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Experimental Research and Mathematical Modeling of Parameters Effecting on Cutting Force and Surface Roughness in CNC Turning Process

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Abstract: In this paper, the effects of cutting parameters on cutting forces and surface roughness based on Taguchi experimental design method are determined. Taguchi L9 orthogonal array is 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 surface roughness and cutting force. Using results of analysis, effects of parameters on both average surface roughness and cutting forces are calculated on Minitab 17 using ANOVA method. The material that was investigated is Inconel 625 steel for two cases with heat treatment and without heat treatment. The predicted and calculated values with measurement are very close to each other. Confirmation test of results showed that the Taguchi method was very successful in the optimization of machining parameters for maximum surface roughness and cutting forces in the CNC turning process.

Keywords: Inconel 625, Taguchi design of experiments, Surface roughness, Cutting force, vibrations and temperature.

1. Introduction

Inconel-625 is one material that has high mechanical properties, and high resistance to oxidation and corrosion. This material is widely used in the gas turbine blades, aerospace components and nuclear plants. Mostly industrial and engineering applications include gas turbine components, space vehicles, submarines, steam power plants and rockets/missiles components may be used. Cutting forces and surface roughness are two important during the machining process of Super alloys materials. Therefore, experimental measurement of the cutting forces and surface roughness became unavoidable. According this in different laboratories are made research to understand the principles of chip formation, developing cutting force models, cutting process control, tool geometry optimization, tool condition monitoring and for detection and suppression of chatter vibrations.

According the values of cutting parameters, the experiment is designed by Taguchi L9 in Minitab 17 software. The regression model of surface roughness is done with ANOVA and was presented the optimization of parameter impact, [2, 4]. Nowadays a lot of works have been done to improve the capability of machine tools. The continuing development and trends in manufacturing and operations



engineering cannot be sustained using current methods and processes. Some set up parameters or machining processes are affected on main parameters such as tool life. One way to reduce work hardening effect on tool life is to conduct end-milling operations at high speed rates. The study of criteria for evaluating the surface roughness represents, today, one of the most important problem for the production of some specific and functional characteristics. For this reason many authors consider the roughness as the fourth dimension of the design. Increasing productivity, decreasing costs, and maintaining high product quality at the same time are the main challenges manufacturing face today. The importance of monitoring and controlling the cutting force in CNC turning process has been well recognized in machine tool communities, [4]. A considerable amount of investigations has been directed for the purpose of the prediction and measurement of cutting forces. That is because the cutting forces generated during metal cutting have a direct influence on the generation of heat because the experiment is taking without unloading, tool wear, vibration, quality of machined surface and accuracy of the work piece. This research paper presents the use of coated tool for dry turning of Inconel 625 with heat treatment and without heat treatment investigating the cutting force and surface roughness. The specimens were annealed at 1350 °C for 1 hour and were cooled in room temperature, [5]

2. Experimental work - work piece material

Round bars with Ø62mm diameter and 180mm length were used as work piece materials. The work material used for the present investigation is Inconel 625. The chemical composition of the work piece materials is given in table 1.

Table 1: Chemical composition of the Inconel 625

Ni	Cr	Mo	Nb	Fe	S	Al
59.64*	22.34	9.20	3.57	4.29	0.002	0.16
Co	Cu	C	Mn	P	Ta	Si
0.032	0.091	0.020	0.057	<0.005	0.014	0.28

*Calculated as the difference between 100% and the sum of the measured elements.

2.1 Material and method

The experiments were conducted under dry cutting conditions on champions made all geared CNC lathe machine. The cutting tool used was CNMG 120408NN with grade coating of TiN/TiCN PVD coated. Based on the research Inconel 625 is hard processed, for turning it is decided to use the tool holder PCLNR 2525 12A product of renowned company ISCAR.

2.2 Cutting force and surface roughness measurement.

For the experiment is used Force Measurement aperture *Kistler Type 5070A*. The cutting force Measurement, dynamometers which were mounted on the CNC lathe. The measurement equipment for the temperature measure was used *Pyrometer Cella Temp PQ 38* which is specially designed for measuring the temperature. The measures of vibration are made with equipment *Kistler Type 5134B*, and for surface measurement is used machine for Surface Measurement Talsurf, *Taylor Hobson*. In this paper we will use two basic methods of determination of cutting forces and their characteristics:

- Analytical by Taguchi method and ANOVA :
- Experimental methods: direct measurement characteristics F_x , F_y and F_z , vibration, temperature and surface roughness.

