Experimental Finalization of Levels of Predictor Variables for Accelerated Degradation Testing of Cutting Tools

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Abstract

During accelerated degradation testing (ADT), the component is exposed to higher levels of parameters that cause it to fail faster than it would under normal operating conditions. This approach saves time and reduces expenses associated with tool life tests for valuable workpieces. The fundamental assumption of ADT is that failure modes observed at elevated levels of parameters are similar to those under recommended usage conditions. In this study, tool failure modes are utilized to determine the appropriate levels of predictor variables, like cutting parameters and tool nose radius, for ADT of PVD-coated carbide tools during dry machining of Inconel 800. To study tool failure modes, experiments are done at three levels of cutting speed (V_c), feed rate (f), depth of cut (a_p), and nose radius (r) by following the Taguchi L_9 orthogonal array. Notably, a favourable tool failure pattern is observed when employing the middle level of the nose radius and operating at relatively higher cutting speeds while ensuring that f and a_p fall within the recommended range. In the future, with the parameters' levels established through this study, full-scale ADT will be performed and extrapolated to predict the reliability function of the cutting tool under normal conditions. The suggested method holds potential for various applications, including estimating the reliability of cutting tools and monitoring tool condition, among others.

Keywords
Inconel 800, PVD-coated Carbide, ADT, and Tool Wear.

1. Introduction
Cutting tool life prediction is crucial for effectively managing tool life, cost, machine tool availability, and machining process quality. Generally, cutting tools degrade stochastically, influenced by factors such as machining time, tool material and type, cutting parameters, machine tool type, workpiece, and so on (Zaretalab et al. 2019). To model the reliability function of cutting tools in a specific experimental setup, machining parameters like cutting speed (V_c), feed rate (f), depth of cut (a_p), and geometric parameters like tool nose radius (r) must be considered. However, run-to-fail tests for predicting tool reliability are expensive and time-consuming. Predicting cutting tool life without event data is difficult. This challenge is especially evident with new tools or in high-value operations where tool failure is unacceptable. It appears that the concept of accelerated degradation testing (ADT) of cutting tools offers a potential solution by reducing the consumption of costly workpiece materials and time.

The fundamental assumption in ADT is that failure modes or patterns at higher levels of parameters are similar to those observed under normal working conditions. Among various types of tool wear, flank wear is a predictable pattern that significantly affects the surface quality and dimensional accuracy of the final product. Therefore, the width of wear on the flank face serves as a criterion for predicting tool life (Siddhpura and Paurobally 2013). A cutting edge typically experiences flank wear as its primary failure mode, provided it does not fail due to other types of wear during the initial phase of machining. In machining superalloys like Inconel, tool wear and limited tool lifespan pose significant challenges due to the intense strain hardening, poor thermal conductivity, exceptional strength, and heightened chemical activity of these alloys (Liu et al. 2020). To ensure favourable tool wear during accelerated degradation testing (ADT), careful selection of the levels of cutting parameters must be performed prior to conducting tool life tests under ADT. This underscores the significance of the present study, which utilizes tool life tests with cutting speeds significantly higher than the manufacturer's recommendation to ascertain the appropriate levels of predictor variables for accelerated degradation testing (ADT) of cutting tools.

1.1 Objectives
The purpose of this investigation is to pinpoint the ideal range of cutting speeds for use in accelerated degradation testing (ADT). The design-of-experiments methodology is utilized in order to carry out tool failure testing at varying levels of predictor variables. The study involves observing the tool failure modes for each combination of parameters specified in the selected design of experiments. The objective is to identify and validate the levels of machining parameters (V_c, f, and a_p) along with the appropriate tool nose radius (r) that lead to the most favourable tool wear mode.

2. Literature Review
A cutting tool fails due to one or a combination of the following reasons (Ghosh and Mallik 2010):

i. Plastic deformation in a tool caused by high temperatures and large stresses
ii. Mechanical breakage of the cutting tool due to large force and inadequate strength and toughness of the tool
iii. Blunting of the cutting edge of the cutting tool through the mechanism of gradual wear

Plastic deformation and mechanical breakage in a tool can be mitigated by selecting the appropriate cutting tool material along with suitable tool geometry and machining conditions. But wear is a natural and inevitable phenomenon. It is not possible to completely prevent the gradual wearing process. It is commonly accepted that the mechanical and chemical interactions that take place between the tool and the workpiece during machining are the root cause of tool wear (Zhu et al. 2013).

