Research Article



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A comparative study on optimization of machining parameters by turning aerospace materials according to Taguchi method

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Received 4 July 2016 / Accepted 21 November 2016

Abstract – The effects of cutting tool coating material and cutting speed on cutting forces and surface roughness were investigated by Taguchi experimental design. Main cutting force, F_z is considered as a criterion. The effects of machining parameters were investigated using Taguchi L₁₈ orthogonal array. Optimal cutting conditions were determined using the signal-to-noise (S/N) ratio which is calculated for average surface roughness and cutting force according to the "the smaller is better" approach. Using results of analysis of variance (ANOVA) and signal-to-noise (S/N) ratio, effects of parameters on both average surface roughness and cutting forces were statistically investigated. It was observed that feed rate and cutting speed had higher effect on cutting force in Hastelloy X, while the feed rate and cutting tool had higher effect on cutting force in Inconel 625. According to average surface roughness the cutting tool and feed rate had higher effect in Hastelloy X and Inconel 625.

Key words: Machinability, Taguchi method, Hastelloy X, Inconel 625, Surface roughness, Cutting force.

1 Introduction

Advanced materials, such as nickel-base and titanium alloys as well as composites are generally used at 650 °C or higher temperatures at which high stresses occur and surface integrate required. These materials are widely used in industrial gas turbines, space vehicles, rocket engines, nuclear reactors, submarines, stream production plants petrochemical devices, hot tools and glass industries [1]. Inconel 625 has been used in aqueous corrosive environments due to its excellent overall corrosion resistance [2]. Inconel 625 (Alloy 625) is a nickel-based super alloy strengthened mainly by the solidsolution hardening of the refractory metals, niobium and molybdenum, in a nickel-chromium matrix. Alloy 625 was originally developed as a solid-solution strengthened material. It was determined that the alloy is hardenable [3–6]. Inconel 625 exhibits precipitation hardening mainly due to the precipitation of fine metastable phase (Ni3Nb) after annealing over a long period in the temperature range 550-850 °C [4, 5]. Moreover, various forms of carbides (MC, M6C and M23C6) can also precipitate depending upon the time and temperature of aging. Alloy 625 has extensive use in many industries for diverse applications over a wide temperature range from cryogenic conditions to ultra hot environments over 1000 °C [6-9]. Hastelloy X and Inconel 625 is a nickel chromium-iron molybdenum alloy is developed for high temperature applications and it is derived from the strengthening particles, Ni2 (Mo, Cr), which formed after the two-step age-hardening heat treatment process. With face-centered cubic (FCC), Ni-Cr-Mo-W alloys, named as Hastelloy used for marine engineering, chemical and hydrocarbon processing equipment, valves, pumps, sensors and heat exchangers. Nickel-based super alloys have heat resistance, excellent mechanical properties, corrosion resistance and ability to operate in high temperature, attracting in nuclear industries [10, 11]. Nickel-based alloys and super alloys are very difficult to process [12–15]. A nickel-based super alloy has generally chemical content 38-76% nickel (Ni), more than 27% chromium (Cr) and 20% cobalt (Co) [16]. Such materials having high corrosion resistance and high strength at high temperatures are used [12, 13, 17–21]. The commercially available nickel-based super alloys are: Inconel (587, 597, 600, 601, 617, 625, 706, 718, X750, 901), Nimonic (75, 80A, 90, 105, 115, 263, 942, PA 11, PA 16, PO 33, C-263), Rene (41,95), Udimet (400, 500, 520, 630, 700, 710, 720), Pyrometer 860, Astrology, M-252, Waspaloy, Unitemp AF2 IDA6, Cabot 214 and Haynes 230 [16, 22]. These alloys have excellent mechanical properties, workability and corrosion resistance in aviation and extensively in the chemical industry heaters, condensers, evaporator tubes, pipes mirrors. However, low thermal conductivity and high cutting strength is still considered as challenging [16, 23].

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Malzeme Adı	Ni	Cr	Fe	Si	Mn	Мо	Со	Nb+Ta	Al	Р	Ti
Inconel 625	58	22	4.73	0.1	0.11	9.1	0.08	5.32	0.2	0.01	0.3
Malzeme Adı	Ni	Cr	Fe	Si	Mn	W	С	В	Мо	Co	Al
Hastelloy X	50	21	2	0.08	0.8	1	0.01	0.01	17	1	0.5

Table 1. The chemical composition of specimens.