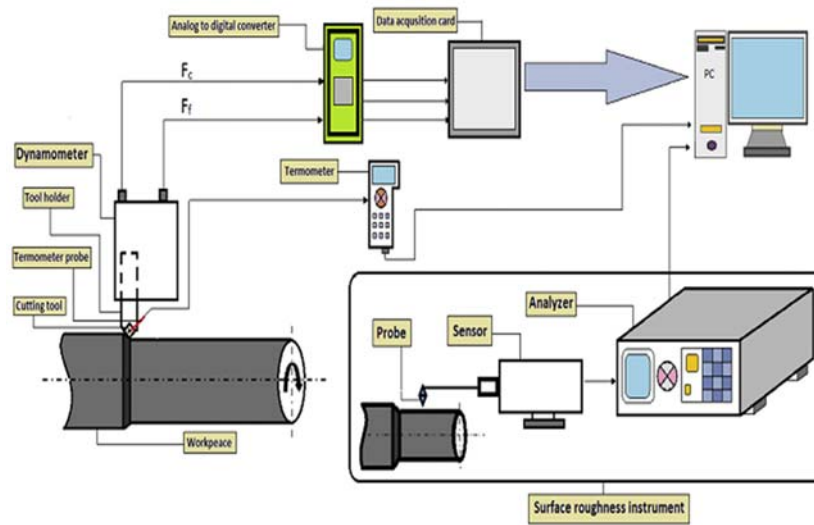


Figure 1. Diagram of experimental setup.

3. Design of the experiment

In our study paper was use Taguchi standard orthogonal array L9 with 9 DOF as the experimental design. Taguchi's orthogonal arrays are the most suitable techniques for conducting results with a less time and cost, [1, 3]. Compatible results can be achieved with these design of experiment as compare to full factorial design. Experiments were planned using 3 levels for each input parameter as shown in table 1.

Table 2. Experimental results using L₉ orthogonal array.

Cutting parameters		Exp.	Speed	Feed	Depth of cutting
Speed (v)	50	1	50	0,04	0,4
	65	2	50	0,06	0,7
	80	3	50	0,08	1,0
Feed (f)	0.04	4	65	0,04	0,7
	0.06	5	65	0,06	1,0
	0.08	6	65	0,08	0,4
Depth of cutting (d)	0.4	7	80	0,04	1,0
	0.7	8	80	0,06	0,4
	1.0	9	80	0,08	1,0

Table 3: Experimental results for cutting force.

Exp.	Experimental results					Experimental results after annealed.				
	T °C	Amplitude	Fx1	Fy1	Fz1	T °C	Amplitude	Fx2	Fy2	Fz2
1	329,05	0,4930	134,98	179,28	260,14	399.63	0.5988	150.73	214.81	298.24
2	361,21	0,3999	276,04	272,05	478,31	407.81	0.4514	305.02	299.12	517.90
3	374,29	0,1083	442,98	433,18	687,93	467.70	0.1354	512.76	490.68	729.58
4	333,22	0,3108	262,06	230,25	383,37	404.28	0.3771	299.74	266.25	428.25
5	286,44	0,4281	282,97	206,21	622,56	343.72	0.5137	325.78	243.12	660.19
6	299,44	0,4617	174,01	236,20	419,92	376.24	0.5800	198.21	273.59	461.24
7	443,66	0,4322	262,1	164,92	460,55	532.61	0.5189	308.56	200.24	515.52
8	333,75	0,5217	145,71	251,37	342,28	416.19	0.6506	184.84	369.06	449.12
9	372,71	0,6544	371,15	348,75	642,74	438.30	0.7695	425.23	406.66	682.39

Table 4: Experimental results for surface roughness.

