
Analysis of the Effect of Variations in Feed Rate on the Wear of HSS End Mill Cutters in CNC Milling Processes Using the Finite Element Method

Muhammad Hisyam Rizqulloh¹, Mochamad Mas'ud²

^{1,2}Mechanical Engineering Study Program, Faculty of Engineering, Yudharta University, Pasuruan
Email: ¹hisyam020503@gmail.com , ²masud.teknik@yudharta.ac.id

Abstract

This study investigates the effect of feed rate variations on the wear of High-Speed Steel (HSS) end mill cutters during the CNC milling of Aluminum 5052. The research addresses the challenge of optimizing tool life by exploring the complex interplay between feed rate, temperature, and wear. A quantitative approach was adopted, combining experimental tests with a Finite Element Method (FEM) simulation. The experiment used a fixed cutting depth of 1.5 mm and varied feed rates at 30, 40, and 50 mm/min. Data on temperature and tool wear were collected using an infrared thermometer and a digital microscope, respectively, while FEM simulations were performed using ANSYS to analyze thermal and mechanical stresses. The results showed that tool wear was not linearly proportional to temperature, with the highest wear occurring at 40 mm/min, despite lower temperatures. The FEM simulations successfully visualized critical zones of stress and deformation, confirming that tool performance is a function of both thermal and mechanical factors. In conclusion, optimizing feed rate is crucial for minimizing wear, and this integrated approach provides a robust framework for enhancing machining efficiency.

Keywords: *Cutting Temperature, Feed Rate, Finite Element Method, HSS End Mill, Thermal Stress*

INTRODUCTION

The field of manufacturing has long relied on machining processes, where the selection of appropriate tools, materials, and methods is critical for achieving high-quality final products. A common challenge in this area is tool wear, which is a natural consequence of the continuous interaction between the cutting tool and the workpiece. This phenomenon is particularly relevant for High-Speed Steel (HSS) tools, where the intense friction and high temperatures generated at the cutting zone can reduce tool hardness, thereby accelerating wear and impacting surface roughness and cutting forces (Kalpakjian & Schmid, 2014; Stephenson & Agapiou, 2016). Understanding and mitigating this wear is paramount for optimizing machining efficiency and maintaining product quality. Various forms of tool wear, such as flank wear, crater wear, plastic deformation, and chipping, are well-documented and are directly influenced by the machining conditions (Trent & Wright, 2000; Davim, 2008).

Beyond the physical interaction, the tribological and thermal effects in the cutting zone are critical factors influencing tool life. High temperatures resulting from friction can lead to the softening of the tool's material, but the relationship between temperature and wear rate is not always linear (Korkut et al., 2007; Stephenson & Agapiou, 2016). The inherent properties of both the tool and workpiece materials also play a significant role. For instance, high carbon content in the workpiece can accelerate tool wear, while the use of a proper cutting fluid can help manage temperature and slow down degradation (Groover, 2015). This complex interplay of forces, heat, and material properties underscores the need for a comprehensive analysis of tool wear phenomena, especially in advanced manufacturing contexts like CNC milling.

Despite extensive research on tool wear, there remain complexities in predicting and controlling the wear of HSS end mills, particularly under varying cutting conditions. The influence of feed rate, a critical machining parameter, on tool wear and temperature has been a subject of numerous studies, yet contradictory results are often reported. Some studies suggest a direct correlation between higher feed rates and increased wear due to higher cutting forces (Arizmendi et al., 2009; Kalpakjian & Schmid, 2014), while others argue that a lower feed rate can prolong the cutting time and lead to excessive heat accumulation, which also accelerates wear (Groover, 2020). This apparent contradiction highlights the

need for a more nuanced understanding of the dominant wear mechanisms under specific machining conditions. For example, the effect of machine vibration, cutting stability, and workpiece material quality can significantly alter the wear rate, making a simple, linear relationship between feed rate and wear insufficient for optimal process control (Li et al., 2002; Wang et al., 2005).

To address this, traditional experimental approaches, while valuable, are often time-consuming and costly. They may not provide a complete picture of the thermal and mechanical stresses within the cutting zone. The integration of numerical simulation techniques, such as the Finite Element Method (FEM), offers a powerful tool to complement experimental work. FEM can model complex phenomena like heat distribution, stress concentration, and material deformation with high precision, offering insights that are difficult to obtain through physical measurements alone (Cong & Zhang, 2018; Marzuki & Syukran, 2020). Although FEM has been widely applied in machining simulations, its specific application to analyze the combined effects of varying feed rates on the wear and temperature of HSS end mill cutters for a specific material, such as Aluminum 5052, requires a dedicated and systematic investigation to validate and calibrate the simulation models with experimental data.

