ V_s = Sliding\ velocity\ d = depth\ of\ cut$ $R = Universal\ gas\ canstant$	

For this reason, there is no need for a chip separation criteria, as the dense grid of nodes are very effective in the metal cutting simulating [19].

The Johnson-Cook model which is particularly used for modeling high deformation rate of metals in the computational plasticity is given in Eq.1 [20]. This model also is used for machining simulations. In a study by Dorogoy and Rittel [21], it was mentioned that the hardening is a particular type of isotropic hardening and the assumed yield stress σ0 as shown in Eq. 1.

$$\sigma^0 = (A + B(\varepsilon^p)^n)\left(1 + C\log\left(\frac{\dot{\varepsilon}^p}{\dot{\varepsilon}_0}\right)\right)\left(1 - \left(\frac{T-T_r}{T_m-T_r}\right)^m\right) \quad (1)$$

In Eq. 1, A is the yield strength at room temperature; B is strain hardening; C is strain rate constant, whereas, n and m are strain hardening and thermal softening constants, respectively. The parameters ε^p, $\dot{\varepsilon}^p$ and $\dot{\varepsilon}_0$ denote plastic strain, plastic strain rate, and reference strain rate, respectively, whereas T, Tr, and Tm are reference temperature, room temperature, and melting temperature, respectively.

Literature review showed that there are several wear rate models to predict the tool wear. These models are given in Table 3. In this study, Usui's wear rate model was used to calculate the wear rate on the cutting tool. The Usui's model which is widely used for the estimate of tool wear is shown in Eq. 2 [23]. After the worn tool area was formed, the flank wear was determined to measure the largest Vb from the side.

$$\frac{dW}{dt} = A\sigma_n \vartheta_s e^{(-B/T)} \quad (2)$$

The model information of cutting tools for numerical analysis was obtained by using a three-dimensional scanner. Scanning was done with AICON Smart Scan brand scanner. The mesh parameter was determined as 0.02 mm for minimum and maximum element size. The coating materials, AlTiN and TiCN/Al2O3/TiN, were selected for the modelling of the cutting tool and thermal and mechanical loads by increasing temperatures in the cutting tool and accelerates the deformation of tool the coating thicknesses were defined as 0.4 µm and 0.3 µm, respectively. Deform 3D material library was used in these descriptions [26]. The mesh structure for the cutting simulation are given in Fig. 2. And the Johnson–Cook parameters and the mechanical and physical properties parameters for Inconel 625 alloy are given in Tables 4 and 5, respectively.

Table 4. Johnson-Cook parameters for Inconel 625 alloy [27-28]

Materials	A (MPa)	B (MPa)	n	C	m	T_{ref} (°C)	$\dot{\varepsilon}_{ref}$ (s^{-1})
Inconel 625	558.8	2201.3	0.8	0.000209	1.146	23	1670

Table 5. Mechanical and physical properties of the workpiece [29-31]

Density (g/cm^3)	Elastic modulus (kN/mm^2)	Poisson's ratio	Specific heat (Btu/lb x°F	Thermal expansion (10^{-6})	Thermal Conductivity (W/m K)	T_m (°C)
8.44	205.8	0.278	0.098	13.3	9.8	1350