Table 2. Mechanical properties of specimens.

Material	Thermal conductivity (W/mK)	Hardness (RB)	Yield strength (MPa)	Breaking extension (5do)	Tensile strength (MPa)
Inconel 625	9.8	97	758	60–30	885
Hastelloy X	11.4	388	1170	23.3	1370

2 Materials and method

2.1 Experiment specimens

Specimens of Hastelloy X and Inconel 625 which has an industrial usage, are prepared as the dimension of diameter \emptyset 25 × 40 mm then used for the experiments. The chemical composition and mechanical properties of specimens are given in Tables 1 and 2. These materials are hard to machine which make them suitable for high temperature applications.

2.2 Machine tool and measuring instrument of cutting forces

In the experimental study machining tests are carried out on JOHNFORD T35 industrial type CNC lathe maximum power of which is 10 kW and has revolution number between 50 and 3500 rev/min (Figure 1). During dry cutting process, Kistler brand 9257 B-type three-component piezoelectric dynamometer under tool holder with the appropriate load amplifier is used for measuring three orthogonal cutting forces (F_x , F_y , F_z). This allows direct and continuous recording and simultaneous graphical visualization of the three cutting forces (Figures 2 and 3).

2.3 Cutting parameters, cutting tool and tool holder

The cutting speeds 65, 80, and 100 mm/rev were chosen by taking into consideration ISO 3685 standard as recommended by manufacturing companies. The depth of cut 1, 5 mm feed rate 0.10-0.15 mm/rev. During cutting process, the machining tests were conducted with three different cemented carbide tools namely Physical Vapor Deposition (PVD) coated with TiN/TiCN/TiN; Chemical Vapor Deposition (CVD) coated with TIN+AL2O3-TICN+TIN; and WC/CO. The test specimens were chosen Ø 25×40 mm Properties of cutting tools and level of independent variables are given in Tables 3 and 4. Surtrasonic 3-P measuring equipment is used for the measurement of surface roughness. Measurement processes are carried out with three replications. For surface roughness on work-piece during machining, cut-off and sampling length are considered as 0.8 and 2.5 mm, respectively. Ambient temperature is 20 ± 1 °C. The following details tool geometry

CNMG inserts when mounted on the tool holder: (a) CNMG shape; (b) axial rake angle: 6° ; (c) end relief angle: 5° ; and (d) sharp cutting edge. The insert type CNMG 120404 with 75° approaching is mounted on PCLNR 2525 M 12 type tool holder. The levels for the determination of parameters estimated and actual test results S/N ratio and cutting values are given in Table 5. ANOVA results for the main cutting force (F_z) and surface roughness S/N ratio in Inconel 625 and Hastelloy X are given in Tables 6–9 (Figures 4 and 5).

3 Results and discussion

3.1 The change of main cutting force depending on cutting speed and coating material of cutting tool

Parameter in the determination of the maximum cutting force values for each level of the small S/N ratio determined and created new verification experiment was conducted according to the test combination. Tolerances specified for the product and quality in the design stage towards achieving the goal around the nominal value of each selected parameter to determine tolerance values. Product losses in the case where a different result from the target value by determining deviations calculated. Taguchi loss function, the expected target value and the deviation between the experimental values and the signal/noise (S/N) ratio is calculated by converting [24–26]. S/N ratio in calculating three different characteristics which are frequently used; nominal (face) value the better, smaller is better and bigger is better. In this study, the low surface roughness value, best performance will refer to the literature processed surfaces the lowest surface roughness values for the smaller the better S/N characteristic Due to the use in the analysis of at least the surface roughness and cutting forces for the smaller the better S/N characteristic is used. However, in experiments bigger the better S/N characteristic may be used [26, 27].

The aim here is S/N ratio is to maximize. Thus assessment for each parameter the average S/N ratio and the largest S/N ratio with a level, is used to determine the best results. In this study, the low surface roughness and low cutting force value represents the best performance. Parameters for each level of the average S/N ratio by utilizing a graphical representation



Figure 1. Cutting force measuring system used in the dynamometer, CNC JOHNFORD T35 lathe and computer unit.



Figure 2. Kistler 9257B (1997) dynamometer (10 KW), cutting force measuring unit with JOHNFORD T35 CNC lathe.



Figure 3. Measurement of cutting forces and schematically figure of dynamometer unit.