The objective of this research is to comprehensively analyze the effect of varying feed rates on the wear of HSS end mill cutters during the CNC milling of Aluminum 5052. This study aims to investigate the complex relationship between feed rate, cutting temperature, and tool wear by combining experimental analysis with numerical simulation using the Finite Element Method (FEM). This research is urgent as it provides practical guidelines for optimizing machining parameters to enhance tool life and improve production efficiency in the manufacturing industry. The novelty of this study lies in its integrated approach, which combines physical experiments with validated FEM simulations to provide a deeper, more predictive understanding of the wear mechanisms. By doing so, this research contributes a novel methodology that can reduce the need for extensive trial-and-error, thereby saving costs and improving the sustainability of machining processes. The findings are expected to serve as a valuable reference for engineers and researchers seeking to optimize their CNC milling operations for both economic and quality-related outcomes.

RESEARCH METHODS

This study employs a quantitative research approach, utilizing a mixed-methods design that integrates both experimental and numerical simulation methods to analyze the relationship between feed rate variations and tool wear (Reddy, 2019; Sugiyono, 2022). The research focused specifically on CNC milling of Aluminum 5052 using High-Speed Steel (HSS) end mill cutters. The experimental phase was conducted with a specimen size of 50×50 mm under a constant cutting speed and a fixed depth of cut (1.5 mm), while varying the feed rate at three levels: 30 mm/min, 40 mm/min, and 50 mm/min. The tool used was a 10 mm diameter, four-flute end mill with a total length of 150 mm (Groover, 2020; Widhiantoro, 2017). This controlled experimental setup allowed for the isolation and systematic investigation of the feed rate's direct impact on tool wear.

The primary data collection instruments included an infrared thermometer for non-contact temperature measurement and a USB digital microscope for the detailed observation and documentation of tool wear (AmScope, 2020; Zhang & Yang, 2015). Prior to experimentation, all instruments were calibrated to ensure measurement accuracy. The machining process followed a single-pass, one-directional cutting method (Kalpakjian & Schmid, 2014). For data analysis, tool wear was classified based on microscopic observations, identifying specific types such as flank wear or crater wear as per ISO 3685 (1993) standards. The temperature data were processed by calculating the average temperature for each feed rate variation. Statistical analysis, including the calculation of standard deviation, was performed to assess the consistency and variation of the experimental results (Montgomery & Runger, 2014; Walpole et al., 2012).

Simultaneously, a Finite Element Method (FEM) simulation was conducted using ANSYS or Autodesk Inventor Nastran software to model and predict thermal and mechanical behavior during the milling process (ANSYS Inc., 2024; Zienkiewicz, Taylor, & Zhu, 2013). The FEM procedure involved three main stages: pre-processing (geometrical modeling, material property definition, and load application), solving (calculation of elemental responses), and post-processing (analysis and visualization of simulation results) (Logan, 2017; Syaiful Arif, 2022). Material properties such as elastic modulus, Poisson's ratio, tensile strength, density, and shear modulus were incorporated into the model (Callister

& Rethwisch, 2021). The results from the FEM simulation were then compared with the experimental data to validate the computational model and ensure its accuracy in representing the real-world phenomena (Reddy, 2019; Sudaryono, 2021). This mixed-methods approach provides a more comprehensive understanding by not only observing the outcomes but also simulating the underlying physical processes.

The research was executed over six months, structured into several key stages: literature review, proposal development, equipment preparation and calibration, data collection, data analysis, report writing, and article drafting (Emzir, 2024). The sequential and systematic nature of this procedure ensured that all research objectives were met, from the initial hypothesis formulation to the final presentation of findings. The integration of both empirical and computational methods represents a robust and comprehensive strategy for analyzing complex manufacturing processes and provides a strong foundation for the conclusions drawn.

RESULTS AND DISCUSSION

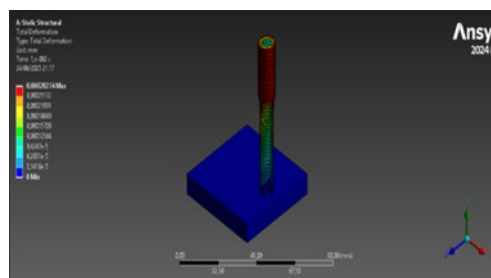
Results

Chisel Wear Test

Wear on the *end mill cutter* chisel made of *High Speed Steel* (HSS) is a natural consequence of the continuous interaction between the tool and the workpiece during the machining process (Kalpakjian & Schmid, 2014). One of the parameters that most affects the rate of wear is *feed motion* (ISO 3685, 1993; Altintas, 2012). Too high a feeding motion increases friction and pressure at the tip of the chisel, thereby accelerating the occurrence of *flank wear* and *crater wear* (Shaw, 2005). Conversely, too low a feeding motion can prolong the contact time of the tool with the workpiece, triggering the accumulation of excess heat, which also accelerates wear (Stephenson & Agapiou, 2016).

