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PARAMETRIC ANALYSIS ON EFFECTS OF CUTTING PARAMETERS OF TAGUCHI METHOD OVER SURFACE ROUGHNESS IN HARD TURNING

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ABSTRACT

This study focuses on optimizing turning parameters based on the Taguchi method to min-imize surface roughness (Ra and Rz). Experiments have been conducted using the L9 orthogonal array in a CNC turning machine. Dry turning tests are carried out on hardened AISI 4140 (51 HRC) with coated carbide cutting tools. Each experiment is repeated three times and each test uses a new cutting insert to ensure accurate readings of the surface roughness. The statistical methods of signal to noise ratio (SNR) and the analysis of vari-ance (ANOVA) are applied to investigate effects of cutting speed, feed rate and depth of cut on surface roughness. Results of this study indicate that the feed rate has the most sig-nificant effect on Ra and Rz. In addition, the effects of two factor interactions of the feed rate-cutting speed and depth of cut-cutting speed appear to be important. The developed model can be used in the metal machining industries in order to determine the optimum cutting parameters for minimum surface roughness.

INTRODUCTION

Hard turning is a turning process in which work pieces whose hardness ranges between 50 and 70 HRC are machined by using single point cutting tools which have high hardness and wear resistance. The hard turning exhibits a unique behavior, which is different than conven-tional turning operations. The application of hard turning technology can be improved by utilizing advanced optimi-zation algorithms, which helps manufacturers to make educated decisions in the presence of multiple objectives that need to be satisfied [1,2].

Significant advances have been seen in cutting tools and machine tools in recent years. Cutting parameters may be specified according to hardness of materials and roughness of the surface of a work piece. The advantages in machining materials with higher hardness are decreasing machining costs, saving time, improving surface quality, and eliminat-ing of deformities in parts caused by temperature [3,4]. Aslan et al. [4] conducted an optimization study by machin-ing a hardened AISI 4140 grade (63 HRC) steel on a lathe by using Al_2O_3 + TiCN coated ceramic inserts. They determined that Al_2O_3-base ceramics are required for cutting tools in machining hard steels during wear resistance and high hardness. They ensured optimization in their experi-mental studies by using the Taguchi method. The experi-mental parameters chosen were: three different cutting speeds, feed rates and depths of cut. Blank wear (VB) and surface roughness were chosen as criteria for performance. The obtained results were analyzed by using variance anal-ysis (ANOVA). As a result, it was seen that the VB value de-creased as the cutting speed and the depth of cut increased; however, it first decreased and then increased as the feed rate increased. On the other hand, the surface roughness decreased as the cutting speed increased. In contrast sur-face roughness increased when the feed rate increased.

Ucun and Aslantas [5] investigated the effects of the cutting parameters on surface roughness in hard turning. They examined machining performance with respect to tool wear and surface roughness in machining hardened AISI 52100 grade bearing steels with coated carbide cutting tools. Four different cutting speeds, three different feed rates and two different depths of cut

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were used during their experimental studies. As a result, they observed that carbide cutting tools were not suitable for the hard turning process, especially at high cutting parametric values. Derakhshan and Akbari [6] used Cubic Boron Nitride (CBN) tools in their study on hard turning. They researched the effects of hardness on the work piece and cutting speed on surface roughness in machining with CBN tools. They machined the AISI 4140 grade work piece with two differ-ent tools at five different hardness values: HRC 45, 50, 55, 60, and 65. The types of tools, the hardness value of the material and the cutting speed as input were used while Ra, Rz and VB were used as output. Chou et al. [7] obtained the effect of various parameters in machining hard steels with CBN inserts and blank wear depending on surface roughness. They specified cutting speed, CBN content per-centage and length of insert as factors. Yang and Tarng [8] used the Taguchi method for determining optimum cutting parameters. They machined S45C steel work piece with carbide cutting tools. The cutting parameters chosen were cutting speed, feed rate and depth of cut. Taguchi's signal– noise ratio and variance analysis were used to determine the effect of the cutting parameters on tool life and surface roughness. They obtained optimum cutting parameters as a result of their studies. Zhang and Chen [9] experimented to optimize the surface quality in a CNC drilling operation using Taguchi design. The control factors in their study were feed rate, spindle speed, peck rate and tool type, while the noise factors simulated were machine shop vibration and the presence or absence of magnetism in the work piece material. Through statistical analysis of response variables and signal-to-noise ratios, the deter-mined significant factors were the spindle speed, tool type and peck rate, and the optimal combination of cutting parameters were selected. They verified that the selected optimal combination through Taguchi design achieved the desired surface roughness. Bhattacharya et al. [10] investigated the effects of cutting parameters on finish and power consumption by employing Taguchi techniques. Their results showed a significant effect of cutting speed on the surface roughness and power consumption, while the other parameters did not substantially affect the responses. Therefore, optimal cutting parameters were obtained.

