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Optimization of Cutting Speed and Feed Rate on Surface Roughness and Vibration using Taguchi Method: A Review

The result of a turning process is strongly influenced by the process parameters that could result in the product to be unacceptable. The cutting parameters may be determined according to the material hardness and roughness of the workpiece surface. The purpose of this paper is to investigate the effects of cutting speed and feed rate on surface roughness and vibration. In Taguchi method, the number of experiments is reduced by orthogonal arrays while the effects of uncontrollable factors are also reduced. The Taguchi method is used to reduce track, experimental time and production cost. Simple and precise are the most benefits of this method. Unstable vibrations in machining operations, known as chatters, can cause damage to tools, workpieces, and machine tools. Cutting force is found to be the most dominant factor affecting surface roughness.

Keywords: Surface Roughness, Taguchi, Cutting Speed, Feed Rate, Vibration.

1. INTRODUCTION

Turning is one of the widely used machining processes in industries. [1]. Material is removed from the surface of a rotating cylindrical work piece by a single-point cutting tool in turning. The cutting tool is linearly feeding in a direction parallel to the axis of rotation. Turning machine was called lathe that provides the power to turn the work piece at a given rotational speed and to feed the cutting tool at a specified depth of cut and feed rate (**Figure 1**). Therefore, three cutting parameters, i.e. cutting speed, feed rate and depth of cut should be determined in a turning operation. The important task in turning is to select cutting parameters in order to achieve the highest cutting performances. Those are surface roughness, material removal rate, tool wear and power consumption.

Figure 1: Basic turning operation [1]

The selection of optimal process parameters in turning is crucial because it directly influences the cost efficiency and the workpiece quality [2]. Process parameters, such as feed rate, cutting speed, and depth of cut are normally selected carefully based on previous knowledges. Previous knowledge was regarding the process, coolant, machine, cutting tool and response of the workpiece in machining or in the traditional way by experienced operators. The initial process parameters are adapted depending on the required quality of the workpiece, tool wear, machine tool capability, manufacturing time and process requirements. In particular, for

the turning process in micromachining applications, the final product quality is of high importance and small variations in the process parameters can lead to unacceptable products. Finding the right combination of parameters requires specific expertise, or sometimes brute-force search and long series of experimental trials. Automatic approaches can optimize the performance of a given sequence of operations to manufacture a desired workpiece by selecting the optimal or most feasible ranges of process parameters.

Among optimization techniques, Taguchi method is a powerful and consistent tool for the design of high quality systems [3]. It provides a simple, efficient, and systematic approach to optimize output such as performance, quality, and cost [3]. Surface roughness is one of the significant surface qualities of hardened steels. It has a specific application for manufacturing of bearings, shafts, tools and dies. Turning of materials having hardness above 45 HRC is abbreviated as a hard turning [4]. Hard turning is a complex oblique cutting process. It is quite difficult to inculcate all possible factors affecting the surface roughness of the machined part for analysis. Various researchers have considered the effect of cutting conditions like speed, feed and depth of cut [4-6]. The flank wear and the surface roughness (arithmetic average, Ra) was also measured [6].

2. AVAILABLE TECHNOLOGY

2.1 Surface Roughness

The value of surface roughness is greatly influenced by the feed rate followed by cutting speed, cutting fluids and approach angle, respectively [6]. Cutting speed, feed rate, approach angle and cutting fluids strongly influence surface roughness [6]. The value of surface roughness are mildly increase by increase in cutting speed but it abruptly increases with the increase in feed rate. The main possible reason is that, at high cutting speeds and feed rates, large amount of chips flow on the cutting edge of tool causes the high friction, which may lead to high surface roughness values. In addition, this high friction generates the high cutting temperature and changes the physical state of the titanium alloy thus making the surface roughness.

The higher surface roughness and residual tensile stresses may be easily obtained at high level of feed rate [7]. However, the higher cutting speed can achieve less tensile stresses and resulted in significant increase in surface quality [8,9]. According to the analysis of variance and the regression model, the feed rate is great effect on the surface roughness [10]. An interaction effect of cutting parameters on surface roughness was investigated in many works, e.g. [11-13]. The experimental results show that the minimal surface roughness strongly affects the corrosion resistance of workpiece [12]. So the cutting parameters can be optimized by desirability function analysis to decrease the surface roughness and increase the corrosion resistance.

