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Exploiting Tool Toughness through Turning Process Parameter Optimization

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ABSTRACT

Modern manufacturers aim to maintain competitiveness by relying on their manufacturing engineers and production personnel to efficiently establish manufacturing processes for new products. The focus of the current experimental study is on identifying optimal controlled process parameters to achieve both a good surface finish and accurate tool life prediction. This study investigates process parameters such as cutting speed, feed rate, and depth of cut in machining grey cast iron. Experiments are meticulously designed and conducted using the Taguchi method, and corresponding surface roughness measurements are recorded. Analysis of Variance (ANOVA) is employed to validate the working ranges of the process parameters. Ultimately, the study aims to determine the optimum cutting parameters necessary for achieving the desired surface finish and enhancing tool life.

Keywords: ANOVA, Surface Finish, Feed, Depth of Cut, Speed.

1. Introduction

Tool life typically holds paramount importance when selecting cutting conditions. Prediction equations for tool life serve as crucial inputs for optimization models in machining processes [1-2]. These approaches aim to identify a combination of cutting parameters that fulfil cost or productivity objectives. Generally, the overarching goal of a machining process is to maximize the amount of work completed within the shortest timeframe and at the lowest cost feasible. However, these objectives are not always mutually compatible [3-5]. For instance, while setting cutting parameters to their highest values may seem intuitive to maximize output rate (the quantity of work completed within a specific time frame), it often results in significantly reduced tool life, thus escalating tool costs. Moreover, frequent tool replacements lead to substantial loss of productive time, ultimately diminishing the output rate. Conversely, machining at extremely low cutting speeds, feeds, and depths of cut proves ineffective. Although this approach decreases tool-related costs, it significantly extends machining time, resulting in a lower output rate [6-8]. Consequently, accomplishing the same amount of work necessitates more man-hours and machine-hours, thereby increasing operating costs. Furthermore, various constraints such as part quality, machine tool rigidity, and available power must be considered when determining machining parameters [9-10]. Taking all these factors into consideration aids in determining the optimal set of cutting conditions.

1.1 Metal Removal

Turning is a machining process wherein a tool follows a helical path by moving linearly while the workpiece rotates. The tool's movement axis may be straight or incorporate curves or angles, but fundamentally remains linear. "Turning" typically refers to the creation of external surfaces through this cutting action, whereas the same action applied to internal surfaces (such as holes) is termed "boring". Cutting faces on the workpiece (perpendicular to its rotating axis), whether using a turning or boring tool, is referred to as "facing" and is categorized as a subset of either. In turning, the speed and motion of the cutting tool are determined by several parameters, including those influencing the surface roughness of metal. These parameters are selected for each operation based on factors such as workpiece and tool material, tool size, etc are shown in figure 1.

1.2 Cutting Speed (Vc)

The cutting speed of a tool refers to the rate at which the tool removes material from the workpiece given in equation 1. In lathe work, it equates to the peripheral speed of the workpiece, measured in meters per minute (mm/min or m/min).

$$V_c = \frac{\pi \times D \times N}{1000} \qquad (1)$$

Where D represents Diameter in mm and N is the speed in rpm of the workpiece.

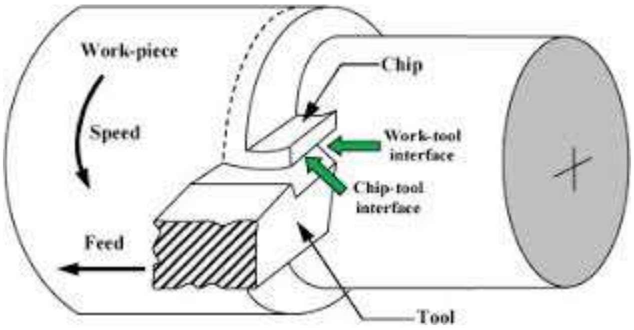

Fig. 1 - Turning Operation with parameters

A research group has discovered that cutting parameters play a direct role in determining the surface finish of machined components. However, among these parameters, cutting force and feed force notably impact power consumption, with this study focusing solely on cutting force as a key factor. Surface roughness is also crucial, as it can affect frictional resistance and the fatigue strength of machined components. In the context of turned components, achieving a superior surface finish is important as it reduces the need for additional machining [11]. Numerous researchers have observed that surface roughness affects heat transmission during machining, the ability to retain lubricants, surface friction, and wear, among other factors. When determining the optimal cutting parameters for any machining operation, striking a balance between minimizing surface roughness and maximizing material removal rate poses a significant challenge.