Kopac et al. [11] considered cutting speed, cutting tool materials, feed rate and depth of cut as cutting parameters in machining C15 E4 steel on a lathe. They used the Tagu-chi orthogonal array of L16 (25), which has two levels and a degree of freedom of 13 in the experimental design. The quality determinant of ''the smaller the better'' was used in calculating the signal–noise ratio. It was observed that the control parameter having the highest effect on surface roughness is the cutting speed, and better surface rough-ness values were obtained at higher cutting speeds.

Sahin [12] compared the tool life of CBN and ceramic inserts in turning hard steels using the Taguchi method. The effects of cutting parameters on tool life were deter-mined by using orthogonal array, signal–noise ratio and variance analysis. He chose cutting speed, feed rate and tool hardness as cutting parameters. As a result, it was concluded that the effects of cutting speed, tool hardness and feed rate on tool life were 41.63%, 32.68% and 25.22%, respectively.

Abu-Sinna et al. [13] investigated the effect of the load-ing frame stiffness on the deadweight force machine– loadcell interaction. In order to perform the finite element analysis efficiently, they utilized the Taguchi technique, as this typically reduces the total required simulations. The validity of the finite element analysis was confirmed through experiments.

The Taguchi method for finding out the optimal value of surface roughness under optimum cutting condition in turning SCM 440 alloy steel was applied by Thamizhmanii et al. [14]. They detected that the causes of poor surface finish were machine tool vibrations and tool chattering whose effects were ignored for analysis. The authors con-cluded that depth of cut was the only significant factor which contributed to the surface roughness.

Kilickap [15] investigated the use of the Taguchi method and the Response Surface Methodologies (RSM) for mini-mizing the burr height and the surface roughness in drilling Al-7075. The Taguchi method, a powerful tool to optimize design quality, was used to find optimal cutting parame-ters. The optimization results showed that the combination of low cutting speed, low feed rate and high point angle were necessary to minimize burr height. The best results of the surface roughness were obtained at lower cutting speed and feed rates and at higher point angles.

Wang and Lan [16] used orthogonal array of Taguchi method coupled with the Grey Relational Analysis (GRA) in considering the four parameters of cutting speed, depth of cut, feed rate and tool nose radius. The stated four parameters were used for optimizing the following three responses: surface roughness, tool wear and material re-moval rate in precision turning on an ECOCA-3807 CNC lathe. They studied the proposal of optimization approaches using Orthogonal Array and the GRA and contrib-uted a satisfactory technique for improving the multiple machining performances in precision CNC turning with profound insight.

Neseli et al. [17] observed on the influence of tool geometry on the surface finish obtained in turning of AISI 1040 steel. Their study focused on the effect of tool geom-etry parameters on the surface roughness during turning. The RSM and a prediction model were developed related to average surface roughness (Ra) using experimental data. The results indicated that the tool nose radius was the dominant factor on the surface roughness.