Ruibin and Wu [14] found the results where the feed rate and depth of cut have great influence on surface roughness. According to Sergio *et al.* [15], the surface roughness increases slightly with the increasing of depth of cut. Moreover, the surface roughness decreases with the increase of spindle speed or the increase of the cutting speed. This can occur because the feed rate has a strictly relationship with nose radius where the decrease of feed rate, without change the nose radius of tool, provides a great improve of surface roughness, because in some situations an overlapping phenomenon can occur and reduce the crests generated with displacement of the tool. In the actual field of machining, it is imperative to adopt the optimization of the processes since, by doing so, the resources are consumed economically [16].

The previous investigations based on Taguchi method explore that tool geometry (flank wear) and cutting force are affected by the cutting speed and most significant factor which influence the surface roughness is feed rate [17,18]. The findings supported that Taguchi method and analysis of variance (ANOVA) are powerful techniques to develop predictive models [19]. Mia *et al.* [7] optimized roughness parameter by applying Taguchi method. Taguchi orthogonal array-based design of experiment and signal-to-noise ratio-based optimization have been utilized. Furthermore, the analysis of variance determined the influences of cutting speed, feed rate and depth of cut on the aforementioned responses. Moreover, different types of tool wear, prevailed in principal and auxiliary flank faces, have been identified. The quantitative analysis revealed that the cutting speed impacted the surface roughness; the depth of cut influenced the tool wear; the feed rate afflicted the material removal rate predominantly. Several studies have been conducted to optimize the machining responses under different machining conditions, e.g. Gupta *et al.* [20]. Respond surface methodology (RSM) and particle methodology have been used to optimize the machining system of Ti alloy under minimum quantity lubrication (MQL) condition. Then, in another study, Gupta and Sood [21] RSM based desirability approach were used to optimized the machining parameter for minimum values of surface roughness parameter (Ra, Rq, Rz) under nano-fluid MQL conditions. Optimum values of the parameters are used to improve the surface quality and to find the optimum results.

Then Gupta *et al.* [12] optimized the machining responses for MQL assisted sustainable machining of Ti alloy. Among different optimization techniques[18,21], Taguchi based signal-to-noise (S/N) ratio method is

one of the mostly used and reliable techniques for optimization and has found its way in numerous presented works [12,18,22]. In turning of hardened steel under high pressure coolant system Mia and Dhar [7] applied Taguchi S/N ratio method to optimize the machining parameters for minimum chip-tool interface temperature and surface roughness. In another study, Mia [10] integrated Taguchi technique with grey relational analysis to optimize multiple quality indices in turning of Ti-6Al-4 V superalloy under double jet high pressure coolant condition. Zerti *et al.* [3] embraced Taguchi S/N ratio and ANOVA to study the surface roughness, cutting force and power by using ceramic insert in machining of AISI D3 steel. Experiment in high-speed dry turning of 300M highstrength steel with coated carbide tool is conducted [8]. The result is that the cutting speed has the most important effect on the cutting force, cutting temperature and tool life, while the feed rate has great influence on surface roughness.

Wibolo *et al.* [23] In their study also found that cutting speeds are very dominant affecting surface roughness followed by motion feeding and radius of chip Breaker. Gapsari [24] reported that the machining parameters, e.g. depth of cut, length of cutting, cutting speed, have significant impact to the surface roughness. Kuzu *et al.* [25] in their study also found that under MQL condition the effect of feed rate is insignificant. An increase of cutting speed gradually reduced the surface roughness values; hence the range of change of the roughness is wide enough to accredit the cutting speed as more impactful factor. A possible reason of this incidence is that at higher cutting speed the chances of BUE formation reduces and also the machine chatter is unlikely to become prominent.

Various analytical methods for predicting surface roughness, tool life and cutting forces have been investigated by researchers [26]. Development of empirical models for machinability parameters in a variety of machining process have been performed based on data mining techniques such as statistical design of experiments, e.g., The Taguchi method, response surface methodology, etc., computational neural networks, and genetic algorithms. All these methods provide the impact of each individual factor as well as the interactions between factors on the functional objective. Taguchi method is a systematic approach to find optimum values of design factors that lead to an economical design with low variability.