Inconel 800, a nickel-based superalloy, is a newer “difficult-to-cut” alloy. This alloy is employed in a variety of industries, including marine, automotive, aerospace, defence, and so on. The properties, like superior toughness, high tensile strength, good corrosion resistance, high temperature strength, and so on, make this alloy highly demanded (Hsiao et al. 2021). However, due to their severe work hardening, poor thermal conductivity, and extremely high toughness, nickel-based superalloys fall into the category of materials that are hard to machine (Gupta et al. 2018). So, during the machining of these alloys, severe tool wear and poor tool life are major problems (Wang et al. 2022).

Commonly observed tool wear patterns on cutting tools generally include flank wear, crater wear, built-up edges, chipping, notch wear, thermal cracking, and so on. Among the various patterns of tool wear, the quality of the machined surface depends on the flank wear of the cutting tool insert (Senthilkumar and Tamizharasan 2015). Flank wear represents the most desirable tool wear condition due to its predictability, as it exhibits a well-defined relationship between flank wear and achievable tool life. Thus, tool life is generally estimated based on using the threshold value of the flank wear width (FWW) as the criterion for tool failure. Gupta et al. (2021) consider the threshold value of the maximum FWW to be 0.3 mm as the tool life criterion during the machining of Inconel 800 by using coated carbide inserts.

Accelerated degradation testing (ADT) is carried out under severe conditions in order to expedite the performance degradation of a product and gather reliability analysis data in a short amount of time with limited funds (Liu et al. 2016). In an ADT plan, it is essential to ensure that the failure mode and mechanism of products remain consistent across various accelerated stresses. This allows for the extrapolation of lifetime characteristics at normal use stress levels based on the data obtained from accelerated degradation (Wang et al. 2015).

In view of this survey, the main goal of this paper is to finalize the levels of cutting parameters in general and cutting speed in particular, along with the identification of a suitable nose radius, so that these levels of parameters can be used for accelerated degradation testing of cutting tools.

3. Methods

To extrapolate the reliability function under normal working conditions from the ADT data, it is essential to ensure that the failure modes observed during ADT are similar to those occurring under normal conditions. Since flank wear is a desirable failure mode for a cutting tool during regular usage, experiments are conducted to determine the appropriate levels of predictor variables for ADT. After each experimental run, the cutting edges of the tool are observed using an optical microscope. Based on these observations, the levels of cutting parameters are finalized to ensure the occurrence of the desired tool failure mode during ADT at the specified cutting parameters' levels.

The turning tests of nickel-based heat-resistant superalloy Inconel 800 bar (diameter: 127 mm, length: 300 mm) are carried out on a lathe machine tool (spindle speed: 13–800 rpm) under dry condition by using PVD-coated carbide tools (Kyocera's CNMG MS PR1535 grade inserts). To hold the insert, a DCLNR 2020K12 tool holder is used. The orthogonal rake angle, inclination angle, and principal cutting edge angle obtained by combining the insert and tool holder are -6°, -6°, and 95°, respectively.

To determine the appropriate levels of cutting parameters and nose radius for accelerated degradation testing (ADT), machining tests are conducted at three different levels of V_c, f, a_p, and r values. The recommended cutting speed range by the tool manufacturer is between 40 and 60 m/min. However, in this study, the experimental cutting speed values are intentionally set significantly higher than the recommended range, while the f and a_p values remain within the recommended conditions. The current work adopts the Taguchi L_9 orthogonal array experimental design. For each machining test, a fresh cutting insert is used. The tool wear morphology and failure modes are observed through an Olympus optical microscope after each test. Additionally, the tool failure time is monitored. Figure 1 illustrates the experimental setup.