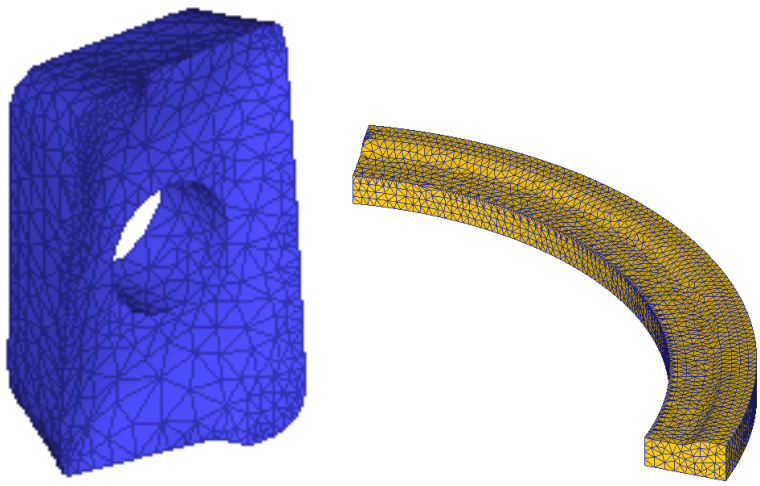


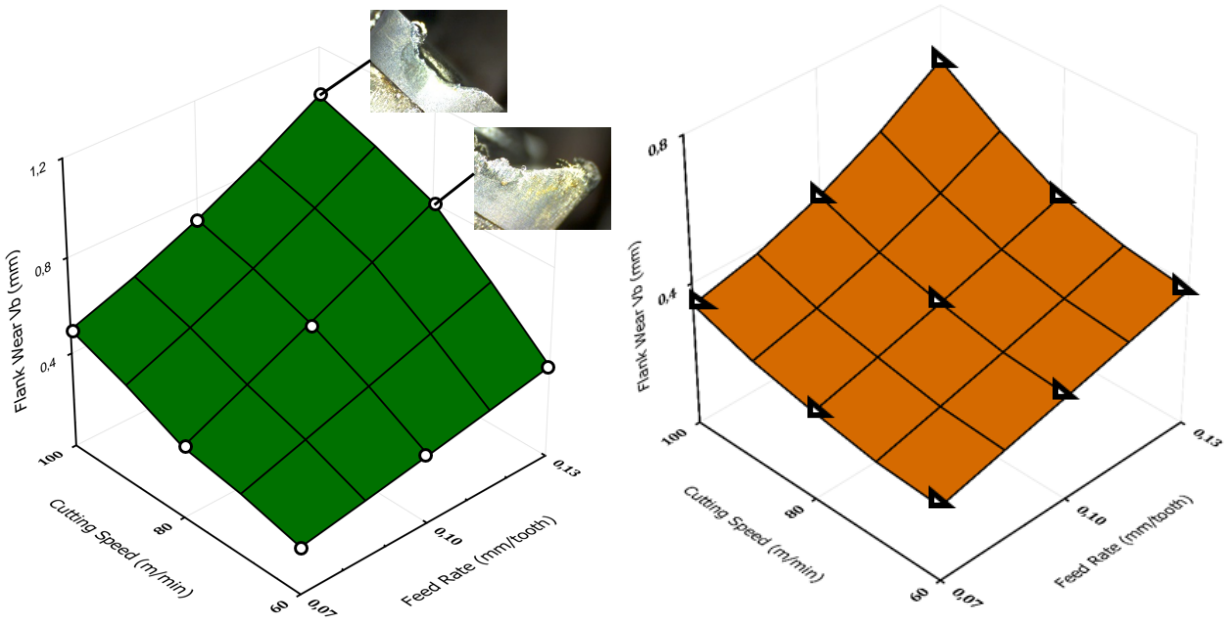
Figure 2. Mesh structure for the cutting simulation