In the practice of cutting using HSS *end mill* chisels, the right setting of the feeding motion is key to maintaining the life of the tool while maintaining the quality of the machining surface (Groover, 2020). A controlled increase in feeding motion can result in an even wear pattern, but excessive increases risk of causing non-uniform wear and premature damage to the tool (Shaw, 2005; Stephenson & Agapiou, 2016). Therefore, determining optimal feeding motion parameters is very important to minimize the frequency of tool replacement and improve the efficiency and consistency of the milling process (Altintas, 2012).

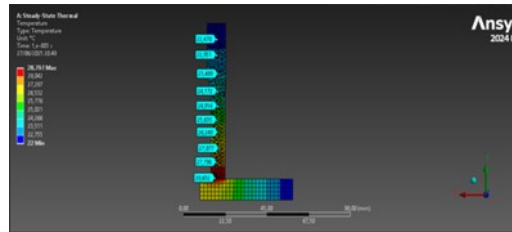
Sculpt Wear & Temperature FEM Simulation Test (ANSYS)



Fem Simulation of Tool Wear (Ansys)

Finite *Element Method* (FEM) simulation with ANSYS 2024 R1 was conducted to analyze the effect of feeding motion variations on wear and heat distribution on *end mill cutter* chisels made of *High Speed Steel* (HSS) in the CNC milling process (ANSYS Inc., 2024; Zienkiewicz et al., 2014).

The 3D model of the tool is made according to specifications, then tested with parameters such as cutting speed, cutting depth, and variation in feeding motion (Altintas, 2012). The simulation results showed that high feeding motion triggered an increase in tension, temperature, and deformation with a maximum deformation critical point of 0.00028274 mm at the tip of the tool, which accelerated abrasive and adhesive wear (Shaw, 2005).



Fem Simulation Test Tool Temperature (Ansys)

Steady-state *temperature analysis* showed a high temperature of 28.797°C at the horizontal bottom of the workpiece and a low temperature of 22°C at the top vertical, indicating a bottom-to-top heat flow or faster cooling of the vertical (Stephenson & Agapiou, 2016). These findings provide a crucial visual and quantitative picture to determine optimal cutting parameters to extend the life of the tool and improve machining efficiency and quality (Groover, 2020).

FEM Simulation Test Results

Finite *Element Method* (FEM) simulation with Ansys was used to visualize the response of an HSS-based *End Mill Cutter* chisel to force and heat during the CNC milling process (ANSYS Inc., 2024; Zienkiewicz et al., 2014). The deformation results showed that the red color at the end of the point with the highest cutting load was the most vulnerable area to deformation, while the blue color at the bottom indicated minimal deformation (Altintas, 2012).

Temperature analysis showed a maximum temperature of 28.77°C at the bottom of the tool due to friction with the workpiece, while the lowest temperature was in the upper area (Stephenson & Agapiou, 2016). This combination of deformation and temperature data reveals critical points that have the potential to accelerate tool wear (Shaw, 2005), so that they can be used to determine optimal cutting parameters and tool replacement schedules before performance degrades. This approach not only reduces the need for hands-on testing but also helps maintain production efficiency and the quality of machining results (Groover, 2020).

Calculations on the Machining Process

The calculation of machining parameters includes cutting speed, spindle rotation, and feeding speed (Groover, 2020; Kalpakjian & Schmid, 2014). In this test, a cutting speed of 121.95 m/min was obtained according to the set parameters, playing an important role in maintaining efficiency and preventing tool wear (Stephenson & Agapiou, 2016). Spindle rotation is calculated from the cutting speed and diameter of the chisel, with unit conversions for accurate results (Shaw, 2005).

Meanwhile, the feeding speed is determined by the spindle rotation, the number of chisels, as well as the feeding motion per tooth; the higher the value of these parameters, the greater the feeding rate produced (Altintas, 2012). The combination of these three calculations is the key to optimal milling process management and maintaining the quality of machining results.

Standard Deviation Calculation

Standard deviation is used to measure the wear consistency of an HSS end mill cutter tool during the CNC milling process (Montgomery & Runger, 2014; Walpole et al., 2012). In this study, the calculation results showed that at a 30 mm/min feeding motion, the standard deviation of 49.59 indicates a fairly high variation in wear. The feeding motion of 40 mm/min had a lower standard deviation, which was 38.95, showing more consistent results (Juran & Godfrey, 1999).