2. Literature Review

The literature on turning operations is abundant due to its significance in metal cutting. Key cutting process parameters in this research include speed, feed, and depth of cut. Furthermore, it relies on several other external factors such as the combination of workpiece and tool materials along with their mechanical properties, the quality and type of machine tool used, lubrication methods, and vibrations occurring between the workpiece, machine tool, and cutting tool [12-16]. To determine optimal cutting conditions, accurate estimation of tool life and cutting forces is crucial, as many process constraints are influenced by these parameters [17-22]. However, due to the lack of sufficient machining theories to predict tool life and cutting forces in practical situations, empirical equations are often relied upon [23]. The Taguchi method proves to be a powerful tool for designing optimization strategies for quality and identifying optimal cutting parameters in turning operations [24-27]. Techniques such as orthogonal arrays, analysis of variance (ANOVA), and signal-to-noise (S/N) ratio analysis are utilized to investigate cutting process characteristics and optimize parameters. Various studies have explored the effect of turning process parameters on surface roughness and developed mathematical models using response surface methodology (RSM) [28-30]. While depth of cut significantly influences cutting force, its impact on surface roughness may be insignificant in some cases [31]. Interaction effects between feed and depth of cut, as well as all cutting parameters, influence cutting force, but do not necessarily impact surface roughness. Adjusted approaches, such as analysis of variance, are adopted for accurate analysis [32-35]. Additionally, new approaches for enhancing cutting tool life by optimizing velocity and feed throughout the process have been proposed [36]. Tool life equations and wear models are established from experimental data, and optimization techniques are implemented to maximize tool life while maintaining a constant metal removal rate [37-38].

Moreover, multi-objective optimization methods based on RSM are applied to milling processes to evaluate trade-offs between sustainability, production rate, and cutting process quality [39]. These methods simultaneously optimize surface roughness and material removal rate. Furthermore, studies have evaluated the effects of cutting or process parameters on tool life and material removal rate during the machining of specific alloys [40-43]. Relationships between machining parameters and output variables are modeled using response surface methodology, and ANOVA is conducted to validate mathematical models and their respective variables. In conclusion, while research on the influence of cutting speed, feed, and depth of cut on cutting force and surface roughness has been active for several decades, there is a continuous need to extend this study to different combinations of tool and work materials.

3. Methodology

Every experimenter initially develops a nominal process that meets the desired functionality according to user demands. Building upon these nominal processes, the goal is to optimize processes or products using suitable methodologies. In the context of the Taguchi method, the term "optimization" refers to determining the best levels of process control factors. These best process control factors are those that maximize the Signal-to-Noise ratios, which are logarithmic functions of desired output characteristics. Experiments conducted to determine the best levels rely on Orthogonal Arrays (OA), which are designed to balance all process control factors while minimizing the number of experiments needed. This ensures that the resources, including materials and time required for the experiments, are kept to a minimum.

3.1 DOE of the Work Process

The design of experiments encompasses the planning of numerous tasks aimed at describing or explaining the variation of information under specific conditions that are hypothesized to influence said variation. This term is commonly associated with true experiments, where the design enables direct manipulation of conditions affecting the variation. However, it also applies to quasi-experiments, where natural conditions influencing the variation are observed.

