

Effect of Spindle Speed Variation on Machining Performance and Tool Life

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ABSTRACT

The speed of the spindle has a great influence on the life of the cutting tool and performance in the process of metal cutting. In order to obtain improved quality of surface finish, accuracy of dimensions, rate of material removal, and extended cutting tool life, correct selection of spindle speed is very important. Although very high spindle speeds increase the heat generated, increase the wear of cutting tool, and cause vibration thus reducing machining efficiency, very low spindle speeds reduce efficiency. This present research is carried out to study the effect of changing spindle speeds on tool life and machining performance in turning process. The lathe machine was run under controlled machining processes during the experimentation process. From the results obtained, optimum spindle speed will yield good machining performance with good surface finish while ensuring that the wear on the tool is minimal. Although increasing the spindle speed increased the rate of production, it was also accompanied by faster tool wear due to overheating of the tool. From the findings of this experiment, it is clear that controlling the spindle speed is crucial in machining processes.

Keywords: *Spindle speed, Machining performance, Tool life, Surface roughness, Cutting temperature, Tool wear, Turning operation.*

1. Introduction

Today in the modern manufacturing industries, machining operations are considered crucial in forming high-quality products in terms of surface finish and dimensions. All industrial manufacturing fields like the automobile industry, aerospace, defense, railroad, and energy production depend on machining operations, where turning, milling, drilling, grinding, and boring are some of the popular machining operations. Machining attributes like spindle speed, feed rate, depth of cut, cutter configuration, workpiece material, and machining environment play a significant role in the quality and efficiency of the machining process. The spindle speed is among the parameters that affect machining efficiency, surface finish, thermal effects, cutter durability, and machining operations [1], [2]. The spindle speed refers to the number of times the machine spindle rotates in a minute and is usually indicated in rotations per minute (RPM). It affects chip formation, cutting temperature, friction, vibrations, and wear process due to its direct influence on cutting speed. Selecting a proper spindle speed ensures a good balance of productivity, machining quality, and tool longevity. Unwanted heat generation, poor surface finish, dimensional inaccuracy, chatter vibrations, accelerated wear, and premature wear out of the cutting tool may happen in case of improper spindle speed selection [3]. Material removal occurs by shearing process and plastic deformation at the point of interaction between cutting tool and material being worked. It causes heat generation in the region of cutting due to friction process. Spindle speed plays an important role in heat generation since high spindle speed creates more friction. Too many spindle speeds, however, cause vibrations, chatter marks, and heat distortion. These phenomena have adverse effects on dimensional accuracy and finish quality. Smoother operation, easier chip formation, and better finishing often result from moderate spindle speeds [7]. Rapid increase in productivity is among the major concerns of modern manufacturing processes. Higher spindle speeds allow for faster material removal and shorter machining time. That is why high-speed machining (HSM) systems become more popular within industries which require precision machining and mass manufacturing operations. High temperatures, thermal distortions, dynamic instability, and quick wearing out are among the problems associated with high-speed machining. For these reasons, experts seek to analyze spindle speed effects on machining to establish optimal parameters [8]. With the development of materials like coated carbide tools, ceramic tools, cubic boron nitride (CBN) tools, and polycrystalline diamond (PCD) tools, there is an improvement in machining with faster spindle speed. Furthermore, the use of advanced CNC machining technologies has made adaptive machining and improved spindle speed control possible, which in turn enhances productivity in industries. To study the machining performance and predict tool

wear during machining operations carried out under varying spindle speeds, the use of modern monitoring techniques that include sensors, thermal imaging, vibration analysis, acoustic emission monitoring, and artificial intelligence techniques is also prevalent [9], [10]. There is a considerable amount of literature on the relationship between machining characteristics and spindle speed. Earlier studies have indicated that cutting forces, wear rates, heat generation, chip formation, and surface finish are significantly affected by spindle speed. The optimum spindle speed changes depending on the properties of the material being worked, the cutting tools used, the machining process, and the cooling method employed. Consequently, an experiment must be performed to obtain the proper spindle speeds for specific machining purposes [11]. It is imperative to understand the effects of changing spindle speed on the life span and performance of machining using turning process. In order to accomplish this, experiments were conducted where the spindle speed was varied while keeping the feed rate and depth of cut constant. In order to establish the effect of spindle speed on machining characteristics, some important factors in machining like surface finish, cutting temperature, material removal rate, and tool wear have been evaluated. The industry would find the findings of this study very helpful in improving production efficiency and the lifespan of cutting tools.