3. RESULTS AND DISCUSSION

3.1 Evaluation of experimental and numerical results

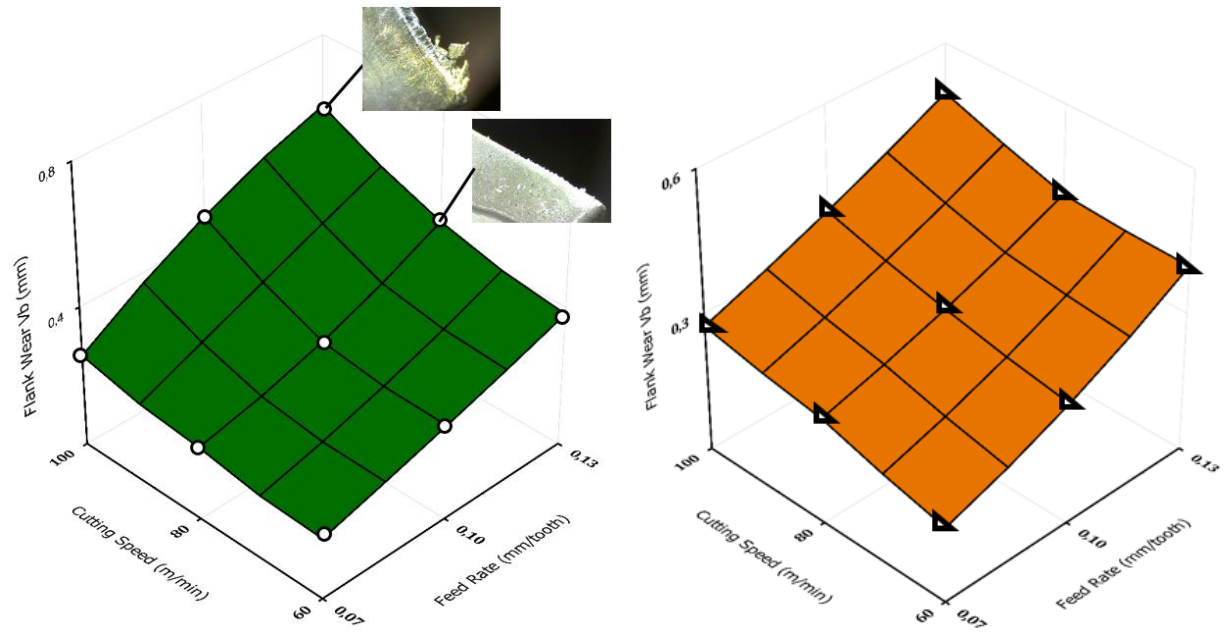
Figure 3 and 4 shows the influences of cutting tool (Ct), cutting speed (Vc) and feed rate (f) on Vb. As can be seen from Fig. 3 (a) and Fig. 3 (b) that the flank wear significantly increase with increasing the feed rate in tests made using AlTiN-PVD coated inserts. The Ct and Vc have also effective on Vb. However, the feed rate were more effective compared to the cutting tool and cutting speed. Fig. 4 (a) and Fig 4 (b) shows the variation of Vb values measured in tests using TiCN/Al_2O_3/TiN-CVD coated inserts. It can be seen clearly from Fig. 4 (a) and Fig 4 (b) that the flank wear significantly increase with increasing the feed rate. This increase is less than measured values of flank wear of PVD coated inserts. This case can be explained by the effect of the heat on the cutting tool. That is, the temperatures in the cutting area during machining is not dissipated rapidly due to the low thermal conductivity of Inconel 625 alloy. This increases inserts. Therefore, a multi-layer coating inserts (TiCN/Al_2O_3/TiN-CVD) were more resistant to abrasion compared to (AlTiN-PVD) coated inserts.

In both of the Ct, tool wear values exhibited a increasing tendency with increasing Vc and f in numerical analysis. As can be seen from Fig. 3 (b) and Fig. 4 (b) that the feed rate is the most effective factor in the increase of flank wear. Table 6 shows the flank wear values according to the measurements obtained in experimental and numerical analysis studies. For experimental and numerical studies, the lowest tool wear value was measured with CVD coated cutting tool, at 0.07 feed rate and 60 cutting speeds of 0.174 and 0.18, respectively. The comparing experimental and numerical analysis results, it was found that there is an average of 9.7% deviation between experimental and simulation results of tool wear. Figure 5 shows the tool wear values obtained in the numerical analysis study.