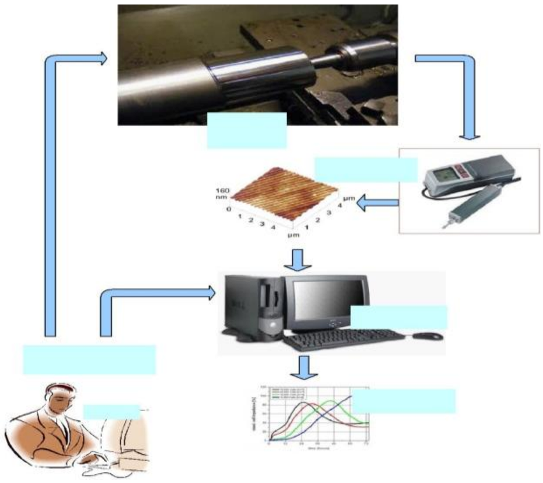
Shetty et al. [18] used Taguchi and Response Surface Methodologies for minimizing the surface roughness in turning of discontinuously reinforced aluminum compos-ites (DRACs) having aluminum alloy 6061 as the matrix and containing 15 vol.% of silicon carbide particles of mean diameter 25 lm under pressured steam jet approach. The effect of cutting parameters on surface roughness was evaluated and the optimum cutting condition for minimiz-ing the surface roughness was also determined.

The literature survey reveals that traditional experi-mental design procedures are too complicated and not easy to use. A large number of experimental works have to be carried out when the number of the process parameters increases. To solve this problem, the Taguchi method uses a special design of orthogonal arrays to study the entire parameter space with only a small number of experiments [19].

The objective of this study is to obtain optimal turning parameters (cutting speed, feed rate and depth of cut) for minimum on surface roughness, while turning hardened AISI 4140 steel with Al_2O_3 and TiC-coated carbide tools. Taguchi's parameter design approach has been used to accomplish this objective. Furthermore, a statistical analy-sis (ANOVA) is performed to see which process parameters are statistically significant.

MATERIAL AND METHOD

In this study, a work piece made of AISI 4140 grade (DIN 42CrMo4) steel was used. Its sizes were Ø110 _ 600 mm. As thermal treatment, the steel was tempered at 880 LC for an hour and quenched at 280 LC for 2 hour to eliminate stresses and to reduce hardness. As a result, hardness of the material was decreased from 62 HRC to 56–57 HRC. The experimental studies were car-ried out on a Mori Seiki NL 2500 CNC Lathe. The experi-ments were conducted under dry cutting conditions. The tool holder used was model MWLNR 2525M-0.8W. Al_2O_3 and TiC-coated (WNMA 080408) inserts were used as the cutting tool material. The surface roughness was measured using a Mitutoyo SJ-301P portable device with-in the sampling length of 2.5 cm. Fig. 1 shows the exper-imental arrangement.



The level of cutting parameter ranges and the initial parameter values were chosen from the manufacturer's handbook recommended for the tested material. These cutting parameters are shown in Table 1.

Symbol	Cutting parameters	Level 1	Level 2	Level 3
A	Cutting speed (m/min)	90	120	150
B	Feed rate (mm/rev)	0.18	0.27	0.36
C	Depth of cut (mm)	0.2	0.4	0.6

THE EXPERIMENTAL DESIGN USING THE TAGUCHI METHOD

The traditional experimental design methods are too complex and difficult to use. Additionally, large numbers of experiments have to be carried out when the number of machining parameters increase. Therefore, the factors causing variations should be determined and checked un-der laboratory conditions. These studies are considered un-der the scope of off-line quality improvement [20–22].

The Taguchi method is an experimental design tech-nique, which is useful in reducing the number of experi-ments dramatically by using orthogonal arrays and also tries to minimize effects of the factors out of control. The basic philosophy of the Taguchi method is to ensure qual-ity in the design phase. The greatest advantages of the Taguchi method are to decrease the experimental time, to reduce the cost and to find out significant factors in a shorter time period [23].