Table 1: Important Machining Parameters Affecting Machining

Machining Parameter	Effect on Machining Performance
Spindle Speed	Influences cutting temperature, tool wear, and surface finish
Feed Rate	Affects material removal rate and surface roughness
Depth of Cut	Controls cutting force and machining load
Tool Geometry	Influences chip formation and cutting efficiency
Cutting Fluid	Reduces heat generation and friction
Workpiece Material	Affects machinability and tool wear
Tool Material	Determines cutting performance and durability

Table 2: Influence of Spindle Speed on Machining Characteristics

Spindle Speed Condition	Observed Effect
Low Spindle Speed	Lower cutting temperature and tool wear
Moderate Spindle Speed	Improved surface finish and stable cutting
High Spindle Speed	Increased productivity and heat generation
Excessively High Speed	Rapid tool wear and vibration problems

Table 3: Common Tool Wear Mechanisms at Different Spindle Speeds

Tool Wear Type	Cause	Effect on Machining
Flank Wear	Friction between tool and workpiece	Poor dimensional accuracy
Crater Wear	High cutting temperature	Weakening of cutting edge
Adhesion Wear	Material sticking on tool surface	Rough surface finish
Abrasion Wear	Hard particles in workpiece	Gradual tool degradation
Oxidation Wear	High thermal exposure	Reduced tool life

Table 4: Effect of Spindle Speed on Surface Finish

Spindle Speed	Surface Finish Quality
Low RPM	Rough surface due to irregular cutting
Medium RPM	Smooth and stable surface finish
High RPM	Better finish initially
Very High RPM	Surface damage due to vibration and heat

Table 5: Comparison Between Low and High Spindle Speed Machining

Parameter	Low Spindle Speed	High Spindle Speed
Material Removal Rate	Low	High
Tool Wear Rate	Lower	Higher
Cutting Temperature	Lower	Higher
Productivity	Lower	Higher
Surface Finish	Moderate	Better initially
Tool Life	Longer	Shorter
Energy Consumption	Lower	Higher

2. Material & Method

The objective of the present experimental study was to study the effect of variation in spindle speed on the tool life and machining performance during turning operations. The study focused on the analysis of machining parameters at different spindle speed values like surface finish, cutting temperature, material removal rate, and tool wear. Lathe machines were used in conducting experiments under controlled machining parameters. The main reason why mild steel was selected as workpiece material is due to its industrial applicability, machinability, and wide usage in manufacturing industries. Cylindrical workpieces of mild steel with constant dimensions were prepared before conducting experiments. As high-speed steel cutting tools are suitable for medium-speed operations and offer toughness and wear resistance, they were used in machining operations. The surfaces of the workpieces were carefully cleaned of dust and rust in order to remove any other unwanted particles prior to machining. In order to minimize vibration and ensure steady cutting conditions throughout the machining process, the samples were held tightly on the lathe. Tool positioning errors that could lead to fluctuations in machining behavior were minimized through consistent geometry and orientation of the cutting tool. Using constant values of feed rate and depth of cut, the machining tests were conducted through manipulation of the spindle speed. A total of four different spindle speeds were considered in the tests: 300 RPM, 500 RPM, 700 RPM, and 900 RPM. During all machining tests, the constant value of 1 mm was used for the depth of cut, and 0.2 mm/rev for the feed rate. To properly determine the effect of spindle speed on tool wear and cutting temperature, dry machining conditions were employed in the absence of any cutting fluid. The cutting tool formed continuous chips when material was removed from the workpiece surface through the process of turning while under controlled machining conditions. To ensure that there is consistency across the different levels of spindle speeds, each test case was performed at a fixed machining length and machining time. The cutting tool was assessed for tool wear and damage after each machining operation. A number of machining parameters were analyzed in the experiment. Surface roughness readings were taken on the machined samples using a surface roughness tester. A digital infrared thermometer was employed immediately after the cutting operation to record the temperature created as a result of the cutting operation. Tool wear was determined through measuring the progress of wear and flank wear on the cutting edge of the HSS tool using a toolmaker's microscope. The MRR was calculated from the machining time and measurements made. The obtained experimental data were then used to conduct comparisons between machining at various spindle speeds. The experiments were carried out repeatedly to achieve high accuracy in the results. The systematic study conducted on the effect of spindle speed in relation to machining operations and cutting tool wear became possible due to the experimental design adopted. The methodology also aided in identifying the optimal conditions for spindle speed in an effort to enhance surface finish and increase machining efficiency.

