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Taguchi method and ANOVA: An approach for process parameters optimization of hard machining while machining hardened steel

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In this paper, Taguchi method is applied to find optimum process parameters for end milling while hard machining of hardened steel. A L_{18} array, signal-to-noise ratio and analysis of variance (ANOVA) are applied to study performance characteristics of machining parameters (cutting speed, feed, depth of cut and width of cut) with consideration of surface finish and tool life. Chipping and adhesion are observed to be main causes of wear. Results obtained by Taguchi method match closely with ANOVA and cutting speed is most influencing parameter. Multiple regression equations are formulated for estimating predicted values of surface roughness and tool wear.

Keywords: ANOVA, End milling, Hard machining, Regression analysis, Taguchi methods

Introduction

Taguchi's parameter design offers a systematic approach for optimization of various parameters with regard to performance, quality and cost[1-4]. Taguchi methodology optimized cutting parameters in end milling when machining hardened steel AISI H13 with TiN-coated P10 carbide insert of high-speed cutting[5]. Further, design optimization for quality[6] was carried out and signal-to-noise (S/N) ratio and analysis of variance (ANOVA) were employed using experimental results to confirm effectiveness of this approach. Taguchi methodology was used to find optimal cutting parameters for surface roughness (SR) in turning operation based on experimental results done on AISI1030 steel bars using TiN-coated tools[7.] Experimental study was carried on machined hardened steels AISI 4140(63HRC) with Al_2O_3+TiCN mixed ceramic tool for turning process by employing Taguchi's techniques[8]. Davim et al[9] obtained machinability evaluation of cold work tool steel by hard turning process using S/N ratio and ANOVA by ceramic cutting tools and observed cutting speed as most influencing parameter for tool wear. A surface finish (<0.8 μm) was obtained using ceramic tools by selecting appropriate process parameters. Taguchi method was applied to study dry sliding wear behavior of metal matrix composites[10]. Oktem et al[11] optimized plastic injection mounding parameters to reduce warpage problem by Taguchi technique and compared results with ANOVA.

Performances of tool life (TL) and SR were studied on AISI D2 steels (58 HRC) using indexable ball nose end mills employing carbide, cermet tools and solid carbide ball nose end mills. Wear pattern studies[12] were carried out to find tool wear mechanism (chipping, adhesion and attrition). Dutta et al[13] evaluated performance of silver toughened alumina inserts on the basis of progressive flank wear. High speed milling of hardened steel comprising of process parameters (TL, SR) has been described[14-20]. Study[14] on machining of AISI D2 steel (hardness, 62 HRC) showed that polycrystalline cubic boron nitride (PCBN) inserts failed by flank wear and following observed in feeds (0.08-0.20 mm/rev) and speeds (70-120 m/min). Tool wear studies[15], conducted on martensitic stainless steel (60 HRC) using alumina based ceramic cutting tools, showed that flank wear could affect TL at lower speed, however crater wear could affect TL at high speed (>200 m/min). Attanasio et al[16] used minimum quantity lubricant (MQL) for turning process and observed that when MQL applied to flank face, TL increased.

High speed end milling of AISI D3 cold-work tool steel hardened to 35 HRC was investigated[17] using coated-

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carbide, coated cermet, alumina (Al_2O_3)- based mixed ceramic and CBN cutting tools and observed that CBN tool yielded best performance than TiCN mixed Al_2O_3 ceramic tool. Performance of cemented carbide chamfered tools during continuous and interrupted turning of medium carbon low alloy steel has been investigated[18]. Chromium carbide-coated inserts (Cr10%C) showed best wear resistance in AISI 1045 steel turning test and inserts (Cr50%C) performed exceptionally well in both copper turning and printed circuit board (PCB) through-hole drilling tests[19]. Machinability of ultra high speed milling of hardened steels has been reviewed [20] for TL, SR /dimensional accuracy and cost data. Effects of cutting conditions and tool wear on chip morphology and surface integrity during high speed machining of D2 tool steel were investigated with CBN tools[21,22]. Influence of edge preparation of cubic boron nitride cutting tools has been investigated[23] on process parameters and tool performance by utilizing finite element simulations and high-speed orthogonal cutting tests to help optimize TL and SR in hard machining of AISI H-13 hot work tool steel. Cutting performance and wear mechanism of a binderless PCBN tool in high speed milling of grey cast iron showed[24] that binderless CBN could provide longer TL and excellent SR.

