Minimization of Cutting Force by Optimizing the Cutting Parameters Using Taguchi Method in Turning

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Abstract. The changes in magnitude of cutting force demonstrate the different occurrences in turning. The pattern of cutting force signal illustrates the cutting tool conditions and also corresponds to the changes in the cutting parameters. Obtaining an optimal cutting condition would significantly minimize the cutting force in turning, can reduce respective power consumption and consequently, extent the life of cutting tool. Choosing the optimal cutting parameters in turning would safeguard the cutting tool from catastrophe and could ensure a better surface finish of workpiece. From the orthogonal array and S/N ratio, the cutting speed of 120 m/min, feed rate of 0.32 mm/rev and depth of cut of 1 mm is found to be optimum cutting parameters. The magnitude of cutting force is found to be minimal and the surface finish is seen to be comparatively low at this cutting condition. The tool life at this cutting condition is found to be the longest for that particular tool – workpiece combination.

Keywords: Cutting parameter optimization, Taguchi method, Cutting force, Flank wear, Surface roughness.

1. Introduction
Turning is one of the mostly used machining techniques in manufacturing industry. In turning, the tool-workpiece combination, and cutting parameters play the most significant role and define the product quality, tool condition and the rate of power consumption in machining. Choosing the optimal cutting speed, feed rate, and depth of cut for machining can reduce tool wear and improve the surface finish of workpiece. Different methods are available to perform this optimization task. Li et al. [1] have used Taguchi method, response surface method (RSM), and multi-objective particle swarm optimization algorithm (MOPSO) to identify the optimal cutting parameters in CNC machining. They have used the Taguchi method to design the experiment, and subsequently employed the signal-to-noise (S/N) ratio to analyze the performance of parameters. In other studies, the cutting speed, feed rate and depth of cut have been optimized with the help of Taguchi design of experiment (DOE), signal to noise (S/N) ratio and analysis of variance (ANOVA) methods [2-3]. Fratila and Caizar [4] have applied Taguchi method to select optimal process parameters for minimum surface roughness and minimum cutting power required in semi-finished cutting. In another study, Camposeco-Negrete [5] has optimized the cutting parameters using Taguchi method focusing on the surface roughness and cutting power consumption in turning. Nalbant et al. [6] have used the Taguchi method to find the optimal cutting parameters for surface roughness in turning. They have employed the orthogonal array, the signal-to-noise ratio, and analysis of variance to study the performance characteristics in turning. Similar method has been applied by and Ravi & Kulkarni [7] and Vijay Kumar et al. [8] in...
different two investigations to find out the optimal cutting condition in CNC turning. In this study, the Taguchi method has been applied in optimization of the cutting parameters based on the cutting force. Then the results obtained from the Taguchi analysis have been cross-verified with the workpiece surface finish and flank wear data measured during turning.

2. Materials and Methods
A round bar (92 mm diameter and 760 mm long) of ASSAB-705, medium carbon steel (hardness HB270-310) has been used as the workmaterial, which contained carbon (0.35%), chromium (1.40%), iron (95.95%), manganese (0.70%), molybdenum (0.20%), and nickel (1.40%) by weight. A DSBNR 2525M 12 tool holder and TiN coated tungsten carbide, type: SNMG 12 04 08-PM tool insert assembly has been employed to cut the material. The experiment was conducted in dry cutting mode for this investigation. The cutting conditions and tool-workpiece combination have a significant effect on tool wear and on the surface roughness. The tool flank wear has been measured by taking the tool insert off from the tool holder after some 12 minutes of cut. A magnification of 40X has been used to capture the image of flank wear by light source microscope, Model: I CAMSCOPE(G). From the captured image, the average flank wear has been measured using a measuring software, ‘Measure IT’. The surface finish of workpiece has been measured with a handy profile-meter type: ‘Mahr Perthometer M1/M1 CNOMO 3755350’ at the end of 12 minutes of cut.

The turning operation is performed on a COLCHESTER VS MASTER3250 (165 mm × 1270 mm) Gap bed Center Lathe machine. A tri-axial force dynamometer Type: KISTLER 9257A have been used to measure the cutting force during machining. The frequency range of the tri-axial force dynamometer is 10 Hz – 400 kHz. A DEWE-43 module and a charge amplifier Type: KISTLER 5019 have been employed as signal processing units to process the captured signal. The DEWE-43 module has a low-pass filter of LP: 1000 kHz and the charge amplifier has a high-pass filter of HP: 180 kHz. The signals captured using the force dynamometer have been processed inside these modules before storing for analysis. The schematic diagram of the experiment setup is shown in Figure 1.

3. Design of Experiments
The parameter design has been carried out under the design of experiment using the Taguchi method to optimize the machining process. The cutting parameters used in the experiment are presented in Table 1.

![Figure 1. Setup for capturing the cutting force signals in turning.](image-url)
The design of experiment has been performed with Minitab software. The cutting parameters have been optimized focusing on minimal cutting force requirement in turning. It is expected that the optimal cutting conditions obtained from the parameter design are insensitive to the variation of environmental conditions and other noise factors.

The orthogonal array has been used to study the entire parameter space with a small number of experiments only and thus to identify the optimal cutting condition. A loss function transformed into S/N ratio has been defined to calculate the deviation between the experimental value and the desired value. The ‘lower-the-better’ category of the performance characteristic for the analysis of the S/N ratio has been used in the design of experiment. The S/N ratio for each level of process parameters is computed based on the S/N analysis.