The most reliable of Taguchi's techniques is the use of parameter design, which is an engineering method for product or process design that focuses on determining the parameter (factor) settings producing the best levels of a quality characteristic (performance measure) with minimum variation. The overall aim of quality engineering is to make products that are robust with respect to all noise factors. The most important stage in the design of an experiment lies in the selection of control factors. As many factors as possible should be included in order to it would be possible to identify non-significant variables at the ear-liest opportunity [4,25]. Taguchi creates a standard orthog-onal array to accommodate this requirement. Taguchi used the signal-to-noise (S/N) ratio as the quality characteristic of choice. S/N ratio is used as a measurable value instead of standard deviation because as the mean decreases, the standard deviation also decreases and vice versa. In less technical terms, signal-to-noise ratio compares the level of a desired signal (such as music) to the level of back-ground noise. The higher the ratio, the less obtrusive the background noise is. ''Signal-to-noise ratio'' is sometimes used informally to refer to the ratio of useful information to false or irrelevant data in a conversation or exchange. In other words, the standard deviation cannot be mini-mized first and the mean brought to the target [4,24,25]. Taguchi has empirically found that the two stage optimiza-tion procedure involving S/N ratios indeed gives the parameter level combination, where the standard devia-tion is minimum while keeping the mean on target [26]. This implies that engineering systems behave in such a way that the manipulated production factors can be di-vided into three categories:

1. Control factors, which affect process variability as mea-sured by the S/N ratio.

2. Signal factors, which do not influence the S/N ratio or process mean.

3. Factors, which do not affect the S/N ratio or process mean.

In practice, the target mean value may change during the process development. Two of the applications in which the concepts of S/N ratio are useful are the improvement of quality through variability reduction and the improvement of measurement. The S/N ratio characteristics can be di-vided into three categories given by Eqs. (1)–(3), when the characteristic is continuous [27]:

_ Nominal is the best characteristic,

y
S –
¼ 10 S_y
N log 2 ð1Þ

_ Smaller is the better characteristic,

S 1
¼ _10
N log n −X $_{y2}$− ð2Þ

_ Larger is the better characteristic,

S 1 1
¼ _
log _x _ ð3Þ

This implies that engineering systems behave in such a way that the manipulated production factors can be di-vided into three categories: where y_, is the average of ob-

served data, S^2_y the variation of y, n the number of observations, and y the observed data or each type of the characteristics. With the above S/N ratio transformation, the smaller the S/N ratio, the better the result when we consider tool wear, surface roughness, cutting force and trust force.

Deviation between experimental and desired values is defined as loss function in the Taguchi method. This loss function is further converted into S/N signal–noise ratio [22]. In the Taguchi method, the optimum cutting condi-tions required for the best surface roughness were ob-tained by using Eq. (1), ‘‘the smaller-the better’’ signal– noise ratio. S/N ratios and level values were calculated by using Eq. (2), ‘‘the smaller-the better’’ in the MINITAB 14 Program. S/N ratios obtained from this equation are given in Table 2.

Experimental number	A	B	C	Ra	Rz	Ra for S/N ratios	Rz for S/N ratios
1	1	1	1	1.6	8.79	_4.23	_18.88
2	1	2	2	1.79	14.22	_3.37	_23.058
3	1	3	2	4.22	19.87	_12.48	_25.964
4	2	1	2	1.21	8.62	_2.32	_18.75
5	2	2	2	2.47	11.72	_7.87	_21.379
6	2	3	1	3.78	15.94	_10.79	_24.05
7	3	1	3	1.17	8.66	_3.37	_18.76
8	3	2	1	2.21	9.25	_6.99	_19.323
9	3	3	2	2.51	12.12	_7.76	_21.67

Analyzing and evaluating results of the experiments using the Taguchi method

S/N response table for Ra factor

Level	A	B	C
1	_6.343	_4.024	_7.338
2	_7.709	_5.723	_4.846
3	_6.039	_10.344	_7.907
D	1.67	6.32	3.06

