Hardness Optimization in Turning of Aluminium using Taguchi Technique

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***Abstract*- In this research work, L27 orthogonal array based Taguchi optimization technique is used to find the optimal cutting parameters for change of hardness in turning operation. The orthogonal array, the signal to noise ratio and analysis of variance are employed to study the performance characteristics in wet machining of Aluminium cylindrical work pieces using mild steel cutting tool. Three machining parameters such as cutting speed, feed rate and depth of cut are optimized with consideration of hardness on Rockwell scale. Empirical relations by regression developed to predict the hardness as a function of considered process parameters based on the analysis of experimental results. It is observed that in case of Aluminium, feed and depth of cut are the most significant parameters affecting hardness of the material.**

***Keywords*- Hardness, Taguchi, S/N ratio, main effect, ANOVA**

I. INTRODUCTION

Machining is the most wide spread metal shaping process in mechanical manufacturing industry. The goal of changing the geometry of a raw material in order to form a mechanical part can be met by putting material together or moving material from one region to another or removing unnecessary material. Conventional machining is one of the most important material removal methods. It is a collection of material-working processes in which power-driven machine tools, such as lathes, milling machines and drill presses are used with a sharp cutting tool to mechanically cut the material to achieve the desired geometry. Machining is a part of the manufacture of almost all metal products. The process of machining can be further categorized based on the method of material removal as turning, milling, drilling, grinding etc. Increasing productivity and reducing manufacturing cost have always been the primary objectives for successful business. In turning, higher values of cutting parameters offer opportunities for increasing productivity but it also involves a greater risk of deterioration in surface quality and tool life.

It is a common practice to test most materials before they are accepted for processing, they are put into service to determine whether or not they meet the specifications required. One of these tests is hardness test. Hardness is the characteristic of a solid material expressing its resistance to permanent deformation.

The main objective of the present work has been decided to study the effect of turning parameters on work piece hardness by using Taguchi's method. Al is used as work piece material and identifies ranges of process parameters for the turning of above materials by using L27 orthogonal array for this study. After performing turning experiments and hardness testing, the observed data is analyzed by maximizing signal to noise ratio and ANOVA.

II. LITERATURE REVIEW

The study on the influence of hardness during machining has been going on since 1973. H. D. Merchant et al. [1] studied the high-temperature hardness data for thirty-seven metals, collected from the published literature and seven of these metals were further tested to confirm and improve the hardness-temperature data. He also concluded that the softening parameter of hardness is inversely related and the apparent activation energy for indentation is directly related to the melting temperature of the metal.

L. Ma et al. [2] introduced a reverse computation method to determine the elastic modulus and stress-strain curve of O1 tool steel from the Rockwell C hardness (HRC) indentation test combined with finite element analysis (FEA) simulation. The HRC spheroconical indentation tests and relative FEA simulation model for determining the mechanical properties of O1 steel were described. The reverse computation results were compared with the HRC test results, and showed good agreement.

G.S. Fox-Rabinovich et al. [3] annealed the cemented carbide cutting tools with a nano-crystalline $Al_{0.67}Ti_{0.33}N$ hard PVD coating which was deposited by cathodic arc evaporation within a different range of temperatures with respect to time having vacuum medium. In the analysis of structure and properties of the coating against temperature has been analyzed using TEM as well as high temperature nano-indentation methods. He concluded that during the initial stages of phase de-composition occurring after annealing was beneficial for interrupted cutting conditions such as interrupted turning and end milling of hardened steels.

Genki Sakai et al. [4] studied disks of an Al-Mg-Sc alloy processed by high-pressure torsion (HPT) to refine the grain size up to 0.15 µm. Inspection of the disks after processing revealed a central core region having a relatively coarse and ill-defined microstructure. In the inspection he observed that within the region of hardness saturation, the microstructure was reasonably homogeneous and consisted of ultra fine grains separated by high-angle grain boundaries. It has been suggested that this saturation occurs when there was a balance between the rates of dislocation nucleation and dislocation recovery.

Shakeel A. Shahdad et al. [5] demonstrated the differences between hardness measured with traditional

Vickers and Martens hardness test methods on denture teeth under various loading conditions for acrylic resin, composite resin and porcelain denture tooth materials. He reported about force-indentation depth curves and Indentation creep of the three test materials during Martens hardness testing.