Finally, a confirmation experiment is conducted to verify the optimal process parameters obtained from the parameter design. The results have been tested by the surface roughness and flank wear measured during machining. In this paper, the cutting parameter design by the Taguchi method is adopted to obtain optimal machining performance in turning.

4. Results and Discussions

The orthogonal arrays of the cutting parameters and the S/N ratios have been obtained from the Taguchi analysis to find the optimal cutting parameters among the cutting conditions. From literature, the larger S/N ratio corresponds to the better performance characteristic regardless of the category of the performance characteristic. Therefore, the optimal level of the process parameters is the level with the highest S/N ratio. It has been also reported that the optimal combination of the process parameters can be predicted with the orthogonal array, and the S/N analyses [6].

A three-level, three factors fractional factorial design, L9 has been used to generate an orthogonal array. Each row of the matrix represents one trial. The orthogonal array obtained from the Taguchi method is shown in Table 2.

| SN | Cutting speed (m/min) | Feed rate (mm/rev) | Depth of cut (mm) | Flank wear (mm) | Surface roughness (µm) | Cutting force (N) |
|----|----------------------|--------------------|------------------|-----------------|------------------------|------------------|
| S1 | 120                  | 0.20               | 0.5              | 0.1165          | 3.994                  | 45.8             |
| S2 | 120                  | 0.32               | 1.0              | 0.1185          | 3.912                  | 24.3             |
| S3 | 120                  | 0.50               | 2.0              | 0.1304          | 4.453                  | 48.5             |
| S4 | 150                  | 0.50               | 1.0              | 0.1145          | 3.997                  | 28.2             |
| S5 | 150                  | 0.32               | 2.0              | 0.1289          | 3.896                  | 128.7            |
| S6 | 150                  | 0.50               | 0.5              | 0.1127          | 4.081                  | 118.5            |
| S7 | 170                  | 0.50               | 2.0              | 0.1601          | 4.099                  | 151.3            |
| S8 | 170                  | 0.20               | 0.5              | 0.1483          | 3.998                  | 29.9             |
| S9 | 170                  | 0.50               | 1.0              | 0.1571          | 4.463                  | 81.1             |

The tool life, surface roughness and cutting force graphs for these trials are represented in the Figure 2.
Figure 2. a) Tool life graph, b) Surface roughness profile, and c) Amplitude of RMS force signal.

Though we can have some idea about the possible optimal cutting conditions for the reduced cutting force from the above graphs, however, it is rather difficult to choose a particular trial condition as the optimal cutting condition. From the S/N ration analysis, the most optimal cutting parameters can be identified.

The main effects and the S/N ratios for different combination of the cutting parameters have been obtained to identify the optimal cutting condition. Figure 3 illustrates the changes of mean data and S/N ratios at different cutting conditions.
From the Taguchi analysis results, three different optimal cutting conditions have been obtained for cutting force, flank wear, and surface finish optimization. For cutting force optimization, the optimal cutting speed has been obtained 120 m/min, feed rate 0.32 mm/rev and depth of cut 1 mm; whereas for flank wear optimization, the cutting speed, feed rate and depth of cut have been changed to 150 m/min, 0.20 mm/rev and 0.5 mm respectively. An exceptional drop of tool wear and cutting force has been observed at feed rate of 0.32 mm/rev, which can be attributed to the phenomena of chip breakage taken place during metal-cutting [9]. For surface roughness optimization, the optimal cutting speed and depth of cut have been found to be similar like that of flank wear optimization parameter except the feed rate, which has been changed to 0.32 mm/rev. Therefore, it can be deduced that, when it is to optimize the cutting force and surface roughness, one has to be more concerned about the depth of cut. In case of optimizing the cutting force and flank wear, both the feed rate and the depth of cut are to be given consideration significantly. For the flank wear and surface roughness optimization, the feed rate has to be monitored with great importance.

**Figure 3.** The mean data and single-to-noise ratio graphs.
Figure 4 shows the tool wear and surface roughness graphs obtained from the experiment of these three optimal cutting conditions.

![Graphs of tool wear and surface roughness](image)

**Figure 4.** a) Tool wear curve, b) Surface roughness graph.

From the tool wear and surface roughness graphs of Figure 4, it has been observed that the rate of flank wear was minimal at the optimal cutting condition found for flank wear optimization, and the rate of surface roughness was the least at the optimal cutting condition for surface roughness optimization. Though, both the tool wear and surface roughness graphs obtained for cutting force optimization have shown some similar trends to those for tool wear and surface roughness optimization, the tool life was the longest for the optimal cutting condition gained for cutting force optimization. Therefore, the optimal cutting condition found for cutting force optimization has been chosen to carry out the experiment to investigate the cutting tool condition using force signal in turning.

5. Conclusions
The optimal cutting parameters obtained from Taguchi analysis have been tested with experiment before recording the force signal in tool condition monitoring during turning. The optimal cutting condition of $v = 120$ m/min, $f = 0.32$ mm/rev, and $doc = 1$ mm found for cutting force optimization was the optimum among all three optimal cutting conditions. The flank wear and surface roughness graphs plotted from the experimental results have also supported the optimum cutting condition that obtained for cutting force optimization.

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