In this paper, Taguchi L_{18} orthogonal array is employed to analyze experimental results of machining obtained from 18 experiments for finish machining individually by varying four process parameters [cutting speed (Vc), feed (fz), depth of cut (ap) and width of cut (ae)]. ANOVA has been performed and compared with Taguchi method.

Experimental

Work piece

Pre-annealed tool steel was used as work piece (hardness, 55 HRC). Chromium (Cr), nickel (Ni) and manganese (Mn) alloyed material offers a very good polishability and photo etching properties, which makes it worthy for mould making applications requiring a special surface finish. Material composition of work piece is as follows: C, 0.37; Cr, 2.0; Mn, 1.4; Si, 0.3; Ni, 1.0; and Mo, 0.2 % by wt.

Taguchi Method

Taguchi method based design of experiment has been used to study effect of four machining process parameters (Vc, fz, ap, ae) on two important output parameters (SR and TL). For selecting appropriate orthogonal arrays, degree of freedom (number of fair and independent comparisons needed for optimization of process parameters and is one less than the number of level of parameter) of array is calculated. There are eight degrees of freedom owing to four machining input parameters, so Taguchi based L_{18} orthogonal array is selected (Table 1). Accordingly, 18 experiments were carried out to study the effect of machining input parameters. Each experiment was repeated three times in order to reduce experimental errors. In all tests, flank wear/chipping was measured using optical microscope. Tests were stopped, when maximum flank wear/chipping reached 0.1 mm. SR was measured using perthometer considering average taken at three locations across the lay. Tool wear patterns were analyzed using scanning electron microscope (SEM). Chips were also collected and scanned for analysis. Cutting parameters and three levels are shown in Table 2. Parameter design study involves control and noise factors. Measure of interactions

Table 1—Experimental layout using L_{18} orthogonal array

Exp. No.	End milling machining parameters			
	Vc	*fz*	*ap*	*ae*
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	1	2
5	2	2	2	3
6	2	3	3	1
7	3	1	2	1
8	3	2	3	2
9	3	3	1	3
10	1	1	3	3
11	1	2	1	1
12	1	3	2	2
13	2	1	2	3
14	2	2	3	1
15	2	3	1	2
16	3	1	3	2
17	3	2	1	3
18	3	3	2	1

Vc, Cutting speed; *fz*, feed**;** *ap*, depth of cut; and *ae*, width of cut

Table 2—Machining parameters and their levels

Machining parameters	Level 1	Level 2	Level 3
Cutting speed, m/min	100	150	204
Feed, mm/tooth	0.05	0.1	0.2
Depth of cut, mm	0.05	0.1	0.2
Width of cut, mm	0.1	0.2	0.4

between these factors with regard to robustness is signal-to-noise (S/N) ratio.

Quality Characteristics

S/N characteristics formulated for three different categories are as follows:

Nominal and Smaller are Best Characteristic

Data sequences for SR, which are lower-the-better performance characteristic, are pre-processed as per Eq. (2)

$$S/N = -10 \log (\hat{y}/s^2 y) \quad \ldots(1)$$

$$S/N = -10 \log ((1/n)(\Sigma y^2)) \quad \ldots(2)$$

Larger is Best Characteristic

Data sequences for TL (length of cut, which are higher-the-better performance characteristic) are pre-processed as per Eq. (3)

$$S/N = -10 \log ((1/n)(\Sigma(1/y^2))) \quad \ldots(3)$$

where, $\hat{y}$ is average of observed data y, s^2y is variance of y, and n is number of observations.

Analysis of Variance (ANOVA)

ANOVA can be useful for determining influence of any given input parameter from a series of experimental results by design of experiments for machining process and it can be used to interpret experimental data. A concept may be represented that any high dimensional function may be broken down into a subset of terms as

$$f(\mathrm{x}) = f_0 + \textstyle\sum_{i=1}^{n} f_{\mathrm{i}}(x_i) + \sum^{\mathrm{n}}_{=1} \sum_{j=i+1}^{n} f_{\mathrm{i,j}}(\mathrm{x_i}, \mathrm{x_j}) + f_{1,2,\ldots\ldots\ldots,n}(\mathrm{x}) \quad \ldots(4)$$

where n represents number of inputs, f_o is a constant (bias term) and other terms on right hand side represent univariate, bivariate, trivariate, etc., functional combinations of input parameters.