A. Elmustafa et al. [6] proposed various mechanisms for the size-dependent hardness and rate-effects responsible for the indentation hardness size effect (ISE) for aluminum and α-brass in terms of the rate sensitivity. In which one of the proposed mechanism for increased dislocation density was strain gradient plasticity, which resulted in increase in dislocation density for shallow indents and suggested that indenter–specimen friction and presence of oxides on the sample surface is responsible for the ISE.

From the literature survey presented above, it is evident that although researchers have tried to investigate the relation of hardness with different process parameters of different machining operations like milling, drilling etc., but there is a gap in determining of the exact effect of speed, feed and depth of cut on the hardness of work piece in turning operation. Therefore this aspect has been selected for the study in the present research work on Al work piece material.

Taguchi approach uses three major steps namely system design, parametric design and tolerance design for optimizing a process or product. In system design, scientific and engineering knowledge is applied to produce a basic functional prototype design. It contains selection of materials, components, production equipment, process parameter values, etc. Next to the system design is the parameter design, which is used to optimize the settings of process parameter values for improving quality characteristics. Final step of the optimization is tolerance design, used to determine and analyze tolerances around the optimal settings recommend by the parameter design. This approach is based on the use of orthogonal arrays to conduct small, highly fractional factorial experiments up to larger, full factorial experiments. Taguchi proposed an experimental plan in terms of orthogonal array that gives different combinations of parameters and their levels for each experiment. According to this technique, entire parameter space is studied with minimum number of experiments. L27 orthogonal array for this research work is given in table no. I.

Hardness covers several properties such as resistance to deformation, resistance to friction and abrasion. The well known correlation links hardness with tensile strength, while resistance to deformation is dependent on modulus of elasticity. The frictional resistance may be divided in two equally important parts: the chemical affinity of materials in contact, and the hardness itself.

In the present work Rockwell hardness test is used for measuring the hardness of Al work piece due to its speed, freedom from personal error, ability to distinguish small hardness difference and small size of indentation. The hardness is measured according to the depth of indentation, under a constant.

TABLE I L27 Orthogonal Array

Trial No	Column Factors												
	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	1	2	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

III. DESIGN OF EXPERIMENTS

In the present research work, Aluminium is used for machining due to their ductility and hardness.

The turning experiments were conducted under wet conditions on centre lathe having a maximum spindle speed of 2000 rpm and a maximum power of 8 kW. The Al bars were cut into pieces of 40 mm diameter and 60 mm length. The pieces were subjected to step turning on the lathe using cutting oil as the coolant. The values of process parameters for Al are mentioned in table no. II. In the turning operation, Mild Steel cutting tool was selected for Aluminium work piece.

After the turning operation, hardness of the work pieces was measured with the help of Rockwell testing machine and the obtained results for Aluminium are listed in the table no. III along with the data of process parameters.

TABLE II Details of process parameters for Aluminium

Level	**Cutting speed ‘S’ m/min**	**Feed rate F (mm/rev)**	**DOC (mm)**
1	93.41	0.1	0.6
2	126.38	0.2	0.8
3	159.35	0.3	1

TABLE III The result of hardness test under different process parameter

Aluminium				
Test No	**Speed (m/min)**	**Feed (mm/rev)**	**DOC (mm)**	**Hardness in HRB**
1	93.41	0.1	0.6	29.0
2	93.41	0.1	0.8	29.0
3	93.41	0.1	1.0	29.0
4	93.41	0.2	0.6	29.0
5	93.41	0.2	0.8	29.0
6	93.41	0.2	1.0	29
7	93.41	0.3	0.6	31.0
8	93.41	0.3	0.8	33.5

9	93.41	0.3	1.0	31.0
10	126.38	0.1	0.6	29.0
11	126.38	0.1	0.8	29
12	126.38	0.1	1.0	31.0
13	126.38	0.2	0.6	29.0
14	126.38	0.2	0.8	33.5
15	126.38	0.2	1.0	31.0
16	126.38	0.3	0.6	31.0
17	126.38	0.3	0.8	35.0
18	126.38	0.3	1.0	33.5
19	159.35	0.1	0.6	31.0
20	159.35	0.1	0.8	31.0
21	159.35	0.1	1.0	31.0
22	159.35	0.2	0.6	29.0
23	159.35	0.2	0.8	31.0
24	159.35	0.2	1.0	29.0
25	159.35	0.3	0.6	29.0
26	159.35	0.3	0.8	35.5
27	159.35	0.3	1.0	33.5