Meanwhile, a feeding motion of 50 mm/min yields a standard deviation of 45.52, which indicates a moderate wear variation. This analysis helps to determine the stability of the machining process and serves as a reference for the optimization of cutting parameters to maintain quality and efficiency (ISO 4287, 1997).

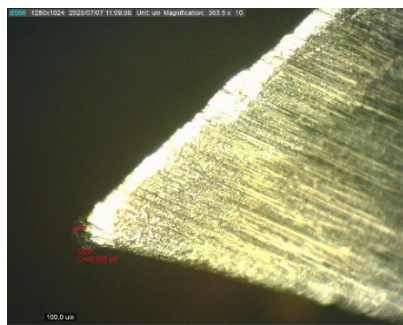
Tool Wear Test

Standard deviation plays an important role in seeing the wear consistency of the HSS end mill cutter tool in the CNC milling process (Montgomery & Runger, 2014; Walpole et al., 2012). The calculation results showed that the 30 mm/min feeding motion had a standard deviation of 49.59, indicating a fairly high wear variation.

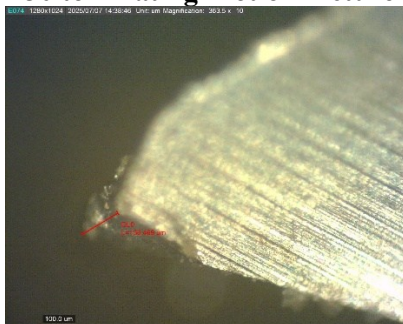
Table 1. Tool Wear Results

No	Parameter		VB	Standard Deviation
	f	a		
1	30	1,5	40,926 um	49,591 um
2	30	1,5	160,494 um	
3	30	1,5	85,663 um	
4	40	1,5	85,451 um 136,469 um	38,95 um
5	40	1,5	72,372 um	
6	40	1,5	136.187 um	
			164,333 um	
7	50	1,5	31,915 um	45,52 um

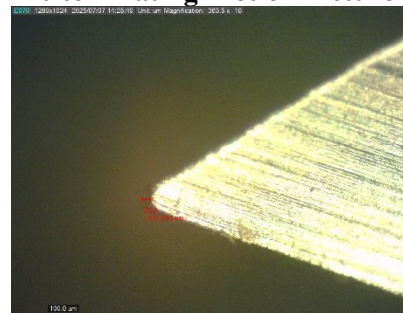
The feeding motion of 40 mm/min showed the most consistent results with a standard deviation of 38.95 (Juran & Godfrey, 1999), while at 50 mm/min, the value was 45.52, which means the variation was moderate.



30 to 1 Eating Motion Picture



40 to 1 Eating Motion Picture



Picture of Eating Motion 50 to

These findings provide an idea that the selection of the right feeding motion parameters can maintain process stability, extend the life of the chisel, and improve machining efficiency (ISO 4287, 1997).

Tool Temperature Test

Table 2. Chisel Temperature

No	Parameter		Temperature	Average
	f	a		
1	30	1,5	27.8	28.3
2	30	1,5	28.4	
3	30	1,5	28.7	
4	40	1,5	27.5	28.03
5	40	1,5	28.5	
6	40	1,5	28.1	
7	50	1,5	27.5	27.73

The results of the temperature measurement of the HSS end mill tool in the CNC machining process with a fixed cutting depth of 1.5 mm showed that the variation in feeding speed (30, 40, and 50 mm/min) provided only a relatively small temperature difference (Kalpakjian & Schmid, 2014). At a speed of 30 mm/min, the average temperature was recorded at 28.3°C; speed of 40 mm/min of 28.03°C; and at a speed of 50 mm/min, 27.73°C.

Although there was a slight fluctuation in each experiment due to external factors such as environmental conditions, chisel wear, and machine stability (Drozda & Wick, 1983), data trends show that an increase in feeding speed actually slightly lowers the chisel temperature. This indicates that under conditions of constant cutting depth, the cutting process is stable and the machine can maintain the chisel temperature in a safe range (ISO 3685, 1993).

HSS Tool Wear and Temperature Relationship

The relationship between wear and temperature on HSS end mill chisels is influenced by the interaction between cutting forces and high friction during the machining process (Shaw, 2005). This friction triggers an increase in temperature, especially at the end of the tool that is in direct contact with the material, potentially accelerating softening and weakening the microstructure of the tool (Groover, 2010).