Taguchi DoE is a powerful tool for the design of high quality systems [27]. Taguchi provides a simple, systematic approach and efficient to optimize designs for quality, performance, and cost. A set of orthogonal arrays is proposed by Taguchi to investigate the effect parameters on specific quality characteristics and determine the optimum parameters combination. These arrays use a small number of experiments which save time and resources. However, these arrays do not test all variables combinations and interactions which could make their risk of error very large. Then, these designs should not be used when all relationships between all variables are needed.

Taguchi design is widely accepted and used in engineering analysis and optimization [28]. It is a powerful design. In Taguchi methods, the number of experiments were reduced by orthogonal array and also reduce the effects of uncontrollable factors [28]. The quality of Taguchi design is ensured in the design phase itself. Taguchi method is used to reduce trials, decreased experimental time, decreased the production cost, simple and precision are the most advantages in this technique. This also used to determine the significant factors in a minimum time. Taguchi method used to calculate loss function. Loss function is the difference among the experimental and desired values. Then the loss function is converted in the form of signal-noise (S/N) ratio.

2.2 Vibration

Taylor who first identified the chatter as a limitation of machining productivity [29], who carried out extensive studies on metal cutting processes as early as in the 1800s. A $3/4$ power law cutting force model was derived and it was stated that chatter is the “most obscure and delicate of all problems facing the machinist”. Arnold [30] examined numerous influences to which a tool is subjected during cutting analytically as well as experimentally for lathes and other machines and explained the mechanisms generating chatter and proposed cutting forces as a function of speed. It was shown that the most important characteristic property of chatter vibration is that it is not induced by external periodic forces, but rather that the forces which bring it into being and maintain it are generated in the vibratory process (dynamic cutting process) itself. Chatter is caused by instability in the cutting processes, which was first understood by Tobias and Fishwick [31] as well as by Tlustý and Poláček [32] almost simultaneously but independently. It was observed that modulated chip thickness due to vibration affects cutting forces dynamically, which in turn, increases vibration amplitudes yielding a process known as regenerative chatter. It was also observed that in the cutting process stability, the key process parameter was the depth of cut [32].

Vibrations of the tool or the workpiece during one tool (or workpiece) revolution leave waves on the machined surface, which in turn modulate the cutting forces in the succeeding revolution[29]. This feedback between vibrations in subsequent cuts can lead to self-excited vibrations during machining processes. If the spindle speed and depth of cut are not selected properly, such self-excited vibrations may become unstable and damage the tool and the workpiece. Stable spindle speeds and depth of cuts are usually selected according to the vibration models of the machining process. Zhang *et al.* [33] had found that Spindle imbalance induces unbalanced magnetic forces, unbalanced air bearing pressure, and spindle whirling and spindle tilting, which act on the spindle to yield forced vibration, i.e. spindle imbalance induced forced vibration. It further affects surface generation.

3. FUTURE OPPORTUNITIES

Struzikiewicz *et al.* [34] mentioned that the machined surface quality obtained after turning of two parts made of AISi10MG alloy, the first manufactured by laser sintering of powder, the second one made as a cast. Taguchi method has been applied in methodology. Sintered material showed the occurrence of breaches and burrs which negatively affected the roughness parameters and shape errors. The reason was incomplete remelting of sintered particles, which does not form a homogeneous structure and in which the cohesion forces are smaller than in the cast material. The algorithm for the feed value selection was developed considering the dimensional accuracy. A correction factor for the theoretical roughness value determination on the basis of the machined surface measurements was proposed. Additionally, it is necessary to verify the correctness of the operating algorithm for other materials and the appropriate cutting parameters for them.

Debnath *et al.* [26] the effect of various cutting fluid levels and cutting parameters on surface roughness and tool wear was studied. Taguchi orthogonal array was employed to minimize the number of experiments (To minimize the number of experiments employs Taguchi orthogonal array. The experiments were carried out on mild steel bar using a TiCN + Al₂O₃ + TiN coated carbide tool insert in the CNC turning process. The effect of feed rate was the dominant factor contributing to surface roughness of the workpiece. However, Depth of cut and cutting speed had little contribution to surface roughness. Manivel *et al.* [35] the cutting parameters are optimized in hard turning of ADI using carbide inserts based on Taguchi method. The cutting insert CVD coated with AL₂O₃/MT TiCN. The cutting parameters selected for machining are cutting speed, feed rate and depth of cut with each three levels, nose radius in two levels maintaining other cutting parameters constant. The Analysis of variance (ANOVA) and signal to noise ratio are used to optimize the cutting parameters. The surface roughness and tool wear are most influenced by the cutting speed. Confirmation tests are carried out in optimum cutting condition. Regression analysis and signal to noise are used to predicted the optimum cutting condition results.

