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Experimental Research and Mathematical Modeling of Parameters Affecting Cutting Tool Wear in Turning Process of Inconel 625

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Abstract

This study aims to present the effects of cutting parameters on cutting tool wear during turning process of material Inconel 625 using Taguchi experimental design. Taguchi L9 orthogonal array was used to investigate the effects of machining parameters. Optimal cutting conditions are determined using the signal/noise (S/N) ratio which is calculated by average cutting tool wear. Using results of analysis, effects of parameters on both average of cutting tool wear calculated on Minitab 18 using ANOVA method. It was clear from the ANOVA that the regression model is capable to predict the tool wear with high accuracy. Numerical simulation of orthogonal cutting operation is presented using FEM modeling with Deform 3D v.11.0. The results of tool wear during the turning of Inconel 625 material are obtained by changing the cutting regimes (v, f, d), without cooling means. After using the three cutting regimes levels, we found that the optimal parameters go to the numerical level so that the cutting speed remains the same used in the experiment (v=65m/min), while the other optimal parameters come out the depth of cut (d=0.733mm) and feed (f=0.06mm/rev) so it can be seen in the two forms of research, the theoretical one with FEM and the experimental one. During the research, numerical methods and FEM simulations analysis were used for turning process. Confirmation test of results showed that the Taguchi method was very successful in the optimization of machining parameters for minimum cutting tool wear during CNC turning process.

Keywords: Inconel 625, Taguchi design, Deform 3D, tool wear, FEM modeling.

1. Introduction

The machining industry always intends to be perfect. Cutting process also requires a high degree of machined surfaces. As the quality of machined materials is growing, there is a growing need for cutting tools to be of high quality. One of the factors that are affecting the processing accuracy is the cutting tool wear. The use of different methods in this case Taguchi and ANOVA have greatly facilitated the research of cutting tool wear. The turning of Inconel 625 and tracking tool wear is the primary task in this paper. Many authors have dealt with tool wear using different methods and achieving results in their own forms [1 – 3].

The Finite element simulation and experimental validation of tool wear effect on cutting forces in turning operation was investigated by authors, which obtain results that the finite element results correlates with the experimental results for no wear condition with less than 10% error. Tool wear is mostly affected by different parameters like feed rate, cutting speed, and depth of cut [4 – 6].

Taguchi method is a powerful tool for the design of high quality systems. It provides simple, efficient and systematic approach to optimize designs for performance, quality and cost. Taguchi method is efficient method for designing process that operates consistently and optimally over a variety of conditions [7 – 10]. One of the most important and effective factors of the manufacturing standards is tool wear [11, 12].

With Wear estimation of ceramic and coated carbide tools in turning of Inconel 625 3D FE analysis deal authors, which develop an accurate 3D finite element model to predict the tool wear of PVD-TiAlN coated carbide and ceramic inserts in turning of Inconel 625 [13 – 15].

The present work will be helpful to predict the influence of cutting speed, feed, depth of cutting, amplitude and temperature in used tool (CNMG 120408 NN) without cooling means [14 – 22].

Tool wear design of experiments (DOE) and statistical techniques Design of Experiments (DOE) method is regarded by several researchers, in the reported literature, as a inconvenient method for monitoring of influence of different parameters on tool wear during turning process [23 – 25].

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2. Design of The Experiment

Taguchi's technique makes use of a special design of orthogonal array (OA) to examine the quality characteristics through a minimum number of experiments. The experimental results based on the orthogonal array are then transformed into S/N ratios to evaluate the performance characteristics. Taguchi's Design of experiments is used to design the orthogonal array for three parameters varied through three levels. The control parameters and their levels chosen are shown in Table 2.1.

Table 2.1. Experimental results using L_9 orthogonal array.

Exp.	Process parameters and its level			Experimental results		
	Speed	Feed	Depth of cutting	T ^{0}C	Amplitude	VB [µm]
1	50	0.04	0.4	329.05	0.493	215.33
2	50	0.06	0.7	361.21	0.400	232.21
3	50	0.08	1.0	374.29	0.108	348.24
4	65	0.04	0.7	333.22	0.311	253.22
5	65	0.06	1.0	286.44	0.428	356.13
6	65	0.08	0.4	299.44	0.462	253.34
7	80	0.04	1.0	443.66	0.432	361.36
8	80	0.06	0.4	333.75	0.522	265.57
9	80	0.08	1.0	372.71	0.654	371.02

3. Measurement of Tool Wear, Equipment and Measuring Process

Measurement of tool wear was conducted with equipment TOOL MASTER 10 which is digital apparatus and allows displacement according to three axes. Cutting blade was cleaned from micro particles by cloth with alcohol after each experiment and then the measurements were realized. The experiment was conducted with the clutch with new cutting edge without coolant tool. Circular cutting length of 0.5 km and increased cutting regimes until gaining an adopted wear value as the basic criterion VB=221µm was taken for determining the wear.