Exp.	Experimental results					Experimental results after annealed.				
	T °C	Amplitude	Ra1	Rz1	Rt1	T °C	Amplitude	Ra2	Rz2	Rt2
1	329.05	0.4930	0.9111	7.7501	5.1382	399.63	0.5988	0.9974	8.4336	5.5721
2	361.21	0.3999	1.5957	16.4656	7.7612	407.81	0.4514	1.6015	11.6238	7.4998
3	374.29	0.1083	1.5733	14.5312	8.7791	467.70	0.1354	1.6281	10.4363	8.3869
4	333.22	0.3108	1.1743	10.3691	6.4573	404.28	0.3771	1.2317	8.6635	6.8242
5	286.44	0.4281	1.5142	9.7913	7.842	343.72	0.5137	1.6202	10.7137	8.5033
6	299.44	0.4617	2.0923	15.9306	10.3342	376.24	0.5800	2.2018	19.3488	10.6679
7	443.66	0.4322	0.8837	6.8065	5.411	532.61	0.5189	0.9604	8.2655	5.381
8	333.75	0.5217	1.3552	8.7036	7.1143	416.19	0.6506	1.2709	17.8425	7.6771
9	372.71	0.6544	2.3455	11.6071	10.2512	438.30	0.7695	2.3214	11.8395	10.2814

3.1 Main effect plots of S/N ratio for output responses

S/N ratio is the Signal-to-noise ratio, measuring the variation of the observation in a run. It is generally calculated to select the optimal conditions of input parameters for getting the best output results under a particular working conditions, [2-4]. The value of S/N ratio should be always maximum to reduce the effect of noise. There are three different formulae for calculating the S/N ratio depending on the type of responses. Here, smaller-is-better methodology has been implemented for each output

responses which can be calculated as below: $SN_s = -10 \cdot \log \left(\frac{1}{n} \sum_{i=1}^n y_i^2 \right)$

3.2 Analysis of Variance (ANOVA)

ANOVA table is generally prepared to find the significant input parameters which will mostly effect the output responses. Analysis of variance table was prepared for each output response with a significant level of $\alpha = 0.05$ 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. In the table given the analysis with ANOVA, for cutting force and surface roughness without heat treatment.

Table 5: Analysis of Variance for cutting force F_{x1} .

	df	SS	MS	F	Significance F
Regression	5	90751.12	18150.22	3.23	0.181
Residual	3	16852.82	5617.60		
Total	8	107603.95			
	Coefficients	Standard Error	P-value	Regression Statistics	
Intercept	-214.39	274.88	0.492	Multiple R	0.91
Speed	-0.74	3.21	0.832	R Square	0.84
Feed	3336.74	1554.82	0.121	Adj R Square	0.58
Depth of cutting	288.39	137.62	0.127	Standard Error	74.95
Temperature	0.435	0.596	0.518	Observations	9
Amplitude	-42.28	257.01	0.87		

Table 6: Analysis of Variance for cutting force F_{y1} .

	df	SS	MS	F	Significance F
Regression	5	44988.729	8997.746	2.082	0.290
Residual	3	12964.480	4321.493		
Total	8	57953.209			
	Coefficients	Standard Error	P-value	Regression Statistics	
Intercept	-42.221	226.125	0.469	Multiple R	0.881
Speed	-0.655	2.486	0.660	R Square	0.776
Feed	3955.160	1374.106	0.118	Adj R Square	0.403
Depth of cutting	-17.608	119.349	0.126	Standard Error	65.738
Temperature	0.555	0.592	0.450	Observations	9
Amplitude	-177.843	236.637	0.948		

Table 7:Analysis of Variance for cutting force F_{z1} .

	df	SS	MS	F	Significance F	
Regression	5	166360.228	33272.046	23.426	0.013	
Residual	3	4260.898	1420.299			
Total	8	170621.126				
		Coefficients	Standard Error	P-value	Regression Statistics	
Intercept		-146.115	129.635	0.342	Multiple R	0.987
Speed		-0.920	1.425	0.564	R Square	0.975
Feed		5329.360	787.759	0.007	Adj R Square	0.933
Depth of cutting		481.723	68.422	0.006	Standard Error	37.687
Temperature		-0.155	0.339	0.679	Observations	9.000
Amplitude		189.862	135.661	0.256		