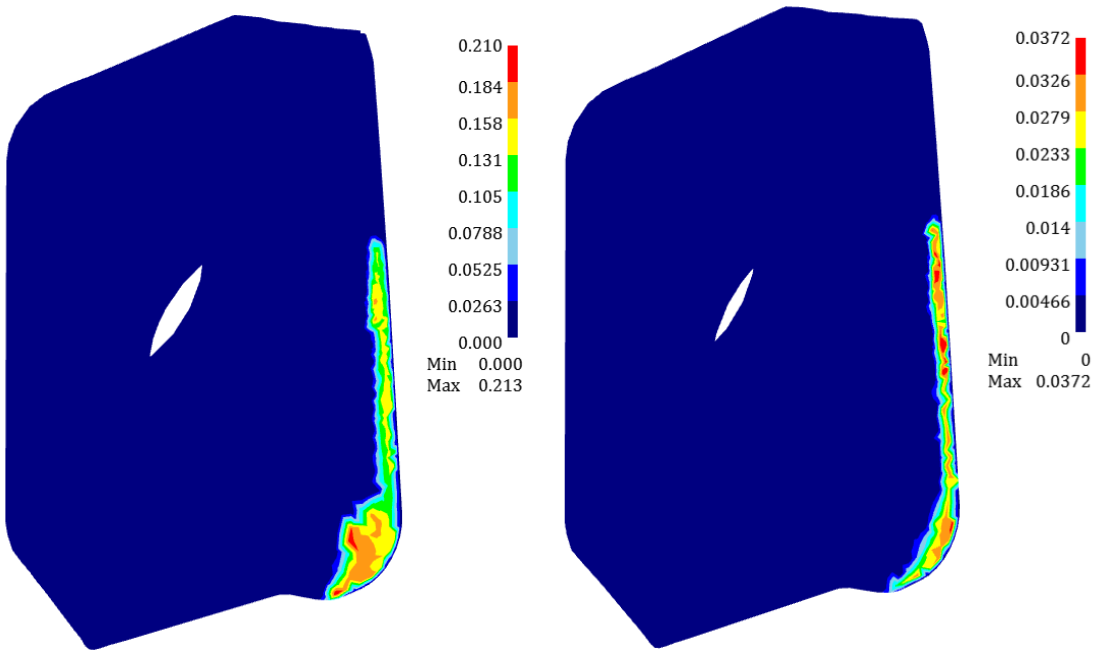
a **b**

Figure 3. The results of (a) experimental and (b) numerical analysis for PVD



a **b**

Figure 4. The results of (a) experimental and (b) numerical analysis for CVD



(a) **(b)**

Figure 5. The cutting speed (60 m/min) feed rate (0.07 mm/tooth), (a) tool inserts (TiAlN-PVD) and (b) tool inserts (TiCN/Al2O3/TiN-CVD)

Table 6. The results of experiments and numerical

Test Id	Control factors			Vb (mm) EXP	S/N–Vb EXP (dB)	Vb (mm) FEA	S/N–Vb FEA (dB)
	A Cutting tool (Ct)	B Cutting speed (*Vc*)	C Feed rate (*f*)				
1	PVD	60	0.07	0.200	13.974	0.210	13.555
2	PVD	60	0.1	0.290	10.752	0.295	10.603
3	PVD	60	0.13	0.387	8.245	0.38	8.404
4	PVD	80	0.07	0.300	10.457	0.250	12.041
5	PVD	80	0.1	0.550	5.192	0.345	9.243
6	PVD	80	0.13	0.805	1.884	0.450	6.935
7	PVD	100	0.07	0.500	7.958	0.340	9.370
8	PVD	100	0.1	0.710	2.974	0.450	6.935
9	PVD	100	0.13	0.998	0.0174	0.650	3.741
10	CVD	60	0.07	0.174	15.289	0.162	15.809
11	CVD	60	0.1	0.272	11.308	0.261	11.667
12	CVD	60	0.13	0.380	8.404	0.400	7.958
13	CVD	80	0.07	0.210	13.555	0.230	12.765
14	CVD	80	0.1	0.300	10.457	0.309	10.200
15	CVD	80	0.13	0.450	6.935	0.410	7.744
16	CVD	100	0.07	0.260	11.700	0.272	11.308
17	CVD	100	0.1	0.465	6.650	0.375	8.519
18	CVD	100	0.13	0.600	4.437	0.495	6.107

3.2 Optimization of cutting parameters

The Taguchi method has been mostly used in the manufacturing industry in terms of determining the optimum process parameters. The goal of this work was to minimize Vb. Therefore, the tests were designed to define the ideal milling parameters using the Taguchi (L18 orthogonal array) technique. For the calculation of the S/N values of each level of the cutting parameters, "The smallest-the-better" principle was used as shown in Eq. (3).

$$n = \frac{S}{N} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \quad (3)$$

The lowest values of tool wear are very significant for lowering manufacture costs. For this cause, Eq.3 used to calculate the equal S / N ratio. The examination of the impact of each input factor (Ct, Vc, f) on Vb was made

using S/N response table. Table 7 are given the response table of S/N for Vb. As can be seen from Table 7, the ideal levels of the control parameters for Vb (EXP) and Vb (FEA) were determined as follows: CVD-coated tool (A2), Vc of 60 m/min (B1) and f 0.07 mm/tooth (C1).