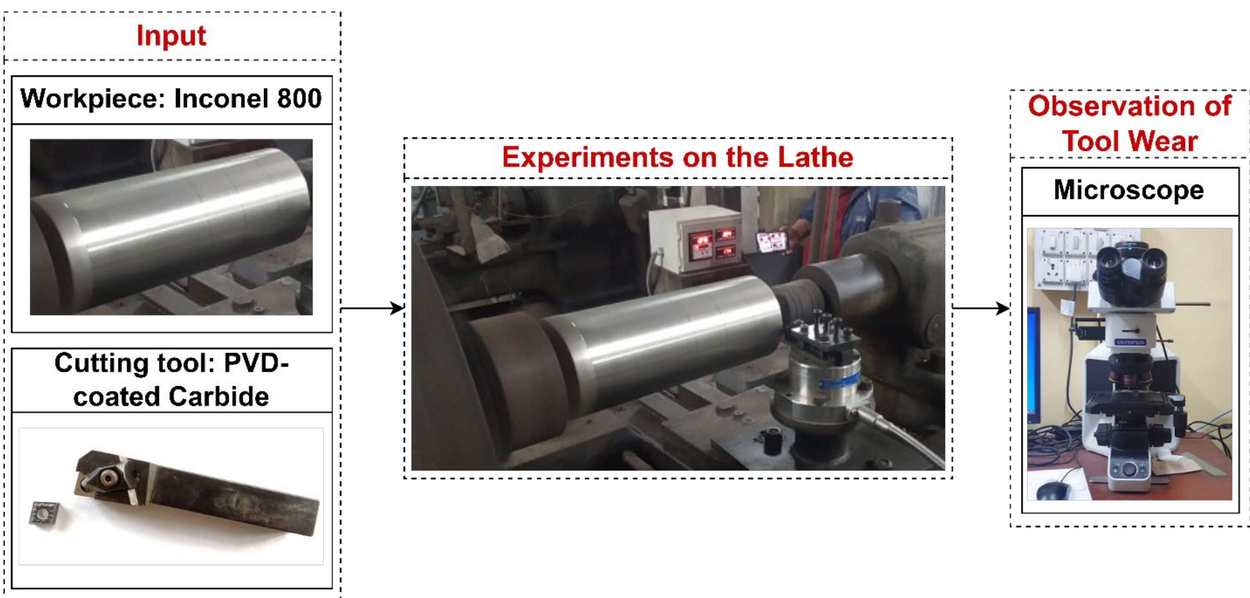

Figure 1. The experimental setup

4. Data Collection

As mentioned previously, this study involves conducting machining tests on cutting tools. Four factors, namely V_c, f, a_p, and r, have been selected, and three levels have been assigned to each of these factors. Following each machining test, the flank face of the cutting tool is examined using an optical microscope to analyze the tool failure mode. The time taken to reach a maximum flank wear width (FWW) of 0.3 mm, or the occurrence of notch wear or chipping on the tool edge, is recorded after each machining test. Table 1 displays the experimental factors, their respective levels, and the time to failure and failure modes observed. In Table 1, the numbers 1, 2, and 3 indicate the lowest, middle, and highest levels for each parameter.

Table 1. The experimental results

Run no.	Level of cutting speed	Level of feed rate	Level of depth of cut	Level of nose radius	Failure time (s)	Tool failure mode
1	1	1	1	1	50.04	Notch wear
2	1	2	2	2	91.28	Notch wear
3	1	3	3	3	168.31	Chipping
4	2	1	2	3	85.71	Notch wear
5	2	2	3	1	59.51	Notch wear
6	2	3	1	2	77.87	Flank wear
7	3	1	3	2	93.78	Flank wear
8	3	2	1	3	57.07	Notch wear
9	3	3	2	1	20.21	Notch wear

5. Results and Discussion

The cutting edges of the tools are observed microscopically after each machining test to identify the failure modes. Figure 2 displays the microscopic view of the flank face of the cutting tools for all nine machining runs. The results indicate that in Runs 6 and 7, where the cutting speeds are relatively high and the nose radius is at the middle level, the tools fail by reaching the threshold flank wear width of 0.3 mm. In the remaining runs, before reaching the threshold of flank wear, either notch wear or chipping occurs on the cutting edge of the tools.