Table 8:Analysis of Variance for cutting force R_{a1} .

	df	SS	MS	F	Significance F	
Regression	5	1.728	0.346	5.030	0.107	
Residual	3	0.206	0.069			
Total	8	1.934				
		Coefficients	Standard Error	P-value	Regression Statistics	
Intercept		-0.203	0.902	0.836	Multiple R	0.945
Speed		-0.001	0.010	0.911	R Square	0.893
Feed		24.979	5.479	0.020	Adj R Square	0.716
Depth of cutting		0.185	0.476	0.723	Standard Error	0.262
Temperature		-0.001	0.002	0.708	Observations	9
Amplitude		1.147	0.943	0.311		

Table 9:Analysis of Variance for cutting force R_{z1} .

	df	SS	MS	F	Significance F	
Regression	4	72.336	18.084	2.495	0.199	
Residual	4	28.995	7.249			
Total	8	101.331				
		Coefficients	Standard Error	P-value	Regression Statistics	
Intercept		9.905	8.989	0.332	Multiple R	0.845
Speed		-0.136	0.077	0.152	R Square	0.714
Feed		146.165	56.252	0.060	Adj R Square	0.428
Depth of cutting		-1.224	4.132	0.782	Standard Error	2.692
Temperature		0.007	0.024	0.797	Observations	9
Amplitude		9.905	8.989	0.332		

Table 10:Analysis of Variance for cutting force R_{t1} .

	df	SS	MS	F	Significance F	
Regression	5	26.181	5.236	7.341	0.066	
Residual	3	2.140	0.713			
Total	8	28.321				
	Coefficients		Standard Error	P-value	Regression Statistics	
Intercept	2.092		2.905	0.523	Multiple R	0.961
Speed	0.010		0.032	0.784	R Square	0.924
Feed	100.458		17.654	0.011	Adj R Square	0.799
Depth of cutting	0.434		1.533	0.796	Standard Error	0.845
Temperature	-0.005		0.008	0.535	Observations	9
Amplitude	1.143		3.040	0.732		

In the table: 11-16 given the analysis with ANOVA, for cutting force and surface roughness after heat treatment (annealed).

Table 11: Analysis of Variance for cutting force F_{x2} .

	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	5	69713.56	13942.71	3.220	0.182
Residual	3	12986.47	4328.82		
Total	8	82700.04			
		Coefficients	Standard Error	P-value	Regression Statistics
Intercept		-187.274	226.316	0.469	Multiple R0.91
Speed		-1.209	2.488	0.660	R Square0.84
Feed		2994.792	1375.271	0.118	Adj R Square0.58
Depth of cutting		250.989	119.450	0.126	Standard Error65.79
Temperature		0.514	0.593	0.450	Observations9.00
Amplitude		-16.785	236.838	0.948	

Table 12: Analysis of Variance for cutting force F_{y2} .

	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>	
Regression	5	51805.03	10361	1.38	0.420	
Residual	3	22533.07	7511			
Total	8	57953.20				
		Coefficients	Standard Error	P-value	Regression Statistics	
Intercept		-24.284	317.850	0.943	Multiple R	0.83
Speed		1.108	3.71476	0.784	R Square	0.69
Feed		4253.220	1797.85	0.098	Adj R Square	0.19
Depth of cutting		-79.192	159.136	0.652	Standard Error	86.66
Temperature		0.4250	0.6899	0.581	Observations	9
Amplitude		-233.652	297.184	0.489		

Table 13: Analysis of Variance for cutting force F_{z2} .

	df	SS	MS	F	Significance F
Regression	5	149968.07	29993.62	15.94	0.022
Residual	3	5643.14	1881.04		
Total	8	155611.22			
		Coefficients	Standard Error	P-value	Regression Statistics
Intercept		-103.352	159.064	0.562	Multiple R0.98
Speed		0.771	1.859	0.706	R Square0.96
Feed		5200.68	899.717	0.010	Adj R Square0.90
Depth of cutting		422.454	79.638	0.013	Standard Error43.37
Temperature		-0.1427	0.345	0.707	Observations9
Amplitude		63.558	148.722	0.697	

Table 14: Analysis of Variance for cutting force R_{a2} .