In its simplest form, an experiment seeks to predict outcomes by altering preconditions, represented by a variable known as the predictor. The change in the predictor is expected to result in a change in the second variable, hence referred to as the outcome variable. Experimental design involves selecting suitable predictors and outcomes, as well as planning the execution of the experiment under statistically optimal conditions. Key concerns in the design of experiments include establishing validity, reliability, and replicability. These concerns can be addressed in part by carefully selecting predictors to minimize the risk of measurement error and ensuring detailed documentation of the chosen method. Additional related concerns involve achieving appropriate levels of statistical power and sensitivity.

3.2 Machine Setup and Workpiece material

The turning operation was performed utilizing a Hyundai-Kia VTL (Vertical Turning Lathe), an industrial CNC lathe machine with a spindle speed operating range of 100 rpm to 3000 rpm and equipped with a 12-kW motor drive. This type of machine is typically employed for machining heavy and tall parts. The inserts used were CNMG120408-TM T9125 and CNMG432 TM T9125, and the material machined was EN GJS-500-7 grey cast iron. The workpiece, measuring 400 mm in diameter and 150 mm in height, was machined under wet conditions. Before machining, the work material was trued, centered, and cleaned by removing a 1.0 mm depth of cut from the outside surface. The setup was then utilized for experimentation according to the designed arrays. Figure 2 illustrates the workpiece, and Figure 3 depicts the cutting tool setup. The selection of the tool and workpiece material combination was based on considerations of cost and machining time.

Fig. 2 - Cutting Tool

Fig. 3 - Experimental set for the Workpiece

3.3 Analysis of Variance (ANOVA)

ANOVA, originating from the statistical design of experiments, involves adjusting factors and measuring responses in an attempt to ascertain effects. These factors are allocated to experimental units using a combination of randomization and blocking to ensure result validity, with responses demonstrating variability stemming from both effects and random error. Analysis of variance amalgamates various concepts and serves multiple purposes, making it challenging to precisely define. Nevertheless, in the realm of psychological research, ANOVA has long been the predominant statistical technique, epitomizing the usefulness of statistical inference analysis.

3.4 Selection of process parameters

After conducting a thorough literature review, the process parameters influencing the machining characteristics of parts via CNC turning machines have been identified. These parameters include:

- Tool-related parameters: such as tool material, tool geometry, insert coating, grade, and insert condition.

- Machining-related parameters: encompassing cutting speed, feed rate, and depth of cut.

The ranges for these cutting process parameters in the experimental setup have been determined through a combination of literature survey findings and the outcomes of pilot experiments conducted using a one-parameter-at-a-time approach as shown in table 1.

Table 1 - Parameters

Parameters	Test 1	Test 2	Test 3
Feed(mm/rev)	0.20	0.30	0.4
Speed of Cut(m/min)	200	300	400
Depth of Cut(mm)	0.3	0.4	0.5

4. Experimental Procedure

The experimental setup depicted in Figure 4 facilitated the execution of nine experiments based on the predetermined experimental array. Wet cutting was conducted utilizing a suitable cutting fluid manufactured by Mobil, characterized as a conventional milky soluble oil that forms a stable emulsion when mixed with water. This cutting condition was realized using a specially developed cutting fluid delivery system, with parameters set at a delivery rate of 10 ml/h. The nozzle, affixed to a flexible holder, allowed for adjustable direction of cutting fluid delivery, ensuring efficient fluid dispersal. The nozzle remained fixed on the tool holder throughout the entire cutting process to ensure continuous fluid delivery at the cutting point. The tool employed throughout the study was confirmed to adhere to ISO designation CNMG120408. A preliminary study on the tool wear behavior of this specific tool was conducted prior to the experiment to comprehend its wear characteristics. The cutting parameters, including cutting speed (150-450 m/min), feed rate (0.1-0.45 mm/rev), and depth of cut (0.25-0.5), were selected based on the condition of the cutting tool and the workpiece material. The duration of each run was recorded to determine the total tool life in terms of time, while the corresponding Ra value was also recorded for each trial, which is crucial from a quality perspective as shown in table 2.