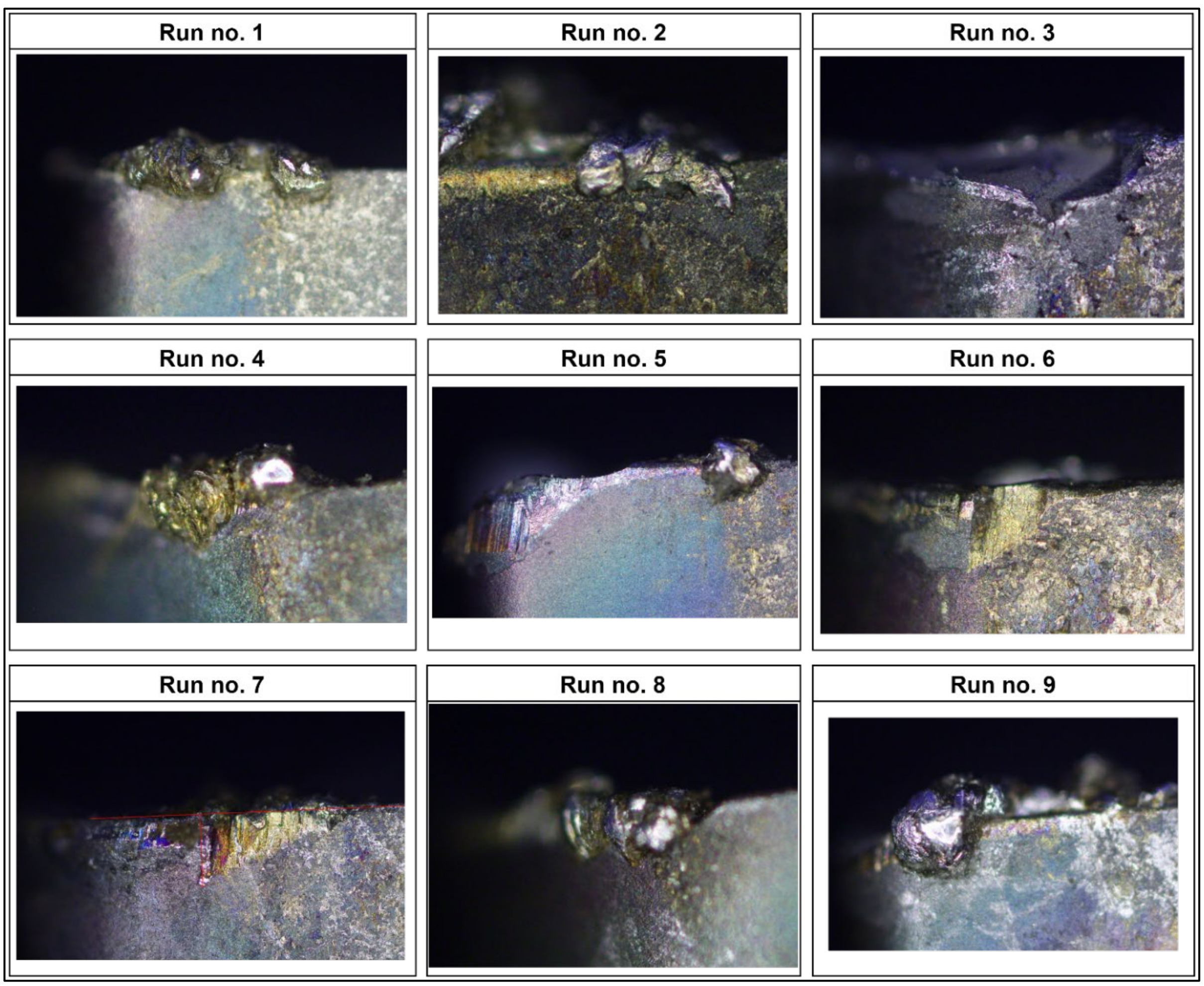

Figure 2. Microscopic view of the flank face of cutting tools

Scatterplots are prepared and analyzed for the input variables of cutting speed and nose radius, with failure time as the output variable. The scatterplots categorize the data based on failure modes represented as categorical variables. These scatterplots are presented in Figure 3. Based on these plots, it has been observed that one failure resulting from reaching the threshold value of flank wear occurs at the 2^{nd} level of cutting speed, and another failure due to the same reason occurs at the 3^{rd} level of cutting speed. Additionally, both of these failures occur at the second level (middle level) of the nose radius. This analysis reveals that a favourable tool wear mode, specifically flank wear, occurs when increasing V_c while maintaining f and a_p within the recommended range. Notably, at high cutting speeds, the tools with a middle-level nose radius experience failure due to flank wear, while unfavourable wear is observed for both the lowest and highest nose radius levels.