IV. RESULT AND DISCUSSION

A. Analysis using signal to noise ratio

In Taguchi method, S/N ratio is measure of quality characteristics and deviation from the desired value. The term signal represents the desirable value (mean) and the noise represents the undesirable value (Standard Deviation from Mean) for the output characteristic [7]. The S/N ratio (η) is defined as

$$\eta = -10\, log(M.S.D.)$$

where, *M.S.D.*is the mean-square deviation for the output characteristic.

$$M.S.D. = \frac{1}{n}\sum_{i=1}^{n} Y_i^2$$

Smaller the better type of S/N ratio is used in analysis for better accuracy. For smaller the better case, the S/N ratio is obtained by [8].

where, n is the total number of the experiments in the orthogonal array and Y_i is the mean percentage hardness for the i^{th} experiment. An S/N ratio for each of the experiment is calculated and presented in table no. IV. The effect of a factor level is defined as the deviation it causes from the overall mean. The overall mean S/N ratio (m) of the experiments is calculated by [8]

$$m = \frac{1}{n}\sum_{i=1}^{n} \eta_i$$

Where, η_i is the mean S/N ratio of the i^{th} experiment.

TABLE IV S/N ratios for each of the experiments in Al

Expt. No.	S/N ratio	Expt. No.	S/N ratio	Expt. No.	S/N ratio
1	-29.2480	10	-29.2480	19	-29.8272
2	-29.2480	11	-29.2480	20	-29.8272
3	-29.2480	12	-29.8272	21	-29.8272
4	-29.2480	13	-29.2480	22	-29.2480
5	-29.2480	14	-30.5009	23	-29.8272
6	-29.2480	15	-29.8272	24	-29.2480
7	-29.8272	16	-29.8272	25	-29.2480
8	-30.5009	17	-30.8814	26	-31.0046
9	-29.8272	18	-30.5009	27	-30.5009

All three levels of each factor are equally represented in the twenty seven experiments. Thus m is a balanced overall mean for the entire experiment. Since the experimental design is orthogonal, it is possible to separate out the effect of each factor at each level. S/N ratio and hardness for each parameter at each level can be calculated from mean S/N ratio and hardness value of each of the experiment. Hardness for each of the parameter at each level is calculated. These are also called as main effects. Average S/N ratio for each parameter at each level is given in table no. V.

TABLE V Average S/N ratio for Al

S. No	**Parameter**	**Level**		
		1	**2**	**3**
1	Speed	-29.5159*	-29.9010	-29.8398
2	Feed	-29.5054*	-29.5159	-30.2354
3	Depth of Cut	-29.4411*	-30.0318	-29.7838

The optimum level for a factor is the level that gives the highest value of η in the experimental region denoted by '*' in table no.V. The estimated main effects can be used for this purpose provided the variation of η as a function of the factor levels follows the additive model. The ideal product or process will only respond to the operator's signals and will be unaffected by random noise factors.