Figure 3.1. Equipment for measurement wears TOOL MASTER 10.

4. Analysis of Variance (Anova)

ANOVA table is generally prepared to find the significant input parameters which will mostly affect the output responses. Analysis of variance table was prepared for each output response with a significant level of α = 0.05 and confidence level of 95%. The sources present in the ANOVA table having P-Value less than 0.05 had been treated as the significant parameter for the respective output response. The following table shows the analysis with ANOVA, for cutting tool wear.

ANOVA results for means of tool wear are given in Table 4.1. It can be observed that the percentage contribution on tool wear was depth of cutting (59.49) followed by cutting speed (21.70%), feed (10.81%), temperature (0.08%), and amplitude (0.21%). From the present analysis, it is also observed that depth is the most influencing parameter in tool wear. Table 2.1 and 4.1, shows the influence of cutting speed, feed, depth of cutting; temperature and amplitude which are illustrated in Figure 4.1, 4.2 and 4.3.

Table 4.1. Analysis of Variance for cutting tool wear VB.

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	Contribution
Regression	5	28968.7	28968.7	5793.7	7.18	0.068	92.28%
v	1	6812.1	2528.7	2528.7	3.13	0.175	21.70%
f	1	3393.4	1089.7	1089.7	1.35	0.329	10.81%
d	1	18673.2	12422.3	12422.3	15.39	0.029	59.49%
t	1	23.8	35.6	35.6	0.04	0.847	0.08%
a	1	66.2	66.2	66.2	0.08	0.793	0.21%
Error	3	2422.3	2422.3	807.4			7.72%
Total	8	31391.0					100.00%

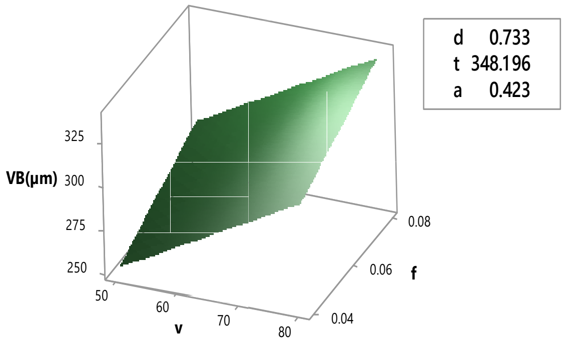

Figure 4.1. Effect of *speed cutting* and *feed* on the main V_B.

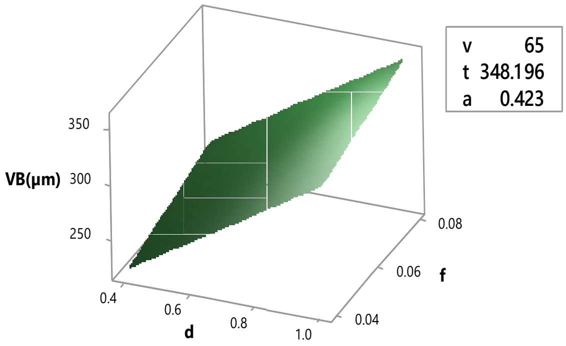

Figure 4.2. Effect of *depth cutting* and *feed* on the main V_B.

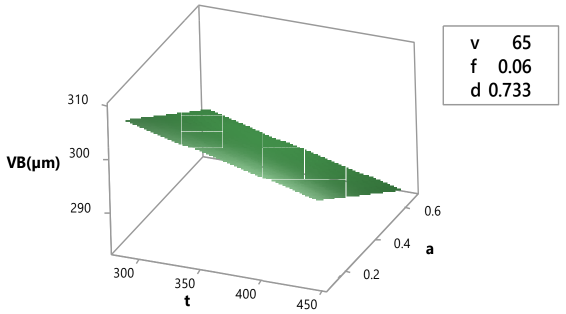

Figure 4.3. Effect of *temperature* and *vibration* on the main V_B.