Table 3. Properties of cutting tools.

Coating material (top layer)	Coating method and layers	ISO grade of material (grade)	Geometric form	Manufacturer and code
TiN	CVD (TiN, AL2O3, TiCN TiN, Wc)	P25-P40, M20-M30	CNMG120412R	Kennametal KC9240
TiN	PVD (TiN, TiCN, TiN, Wc)	P25-P40, M20-M30	CNMG120412FN	Kennametal KT315
WC-CO	Uncoated	P25-P40, M20-M30	CNMG120412MS	Kennametal K313

Table 4. Level of independent variables.

Variables		Level of	variables	
	Lower	Low	Medium	High
Cutting force, v (m/min)	50	65	80	100
Feed rate, f (mm/rev)	0.1-0.15	0.1-0.15	0.1-0.15	0.1-0.15
Depth of cut (mm)	1.5	1.5	1.5	1.5

Table 5. Average surface roughness and the data obtained from actual experiments cutting force and the S/N ratio in Hastelloy X and Inconel 625.

			Haste	lloy X						Incone	el 625		
Feed rate mm/rev	Cutting force m/min	Cutting tool	R _a (µm)	$F_{z}(N)$	S/N rate For Ra	S/N rate for F _z	Feed rate mm/rev	Cutting force m/min	Cutting tool	$R_{\rm a}$ (µm)	<i>F</i> _z (N)	S/N rate for R_a	S/N rate for F_z
0.10 0.10	65 65	K313 KT315	1.70 1.605	691 622	-4.6090 -4.1095	-56.7896 -55.8758	0.10 0.10	65 65	K313 KT315	1.452 3.179	695 560	$-3.2393 \\ -10.0458$	-56.8397 -54.9638
0.10 0.10	65 80	KC9240 K313	1.455 1.599	715 655	-3.2573 -4.0770	-57.0861 -56.3248	0.10 0.10	65 80	KC9240 K313	0.725 1.691	505 705	2.7932 -4.5629	-54.0658 -56.9638
0.10	80 80	KT315 KC9240	1.410 1.368	601 694	-2.9844 -2.7217	-55.5775 -56.8272	0.10 0.10	80 80	KT315 KC9240	1.235 0.576	550 508	-1.8333 4.7916	-54.8073 -54.1173
0.10 0.10	100 100	K313 KT315	1./1/ 1.667	658 598 538	-4.6954 -4.4387 2.4411	-56.3645 -55.5340 54.6156	0.10 0.10	100 100	K313 KT315 KC0240	1.001	695 568 483	-0.008/ -0.2314 2.4411	-56.839/ -55.0870 53.6780
0.10	65 65	KC9240 K313 KT315	3.649 2.669	919 863	-11.243 -8.5269	-59.2663 -58.7202	0.15	65 65	KC9240 K313 KT315	0.958 4.785	485 875 785	0.3727	-58.8402 -57.8974
0.15 0.15	65 80	KC9240 K313	1.492 3.462	966 901	-3.4754 -10.786	-59.6995 -59.0945	0.15 0.15	65 80	KC9240 K313	1.580 1.307	691 876	-3.9731 -62.3255	-56.7896 -58.8501
0.15 0.15	80 80	KT315 KC9240	1.880 1.405	855 696	$-5.4832 \\ -2.9535$	-58.6393 -56.8522	0.15 0.15	80 80	KT315 KC9240	1.533 1.476	707 555	$-3.7108 \\ -3.3817$	-56.9884 -54.8859
0.15 0.15	100 100	K313 KT315	3.137 3.132	854 830	-9.9303 -9.9164	-58.6292 -58.3816	0.15 0.15	100 100	K313 KT315	0.812	887 724	-58.1911 0.4455	-58.9585 -57.1948
0.15	100	KC9240	1.085	697	-0.7086	-56.8647	0.15	100	KC9240	1.380	1.511	-2.7976	-63.5853

Table 6. ANOVA results for the main cutting force (F_z) S/N ratio in Inconel 625.