	df	SS	MS	F	Significance F	
Regression	5	1.634	0.327	4.254	0.132	
Residual	3	0.230	0.077			
Total	8	1.864				
	Coefficients		Standard Error	P-value	Regression Statistics	
Intercept		0.229	1.016	0.836	Multiple R	0.936
Speed		-0.001	0.012	0.919	R Square	0.876
Feed		24.022	5.750	0.025	Adj R Square	0.670
Depth of cutting		0.295	0.509	0.603	Standard Error	0.277
Temperature		-0.002	0.002	0.519	Observations	9
Amplitude		0.829	0.950	0.447		

Table 15: Analysis of Variance for cutting force R_{z2} .

	df	SS	MS	F	Significance F	
Regression	5	107.674	21.535	2.877	0.207	
Residual	3	22.454	7.485			
Total	8	130.128				
	Coefficients		Standard Error	P-value	Regression Statistics	
Intercept		12.586	10.034	0.299	Multiple R	0.910
Speed		0.189	0.117	0.206	R Square	0.827
Feed		126.441	56.753	0.112	Adj R Square	0.540
Depth of cutting		-11.108	5.023	0.114	Standard Error	2.736
Temperature		-0.018	0.022	0.463	Observations	9
Amplitude		-9.918	9.381	0.368		

Table 16: Analysis of Variance for cutting force R_{t2} .

	df	SS	MS	F	Significance F	
Regression	5	25.665	5.133	11.084	0.038	
Residual	3	1.389	0.463			
Total	8	27.055				
		Coefficients	Standard Error	P-value	Regression Statistics	
Intercept		4.976	2.496	0.523	Multiple R	0.974
Speed		0.036	0.029	0.784	R Square	0.949
Feed		91.039	14.117	0.011	Adj R Square	0.863
Depth of cutting		0.049	1.250	0.796	Standard Error	0.681
Temperature		-0.012	0.005	0.535	Observations	9
Amplitude		-0.060	2.334	0.732		

4. Regression analysis equations

Regression analysis is a statistical process for estimating the relationships among variables. It includes many techniques for modelling and analysing several variables, when the focus is on the relationship between a dependent variable and one or more independent variables. Regression analysis was employed to derive the predictive equations of the cutting forces, and roundness error. The predictive equations generated for cutting force and surface roughness in Minitab 17 by ANOVA analysis.

Regression analysis equations for cutting force:

$$\begin{aligned}
 F_{x1} &= -187 - 1.21 \cdot v + 2995 \cdot f + 251 \cdot d + 0.514 \cdot t - 17 \cdot a, & R^2 &= 84\% \\
 F_{y1} &= -42 - 0.66 \cdot v + 3955 \cdot f - 18 \cdot d + 0.555 \cdot t - 178 \cdot a, & R^2 &= 77\% \\
 F_{z1} &= -146 - 0.92 \cdot v + 5329 \cdot f + 481.7 \cdot d - 0.155 \cdot t + 190 \cdot a, & R^2 &= 97\% \\
 F_{x2} &= -187 - 1.21 \cdot v + 2995 \cdot f + 251 \cdot d + 0.514 \cdot t - 17 \cdot a, & R^2 &= 84\% \\
 F_{y2} &= -42 - 0.66 \cdot v + 3955 \cdot f - 18 \cdot d + 0.555 \cdot t - 178 \cdot a, & R^2 &= 77\% \\
 F_{z2} &= -146 - 0.92 \cdot v + 5329 \cdot f + 481.7 \cdot d - 0.155 \cdot t + 190 \cdot a, & R^2 &= 97\%
 \end{aligned}$$