ANOVA partitions total variation into its appropriate components. Total sum of squares term can be defined as

$$SS_T = \Sigma y_i^2 \quad \text{for i= 1, 2,.....n} \quad \ldots(5)$$

This can be given as

$$SS_T = SS_m + SS_e \quad \ldots(6)$$

where, $SS_m = nM^2$ and $SS_e = \Sigma(y_i - M)^2$ are mean sum of squares and error sum of squares respectively, with $M = 1/n\, \Sigma y_i (i = 1,2, \ldots, n)$.

In case of two-way ANOVA, when interaction effect of main factors affects output values, total variation may be decomposed into more components as

$$SS_T = SS_A + SS_B + SS_{AB} + SS_e \quad \ldots(7)$$

where, $SS_A = (A1\text{-}A2)$ and $SS_B = (B1\text{-}B2)$ are variations due to factors A and B respectively, while $SS_{AB} = \Sigma(AB)i^2/n_{ABi}$ *for* $i = 1, 2, \ldots, k$ is variation due to interaction of factors A and B, where k represents number of possible combinations of interacting factors and n_{ABi} is number of data points under this condition.

While performing ANOVA, degrees of freedom should also be considered together with each sum of squares. In ANOVA studies with certain test error, error variance determination is very important. Obtained data are used to estimate F value of Fisher test (F-test). Variation observed (total) in an experiment attributed to each significant factor or interaction is reflected in percent contribution (P), which shows relative power of a factor or interaction to reduce variation. Factors and interactions with substantial P play an important role.

Experimental Procedure

High performance Heyligenstaedt FH1 CNC milling machine (working space, *X, Y* and *Z* movements being 1550 × 880 × 550 (mm); variable spindle speeds, max. 30,000 rpm; main spindle power, 75 *kW*; and feed rate, 10 m/min) was employed to perform experiments for ball end mill (diam, 10 mm; rake angle, -10°; clearance angle, 10°; and helix angle, 30°). Flank wear and work piece *SR* were measured. *TL* in terms of length of cut and work piece *SR* was investigated. *S/N* ratio for *TL* and *SR* was calculated (Table 3).

Results and Discussion

Taguchi Method

Tool Wear Mechanisms

Characterization of wear on cutting tool insert is specified mainly by flank wear and its progressive growth[25]. During metal cutting, flank of cutting tool contacts with work piece and thus abrasion takes place at contact surface. Due to this, flank wear causes increase in cutting speed and rise in cutting temperature. Cutting tool has to be replaced and perceived to be failed, when average flank wear reaches a certain limit. Rejection of cutting tool is based on the criteria as per

Table 3—Experimental results for surface finish, tool wear and tool life

Exp. No.	Surface finish, µm			Tool wear, µm			Tool life, m			Calculated S/N ratio for surface finish	Calculated S/N ratio for tool life (length of cut)
	R1	R2	R3	R1	R2	R3	R1	R2	R3		
1	0.90	0.92	0.95	110	110	105	290.20	280.00	270.03	0.6906794	48.9342726
2	0.80	0.85	0.86	120	110	100	420.00	410.03	400.10	1.54467883	52.251479
3	0.91	0.92	0.94	90	90	110	310.10	290.20	305.03	0.69203737	49.5833072
4	0.90	0.90	0.92	105	100	110	250.08	250.25	252.00	0.85057743	47.985587
5	0.92	0.93	0.70	110	95	85	300.13	310.30	302.10	1.34442021	49.6598181
6	0.80	0.70	0.90	100	90	110	448.00	409.50	406.35	1.89319525	52.4662054
7	0.61	0.62	0.70	110	95	95	437.50	446.25	439.25	3.81428972	52.8878208
8	0.41	0.42	0.43	90	85	110	910.00	918.75	915.25	7.53337318	59.2250554
9	0.85	0.90	0.75	95	100	100	782.25	784.00	780.50	1.55937227	57.866868
10	0.91	0.82	0.92	100	110	110	250.10	252.00	249.40	1.0662667	47.9759048
11	0.95	0.82	0.92	95	90	95	320.10	321.12	322.00	0.93072653	50.1320085
12	0.81	0.79	0.75	110	120	105	420.00	427.00	418.25	2.11666619	52.5000624
13	0.95	0.96	0.85	100	125	90	300.13	320.25	315.00	0.7116052	49.8674166
14	0.90	0.95	0.96	105	100	120	450.10	410.40	470.10	0.56488996	52.8964745
15	0.76	0.82	0.85	100	100	105	822.15	830.03	841.05	1.82104243	58.3916911
16	0.61	0.55	0.50	105	100	105	420.00	410.03	405.13	5.11167366	52.2891193
17	0.85	0.81	0.83	110	105	110	800.10	791.35	780.15	1.61675736	57.9570109
18	0.52	0.51	0.49	90	95	100	890.05	885.15	900.03	5.9029225	59.0041716