Fig. 4 - Experimental Testing Setup

Table 2 - Design Parameters Elements

Speed (m/min)	Feed (mm/rev)	Depth of Cut (mm)	Surface Roughness (μm)	Time in sec	Metal Removal
200	0.2	0.3	0.6	1280	198.1
200	0.3	0.4	0.7	1604	512.2
200	0.4	0.5	1.4	780	581.1
300	0.2	0.3	0.9	1120	364.55
300	0.3	0.4	1.1	850	290.1
300	0.4	0.5	1.3	641	311.1
400	0.2	0.3	0.8	721	389.5
400	0.3	0.4	1.3	790	321.23
400	0.4	0.5	1.8	410	401.52

5. Result and Discussion

In this experiment, the results of the experiments are converted into a signal-to-noise ratio to gauge the deviation of the performance characteristics from the desired values as given by equation 2. Specifically, for the characteristic of Tool Life, a larger value is considered better as shown in table 3.

$$\frac{S}{N} = -10log\left[\frac{1}{n}\sum(y_i)^2\right] \qquad (1)$$

Table 3 - S/N for Tool life

Cutting Speed (Vc)	Feed	DOC	Tool Life	S/NRa
200	0.2	0.3	22.45	27.11
200	0.3	0.4	27.52	28.35
200	0.4	0.5	11.45	24.21
300	0.2	0.4	20.12	25.12
300	0.3	0.5	13.99	22.12
300	0.4	0.3	8.98	21.24
400	0.2	0.5	12.45	22.89
400	0.3	0.3	13.45	22.45
400	0.4	0.2	6.80	18.10

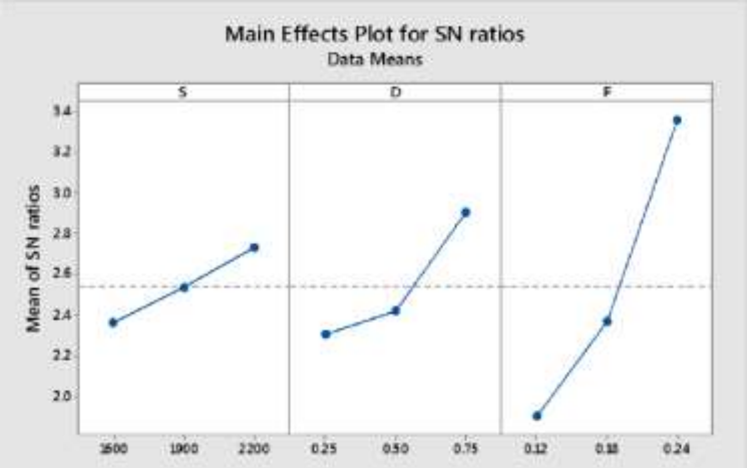

Fig. 5 - Tool life using Main Effects Plot

Table 4 - ANOVA for Tool life

Parameters	DF	SS	Adj MS	Adj SS	Feed	P
Speed	2	48.65	24.55	49.12	38.12	0.031
DOC	2	41.35	19.12	41.21	29.78	0.038
Feed	2	4.86	2.12	4.98	3.21	0.321
Error	2	1.24	0.51	1.54	--	--
Total	8	96.1				

The analysis of variance (ANOVA) results reveals that cutting speed and feed significantly influence tool life as shown in table 4. This study was conducted by a group of researchers using various combinations of tools and materials.

6. CONCLUSION

In this study, CNC turning operations were conducted under various experimental conditions, with measurements taken for material removal rate, surface roughness, and tool life in terms of time. Nine levels of experiments were carried out, revealing that the most influential factors on tool life were cutting speed and feed, as observed after experimentation. The optimal parameters identified for this specific tool and material condition were determined to be Cutting speed: 270m/min, Feed: 0.2mm/rev, and Depth of cut: 0.4m. Additionally, it was concluded that tool life decreases with an increase in cutting speed and feed during the machining process for this particular tool and material combination.

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