Regression analysis equations for surface roughness:

$$\begin{aligned}
 Ra_1 &= -0.203 - 0.00121 \cdot v + 24.98 \cdot f + 0.185 \cdot d - 0.00097 \cdot t + 1.147 \cdot a, & R^2 &= 89\% \\
 Rt_1 &= 10.6 - 0.116 \cdot v + 145.7 \cdot f - 1.99 \cdot d + 0.0062 \cdot t - 2.8 \cdot a, & R^2 &= 71\% \\
 Rz &= 2.09 + 0.0095 \cdot v + 100.5 \cdot f + 0.43 \cdot d - 0.00532 \cdot t + 1.14 \cdot a, & R^2 &= 92\% \\
 Ra_2 &= -0.23 - 0.0013 \cdot v + 24.02 \cdot f + 0.295 \cdot d - 0.00161 \cdot t + 0.829 \cdot a, & R^2 &= 87\% \\
 Rt_2 &= 4.98 + 0.0359 \cdot v + 91.0 \cdot f - 0.05 \cdot d - 0.01167 \cdot t - 0.06 \cdot a, & R^2 &= 97\% \\
 Rz_2 &= 12.6 + 0.189 \cdot v + 126.4 \cdot f + 11.11 \cdot d - 0.0183 \cdot t - 9.92 \cdot a, & R^2 &= 82\%
 \end{aligned}$$

4.1 Normal probability plots

To check the validation or the authenticity of the above statistical model normal probability plot. There will be no inadequacy in the model and there will no unusual structure in the model. It will predict better result in future. So from the graphs as shown in figure 2 and 3, it has been cleared that our statistical model is an authentic model.

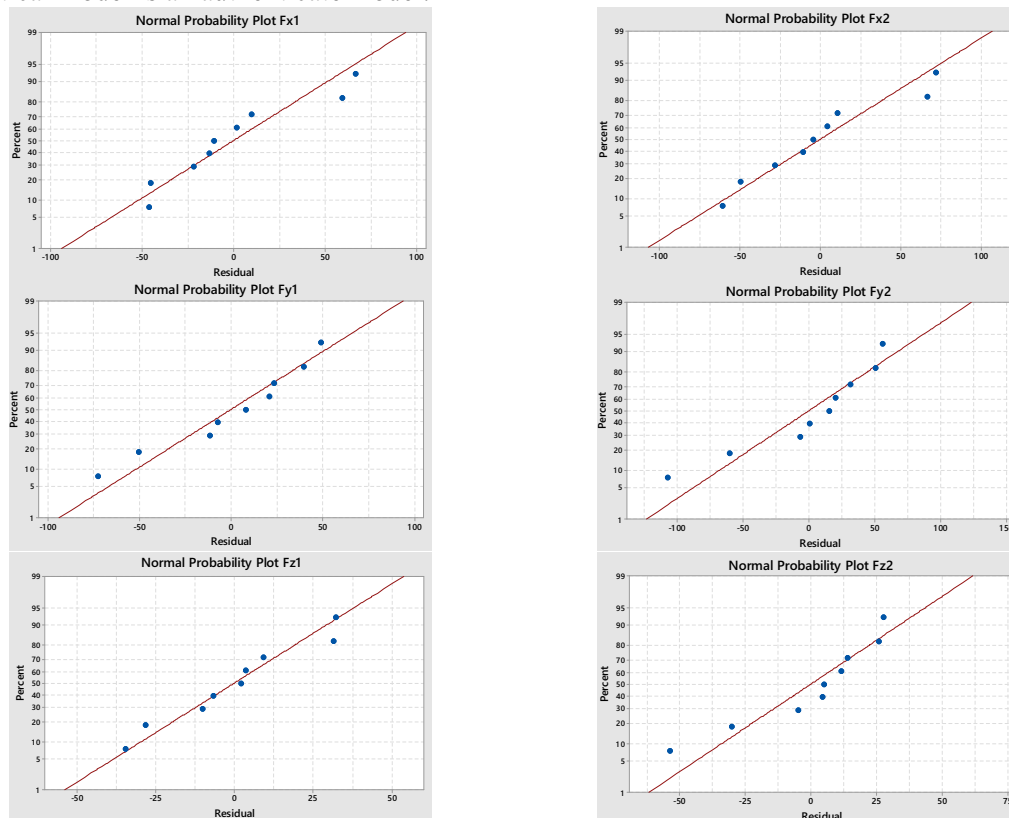


Figure 2. Normal Probability plots for cutting force.