ISO 8688-2[26]. In present study, average or maximum flank wear is considered to be limiting factor. During metal cutting, nature, mode of wear failure and its cutting edge after certain regular intervals were measured using optical microscope. Wear patterns were also analyzed using SEM. Magnitude of cutting forces generated during metal cutting is higher with increasing ap and fz, which raise temperature at cutting zone causing adhesion phenomenon from work piece to tool face. These high cutting forces cause higher wear because of increase of stresses at contact region. Work piece material contains hardness chromium carbide, which imparts good wear resistance that promotes attrition wear of cutting tool inserts and renders materials very difficult-to-machine. During milling process, when cutting edge makes contact with work piece material, chipping thickness changes constantly for orthogonal cutting. Best results are obtained when fz is between 0.1-0.2 mm/tooth (Fig. 1a). TL is optimum (1150 m) corresponding to process parameters as (Fig. 1b): Vc, 204 m/min; fz, 0.2 mm/tooth; ap, 0.2 mm; and ae, 0.2 mm. Surface finish (Ra) is measured as in the range of 0.4-0.52 µm (Fig. 1c). TL is longer (fz 0.2 mm/tooth) and becomes shorter (fz 0.05 mm/tooth). It is also observed that TL becomes shorter when cutting speed exceeds a limit (Vc 204 m/min), because tool interface temperature at flank surface increases when Vc increases. This causes high wear shortening TL of inserts. Undeformed chip thickness for milling process varies from zero to feed per revolution per tooth during one cycle of cutter revolution. Cutting forces also vary with changes in chip thickness, which encourages flank wear and attrition wear due to fluctuating stresses imposed on cutting edge. When undeformed chip thickness is < 0.05 mm, size effect exists and has been elaborated that rate of increase of cutting force is less than that of undeformed chip thickness[27,28]. When chip thickness is > 0.05 mm, specific cutting pressure acting on tool-chip interface approaches a constant value[27]. Therefore, effect of specific cutting pressure at tool-chip interface is not varying significantly with feeds. However, average undeformed chip thickness is larger at higher feeds, causing increase in radial cutting force and thus higher normal stress at cutting edge, which determines feasibility of high speed machining. Within same cutting time, volume of material removed at higher fz and Vc is more than those at higher fz and lower Vc, causing tool inserts to undergo more stress at higher frequency and therefore tend to wear quickly. Dominant wear pattern is observed to be non-uniform wear at flank surface under all cutting conditions. Chipping and adhesion are primarily tool wear mechanism while machining with ball end mill cutters (Figs 2 & 3).

Ball Nose End Mills (BEMs)

BEMs have unique cutting properties for wear resistance and can resist high temperatures at periphery.

