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Evaluation and Machining Parameter Process Optimization of Hardened Alloy Steel: A Case Study of Taguchi Method and Anova

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Abstract – In this paper, an effective procedure of Taguchi method has been, utilized for finding the best working parameters of induction hardening of EN8 D steel. Various parameters such as input power, traverse speed (scanning speed) have been explored by experiments. Hardness, case depth has been considered as performance characteristics. A L9 orthogonal array, signal to noise ratio, analysis of variance (ANOVA) are applied to study performance characteristics of induction hardening parameters with consideration of hardness, case depth. A hardness and case depth results obtained by Taguchi method closely match with ANOVA and traverse speed, power are the most influencing parameters on hardness and case depth respectively. Multiple regression equations are formulated for estimating the predicted values of hardness and case depth. The results have been verified by confirmation experiments.

This paper investigates the parameters affecting the roughness of surfaces produced in the turning process for the material 316L Stainless Steel. Design of experiments was conducted for the analysis of the influence of the turning parameters such as cutting speed, feed rate and depth of cut on the surface roughness. The results of the machining experiments for 316LSS were used to characterize the main factors affecting surface roughness by the Analysis of Variance (ANOVA) method. The feed rate was found to be the most significant parameter influencing the surface roughness in the turning process.

In this paper, Taguchi method is connected to discover best process parameters for closure processing while hard machining of hardened steel. A L]s array, signal-to-noise degree and examination of variance (ANOVA) are connected to study execution qualities of machining parameters (cutting speed, feed, depth of cut and width of cut) with thought of surface complete and tool life. Chipping and bond are watched to be fundamental driver of wear. Effects acquired by Taguchi method match nearly with ANOVA and cutting speed is most impacting parameter. Various relapse mathematical statements are defined for evaluating anticipated qualities of surface harshness and tool wear.

Keywords— ANOVA, induction hardening, regression equation, Signal to Noise ratio, Taguchi method. Surface roughness, DOE, 316L SS, End milling, hard machining.

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INTRODUCTION

Induction hardening process has found ever-increasing applications to improve the performance and life of the parts used in automobile engineering. Thin surface layers i.e 0.25 to 2.3 mm of the work piece made of steel can be hardened by this process. Y. Totic, R.Sadeler, H. Altum investigated the effects of heating time, feed rate and temperature on wear characteristics of AISI 4140 steel in induction hardening process. Julie. K, Timothy James. Studied the effect of feed rate and gap between coil and work piece, quench distance and part temperature by using design of experiment neural network optimization technique on induction hardening process and reported a significant improvement in the process.

R Kolleck, R.Veit focused on reduction of processes cycle time, rising energy, costs ecofriendly process and need of new heating technologies in hardening process and proposes the inductive heating alternative methodology for boron alloyed steel. Robert Cryderman, Nima Sham Saei, Al Fatemi In this paper study investigates the influences of induction hardened parts produced from steel bars.

Resit Unal, Edwin B. Dean In this paper authors were presented the overview of the Taguchi method its steps involved and state that , it is a systematic and efficient approach for determining the optimum experimental configuration of design parameters for performance, quality and cost. Principle benefits include considerable resource savings determination of important factors affecting operation, performance and cost, and quantitative recommendations for design parameters which achieve lowest cost, high quality solutions. In this paper, best working parameters are selected for generation of desired hardness values and pattern in EN8 D steel, by using Taguchi method. Because Taguchi method showed to be a very useful in process improvement provide confident information about influence of factors on a response variable and less number of experiments than traditional method to improve the process while not compromising the desired goals.

Now-a-days, due to the increasing demand of higher precision components for its functional aspect, surface roughness of a machined part plays an important role in the modern manufacturing process. To achieve the desired surface finish, a good predictive model is required for stable machining. Generally, these models have a complex relationship between surface roughness and operational parameters.

Typically, selected cutting operations have limited capability of attaining the required surface roughness. However, it is necessary to determine optimal cutting parameters in order to achieve minimal expenses or minimal cost/production time. Researchers have applied different methods for prediction of optimal cutting parameters.

Taguchi's parameter design offers a systematic approach for optimization of various parameters with regard to performance, quality and cost. Further, design optimization for finish 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.

Gopalsami et. al. studied experimentally the surface roughness of machined hardened steels AISI 4140(63HRC) with Al2O3+TiCN mixed ceramic tool for turning process. By using ANOVA and Taguchi method they concluded that cutting speed is significantly contributing towards the finish. Paulo Davim and Figueira were obtained machinability evaluation of cold work tool steel by hard turning process using S/N ratio and ANOVA by ceramic cutting tools and observed that cutting speed is most influencing parameter.

Hard turning is a process, in which materials in the hardened state (50 to 70 HRC) are machined with single focus cutting tools. This has gotten conceivable with the accessibility of the new cutting tool materials (cubic boron nitride furthermore ceramics). Countless are needed to handle the completed product and if a percentage of the operations might be joined together, or disposed of, or might be substituted by the new process, product process duration might be lessened and productivity might be progressed. The universal method of machining the hardened materials incorporates harsh turning, high temperature medication emulated by the crushing process. Hard turning kills a arrangement of operations needed to process the part and in this way lessening the process duration also henceforth bringing about productivity change.