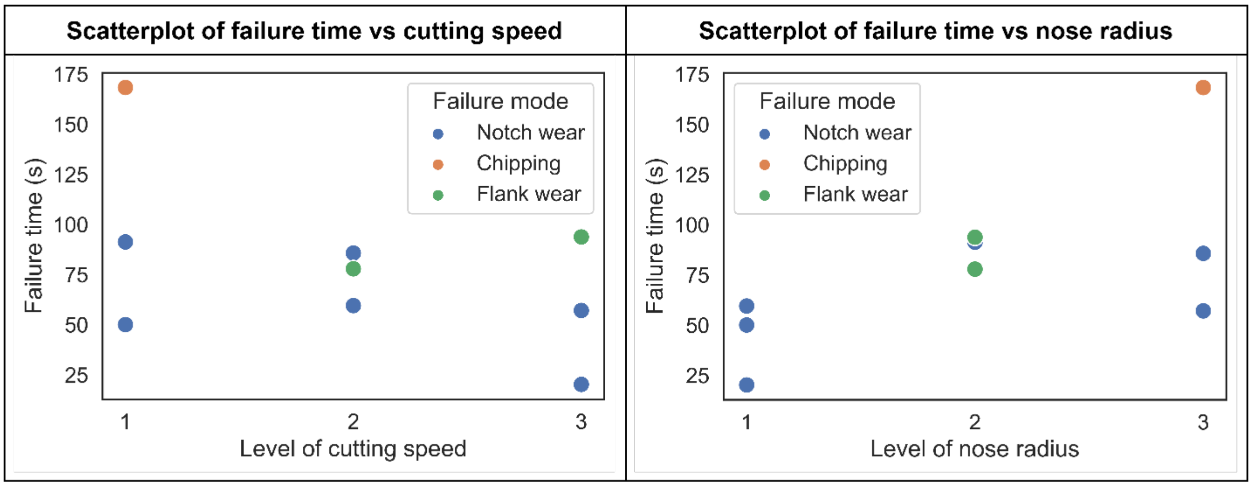

Figure 3. The scatterplots of failure time vs. cutting speed and nose radius

5.1 Validation

To validate the results, further tool failure tests are performed. The levels of the parameters are chosen as mentioned in Table 2.

Table 2. Results of validation runs

Validation run no.	Cutting speed value	Level of feed rate	Level of depth of cut	Level of nose radius	Tool failure mode
1	Between the middle and highest levels	1	3	2	Flank wear
2	Between the middle and highest levels	1	1	2	Flank wear
3	Greater than the highest level	1	1	2	Flank wear

From Table 2, it has been observed that at the selected values of cutting speed, the cutting tools fail through the favourable tool wear mode only, that is, by reaching the threshold value of flank wear width. The microscopic view of tool wear after validation runs is mentioned in Figure 4. The microscopic observation of the flank faces of the three cutting tools after the validation runs ensures threshold flank wear as the tool failure mode.

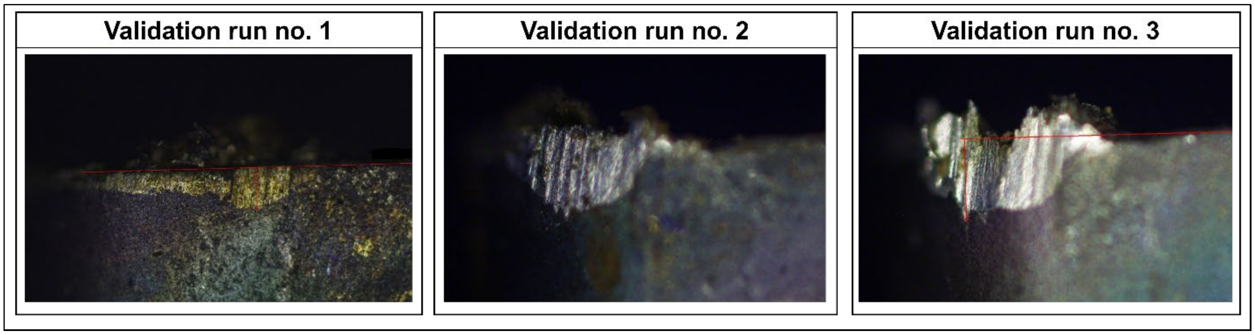

Figure 4. Microscopic view of the flank face of the cutting tools in validation runs

6. Conclusion

This study focuses on high-speed machining of Inconel 800 using PVD-coated carbide tools, with a particular emphasis on observing tool failure modes to identify the levels of parameters that result in a desirable tool wear pattern, specifically flank wear. The experimental results demonstrate that maintaining the feed rate and depth of cut within the manufacturer's recommended range increases the likelihood of flank wear on the cutting tool when cutting at speeds significantly higher than the recommended range, using a middle-level nose radius. Given the challenges associated with machining Inconel 800, this experimental study provides valuable insights into determining the levels of machining parameters suitable for accelerated degradation testing (ADT) and identifying the geometric features, such as the nose radius, of the cutting tool to be utilized during ADT.

In the future, full-scale accelerated degradation testing (ADT) will be conducted using the levels of cutting parameters finalized in this study to obtain degradation data. Subsequently, this data will be utilized to extrapolate and estimate the reliability of the cutting tool under normal operating conditions.

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Biographies

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