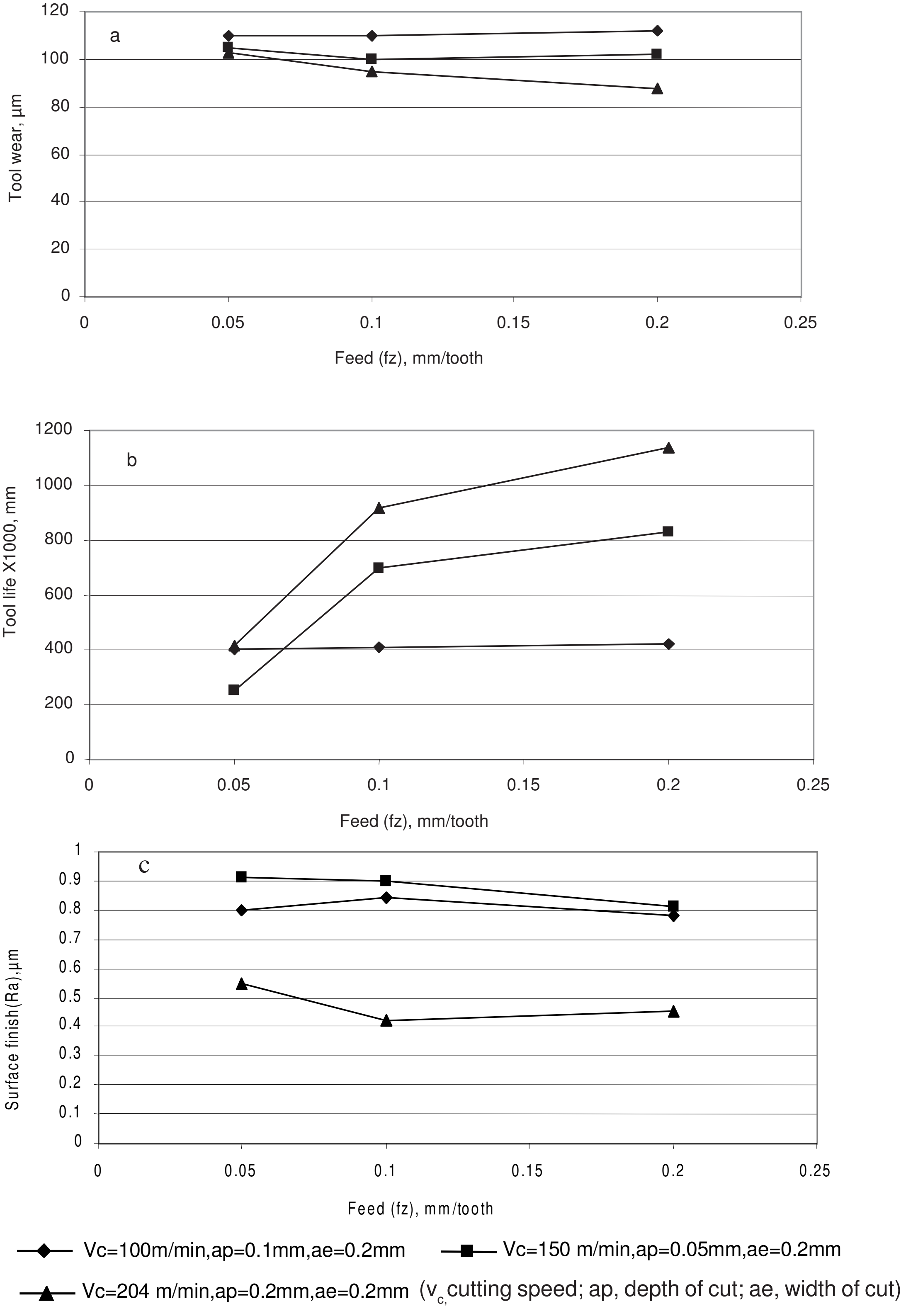
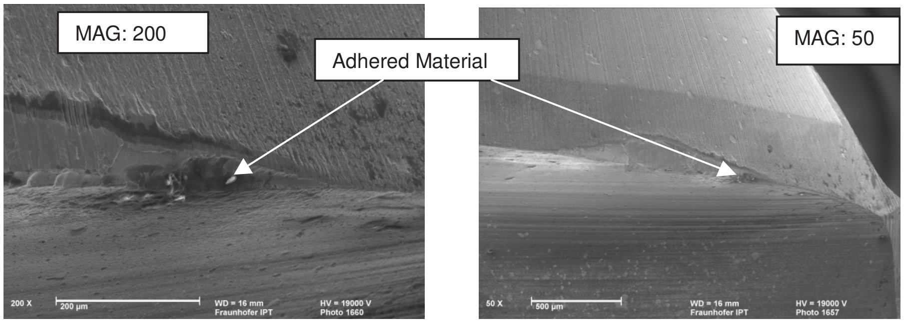
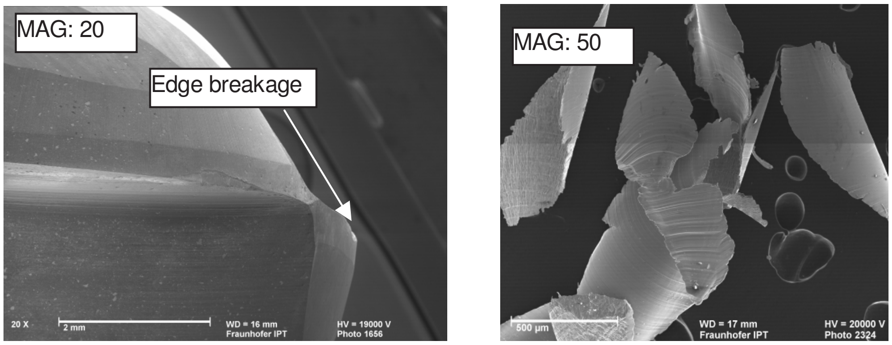