Table 4.2. Residual output and probability output.

Observation	Predicted VB	Residuals	Standard Residuals	Percentile	VB
1	192.68	22.64	1.30	5.555	215.33
2	260.86	-28.65	-1.64	16.666	232.21
3	335.32	12.91	0.74	27.777	253.22
4	278.70	-25.48	-1.46	38.888	253.34
5	345.79	10.33	0.59	50	265.57
6	252.00	1.33	0.07	61.111	348.24
7	350.90	10.45	0.60	72.222	356.13
8	262.48	3.08	0.17	83.333	361.36
9	377.65	-6.63	-0.38	94.444	371.02

Figure 4.4 shows the predicted values for calculated tool wear using: linear equation along with the experimental values. It can be observed that the predicted values are in good agreement with experimental results with average error of less than 6%.

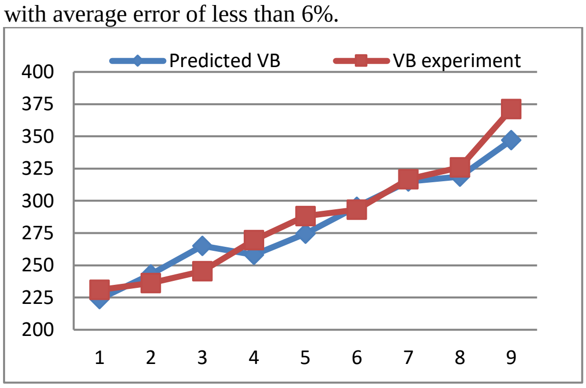

Figure 4.4. Comparison between experimental results and predicted values of cutting tool wear.

5. Fea and Simulation of Tool Wear with Deform 3d

Finite element method has been proved to be an effective technique for analysing chip formation process and predicting machining performance characteristics such as temperatures, forces, stresses etc. (Fagan, 1992; Lorentzon and Jarvstrat, 2008; Lorentzon et al., 2009; Yue et al., 2009;). In this work, finite element method is used to simulate turning of Inconel 625 using PVD coated tungsten carbide tool. Johnson and Cook (1993) developed a material model based on torsion and dynamic Hopkinson bar test over a wide range of strain rates and temperatures. This constitutive equation was established as follows:

$$\bar{\sigma} = \left[A + B\cdot\bar{\varepsilon}^{n}\right]\cdot\left[1 + C\cdot\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_o}\right)\right]\cdot\left[1-\left(\frac{T-T_{room}}{T_{melt}-T_{room}}\right)^{m}\right] \quad (5.1)$$

Johnson-cook model is suitable for material modeling because of high strain, strain rate, strain hardening and non-linear material properties that are involved in turning process (Uhlmann et al., 2007; Ezilarasan et al., 2014). The material model given in 6.3 expression. It is defined in DEFORM 3D material library. The constant of Johnson-cook model is shown in table 5.1.

Table 5.1. Johnson-Cook model constants for Inconel 625.

A (MPa)	B (MPa)	n	C	m	$\dot{\varepsilon}_o$ (1/s)	T_{room} (^0C)	T_{melt} (^0C)
559	22.01	0.8	0.00021	1.146	0.0016	20	1297

Work piece geometry and mesh generation In the *Workpiece Shape* menu, specify the work piece details. Depending upon the work piece diameter user can specify either a flat model or a curved model. The template will prompt for the related data, and will generate the work piece setup in the display area. For the current lab we use a 'simplified model' with 5mm length.