In another study, Taguchi method and regression analysis were used to evaluate the machinability of Hadfield steel [36]. Several experiments were conducted using the L18 (2 x 3 x 3) full-factorial design with a mixed orthogonal array on a CNC vertical machining center. To determine the effects of the machining parameters on surface roughness and flank wear used Analysis of variance (ANOVA). As machining parameter, cutting speed, feed rate and cutting tool were selected. The analysis results revealed that the feed rate was the dominant factor affecting surface roughness Surface roughness was dominantly affected by feed rate.

Zhang and Chen [37] reported that Taguchi Design was applied to optimize the surface quality in a computer numerical control (CNC) drilling operation. In this study, feed rate, spindle speed, peck rate, and tool type were included the control factors. The presence or absence of magnetism in the workpiece material were simulated as the noise factor. The Selection spindle speed, tool type, and peck rate, and the optimal combination of cutting parameters were determined by statistical analysis of response variables and signal-to-noise ratios. the selected optimal combination through Taguchi Design were able to achieve desired surface roughness that was verified Confirmation tests. Bhattacharya *et al.* [38] an experimental study to investigate the effects of cutting parameters on finish and power consumption by employing Taguchi techniques.

Mia *et al.* [16] investigated the high-speed machining of AISI 1045 using coated carbide tools. Quantitative analysis reveals that cutting speeds have an impact on surface roughness; Cut depth affects the chisel wear; Feed levels are affected by the dominant material deletion rate. Based on proof of adhesion, abrasion, and edge buildup is found as a government wear mechanism. Taguchi Signal/Noise (S/N) based optimization is primarily concerned with the variability reduction and the mean alignment to its target value [11]. This variability may arise from several causes, in any process, which cannot be controlled; thereby, these factors are titled as uncontrollable factor or noise. On the other side, the expected value of a response is accredited as target or signal. Analogously, the optimization is accomplished by using signal-to-noise (S/N)

ratio wherein the S/N ratio apparently reflects the impact of expected signal with respect to the unexpected noise [18]. In this manner, the minimum variation to the response is affirmed and also the mean is preserved. Equations. (2) – (4) show three different characteristics of a continuous response function depending on the optimization principle. This means that when the optimization principle is reaching to a target value then Eq. (2) is applicable; when objective is to minimize the response function Eq. (3) is usable; lastly, in case of maximizing the response function Eq. (4) is suggested.

Nominal is the best characteristic:
$$\frac{S}{N} = 10 \log \frac{S}{x^2} \quad (2)$$

Smaller is the better characteristic;
$$\frac{S}{N} = 10 \log \frac{1}{n} (\sum x^2) \quad (3)$$

Larger is the better characteristic;
$$\frac{S}{N} = \left(\sum_{1}^n \frac{1}{x^2} \right) \quad (4)$$

where x represents the measuring responses (i.e. Ra, Rq, Rz, VB, VS, MRR); $\bar{x}$ indicates the average of x; S_x is the variation of response x, n is the number of experimental data. Among the aforementioned responses, it is desired that the surface finish parameters remain at the minimum, same is applicable for the tool flank wear parameters and consequently the Eq. (3) is used for the computation of these responses. On the other hand, for improved productivity the value of material removal rate needs to be the maximum and henceforth Eq. (4) is used.

4. CONCLUSION

The choice of optimal process parameters in turning is very important since it directly affects the cost efficiency and quality of the product. Surface roughness is one factor that is quite important in the materials that applications e.g. in the manufacture of bearings, shafts, tooling, and molds. Cutting force is the largest factor of surface roughness. Unstable vibrations in machining operations, known as chatter, can cause damage to tools, workpieces, or machine tools. Taguchi method, developed by Dr. Genichi Taguchi, is widely accepted and used in technical analysis and optimization. In the Taguchi method, the number of experiments is reduced by orthogonal arrays and also reduces the effects of uncontrollable factors. The Taguchi's design quality is ensured in the design phase itself. Taguchi method is used to reduce cost, experimental time and production costs. Simple and precise is the most advantage of this technique. Taguchi method used to calculate loss function.

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