Fig. 1—Effect of feed on: a) Tool wear; b) Tool life; c) Surface finish



(a) (b)

Fig. 2—Tool wear (cutting speed 204 m/min, feed 0.05 mm/tooth, depth of cut 0.2 mm, width of cut 0.2 mm)



(a) (b)

Fig. 3—Chip formation and tool wear (cutting speed 204 m/min, feed 0.2mm/tooth, depth of cut 0.2 mm, width of cut 0.2 mm)

Between periphery and centre, there is a continuous change of cutting speed through all possible built up edge areas. BEMs are used for very high surface finish. Geometries of BEM normally exist as conventional tools. Material for BEM is wear-resistant cutting material like cemented carbide. BEMs often have a negative rake angle and small chip room in and near centre. However, BEMs generate high cutting forces and have insufficient space for chip in center, which cause uneven wear and risk of edge damages. BEM cutters provide 3-axis machining and highest flexibility that suit applications in tool and die making industries. Experiments have investigated effects of cutting speed on surface integrity produced on difficult-to-machine materials[29,30]. Feed and depth of cut are optimized to obtain a surface of minimum residual stresses, geometrical defects and good surface finish[30]. A low value of SR was always observed for a range of cutting speeds employed[31]. Studies[32] carried out on hardened steel showed that TL is longer for fz of 0.05-0.1 mm/tooth. However, at very low fz (<0.05 mm/tooth), TL is shorter, may be due to inefficient material removal by rubbing rather than by efficient metal cutting (insufficient undeformed chip thickness).

Experiments were performed for a fz in the range of 0.05-0.2 mm/ tooth, corresponding to Vc at 100 -204 m/min, ap at 0.05-0.2 mm and ae at 0.1-0.4 mm. Best process parameters corresponding to SR are (Fig. 4a): Vc, 204 m/min; fz, 0.2 mm/tooth; ap, 0.2 mm; and ae, 0.2 mm. Best process parameters corresponding TL are (Fig. 4b): Vc, 204 m/min; fz, 0.2 mm/tooth; ap, 0.05 mm; and ae, 0.2 mm. Significance of machining parameters (difference between max. and min. values) indicates that cutting speed is significantly contributing towards machining performance as difference gives higher values(Table 4). Therefore, most influencing parameter is cutting speed. Study finds that optimized process parameters are: Vc, 204 m/min; fz, 0.2 mm/tooth; ap, 0.2 mm; and ae, 0.2 mm.

Analysis of Variance (ANOVA)

Taguchi method cannot judge and determine effect of individual parameters on entire process while percentage contribution of individual parameters can be well determined using ANOVA. MATHEMATICA software of ANOVA module was employed to investigate effect