The most essential criterion in the Taguchi method for analyzing experimental data is signal/noise ratio. In this study, the S/N ratio should have a maximum value to ob-tain optimum cutting conditions, according to the Taguchi Table 3 method. Thus, the optimum cutting condition was found as _2.32 and _18.75 S/N ratios for Ra and Rz respectively in L9 orthogonal array in Table 2. The optimum cutting condi-tions, which were the cutting speed of 120 m/min, the feed rate of 0.18 mm/rev and the depth of cut of 0.4 mm (2 1 2 orthogonal array) were obtained for the best Ra and Rz val-ues. Level values of the factors obtained for Ra, according to the Taguchi design, are given in Table 3. Fig. 2 shows the graphic of the level values given in Table 3. Therefore, interpretations may be made according to the level values of A, B, and C factors given in Table 3 and Fig. 2 in deter-mining optimum cutting conditions of experiments to be conducted under the same conditions. The average S/N ra-tio for every level of experiment is calculated based on the recorded value as shown in Table 3.

The different values of S/N ratio between maximum and minimum are (main effect) also shown in Table 3. The feed rate and the depth of cut are two factors that have the highest difference between values, 6.32 and 3.6 respec-tively. Based on the Taguchi prediction that the larger dif-ferent between value of S/N ratio will have a more significant effect on surface roughness (Ra). Thus, it can be concluded that increasing the feed rate will increase the Ra significantly and also the depth of cut. The results of data analysis of S/N ratio for Ra values, which are calcu-lated by Taguchi method, are shown in Table 4 (where df is degree of freedom, F variance ratio, and P significant fac-tor). Thus, it is seen in Fig. 2 and Table 3 that the third level of A factor (cutting speed), the first level of B factor (feed rate) and the third level of C factor (depth of cut) are higher. Consequently, the optimum cutting conditions deter-mined under the same conditions for the experiments to be conducted will be 150 m/min for the cutting speed, 0.18 mm/rev for the feed rate and 0.6 mm for the depth of cut. The Taguchi experimental design was used to obtain optimum cutting parameters on hard turning. Experimen-tal results were analyzed using ANOVA. The results ob-tained in this study are given below:

L9 orthogonal array was selected for three different lev-els of cutting speed, feed rate and depth of cut, which were cutting factors, by using the Taguchi method. As a result, nine experiments were conducted instead of the full factorial 27 experiments. Ra and Rz’ S/N ratios were found as a result of experiments conducted according to the L9 orthogonal array. The maximum value was found by using the S/N ratio equation of ‘‘the smaller-the better,’’ the maximum S/N ratio yielded optimum cutting parameters.

Main Effects Plot (data means) for SN ratios

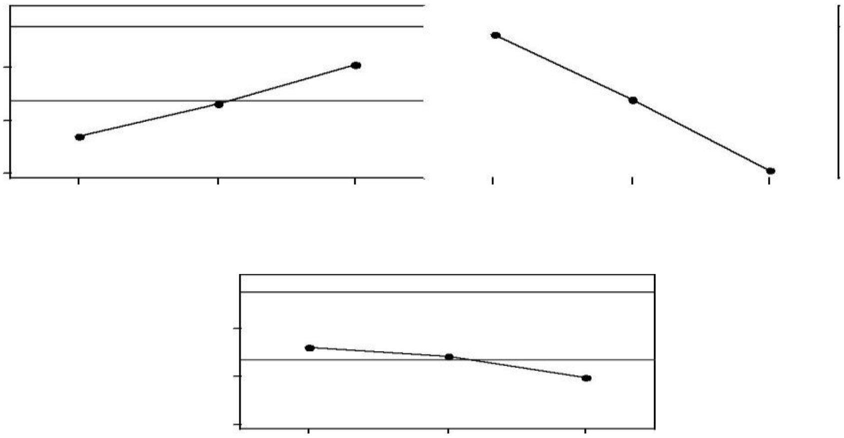


Table 8
The interaction between S/N – cutting speed for Rz factor.

			Sum of squares	df	Mean square	F	P
Rz – V	Between groups	(Combined)	11.235	2	5.617	0.761	0.508
	Within groups		44.287	6	7.381		
	Total		55.522	8			

Table 9
The interaction between S/N – feed rate for Rz factor.