Table 7. S/N response table for Vb and Vb (FEA)

	Milling Factors		
	A	**B**	**C**
EXP			
1	6.829	**11.33**	**12.157**
2	**9.86**	8.081	7.889
3	-	5.623	4.987
Delta	3.031	5.707	7.170
FEA			
1	8.981	**11.333**	**12.475**
2	**10.231**	9.822	9.528
3	-	7.664	6.815
Delta	1.250	3.669	5.660

Analysis of variance (ANOVA) was used to define the most significant milling parameter affecting Vb. This analysis was made with the confidence level of 95%. Table 8 shows the results of ANOVA for Vb. As can be seen from Table 8, the percent contributions (PCR) of (Ct), (Vc) and (f) factors on Vb were found to be 15.01%, 28.86% and 41.5% respectively. This showed that feed rate (f) is the most important parameter with PCR of 41.5% in regard to the tool wear and it is likewise with PCR of 61.78% on Vb (FEA). The cutting speed had secondary importance in Vb (EXP) and Vb (FEA).

Regression is a statistical analysis used for modelling and analyzing of several variables that have the relationship beetween dependent variable and independent variables. In this work, linear and quadratic regression analysis was used to the determinant of the estimated tool wear. The dependent variable was Vb whereas the independent variables were Ct, Vc and f. The predicted tool wear equations that were achieved using the linear regression are given below.

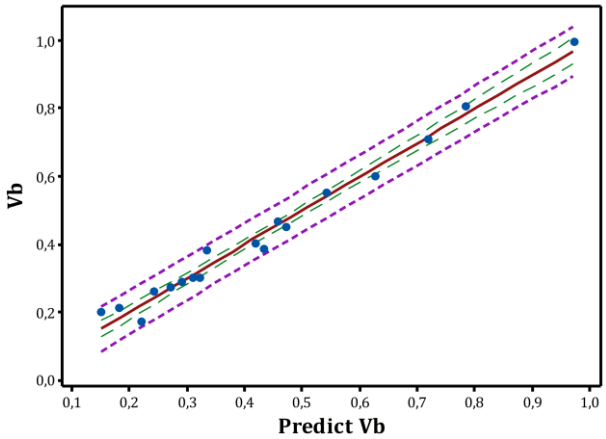
$$Vb = -0.469 - 0.1701Ct + 0.00722Vc + 5.772\,f \quad (4)$$

$$R - S_q = 85.36\% \quad R - S_q(adj) = 82.23\%$$

$$Vb(FEA) = -0.2332 - 0.0507Ct + 0.003642Vc + 3.669f \quad (5)$$

$$R - S_q = 93.16\% \quad R - S_q(adj) = 91.70\%$$

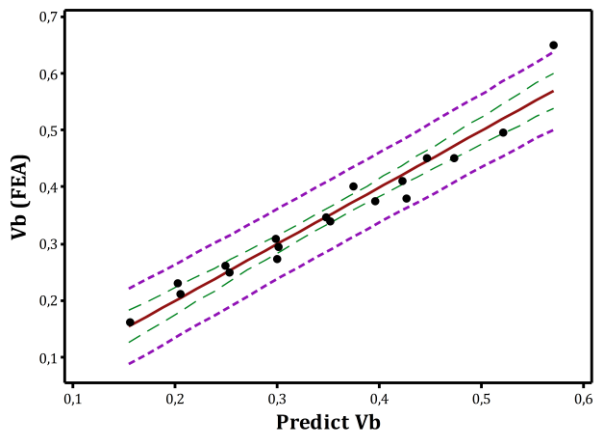
Figure 6 shows the comparison of the experimental and the linear regression results. The coefficient of determination (R2) of the achieved the linear regression for Vb and Vb (FEA) were found to be 85.36% and 93.16% respectively.



(a)

Table 8. ANOVA of Vb (EXP) and Vb (FEA).