B. Main Effects

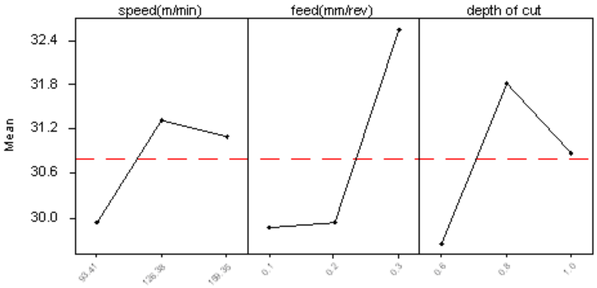

Fig.1 Effect of process parameters on hardness in Al

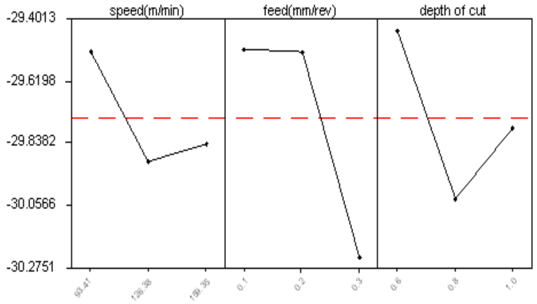

Fig.2 Effect of Signal to noise ratio on hardness in Al

From main effect plots of Al (fig. 1 – fig. 2), it is observed that as the speed is increased from 93.41 m/min to 126.38 m/min, the hardness increases, but when speed is further increased to 159.35 m/min, there is decrease in hardness. The hardness slightly increases when feed rate is changed from 0.1 mm/rev to 0.2 mm/rev, but drastically increases when feed rate is increased to 0.3 mm/rev. Similarly when depth of cut is increased from 0.6 mm to 0.8 mm, hardness increases, but as the depth of cut is further increased to 1.0 mm. hardness decreased considerably.

C. Analysis of Variance (ANOVA)

ANOVA is a standard statistical technique to interpret the experimental results and extensively used to identify the performance of group of parameters under investigation. Purpose of ANOVA is to investigate the parameters, whose combination to total variation is significant. In ANOVA, total sum of squares (SS_T) is calculated by [9]

$$SS_T = \sum_{i=1}^{n} (\eta_i - m)^2$$

Where, *m* is the overall mean S/N ratio.

Total sum of squared deviations SS_T is divided into two sources [16]

$$SS_T = \sum_{j=1}^{n_p} SS_j + SS_e$$

where, SS_j is the sum of squared deviations for each design parameter and is given by

$$SS_j = \sum_{i=1}^{l} (\eta_{ji} - m)^2$$

here, n_p is the number of significant parameters and l is the number of levels of each parameter. SS_e is the sum of squared error without or with pooled factor, which is sum of squares corresponding to the insignificant factors. Mean square of a factor (MS_j) or error (MS_e) is found by dividing its sum of squares with its degrees of freedom. Percentage contribution (ρ) and F - value of each of the design parameters is given by [9]

$$\rho_j = \frac{SS_j}{SS_T}$$

$$F_j = \frac{MS_j}{MS_e}$$

The obtained F -values for hardness in Al in the present work are given in table no. VI. The variance ratio is the ratio of the mean square due to factor and mean square due to error. Larger the F value means the effect of the factor is large compared to the error variance. The Larger the value of F, the more important that factor is influencing the process response η. Therefore, the F value is used to rank order the factors [9].

TABLE VI ANOVA table for hardness of Al

S. No	**Factor**	**DOF**	**Sum of square**	**Mean square**	**F**	**P**	**Contribution**
1	Speed	2	10.02	5.00	2.86	0.08	0.092
2	Feed	2	41.79	20.89	11.90	0.00	0.386
3	DOC	2	21.24	10.62	6.06	0.00	0.196
4	Error	20	35.07	1.75			0.324
5	Total	26	108.1				

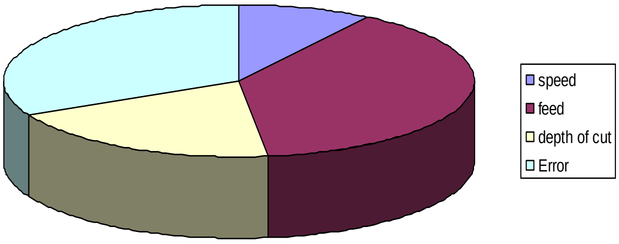

Fig.3 Contribution of the various parameters on hardness of Aluminium

The percentage contribution of various parameters affecting hardness is shown in fig. 3. In case of Aluminium, feed and depth of cut are the most significant parameters as compared to cutting speed affecting hardness of the material after turning.

Empirical models are derived by linear regression using standard statistical software and are given below.

For Aluminium:

Hardness=23.4+ (0.0177×s)-(13.3×F)-(3.06×DOC)

Where S is speed in m/min, F is feed in mm/rev and DOC is depth of cut in mm.

Interaction terms are not considered to develop the above equations for prediction of hardness. There are no insignificant (pooled) parameters in this study. The developed models are able to predict the hardness for any set of parameters within the range of experiments conducted for Al.

V. CONCLUSIONS

In the present work, the relationship between the hardness and various process parameters namely cutting speed, feed and depth of cut has been developed. Taguchi method has been adopted for the design of experiments and the results have been analyzed by minimizing S/N ratio and ANOVA. In case of Aluminium, feed and depth of cut are the most significant parameters as compared to cutting speed affecting hardness of the material after turning.

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