			Sum of squares	df	Mean square	F	P
Rz – f	Between groups	(Combined)	39.252	2	19.626	7.238	0.025
	Within groups		16.270	6	2.712		
	Total		55.522	8			

Table 10
The interaction between S/N – depth of cut for Rz factor.

			Sum of squares	df	Mean square	F	P
Rz – a	Between groups	(Combined)	11.346	2	5.673	0.771	0.504
	Within groups		44.176	6	7.363		
	Total		55.522	8			

CONCLUSION

The Taguchi experimental design was used to obtain optimum cutting parameters on hard turning. Experimen-tal results were analyzed using ANOVA. The results ob-tained in this study are given below:

L9 orthogonal array was selected for three different lev-els of cutting speed, feed rate and depth of cut, which were cutting factors, by using the Taguchi method. As a result, nine experiments were conducted instead of the full factorial 27 experiments. Ra and Rz’ S/N ratios were found as a result of experiments conducted according to the L9 orthogonal array. The maximum value was found by using the S/N ratio equation of ‘‘the smaller-the better,’’ the maximum S/N ratio yielded optimum cutting parameters. Optimum cutting conditions-which correspond to maximum _2.32 S/N value of the smaller Ra value for the smaller surface roughness in hard turning operation (2 1 2)-were found to be 120 m/min for the cutting speed, 0.18 mm/rev for the feed rate and 0.4 mm for the depth of cut. Optimum cutting conditions-which correspond to maximum _18.75 S/N value of Rz value (3 1 1)-were found to be 120 m/min for the cutting speed, 0.18 mm/rev for the feed rate and 0.4 mm for the depth of cut.

Variance analysis was applied to S/N ratios to discover interactions between cutting parameters relating to Ra and Rz. According to the ANOVA analysis, the feed rate has an effect on Ra and Rz at a reliability level of 95%. Any difference (variance) was not observed for the cut-ting speed and the depth of cut at the reliability level of 95%. The number of experiments in the same or similar area in hard turning operations were reduced by using the Taguchi experimental design to determine optimum cutting conditions. Satisfying results were obtained so that they may be used in future academic and industrial studies.

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REFERENCES

[1]. D. Singh, P.V. Rao, A surface roughness prediction model for hard turning process, Int. J. Adv. Manuf. 32 (11–12) (2007) 1115–1124.

[2]. Y. Karpat, T. Özel, Hard turning optimization using neural network modeling and swarm intelligence, Trans. North Am. Manuf. Res. Ins. XXXIII (2005) 179–186.

[3]. S.Z. Chavosh, M. Tajdari, Surface roughness modeling in hard turning operation of AISI 4140 using CBN cutting tool, Int. J. Mater. Form. 3 (2010) 233–239.

[4]. E. Aslan, N. Camuscu, B. Bingören, Design optimization of cutting parameters when turning hardened AISI 4140(63 HRC) with Al2O3 + TiCN mixed ceramic tool, Mater. Des. 28 (2007) 1618–1622.

[5]. I. Ucun, K. Aslantas, Investigation of Performance of Carbide Cutting Tool in Turning Hardened 52100 Tool Steel, IATS’09, Karabük, Turkey, 2009, pp. 1–6.

[6]. E.D. Derakhshan, A.A. Akbari, Experimental investigation on the work piece hardness and cutting speed on surface roughness in hard turning with CBN tools, in: Proceedings of the World Congress on Engineering WCE, London, UK, 2009, pp. 1–3.

[7]. Y.K. Chou, M.M. Barash, C.J. Evans, Experimental investigation on CBN turning of hardened AISI 52100 steel, J. Mater. Process. Technol. 124 (3) (2002) 274–283.

[8]. W.H. Yang, Y.S. Tarng, Design optimization of cutting parameters for turning operations based on the Taguchi method, J. Mater. Process. Technol. 84 (1998) 122–129.

[9]. Z. Zhang, J.C. Chen, Surface roughness optimization in a drilling operation using the Taguchi design method, J. Mater. Manuf. Processes 24 (4) (2009) 459–467.