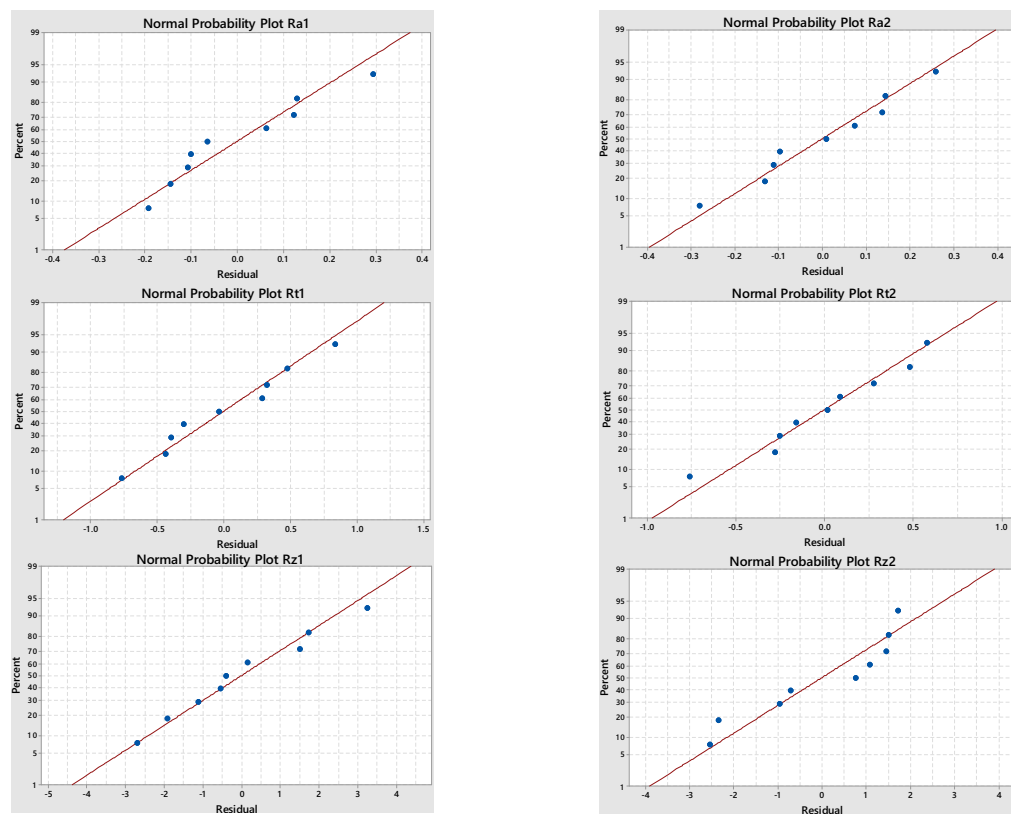


Figure 3. Normal Probability plots for surface roughness.

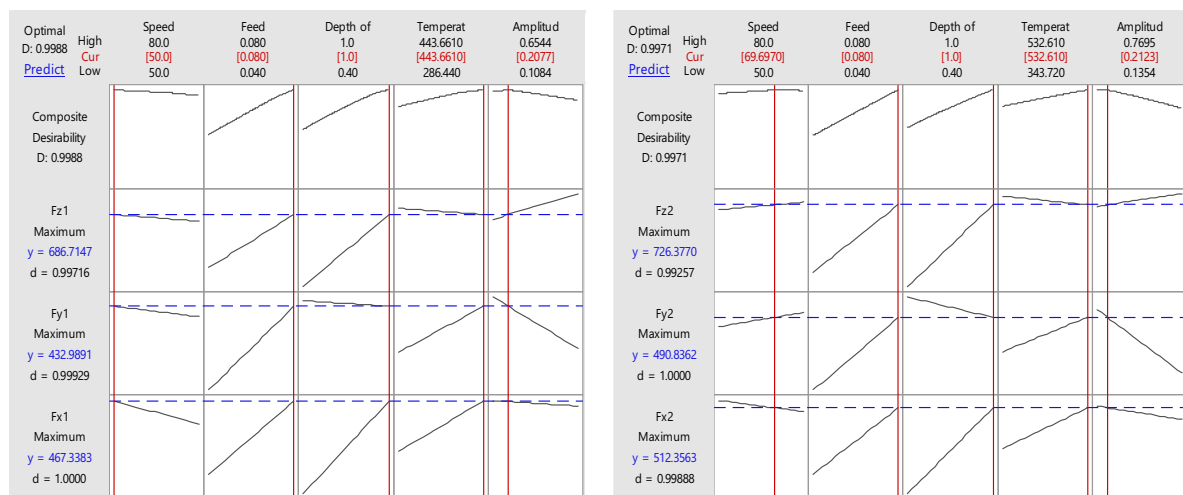


Figure 4. Multi objective optimization plot for cutting force.