Source	Degrees of freedom (DoF)	Sequential sum of squares (SS)	Mean sum of squares (MS)	F-test	P-coefficient (%)
Feed rate	1	39.388	39.388	11.51	0.398
Cutting speed	2	6.631	3.316	0.97	0.067
Cutting tool	2	11.702	5.851	1.71	0.118
Residual error	12	41.063	3.422		0.415
Total	17	98.784			

of an optimal level for each parameter is determined. Accordingly, the parameters determined for each level of the S/N ratio is calculated using the estimated value. Estimated S/N ratio and output (surface roughness or cutting) value is used in calculating the formulas 4. The final step of the

Taguchi experimental design process includes confirmation experiments [27, 28]. Or this aim, the results of the experiments were compared with the predicted values with the Taguchi method and the error rates were obtained. S/N ratios η_{predict} were predicted using the following model [27–30].

Table 7. ANOVA results for the surface roughness (R_a) S/N ratio in Inconel 625.

Source	Degrees of freedom (DoF)	Sequential sum of squares (SS)	Mean sum of squares (MS)	F-test	P-coefficient (%)
Feed rate	1	1046.7	1046.74	3.49	0.165
Cutting speed	2	165.4	82.72	0.28	0.026
Cutting tool	2	1498.3	749.15	2.50	0.237
Residual error	12	3596.3	299.69		0.570
Total	17	6306.7			

Table 8. ANOVA results for the cutting force (F_z) in Hastelloy X.

Source	Degrees of freedom	Sequential sum of squares	Mean sum of squares	F-test	P (p < 0.05)	P-coefficient
	(DoF)	(88)	(MS)			(%)
Feed rate	1	18.1805	18.1805	57.75	0.002	65.99
Cutting speed	2	3.0700	1.5350	4.88	0.085	11.14
Cutting tool	2	1.3213	0.6607	2.1	0.238	4.80
Residual error	12	12.592	3.148			4.57
Total	17	27.5517				100

Table 9. ANOVA results for surface roughness (R_a) in Hastelloy X.

Source	Degrees of freedom (DoF)	Sequential sum of squares (SS)	Mean sum of squares (MS)	F-test	P (p < 0.05)	P-coefficient (%)
Feed rate	1	4.1424	4.1424	56.56	0.002	33.15
Cutting speed	2	0.18817	0.09408	1.28	0.371	1.51
Cutting tool	2	5.04646	2.52323	34.45	0.003	40.38
Residual error	12	0.29294	0.07323			2.34
Total	17	12.4974				100

$$\eta_{\text{predict}} = \eta_m + \sum_{i=1}^{kn} \left(\eta_i - \eta_m \right) \tag{1}$$

Here,

 η : The estimated S/N ratio.

 η_m : Total average S/N ratio.

 η_i : Parameter *i* at the level of the S/N ratio.

Here η_{predict} is the main cutting force or *Fz* with regard to the S/N ratio.

Moreover, the optimum turning parameters were obtained for the performance characteristics using the Taguchi analysis. Where η_m is the total mean of the S/N ratios, η_i is the mean S/N ratio at the optimum level and k is the number of the main design parameters that significantly affect the performance characteristics. After predicting the S/N ratios other than experiments, the main cutting force or F_z were calculated using the following equation. The final step of the Taguchi experimental design process includes confirmation experiments [28, 29]. For this aim, the results of the experiments were compared with the predicted values with the Taguchi method and the error rates were obtained. S/N ratios were predicted using the following model [30]. In this research "smallest is better" was used since the minimum of the cutting force and surface roughness was intended. In the experiment, the S/N ratio can be calculated using the following equation:

$$\eta_i = -10 \log 10 \frac{1}{n} \sum_{1}^{n} Yi^2$$
(2)

 η is the number of replications and Yi is the measured characteristic.

$$Predict = 10^{\frac{-S/N}{20}}$$
(3)

Taguchi method, used to analyze and evaluate the numerical results for the orthogonal experimental design, the S/N ratio and ANOVA combining three tools such as the solution reaches [30-33].

3.2 Results of Taguchi analysis

Experiments conducted with two different cutting tool wear value obtained as a result of the L18 experimental design based on a total of 36 experiments were made orthogonal. L18 orthogonal design, in two levels, corresponding to 8 columns and 18 rows of cylindrical turning experiments (17 degrees of freedom) was formed. Cutting force and the surface roughness is small, as quality characteristics "(S/N) SB, the smaller-better" is selected [32, 33]. The average surface roughness, the main cutting force data obtained in experiments and S/N ratios is given in Table 5. According to the data in Table 5, the lowest main cutting force at 100 m/min was found in Hastelloy X with KC 9240 insert as 538 N and in Inconel 625 as 483 N. In Table 5 the lowest average surface roughness was found with KC 9240 at 100 m/min in Hastelloy X as 0.755 μm and in Inconel 625 as 0.725 µm at 65 m/min. Determining the

According to Fz(N)

According to Ra (µm)

According to Ra (µm)



Figure 4. According to the level of machining parameters in Inconel 625, cutting force (F_z) , surface roughness Ra(μ m) the signal-to-noise (S/N) ratio).