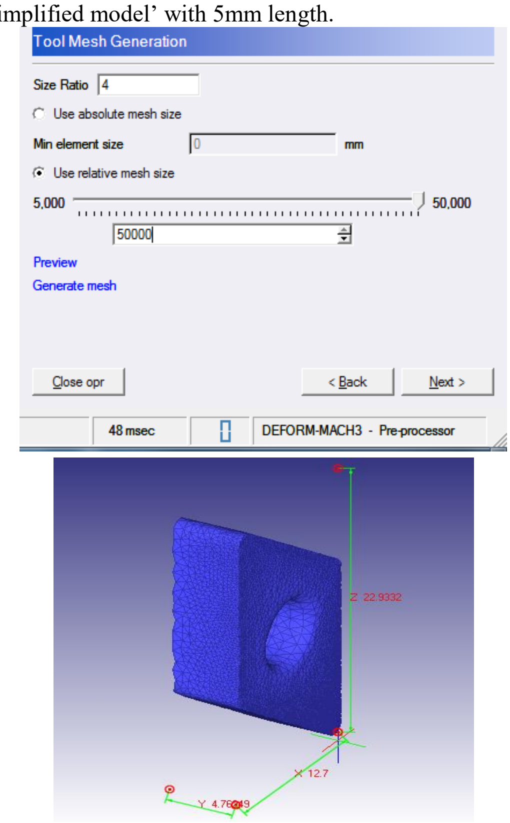

Figure 5.1. Modelling of CNMG 120408 NN tool insert.

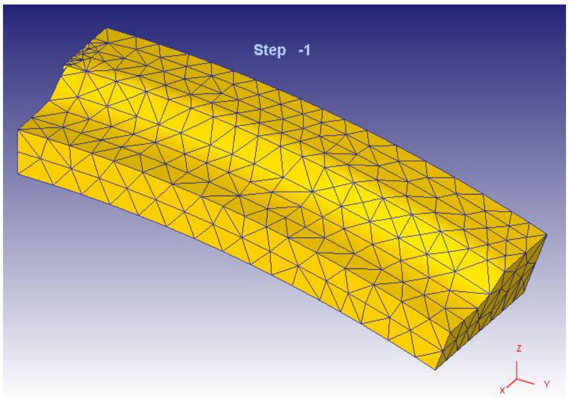

Figure 5.2. Modelling of Inconel 625 work piece.

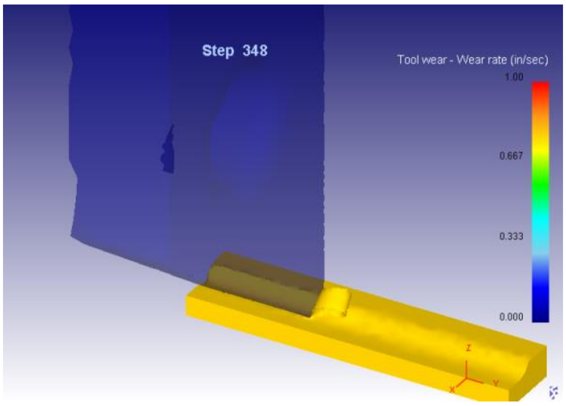

Figure 5.3. Simulation result of tool wear.

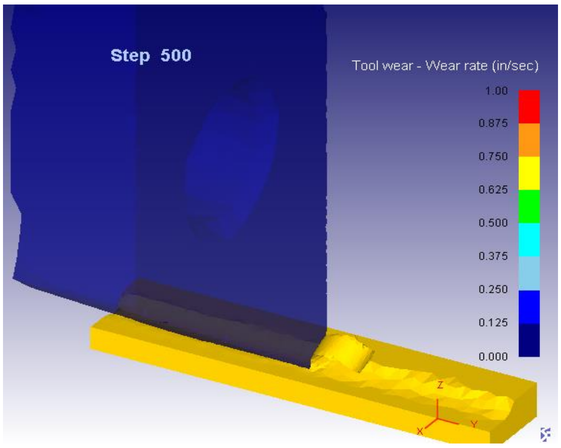

Figure 5.4. Simulation result of tool wear rate (solid).

Table 5.2. Analytical results using L_9 orthogonal array.

Exp.	Process parameters and its level			Analysing data using Deform 3d		
	Speed	Feed	Depth of cutting	T (^{0}C)	Amplitude	VB_{FEA} [μm]
1	50	0.04	0.4	398.15	0.59653	232.863
2	50	0.06	0.7	437.06	0.484	251.431
3	50	0.08	1.0	452.89	0.13068	380.064
4	65	0.04	0.7	403.2	0.37631	278.542
5	65	0.06	1.0	346.59	0.51788	387.743
6	65	0.08	0.4	362.32	0.55902	272.674
7	80	0.04	1.0	536.83	0.52272	391.496
8	80	0.06	0.4	403.84	0.63162	291.127
9	80	0.08	1.0	450.98	0.79134	403.122

ANOVA results for means of tool wear are given in Table 5.3. It can be observed that the percentage contribution on tool wear was depth of cutting (59.80%) followed by cutting speed (21.90%), feed (10.46%), temperature (0.13%), and amplitude (0.38%). From the present analysis, it is also observed that depth of cutting is the most influencing parameter in tool wear.