However, the results of the study show that wear does not always increase as temperatures rise. For example, at a feed rate of 30 mm/min, a higher temperature actually results in greater wear than a feed rate of 50 mm/min, which has a lower temperature.

This proves that, in addition to temperature, factors such as engine vibration, cutting stability, and material quality also affect wear levels (ISO 3685, 1993). By understanding these interactions, operators can precisely set parameters such as feed rate and cutting speed to extend the life of the tool while maintaining the quality of machining results (Kalpakjian & Schmid, 2014).

Laboratory Test Results

In the CNC milling process, the cutting temperature is a crucial factor that arises due to friction between the tool and the workpiece (Shaw, 2005). Based on the results of laboratory tests, with a fixed cutting depth of 1.5 mm, the feeding speed (f) of 30 mm/min produced an average highest temperature of 28.3°C, followed by f = 40 mm/min of 28.03°C, and the lowest temperature at f = 50 mm/min of 27.73°C.

In addition to temperature, tool wear was also observed, where the largest value was recorded at f = 40 mm/min at 164.333 µm, followed by f = 30 mm/min at 160.494 µm, and the lowest at f = 50 mm/min at 133.297 µm. Interestingly, this data shows that wear and tear is not always directly proportional to temperature; At f = 30 mm/min, higher temperatures are followed by greater wear than at f = 50 mm/min with lower temperatures.

This proves that wear is affected by various other factors such as process stability, machine vibration, chisel quality, and material hardness (Groover, 2010; ISO 3685, 1993). By selecting the right cutting parameters, operators can maintain stable temperatures, minimize wear, extend the life of the chisel, and ensure high-quality and efficient machining results (Kalpakjian & Schmid, 2014).

Discussion

In the CNC milling process, the cutting temperature is one of the key factors that need to be considered because it directly affects the performance and life of the tool (Shaw, 2005). This temperature arises due to the continuous friction that occurs between the chisel and the surface of the workpiece during the cutting process (Kalpakjian & Schmid, 2014).

The results of the laboratory test showed that at a constant cutting depth of 1.5 mm, the variation in feeding *speed (feed rate)* made a significant difference to the temperature produced. At a feeding speed of 30 mm/min, the highest average temperature was recorded at 28.3°C, followed by a speed of 40 mm/min with a temperature of 28.03°C, and the lowest temperature was reached at a speed of 50 mm/min, which was 27.73°C.

In addition, tests were also carried out on the level of wear of the chisel, where the results showed that the greatest wear value occurred at $f = 40$ mm/min with 164.333 μm , followed by $f = 30$ mm/min at 160.494 μm , and the lowest wear value at $f = 50$ mm/min at 133.297 μm . Interestingly, this data shows that the level of tool wear is not always directly proportional to the increase in temperature (ISO 3685, 1993).

For example, even though the resulting temperature is higher at $f = 30$ mm/min than at $f = 50$ mm/min, the wear and tear that occurs is greater. This indicates that tool wear is affected by various factors other than temperature, such as the stability of the cutting process, the vibration level of the machine, the quality and durability of the sculpted material, and the mechanical properties of the workpiece (Groover, 2010).

Therefore, the selection of the right cutting parameters is very important to control temperature, minimize wear, extend the service life of the chisel, and ensure optimal and efficient machining results (Stephenson & Agapiou, 2016).

CONCLUSION

This study demonstrated that variations in feed rate significantly affect the wear of HSS end mill cutters in CNC milling of Aluminum 5052, although the relationship between feed rate, tool wear, and cutting temperature is not strictly linear. The experimental results revealed that the highest wear occurred at 40 mm/min, despite lower temperatures compared to other feed rates, suggesting that wear is influenced not only by thermal effects but also by mechanical stresses, vibration, and process stability. FEM simulations further validated these findings by visualizing critical stress and deformation zones, thereby confirming that both thermal and mechanical factors play a crucial role in determining tool performance. These insights highlight the need for precise parameter optimization to enhance tool life, maintain machining quality, and improve overall efficiency in manufacturing practices.

However, the findings of this research are limited by the narrow range of feed rates tested and the focus on a single workpiece material, Aluminum 5052, which restricts the generalizability of the results to other machining contexts. Future research should expand to include a wider range of feed rates, different tool geometries, and various workpiece materials such as steels or titanium alloys, while also incorporating other influential parameters like cutting fluid type and delivery method. Moreover, advanced simulation models that account for dynamic machining factors such as vibration and tool-workpiece interaction should be employed to achieve more comprehensive insights. Practically, the outcomes of this study provide valuable guidance for CNC operators and manufacturing engineers in selecting feed rate parameters that balance productivity with tool longevity, ultimately reducing production costs and supporting sustainable machining processes.

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