Variance	Degree of freedom (DoF)	Sum of squares (SS)	Mean square (MS)	F ratio	P ratio	Contribution rate (%)
EXP						
Ct	1	0.1302	0.13022	12.34	0.004	15.01
Vc	2	0.2502	0.12512	11.86	0.001	28.86
f	**2**	**0.3598**	**0.17992**	**17.05**	**0.000**	**41.5**
Error	12	0.1266	0.01055	-	-	14.63
Total	17	0,8669				100
FEA						
Ct	1	0.01155	0.011552	10.86	0.006	4.88
Vc	2	0.06619	0.033095	31.11	0.000	27.95
f	**2**	**0.14631**	**0.073155**	**68.78**	**0.000**	**61.78**
Error	12	0.01276	0.001064			5.39
Total	17	0.23682				100



(b)

Figure 6. Comparison of the test and the linear regression results for (a) Vb and (b) Vb (FEA)

The predicted tool wear equations that were obtained using the quadratic regression are given below.

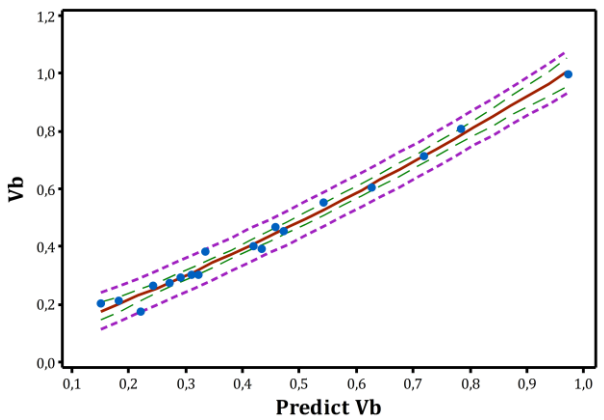
$$Vb = -0.845 + 0.595Ct + 0.0082Vc + 1.13f - 0.000020Vc^2 - 1.1f^2 - 0.00608VcCt - 2.79fCt + 0.1131Vcf \quad (6)$$

$R - S_q = 97.19\%$ $R - S_q(adj) = 94.69\%$

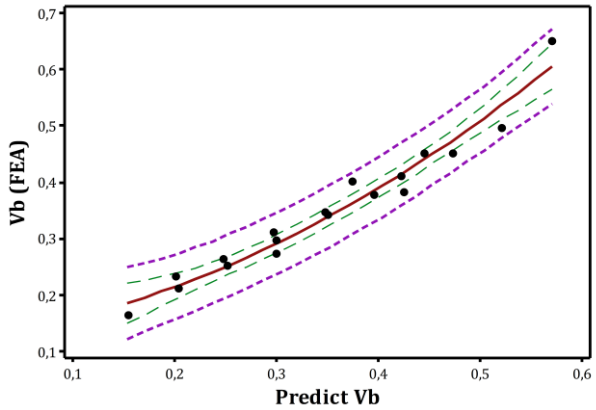
$$Vb(FEA) = 0.248 + 0.1283Ct - 0.00608Vc - 1.4f + 0.000063Vc^2 + 16.6f^2 - 0.001967VcCt - 0.217fCt + 0.0260Vcf \quad (7)$$

$R - S_q = 97.45\%$ $R - S_q(adj) = 95.18\%$

The coefficient of determination (R2) of the achieved using the quadratic regression equations for Vb and Vb (FEA) were obtained to be 97.19% and 97.45% respectively. According to the coefficient of determination, the predicted values achieved using the quadratic regression were very effectively compared to the linear regression. Consequently, the quadratic regression model indicates that it can be successfully applied for the estimate of flank wear (Vb). The comparison of experimental results with predicted values achieved by the quadratic regression models are given in Fig. 7.



(a)



(b)

Figure 7. Comparison of the test results and the quadratic regression results for Vb and Vb (FEA)

A confirmation test was required to prove the accuracy developed equations using the Taguchi technique. For that reason, in the prediction of optimum flank wear, were used equations (8). The best Vb giving parameter group was obtained as A2B1C1 according to the analysis of the test results. TVb is the average of entire of the worth of Vb achieved from the actual tests.

$$Vb_{opt} = (A_2 - T_{Vb}) + (B_1 - T_{Vb}) + (C_1 - T_{Vb}) + T_{Vb} \quad (8)$$

The result of the calculations, it was obtained that $Vb_{opt} = 0.430$ mm. The estimated confidence interval for the control of the optimization was calculated using the following equations (9) and (10).