Table 6: Workpiece Material Properties

Property	Mild Steel
Material Type	Low Carbon Steel
Density	7.85 g/cm ³
Hardness	120–140 BHN
Tensile Strength	400–550 MPa
Thermal Conductivity	50 W/m·K

Machinability	Good
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Table 7: Machining Parameters Used During Experimentation

Parameter	Value
Machining Operation	Turning
Spindle Speeds	300, 500, 700, 900 RPM
Feed Rate	0.2 mm/rev
Depth of Cut	1 mm
Cooling Condition	Dry Machining
Workpiece Material	Mild Steel
Tool Material	HSS

3. Experimental Details

The objective of the experiment was to determine the effects of spindle speed variations on the life span and efficiency of the tool during the turning processes. The experiment was conducted under controlled conditions using a conventional center lathe machine. Since mild steel is commonly used in industrial applications and can be easily worked, it was selected as the material to be machined. To ensure consistency in the experimental results, workpieces were produced with uniform dimensions for each machining operation. The turning process was done using a single-point cutting tool made of high-speed steel (HSS). For consistency in machining operations, the geometry, nose radius, rake angle, and clearance angle were kept constant for the entire experiment. In order to ensure no vibration occurred during the process of machining, the samples were properly cleaned and secured to the lathe chuck. These experiments were performed by adjusting the spindle speed with a constant feed rate and cut depth. To observe their effect on machining processes, four different spindle speeds were selected as 300 RPM, 500 RPM, 700 RPM, and 900 RPM. During each machining process, 1 mm was used as the depth of cut and 0.2 mm/rev as the feed rate. In order to clearly identify the influence of spindle speed on thermal effect in relation to cutting tool wear and machining process, dry machining was conducted without using any coolant. For every test conducted, the material was worked on under consistent operating parameters for a fixed cutting length. During the course of the test, the cutting process was carefully monitored, with continuous chips being formed in the process of turning. Following machining, an infrared thermometer was employed to measure the temperature generated during the cutting process. The surface roughness of the workpieces obtained was measured by a surface roughness tester.

Tool wear analysis was done after each cycle of machining using a toolmaker's microscope. Since flank wear constitutes one of the most common failure mechanisms which affect tool life during turning processes, flank wear was evaluated. The MRR was calculated based on the machining time and dimensions of the material. In order to study the tool's effectiveness as well as the efficiency of the machining process, the collected data were analyzed for different spindle speeds. In order to ensure consistent and repeatable results, the experiments were repeated multiple times under the same conditions. The results of the experiment were averaged for the purpose of analysis and discussion. This experimental approach made the analysis of the effects of spindle speed on the surface finish, cutting temperature, MRR, and tool wear possible.

Table 8: Combined Experimental Details Table

Parameter Category	Parameter	Specification/Value
Machine Details	Machine Used	Conventional Centre Lathe
	Machining Operation	Turning
	Cooling Condition	Dry Machining
Workpiece Details	Workpiece Material	Mild Steel
	Workpiece Shape	Cylindrical
	Workpiece Diameter	25 mm
	Workpiece Length	120 mm
Cutting Tool Details	Tool Material	High-Speed Steel (HSS)

	Tool Type	Single Point Cutting Tool
	Rake Angle	10°
	Clearance Angle	8°
	Nose Radius	0.8 mm
Machining Parameters	Feed Rate	0.2 mm/rev
	Depth of Cut	1 mm
	Spindle Speed Range	300–900 RPM
	Selected Spindle Speeds	300, 500, 700, 900 RPM
Measurement Parameters	Surface Roughness	Measured using Surface Roughness Tester
	Cutting Temperature	Measured using Infrared Thermometer
	Tool Wear	Measured using Toolmaker's Microscope
	Machining Time	Measured using Digital Stopwatch
	Dimensional Accuracy	Measured using Vernier Caliper
Experimental Observations	300 RPM	Stable cutting with low heat generation
	500 RPM	Improved surface finish and smooth cutting
	700 RPM	Higher productivity with acceptable wear
	900 RPM	Excessive heat and rapid tool wear observed