Table 5.3. Analysis of Variance for cutting tool wear VB_{FEA}.

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	Contribution
Regression	5	34557.6	34557.6	6911.5	7.57	0.063	92.66%
v	1	8168.7	3282.3	3282.3	3.60	0.154	21.90%
f	1	3899.4	1191.9	1191.9	1.31	0.336	10.46%
d	1	22301.9	14779.2	14779.2	16.19	0.028	59.80
t	1	46.7	70.8	70.8	0.08	0.799	0.13%
a	1	140.8	140.8	140.8	0.15	0.721	0.38%
Error	3	2737.8	2737.8	912.6			7.34%
Total	8	37295.3					100.00%

From the table 5.2 and 5.3, can be seen the influence of cutting speed, feed, depth of cutting, temperature and amplitude that are illustrated in Figure 5.6, 5.7 and 5.8.

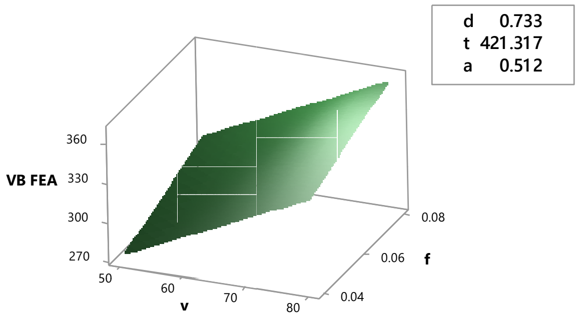

Figure 5.6. Effect of *speed cutting* and *feed* on the main $V_{B\ FEA}$.

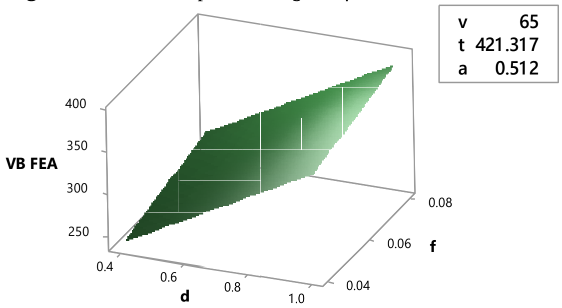

Figure 5.7. Effect of *depth cutting* and *feed* on the main $V_{B\ FEA}$.

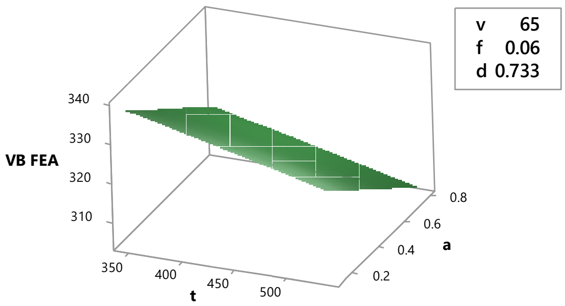

Figure 5.8. Effect of *temperature* and *vibration* on the main $V_{B\ FEA}$.

Table 5.4. Residual output and probability output.

Observation	Predicted VB	Residuals	Standard Residuals	Percentile	VB_{FEA}
1	229.179	1.754	0.155	5.556	232.863
2	228.469	2.002	0.177	16.667	251.431
3	234.018	5.476	0.485	27.778	380.064
4	279.604	6.849	0.606	38.889	278.542
5	251.037	-2.907	-0.257	50.000	387.743
6	275.673	-22.406	-1.983	61.111	272.674
7	289.854	-13.174	-1.166	72.222	391.496
8	335.907	10.048	0.889	83.333	291.127
9	323.862	12.358	1.094	94.444	403.122

Figure 5.9 shows the predicted values for tool wear calculated using: linear equation along with the experimental values. It can be observed that the predicted values are in good agreement with experimental results with average error of less than 7.8%.

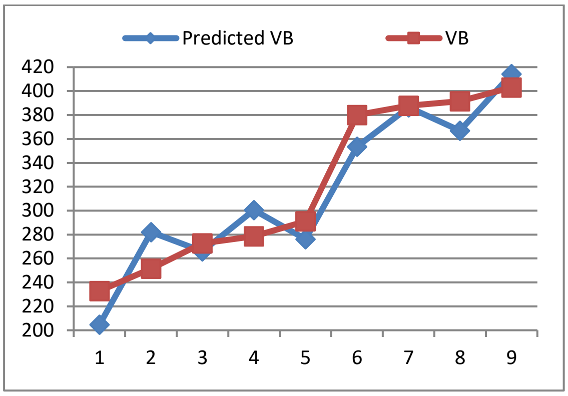

Figure 5.9. Comparison between analysis results and predicted values for cutting tool wear.

