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Machining Analysis of CNC Turning Operations Performed on Tool Steel

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A B S T R A C T

The current research delves into optimizing controlled turning operations by amalgamating traditional experimental design methodologies with advanced machine learning techniques for two commonly used industrial materials: En-24 and tool steel D2. A mixed Taguchi experimental design, facilitated by Minitab software, was employed to assess the impact of crucial process parameters—Object Material, Speed, Feed Rate, and Depth of Cut (DOC)—on surface roughness and material removal rate (MRR). Through Signal-to-Noise (S/N) ratio analysis and Analysis of Variance (ANOVA), significant factors affecting the response parameters were identified. Additionally, machine learning algorithms, including Neural Network (NN), K-Nearest Neighbors (KNN), and Random Forest (RF), were utilized to predict response variables based on selected parameters. Results revealed that DOC and Feed Rate significantly influenced surface roughness and MRR, respectively, as per S/N ratio analysis. ANOVA results validated these findings, highlighting the substantial impact of Speed and Feed Rate on MRR, while Object Material and DOC were significant contributors to surface roughness. Machine learning predictions demonstrated varied accuracies across algorithms, with KNN excelling in predicting surface roughness and NN and RF displaying better explanatory power.

Keywords: CNC turning, Tool Steel, Machining analysis

1. Introduction

The manufacturing industry serves as a cornerstone of technological progress and economic development, relying heavily on various production processes, with machining being a pivotal component. Its significance stems from its broad applicability across diverse materials, necessitating high-quality machining techniques to meet varying industrial demands. Machining plays a crucial role not only in material transformation but also in shaping production costs and, consequently, the competitiveness of final products in the market. In this context, innovation in machining processes becomes not only desirable but imperative, propelling the adoption of computer-controlled machining operations as a central focus of modern research and industrial practices. Numerous factors influence the pursuit of machining excellence, including product design, material selection, machine choice, operator skill, and operational conditions. These factors collaborate to enhance material machinability, vital for achieving desired outcomes in terms of manufacturing process efficiency, quality, and sustainability. The integration of machine learning technologies into this domain holds promise for enhancing these variables in ways previously unattainable with traditional methodologies. Within CNC (Computer Numerical Control) machining, the interaction of multiple input parameters is crucial in determining operational quality and efficiency. This encompasses studies on cutting tool wear, material and design choices, and meticulous calibration of process parameters such as spindle speed, depth of cut, and feed rate. Moreover, the selection of workpiece materials and the properties and application conditions of cutting fluids are pivotal for machining highly resilient materials. The outcomes of the machining process, or response parameters, encompass a wide spectrum, from cutting time and rate to nuanced aspects such as tool wear, power consumption, and surface finish quality. These metrics signify the efficiency and cost-effectiveness of the machining operation, along with its ability to meet the stringent quality and precision standards of contemporary production. This study aims to bridge the gap between traditional machining processes and the potential of machine learning techniques. It concentrates on High-Speed Steel (HSS) turning operations to enhance our understanding of HSS machinability and develop prediction models capable of optimizing machining parameters to minimize dimensional deviations. The integration of machine learning into machining operations marks a significant advancement in the industrial sector's quest for heightened efficiency, reduced production costs, and superior product quality.

2. Literature Review

Research in precision hard turning (HT) has garnered significant attention in the cutting industry due to global market demands for cost reduction, environmental sustainability, and more eco-friendly manufacturing processes (Arsene et al., 2021). Dry cutting and minimal quantity lubrication (MQL) have emerged as methods to address environmental concerns associated with conventional cutting fluids (CFs), with vegetable oils showing potential as substitutes for petroleum-based fluids. However, their efficacy in high-temperature applications with ceramic inserts remains uncertain. A study examining the use of pure corn oil in MQL machining of hardened AISI D2 steel demonstrated improvements in surface roughness by 10-15% and tool life by 15-20%, leading to cost reduction (Arsene et al., 2021). Another investigation focused on creating a model and analyzing the CNC machining process of AA6082-T6 aluminum alloy using a tool with a Tungsten Carbide tip, confirming experimental and analytical results through CATIA V5 for 3D modeling and Ansys R19.2's explicit module for analysis (Aseerullah et al., 2022). Bagga et al. (2022) introduced a new system for predicting tool wear using artificial neural network (ANN) technology, showing promising results for cost-efficient monitoring of tool condition in turning operations under dry cutting conditions. Bhor et al. (2020) emphasized the importance of optimizing cutting parameters on the surface finish of mild steel utilizing a CNC turning center, demonstrating the effectiveness of advanced approaches such as the Artificial Bee Colony optimization strategy within a Design of Experiments framework. Cedzo et al. (2023) investigated surface roughness during turning with forced tool rotation (ADRT) on hardened steel 90MnCrV8, highlighting the potential of Advanced Dynamic Rotary Tool (ADRT) technology in improving productivity for industrial processes involving difficult materials. Other studies focused on specific materials and alloys, such as the machining difficulties presented by EN31-535A99 SS (Hussain et al., 2020) and the challenges associated with machining AF 9628 due to strain hardening (Hasbrouck et al., 2020). These studies underscore the ongoing efforts to optimize machining processes and enhance efficiency, quality, and sustainability in the manufacturing industry.