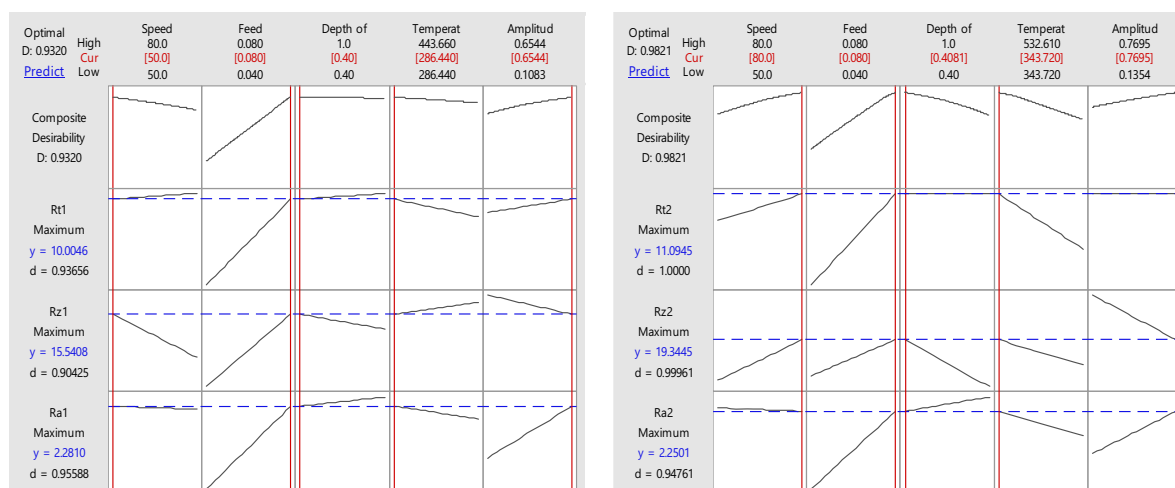


Figure 5. Multi objective optimization plot for surface roughness.

From the analysis of the obtained values in table 3, and from the analysis of figure 4 we can see that after heat treatment (annealed) the values of cutting forces increase. But optimization of maximal cutting forces must be done with: v_{min} , f_{max} , d_{max} and with t_{max} , a_{mes} .

In other hand from the analysis of experimental values on table 4 and analysis of diagrams in figure 5 we cannot see big difference between values of surface roughness. But the optimization of maximal values of surface roughness must be done with: v_{min} , f_{max} , d_{min} and with t_{min} , a_{max} .

Heat treatment more influence has in the cutting forces, which influence in the increase of the tool wear. While in the surface roughness make the structure adjustment so we can reach better surface roughness.

5. Conclusion

The realization of the experiment and analytical researches, as well as complete analysis of so far literature, enables us to come up with conclusions that due the complexity and the conditions under which the cutting occurs, cutting force, temperature, vibration and surface roughness defining is necessary to be presented by mathematical model, by which physical phenomenon changes and technological effects of the treated surface roughness is possible to be foreseen. From results of mathematical models for cutting forces and from their graphic shows we can conclude:

- ✓ With the increase of cutting speed, cutting forces decrease,
- ✓ With the increase of cutting feed, cutting forces increase,
- ✓ With the increase of depth of cutting, cutting force increase,
- ✓ With the increase of temperature and vibration, cutting force increase,

From the obtained results in experimental way, mathematical models and graphics interpretation we can see that with the increase of cutting speed, the roughness parameters Ra, Rt and Rz decrease. While with the increase of cutting depth also increase the roughness parameters. The temperature has a small influence in the surface roughness parameters, while the vibrations have much more influence on the surface roughness parameters.

6. References

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