4. Result & Discussion

The objective of carrying out the experimental analysis was to examine the effects of spindle speed variation on tool life and machining performance while turning. The parameters considered for evaluating machining performance included surface roughness, cutting temperature, rate of material removal, and tool wear at different speeds of spindle. It became abundantly clear from the experimental results that spindle speed had a significant influence on thermal aspects, durability of cutting tool, and machining performance. In other words, the machining process was highly dependable since there was low tool wear and less heat generation at a low spindle speed (300 RPM). Cutting tool durability was improved due to lower temperatures, which minimized thermal stresses. However, the machining performance was somewhat low since cutting speed was quite slow. Moreover, the occurrence of irregular chip formation and the buildup of an edge led to a rather rough surface finish at low spindle speeds. The performance of the machining process became much better with the increase of the spindle speed to 500 RPM and 700 RPM. As a result of regular machining processes and better chip removal, surface roughness values became lower. The high cutting speeds improved machining productivity due to higher rates of material removal. There was no considerable wear progression despite the rise in cutting temperatures. From among the spindle speeds analyzed, the highest machining performance occurred at a spindle speed of 700 RPM. Owing to the increased level of friction and deformation, heat formation significantly occurred between the tool and workpiece at 900 RPM of spindle speed. The tool wear process including flank wear and crater wear became better due to the high temperature. In addition, the tool life decreased and the stability of machining worsened due to the fast wear growth. Moreover, during milling at higher spindle speeds, there occurred vibrations and chatter. As a result, the thermal instability and vibration effect resulted in the deterioration of the surface quality although the maximum material removal rate was reached at 900 RPM. The analysis of the cutting temperature showed that it was directly proportional to the spindle speed because of higher friction and energy dissipation in the cutting zone. The increased cutting temperature affected the tendency for the faster wear of the HSS cutting tool. In comparison with both low and extremely high spindle speeds, moderate spindle speed conditions gave better surface finish as shown in roughness studies on surfaces. Vibration caused poor surface condition when the spindle speed was too high, while uneven surface marks developed when the spindle speed was too low. Hence, it was observed that moderate spindle speed gave the optimum surface condition. The major type of wear in the machining process was flank wear, based on tool wear analysis. As there were fewer mechanical and thermal stresses at low spindle speeds, flank wear developed at a slower rate. But due to the higher temperatures and the interaction between the cutting tool and the work material, rapid flank wear developed at higher spindle speeds. The results from the experiment have shown that higher spindle speed plays a significant role in increasing machining productivity and extending tool life. Although very fast spindle speeds can lead to rapid wear and deterioration due to heating effects, very slow spindle speeds reduce

productivity. For optimum machining with high productivity, tolerable tool wear and better surface finishes, medium spindle speed levels are recommended.

Table 9: Experimental Results and Performance Analysis

Spindle Speed (RPM)	Surface Roughness (μm)	Cutting Temperature (°C)	Tool Wear (mm)	Material Removal Rate (cm ³ /min)	Observation
300	3.2	68	0.12	12	Stable cutting with low productivity
500	2.5	82	0.18	18	Improved surface finish
700	1.9	96	0.24	24	Optimum machining performance
900	2.8	118	0.39	30	Rapid tool wear and vibration

Table 10: Effect of Spindle Speed on Machining Characteristics

Machining Characteristic	Low Spindle Speed	Moderate Spindle Speed	High Spindle Speed
Cutting Temperature	Low	Moderate	High
Tool Wear Rate	Low	Acceptable	Rapid
Surface Finish	Rough	Smooth	Slightly Deteriorated
Material Removal Rate	Low	Moderate	High
Tool Life	Longer	Optimum	Shorter
Machining Stability	Stable	Very Stable	Vibration Observed

Table 11: Tool Wear Observation at Different Spindle Speeds

Spindle Speed (RPM)	Dominant Wear Type	Wear Severity
300	Minor Flank Wear	Low
500	Flank Wear	Moderate
700	Uniform Flank Wear	Acceptable
900	Flank and Crater Wear	Severe

Table 12: Comparative Analysis of Machining Performance

Parameter	Best Condition Observed
Minimum Tool Wear	300 RPM
Best Surface Finish	700 RPM
Maximum Productivity	900 RPM
Optimum Overall Performance	700 RPM
Lowest Cutting Temperature	300 RPM
Highest Material Removal Rate	900 RPM

5. Conclusion

The research sought to investigate the effects of varying spindle speeds on tool life and machine performance in a turning process. Based on experimental results, spindle speed plays an important role in material removal rate, cutting temperature, surface finish, and cutting tool wear behavior. Despite low cutting temperature and cutting tool wear as a result of slow spindle speed, it reduced the efficiency of machining. Despite causing faster cutting tool wear due to high heat production, higher spindle speeds improved material removal rate and efficiency. With low tool wear, better surface finish, and stability in the cutting process, moderate spindle speed (700 RPM) provided the highest efficiency in machining among all experimental variables. In light of experimental results, it is clear that industrial organizations should improve spindle speed for effective machining, quality products, and cutting tool longevity.

6. Reference

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