The preferences of hard tuning are higher productivity, decreased set up times, surface completion closer to crushing and the capacity to machine complex parts. Different work materials which can be machined by the hard turning process incorporate high velocity steels, pass on steels, bearing steels, alloy steels, unfeeling steels, white cast iron and alloy cast iron. Rigid machine tools with sufficient power, quite hard and extreme tool materials with proper tool geometry, tool holders with high solidness and suitable cutting conditions are a portion of the requirements for hard turning. This paper manages the hard turning of hardened alloy steel (AISI 8660) with physical vapour testimony (PVD) covered clay tools.

The fired cutting tools incorporating aluminum oxide, blended alumina, silicon nitride based tools, and covered alumina based fired tools were created in the previous few decades for cutting different hard materials. Then again, some of the new advancements in cutting tools have not been great in enhancing the machinability of hardened steels since an extensive variety of hardened steels has been utilized by the assembling industry. Case in point, AISI H13 arrangement (45 to 56 HRC) are utilized for fashioning, expulsion also bite the dust casting while AISI E52100 (62 to 64 HRC) steels are the most ordinarily utilized steel materials for moving bearings. The hardened workpiece materials are either cut close net-shape in the toughened condition, hotness treated or ground to last measurements and surface completion. Assembling expenses could, accordingly, be high and lead times extreme.

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 AISIH13 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 $Al,0_3$+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 (.mi) 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 war page problem by Taguchi technique and compared results with ANOVA.

Performances o|f tool life (TL) and SR were studied on AISI D2 steels (58 HRC) using index able 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 hared ned 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 poly crystalline 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.

METHODOLOGY

DOE techniques enable designers to determine simultaneously the individuals and interactive effects of many factors that could affect the output results in any design. DOE also provides a full insight of interaction between design elements; it helps turn any standard design into robust one. Simply DOE helps to pin point the sensitive parts and sensitive areas in designs that cause problems in response variable. We are then able to fix these problems and produce vigorous results.

Taguchi envisaged new method of conducting the design of experiments which are based on well-defined guidelines. This method uses a special set of arrays called orthogonal array. This standard array stipulates the way of conducting the minimum number of experiment which could give the full information of all the factors that affect the performance parameter. While there are many standard orthogonal arrays available, each of arrays is meant for a specific number of independent design variables and levels.

ANOVA can be useful for determining influence of any given input parameter for a series of experimental results by design of experiments for machining process and it can be used to interpret experimental data. While performing ANOVA degrees of freedom should also be considered together with each sum of squares. In ANOVA studies a 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 experimental attributed to each significant factor or interaction is reflected in percent contribution (P), which shows relative power of factor or interaction to reduce variation.

The theory of Taguchi is extensively pertinent. He suggested that designing enhancement of a process or product ought to be did in a three-stage approach, i.e., system design, parameter design, and tolerance design (Figure 1).

In system design, the designer applies experimental and designing information to transform an essential functional model design, which incorporates the product design stage and the process design stage. In the product design stage, the choice of materials, parts or experimental product parameter qualities are incorporated. As to the process design stage, the dissection of processing groupings, the choices of production gear alternately conditional process parameter qualities are included. Since system design is a starting functional design, it may be a long way from ideal in terms of value and expense. The goal of the parameter design is to streamline the settings of the process parameter values for moving forward execution aspects and to distinguish the product parameter values under the optimal process parameter values.

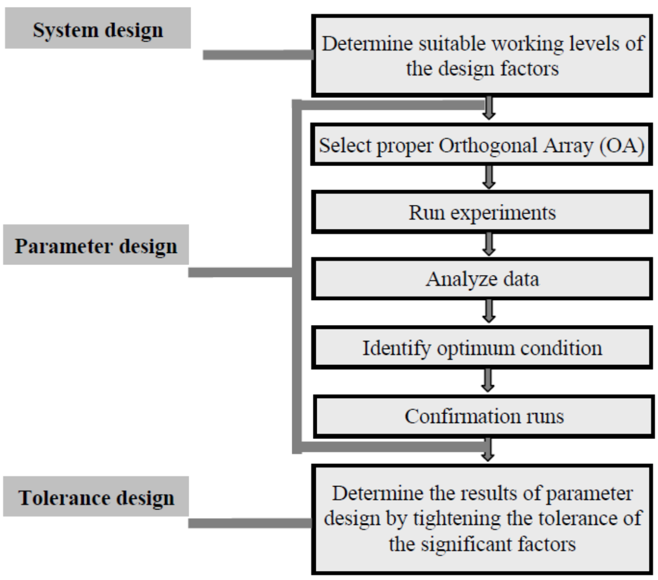

Fig. 1: Taguchi design procedure.