5.1. Regression Analysis Equations

Regression analysis is a statistical process used to estimate the relationships between variables. This analysis is focused on the relationship between a dependent variable and one or more independent variables; it includes many techniques for modelling and analysing various variables. Regression analysis was used to derive the predicted equations of the cutting tool forces and the roundness error in this study. In Minitab 17, equations for Cutting Tool Wear calculation have been formed by ANOVA analysis. Regression analysis equations for cutting tool wear are as follow:

$$VB = 30.1 + 1.88\cdot v + 715\cdot f + 177.5\cdot d - 0.056\cdot t - 26.1\cdot a \quad (5.2)$$

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
28.4153	92.28%	79.42%	14.45%

$$VB_{FEA} = 38 + 2.15\cdot v + 748\cdot f + 193.6\cdot d - 0.065\cdot t - 31.5\cdot a \quad (5.3)$$

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
30.2090	92.66%	80.42%	17.48%

5.2. Normal Probability Charts

The normal probability table was obtained to check the validity or accuracy of the above statistical model. In this way, the model will not be inadequate and unusual structure, and in the future better results will be estimated. The charts given Figure 5.10 and Figure 5.11 clearly show the conformity of our statistical model.

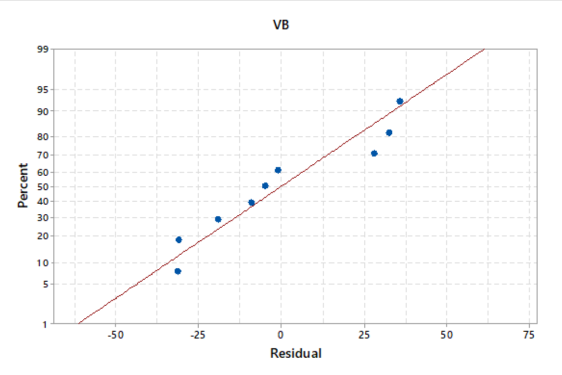

Figure 5.10. Normal probability charts for cutting tool wear V_B.

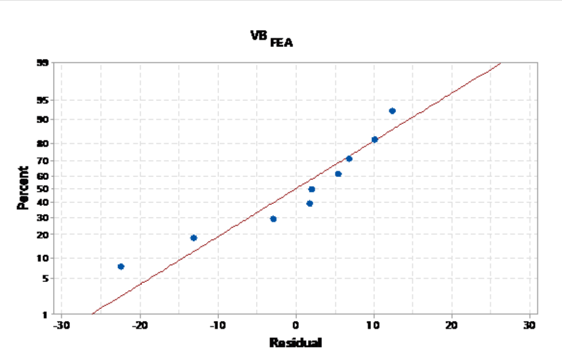

Figure 5.11. Normal probability charts for cutting tool wear VB_{FEA}.

6. CONCLUSIONS

Turning of the Inconel 625 is done with cutting tool CNMG 120408NN. Cutting tool wear is one of the most negative phenomenon in the cutting process, developed in difficult conditions, and differs from the various cutting parameters and the production technology. As we can see from obtained mathematical models presented in expression (5.2) and (5.3) and form the calculation realised with Minitab 2017 (DOE, Taguchi method, ANOVA), where as a point here, we can have discussions of the comparison and reliability of the results. The coefficients of tool wear (R-sq) achieved using the linear regression for VB and VB (FEA) were obtained to be 92.28% and 92.66%. From the calculated result presented above and figure, 4.1 and 5.6, it can be seen that with the increase of the cutting speed, the cutting tool wear increase. Results gained and illustrated in figure (4.2 and 5.7) show that with the increase of the cutting depth, the amount of the cutting tool wear also increases, and that the depth of cut has a greater impact in tool wear. Looking at figures (4.1, and 5.6), it can be seen that cutting feed has a lower impact in tool wear related to the cutting speed and the depth of cutting. Parameters, such as temperature and vibrations have a smaller impact on the consumption of the tool.

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