According to Fz(N)



Figure 5. According to the level of machining parameters in Hastelloy X, cutting force (F_z) , surface roughness Ra(μ m) the signal-to-noise (S/N) ratio).

Table 10. Cutting force (F_z) SN rates and verification test for the optimum results in Inconel 625.

Optimization of Taguchi		Optimal cutting parameters				
	Prediction			Experimental		
Level	1	A1B2C2		A1B2C2		
Parameters	0.10	80	KT315	0.10	80	KT315
Cutting force (N)		453.5		550		
S/N ratio	-	-54.0374		-57.8072		

 Table 11. Average surface roughness and verification test for the optimum results in Inconel 625.

Optimization of Taguchi	Optimal cu	Optimal cutting parameters				
	Prediction	Experimental				
Level	A1B1C3	A1B1C3				
Parameters	0.10 80 KT31	5 0.10 80 KT315				
Average surface roughness	11.7149	0.725				
S/N ratio	-233.656	-2.7932				

minimum mean surface roughness values of the parameters for each level of the large S/N ratio determined and created new verification experiment was conducted according to the test combination. The levels for the determination of parameters estimated and actual test result S/N ratio and the average surface roughness values are provided in Table 5. Determining the minimum mean surface roughness values of the parameters for each level of the large S/N ratio determined and created new verification experiment was conducted according to the test combination. ANOVA results for the main cutting force (F_z), surface roughness and S/N ratio in Inconel 625 and Hastelloy X are provided in Tables 6–9.

 Table 12. Average surface roughness and verification test for the optimum results in Hastelloy X.

Optimization of Taguchi	Optimal cutting parameters				
	Prediction	Experimental			
Level	A1B2C3	A1B2C3			
Parameters	0.10 80 KC9240	0.10 80 KC9240			
Average surface roughness	1.049	-2.72			
S/N ratio	-0.4155	-56.82			

Table 13. Cutting force (F_z) SN rates and verification test for the optimum results in Hastelloy X.

Optimization of Taguchi	Optimal cutt	ing parameters
	Prediction	Experimental
Level	A1B3C3	A1B3C3
Parameters	0.10 100 KC9240	0.10 100 KC9240
Cutting force (F_z)	579.49	538
S/N ratio	-55.2617	-54.61

Results of confirmation tests for Cutting force (N) and surface roughness in Inconel 625 and Hastelloy X are provided in Tables 10-13.

4 Results and conclusions

The experimental design described herein was used to develop a main cutting force and surface roughness prediction model roughness using analysis of Taguchi for turning Inconel 625 and Hastelloy X. Results of this experimental study can be summarized as follows:

- It has seen that while feed rate (39.8%) and cutting tool (11.8%) has higher effect on cutting force in Inconel 625, the feed rate (65.99%) and cutting speed (11.14%) has higher effect on cutting force in Hastelloy X. While cutting tool (23.7%) and feed rate (16.5%) has higher effect on average surface roughness in Inconel 625, cutting tool (40.38%), and feed rate (33.15%) has higher effect on average surface roughness in Hastelloy X.
- According to obtained experiments data, the lowest main cutting force has found in Hastelloy X with KC 9240 insert as 538 N and in Inconel 625 as 483 N both at 100 m/min. In the same KC 9240 insert, lowest average surface roughness has found at 100 m/min in Hastelloy X as 0.755 μ m. And as 0.725 μ m at 65 m/min. in Inconel 625. It was seen the effect of cutting tool on surface roughness has found higher on Hastelloy X and Inconel 625.
- Taguchi orthogonal array arrangement, it has seen appropriate to analyzed the cutting force and average surface roughness defined in this article.

Acknowledgements. The authors would like to express their gratitude to University of Yuzuncu Yıl for the financial support Under Project No. BAP 2012-BYO-013.

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Cite this article as: Altin A: A comparative study on optimization of machining parameters by turning aerospace materials according to Taguchi method. Int. J. Simul. Multisci. Des. Optim., 2017, 8, A1.