[10]. A. Bhattacharya, S. Das, P. Majumder, A. Batish, Estimating the effect of cutting parameters on surface finish and power consumption during high speed machining of AISI 1045 steel using Taguchi design and ANOVA, Prod. Eng. Res. Dev. 3 (2009) 31–40.

[11]. J. Kopac, M. Bahor, M. Sokovic, Optimal machining parameters for achieving the desired surface roughness in fine turning of cold pre-formed steel work pieces, Int. J. Mach. Tools Manuf. 42 (2002) 707– 716.

[12]. Y. Sahin, Comparison of tool life between ceramic and cubic boron nitride (CBN) cutting tools when machining hardened steels, J. Mater. Process. Technol. 209 (2009) 3478–3489.

[13]. A. Abu-Sinna, Yon-Kyu Park, Dae-Im Kang, Min-Seok Kim, The influence of loading frame stiffness on loadcell–deadweight force machine interaction, Measurement 42 (6) (2009) 830–835.

[14]. S. Thamizhmanii, S. Saparudin, S. Hasan, Analysis of surface roughness by using Taguchi method, Ach. Mater. Manuf. Eng. 20 (1–20) (2007) 503–505.

[15]. E. Kilickap, Modeling and optimization of burr height in drilling of Al-7075 using Taguchi method and response surface methodology, Int. J. Adv Manuf. Technol. 49 (9–12) (2010) 911–923.

[16]. M.Y. Wang, T.S. Lan, Parametric optimization

on multi-objective precision turning using grey relational analysis, Inf. Technol. J. 7 (2008) 1072–1076.

[17]. S. Neseli, S. Yaldız, E. Türkes, Optimization of tool geometry parameters for turning operations based on the response surface methodology, Measurement 44 (3) (2011) 580–587.

[18]. R. Shetty, R. Pai, V. Kamath, S.S. Rao, Study on surface roughness minimization in turning of DRACs using surface roughness methodology and Taguchi under pressured steam jet approach, ARPN J. Eng. Appl. Sci. 3 (1) (2008) 59–67.

[19]. E. Bagci, S. Aykut, A study of Taguchi optimization method for identifying optimum surface roughness in CNC face milling of cobalt-based alloy (stellite 6), Int. J. Adv. Manuf. Technol. 29 (9–10) (2006) 940–947.

[20]. A. Hasçalık, U. Çaydas, Optimization of turning parameters for surface roughness, and tool life based on the Taguchi method, Int. J. Adv. Manuf. Technol. 38 (2008) 896–903.

[21]. T.R. Lin, Optimization technique for face milling stainless steel with multiple performance characteristics, Int. J. Adv. Manuf. Technol. 19 (2002) 330–335.

[22]. O. Köksoy, Z.F. Muluk, Solution to the Taguchi's problem with correlated responses, Gazi Univ. J. Sci. 17 (1) (2004) 59–70.

[23]. M. Sanyılmaz, Design Of Experiment And an Application for Taguchi Method in Quality Improvement Activity, M.S. Thesis, Dumlupınar University, Turkey, 2006.

[24]. J.A. Ghani, I.A. Choudhury, H.H. Hassan, Application of Taguchi method in the optimization of end milling operations, J. Mater. Process. Technol. 145 (2004) 84–92.

[25]. S.H. Park, Robust Design and Analysis for Quality Engineering, Chapman and Hall, London, U.K, 1996.

[26]. H.S. Kim, A combined FEA and design of experiments approach for the design and analysis of warm forming of aluminum sheet alloys, Int. J. Adv. Manuf. Technol. 51 (1–4) (2010) 1–14.

[27]. R. Shetty, R.B. Pai, S.S. Rao, R. Nayak, Taguchi's technique in machining of metal matrix composites, J. Braz. Soc. Mech. Sci. Eng. 31 (1) (2009) 12–20.

[28]. I. Asilturk, M. Cunkas, Modelling and prediction of surface roughness in turning operations using artificial neural network and multiple regression method, Expert Syst. Appl. 38 (5) (2011) 5826–5832.