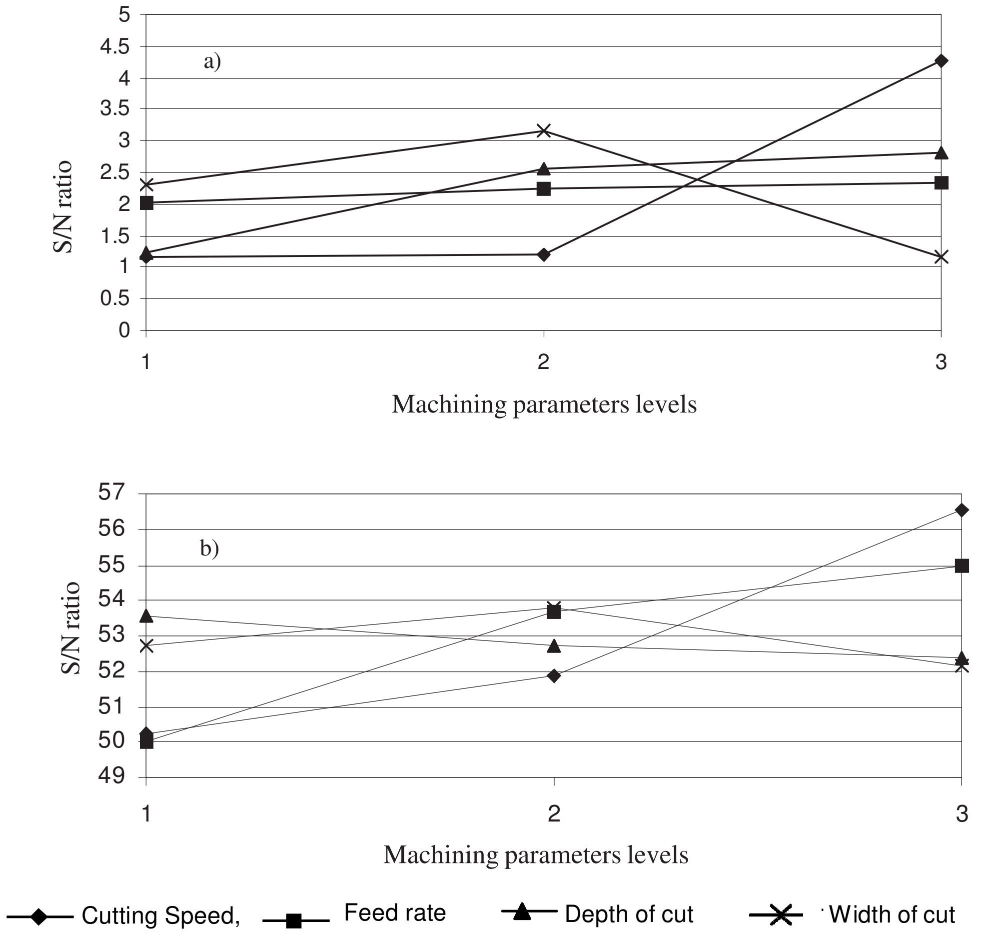


Fig. 4—Signal-to-noise ratio vs machining parameters level for: a) Surface finish; b) Tool life

Table 4—Significance of machining parameter for surface finish and tool life

Machining parameters	Mean S/N ratio			Significance of machining parameters
	Level 1	Level 2	Level 3	Max - Min
Surface finish				
Vc	1.17351	1.19762	4.2564*	3.08289
fz	2.04085	2.25581	2.33087*	0.29002
ap	1.24486	2.57243	2.81024*	1.56538
ae	2.29945	3.16300*	1.16508	1.99792
Tool life				
Vc	50.2295	51.8779	56.5383*	6.3088
fz	49.9900	53.6870	54.9687*	4.9787
ap	53.5446*	52.6951	52.4060	1.1386
ae	52.7202	53.7738*	52.1517	1.6221

*Optimized level of parameters; *Vc*, cutting speed; *fz*, feed; *ap*, depth of cut; and *ae*, width of cut

of process parameters (Vc, fz, ap and ae). P-value (0.001) of parameters indicates that cutting speed is significantly contributing towards machining performance (Table 5). Best parameters for finish machining are found for SR (Table 6) [Vc, 204 m/min (level 3); fz, 0.2 mm/tooth (level 3); ap, 0.2 mm(level 3); and ae, 0.2 mm (level 2)] and TL (Table 7) [Vc, 204 m/min(level 3); fz, 0.2 mm/tooth (level 3); ap, 0.05 mm (level 1); and ae, 0.2 mm (level 2)]. ANOVA results closely match with Taguchi results.