3. Design of Experiment (DOE) and Result

The VX-135 CNC turning machine is a robust and versatile tool designed for modern machining demands. With a standard turning diameter of 135 mm (maximum of 165 mm), it accommodates various workpieces. Its 300 mm swing over bed and 200 mm maximum turning length offer flexibility and precision. Featuring cross (X axis) travel of 100 mm and longitudinal (Z axis) travel of 220 mm, it ensures accurate positioning. Rapid feed rates of 24 m/min for both axes enhance productivity. The main spindle, with a spindle nose of A2-4 and a spindle bore of 36 mm, handles workpieces up to 25 mm bar capacity. Equipped with a chuck size of 135 mm and a speed range of 50 to 4500 rpm, it offers versatility in material machining. The turret with eight stations accommodates tool sizes of 20 x 20 mm and a maximum boring bar capacity of 32 mm for efficient tool changes. It adheres to JIS standards, with positioning accuracy of 0.008 mm and repeatability of 0.007 mm. The tailstock, with a quill diameter of 70 mm, a stroke of 80 mm, and an MT4 taper, provides stability during operations. Combining robust construction, advanced features, and precise performance, the VX-135 meets the diverse needs of modern machining environments. The factors and levels were present in table 1

Table 1 Factor and Levels

Factor	Unit	L-I	L-II	L-III
Object Material	NA	EN-24	D2	NA
Speed	RPM	1200	1400	1600
Feed Rate	mm/min	0.4	0.5	0.6
DOC	mm	0.3	0.4	0.5

Turning operations play a pivotal role in production machining for product development. The advancement in computational technology has made CNC turning highly efficient, driving the operation of CNC-operated lathes. These machines offer significant flexibility for lathe operations, catering to diverse industrial requirements. However, the quality of the final product hinges on the meticulous selection of appropriate criteria. Inadequate parameter settings can result in subpar quality of goods produced by CNC lathes. Our study focuses on investigating the effects of various process parameters on CNC lathe operations, particularly on industrial-grade steels such as En-24 and tool steel D2. To thoroughly examine these impacts, we adopt the Design of Experiment (DOE) approach, specifically utilizing the Mixed Taguchi method to construct our experimental design. As detailed in the preceding chapters of our research thesis, our experimental setup comprises 18 design points, where multiple factors are examined at three distinct levels. These meticulously crafted design points serve as crucial tools for analyzing the influence of machine operational settings and any associated errors.

Table 2 S/N ratio analysis of Surface roughness

Run	Obj_Material	Speed	Feed Rate	DOC	Surface Roughness	S N Ratio
1	EN-24	1200	0.4	0.3	3.42	-10.681
2	EN-24	1200	0.5	0.4	2.39	-7.568
3	EN-24	1200	0.6	0.5	2.63	-8.399
4	EN-24	1400	0.4	0.3	3.75	-11.481
5	EN-24	1400	0.5	0.4	3.53	-10.955
6	EN-24	1400	0.6	0.5	2.95	-9.396
7	EN-24	1600	0.4	0.4	3.43	-10.706
8	EN-24	1600	0.5	0.5	3.05	-9.686
9	EN-24	1600	0.6	0.3	3.25	-10.238
10	D2	1200	0.4	0.5	2.28	-7.159
11	D2	1200	0.5	0.3	2.92	-9.308
12	D2	1200	0.6	0.4	1.97	-5.889
13	D2	1400	0.4	0.4	2.92	-9.308
14	D2	1400	0.5	0.5	2.02	-6.107
15	D2	1400	0.6	0.3	2.68	-8.563
16	D2	1600	0.4	0.5	2.54	-8.097
17	D2	1600	0.5	0.3	2.89	-9.218
18	D2	1600	0.6	0.4	3.14	-9.939

For the case of using Object Material D2 at a Speed of 1200 RPM and a Feed Rate of 0.6 mm/min (Run 12), the Signal-to-Noise (SN) ratio is notably low at -5.889, indicating favorable surface roughness. Additionally, the ranking of factors based on SN ratios reveals the relative importance of each factor in influencing surface roughness. Depth of Cut emerges as the most influential factor, followed by Object Material, Speed, and Feed Rate. These findings offer valuable insights for optimizing machining parameters to attain the desired surface quality in industrial applications.

Conclusion

In the analysis of surface roughness, the Signal-to-Noise (S/N) ratio unveiled Depth of Cut (DOC) as the most influential parameter, holding the top rank with a notable Delta value of 1.774. This underscores the significance of optimizing the DOC to significantly enhance surface quality in controlled turning operations. Following DOC, Object Material secured the second rank, succeeded by Speed and Feed Rate, in descending order of importance. These results underscore the critical role of selecting an optimal DOC level to achieve improved surface finish, highlighting the necessity for meticulous parameter optimization.

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