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 polish ability 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_{fg} 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 between these factors with regard to robustness is signal-to-noise (S/N) ratio.

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 1—Experimental layout using L_{1S} orthogonal array.

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

Table 2—Machining parameters and their levels

High performance Heyligenstaedt FH1 CNC milling machine (working space, X, Y and Z movements being 1550 x 880 x 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.

RESULT AND DISCUSSION

The observed values of hardness and case depth for each run are recorded in table 3. The analysis of results was computed by using software MINITAB.

Runs	Power	Traverse speed	Hardness	Case depth
No	kw	mm/ sec	HRc	mm
1	16	6.5	59	1.30
2	16	7.0	58	1.10
3	16	7.5	56	0.85
4	17	6.5	59	1.55
5	17	7.0	59	1.35
6	17	7.5	57	1.05
7	18	6.5	60	1.95
8	18	7.0	59	1.75
9	18	7.5	58	1.60

Table 3 : Experimental data for L9 orthogonal array.

According to the ANOVA analysis, the most effective parameters with respect to hardness and case depth are traverse speed and power respectively.

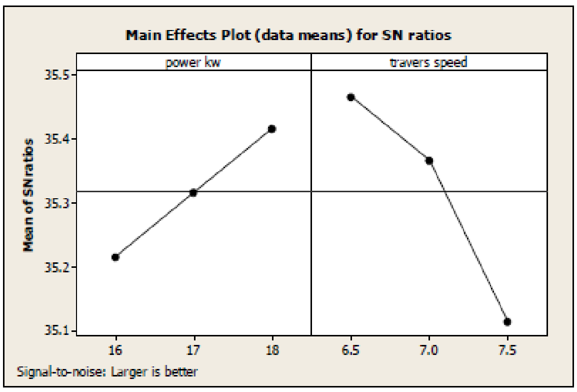

Fig. 2: Main effects slot for SN ratio hardness

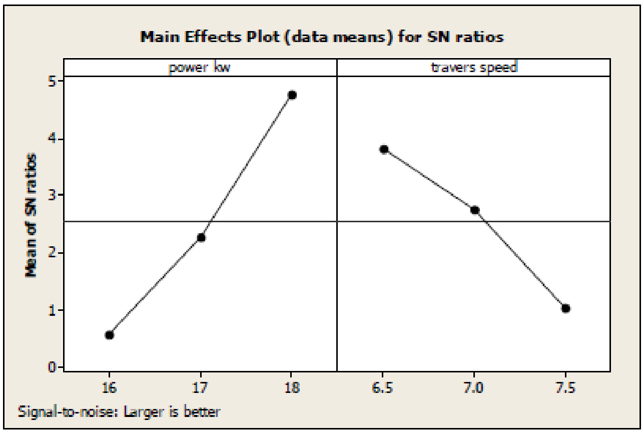

Fig. 3: Main effects slot for SN ratio case depth

Fig. 2 & 3 shows the S/N ratio graphs where the horizontal line is the value of total mean of S/N ratio. Basically larger the S/N ratio better is the quality characteristics for the process. As per the S/N ratio analysis from the graphs the levels of parameters to be set for getting optimum values of hardness and case depth are P3, Tr_S 1.

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 wears 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 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. TL is optimum (1150 m) corresponding to process parameters as : 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 jim (Fig. 2). 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 unreformed 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 unreformed chip thickness.

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 unreformed 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.

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 of process parameters (Vc, fz, ap and ae). P-value (0.001) of parameters indicates that cutting speed is significantly contributing towards machining performance. Best parameters for finish machining are found for SR [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 [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.

CONCLUSION

Taguchi method of experimental design with L9 orthogonal array has been applied for optimizing the process parameters of induction hardening on EN8 D steel. The experimental investigation shows the effects of process parameters such as power, traverse speed on hardness and case depth achieved on EN8 D work piece. The best parameters found are power 18 kw and traverse speed 6.5 mm/sec. Power, traverse speed are most influential parameters corresponding to quality characteristics of hardness and case depth respectively.

Further multiple regression equations are formulated for estimating predicted values of hardness and case depth for a specified range. Experimental values and values obtained by regression equations closely co-relate each other which validate the regression equations developed. Hence it can be concluded that induction hardening can be used intelligently to be alternatives to traditional method for surface hardening of with improved productivity at low expenses and reduced environmental waste.

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 $L_{/g}$ orthogonal array. Results obtained from Taguchi method closely matches 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.

Taguchi method of experimental design has been applied for optimizing multi response process parameter for turning 316LSS are optimized with L9 orthogonal array. Results obtained from Taguchi method closely matches with ANOVA. Best parameters found for finish machining are: cutting speed, 10.55 m/min; depth of cut, 0.16 mm; feed, 0.06 mm/rev.

The parameters found for rough machining are cutting speed, 10.55 m/min; depth of cut, 0.06 mm; feed, 0.3 mm/rev. Feed is most influencing parameters corresponding to the quality characteristics of surface roughness.

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