Table 5—ANOVA results for signal-to-noise ratio for surface finish and tool life

Parameter	D.F.	Sum of Sq.	Mean Sq.	F-ratio	P-value
Surface finish					
Vc	2	37.7218	18.8609	15.47	0.00122393
fz	2	0.271912	0.135956	0.111513	0.895696
ap	2	8.53883	4.26941	3.50184	0.0750072
ae	2	12.0485	6.02423	4.94116	0.0356321
Error	9	10.9727	1.21919		
Total	17	69.5537			
Tool life					
Vc	2	128.477	64.2385	14.3520	0.00158615
fz	2	80.1955	40.0978	8.95857	0.00722706
ap	2	4.20294	2.10147	0.469506	0.639804
ae	2	8.12919	4.06459	0.908104	0.437274
Error	9	40.2832	4.47591		
Total	17	261.288			

Vc, cutting speed; *fz*, feed; *ap*, depth of cut; and *ae*, width of cut

Table 6—Cell mean of parameters in ANOVA for surface finish

Parameter	Level 1	Level 2	Level 3
Cutting speed	1.17351	1.19762	4.2564*
Feed	2.04085	2.25581	2.33087*
Depth of cut	1.24486	2.57243	2.81024*
Width of cut	2.29945	3.16300*	1.16508

All cell mean = 2.20918; *Optimized level of parameters

Table 7—Cell mean of parameters in ANOVA for tool life

Parameter	Level 1	Level 2	Level 3
Cutting speed	50.2295	51.8779	56.5383*
Feed	49.9900	53.6870	54.9687*
Depth of cut	53.5446*	52.6951	52.4060
Width of cut	52.7202	53.7738*	52.1517

All cell mean = 52.8819; *Optimized level of parameters

Verification Test

After identifying best level of process parameters, optimum parameters found are: Vc, 204 m/min; fz, 0.2 mm/tooth; ap, 0.2 mm; and ae, 0.2 mm. Most influencing parameter is Vc, which gives most significant effect to produce low value of SR.

Regression Analysis

Multiple linear regression equations were modeled for a relationship between process parameters in a bid to evaluate tool wear and surface finish for any combinations of factor levels in a range specified. Model for multiple regression equation is

$$y = \beta_0 + \beta_1 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \ldots\ldots + \beta_p x_p + \varepsilon \qquad \ldots(8)$$

where, y is dependent parameter, x_1, $x_2 \ldots . x_p$ are independent parameters, β's are regression parameters and ε is residue.

Methods for fitting into a linear regression models are least square regression, ridge regression and bayesian regression. When predictor variables are correlated, least square estimates of regression coefficients tend to have larger sampling variability. In such a situation, ridge regression offers a method to obtain better estimates of regression coefficients. Partial least square regression technique can also be used for multicollinearity. Bayesian regression provides multiple linear regression models. Prior distribution of regression parameters used in this feature is a multivariate normal gamma distribution or diffuse. Finally, credible intervals for regression coefficients are estimated and computed.

Regression equations, formulated for tool wear (VB) and surface finish (Ra), are

$$Ra = 1.16857 - 0.0024\times Vc - 0.15026\times fz - 0.6898\times ap + 0.35114\times ae + \varepsilon \qquad \ldots(9)$$

$$VB = 112.455 - 0.0429\times Vc - 25.673\times fz - 6.8426\times ap + 1.01433\times ae + \varepsilon \qquad \ldots(10)$$

Expected values of tool wear and surface finish are obtained in any combinations of factor levels as specified in Table 2. Percentage error estimated for Eq. (9) (SR-Ra) is in range of 0.14 - 25.8%, whereas for Eq. (10) (Tool wear-VB) it is calculated as 0.3-12.9%. These values are well compared with reported values[8]. Thus, Eqs (9) and (10) can be used to predict tool wear as well as surface finish for any combinations of factor levels in a specified range.

Conclusions

Taguchi method of experimental design has been applied for optimizing multi response process parameters for end milling while hard machining of hardened steel are optimized with L_{18} orthogonal array. Results obtained from Taguchi method closely match with ANOVA. SEM pictures indicated that causes of tool wear are chipping and adhesion. Best parameters found for finish machining are: cutting speed, 204 m/min; feed, 0.2 mm/tooth; depth of cut, 0.2 mm; and width of cut, 0.2 mm. Cutting speed is most influencing parameters corresponding to quality characteristics of TL and SR. Further multiple regression equations are formulated for estimating predicted values of SR and tool wear for a specified range. Hard machining can potentially be an alternative to grinding and EDM with a scope to improve productivity, increased flexibility, decreased capital expenses and reduced environmental waste.

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