$$CI_{Vb} = \sqrt{F_{a,1,fc}\, V_e \left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \quad (9)$$

$$n_{eff} = \frac{N}{1+T_{dof}} \quad (10)$$

$F_{a,1,fc} = 4.75$ (from F − test table), $V_e = 0.01055$ (Table 8) $R = 1$

$N = 18,\ T_{dof} = 5,\ n_{eff} = 3\ (equation\ (8))\ CI_{Vb} = 0.258\ (equation\ (9))$

According to the calculations obtained using equations (9) and (10), the confidence interval was $CI_{Vb} = 0.258$. The average optimal Vb with the confidence interval at 95% is:

$$[Vb_{opt} - CI_{Vb}] < Vb_{exp} < [Vb_{opt} + CI_{Vb}] = [0.430 - 0.258] < 0.174 < [0.430 + 0.258] = 0.172 < 0.174 < 0.688$$

The Vbexp value ($Vb_{exp} = 0.174$) remained within the confidence interval boundary. Consequently, the system optimization for Vb was successfully performed via the Taguchi method (significance level of 0.05). Confirmation tests were made at optimum and random levels of cutting parameters via the linear, quadratic and the Taguchi method. Table 9 shows the confirmation test results. There is little difference between the values of estimated and the experimental. In similar studies [32-34], it was emphasized that the statistical error must be less than 20%. The calculated error values are in an

Table 9. Confirmation test results

Level	Taguchi Method			Linear regression equations			quadratic regression equations		
	Exp.	**Pred.**	**Eror (%)**	**Exp.**	**Pred.**	**Eror (%)**	**Exp.**	**Pred.**	**Eror (%)**
Vb (EXP)									
$A_2B_1C_1$	0.174	0.180	3.44	0.174	0.198	13.79	0.174	0.158	9.91
$A_1B_2C_2$	0.500	0.518	4.50	0.500	0.515	3.00	0.500	0.519	3.80
Vb (FEA)									
$A_2B_1C_1$	0.162	0.154	4.93	0.162	0.140	13.5	0.162	0.192	18.9
$A_1B_2C_2$	0.345	0.347	0.57	0.345	0.374	8.4	0.345	0.348	0.86

acceptable range and these values show successful optimization.

4. CONCLUSIONS

In this study, experimental and numerical analyzes were performed to determine the tool wear in the milling of Inconel 625 alloy under different cutting parameters using CVD and PVD coated carbide inserts. In addition, optimal cutting parameters were determined via the Taguchi method. The following conclusions may be drawn from the present study:

• Poor performance of PVD AlTiN-coated carbide inserts at can be explained by the greater effect of the heat on the cutting tool due to the low thermal conductivity of Inconel 625 alloy. For that reason, a multi-layer coating tool (such as TiCN/Al_2O_3/TiN-CVD) can be suggested for use in the milling of Inconel 625 alloy.

• The variance (ANOVA) results show that the most important factor is identified as the feed rate for Vb (exp) and Vb (FEA) with a percentage contribution of 41.5% and 61.78% respectively.

• Quadratic regression models showed a very good bond between the test and predicted values for Vb (exp) and Vb (FEA) with a correlation coefficient of 97.19% and 97.76% respectively.

• The lowest Vb value was obtained as 0.174 mm in the optimum cutting parameters (cutting speed = 60 m/min, feed rate = 0.07 mm /tooth, and the cutting tool coating = TiCN/Al_2O_3/TiN-CVD).

• Comparing experimental and numerical analysis results, it was found that there is an average of 9.7% deviation between experimental and simulation results of tool wear.

• Cutting simulations can provide advance knowledge about the machinability of difficult-to-cut materials in the manufacturing industry.

• Statistical results revealed that the Taguchi method was a successful methodology to define the optimum cutting parameters in the milling of Inconel 625.

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List of symbols

Ra	**Average surface roughness (µm)**
Vb	Flank wear (mm)
Ct	Cutting tool
Vc	Cutting Speed (m/min)
f	Feed rate (mm/tooth)
S/N	Signal/noise ratio (dB)
CI	Confidence interval
N	Total number of tests
n_{eff}	Confirmatory test number
FEA	Finite element method
PVD	Physical vapor deposition
CVD	Chemical vapor deposition

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Mahir AKGÜN: Performed the experiments and the analysis of the results. Also, wrote the manuscript.

Halil DEMİR: Conducted the analysis and evaluation of the results

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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