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Investigation of Tool Failure Modes and their Mitigation Strategies

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Abstract: *Due to its direct effect on productivity, dimensional precision, surface finish, machining expense, and product quality, tool failure is among the most critical issues in the manufacturing industry. Contemporary machining systems operate at high speeds, high temperatures, and high loads, thus increasing the rate at which tool wear and tool failure occur. This work attempts to improve tool life and machining performance by analyzing different types of tool failures associated with machining and suggesting measures that could be applied in practice to mitigate such failures. Types of tool failures include abrasion, adhesion, diffusion, oxidation, notch, plastic deformation, thermal fracture, chipping, and catastrophic failure. All the factors responsible for wear of tools, their mechanisms of operation, and various parameters affecting their operations have been discussed in details. The comparative study of materials used in making tools, types of lubricants, cooling, coatings, and techniques of process optimization are also provided in the paper. Selection of proper material, proper use of parameters, and efficient cooling help in preventing failures of tools.*

Keywords: Tool wear, Tool failure, Machining, Cutting tools, Tool life, Tool wear mechanisms, Mitigation strategies, Tool coatings, Dry machining, MQL.

I. INTRODUCTION

The manufacturing industries of today such as the automobile industry, aerospace industry, railroad, biomedical, defense, and energy are reliant on machining processes. The condition and performance of the cutting tool significantly affect the productivity and efficiency of machining processes. The cutting tool is exposed to high temperatures, friction forces, loading conditions, and mechanical stresses while performing the machining operation. The cutting edge ultimately wears out due to such extreme operating conditions, causing wear of the tool, and ultimately failure of the tool. Tool failure not only reduces machining efficiency but also increases production costs, energy consumption, time spent on machines, and component rejection due to poor quality surfaces. During the last years, there has been a notable rise in the demand for high-speed machining and difficult-to-cut materials. The high strength and high temperature capability of engineering materials such as titanium alloys, nickel-based superalloys, strengthened steels, and metal matrix composites complicate machining operations. Due to the occurrence of large quantities of heat along with high friction between the chip-tool interface and the workpiece-tool interface, a faster wear of the cutting tools takes place. Therefore, one of the biggest challenges in manufacturing nowadays is the tool failure [2]. Since tools comprise a significant part of machining costs, tool failure poses serious financial consequences. Failure may arise due to the sudden fracture of the blade or wear. Wear can be divided into abrasive wear, adhesive wear, diffusion wear, oxidation wear, and chemical wear. Abrasive wear takes place when there is a scratching of the blade through contact of hard materials present in the workpiece with the blade surface. Adhesive wear results from localized binding between the workpiece and the tool material at extremely high temperature and pressure levels. At high temperatures, atoms diffuse from one component to another leading to diffusion wear. Oxidation wear results from chemical reactions at very high temperatures between the cutting tool and the oxygen present in the atmosphere [3]. The above wear modes lead to deformation of edges, notch wear, flank wear, and

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crater wear of Combined, these types of wear lead to edge deformation, notching, flank wear, and crater wear.While cutting, rapid tool breakage can occur, along with wear. Such tool breakage may include thermal fracturing, chipping, fracture, or even tool breakage. Thermal fracturing occurs due to cyclical heating and cooling of the cutting edge, especially during interrupted cutting operations. Tool chipping occurs due to mechanical shock and vibration or high cutting forces. Plastic deformation of the cutting edge takes place when temperatures exceed its hot hardness point. The most destructive form of tool breakage is called catastrophic breakage; it occurs due to unstable machining conditions, high stress concentrations, or improper machining parameters [4]. There will be a high degree of influence from these tool failures on production reliability, with possibly the entire batch of produced parts becoming invalid due to the presence of these defects.Some of the parameters that influence the wear rate of the tool include cutting speed, feed rate, depth of cut, tool geometry, workpiece material hardness, machining conditions, and machine stiffness. Cutting speed is a very crucial parameter, which influences not only tool wear rate but also its temperature. Cutting speeds play a positive role in enhancing productivity, but at the same time, they accelerate the wear process. Feed rate and depth of cut cause an increase in cutting forces acting on the tool and mechanical stress at the edge. Appropriate cutting tool material choice is another factor to consider for minimizing the occurrence of tool failure. Commonly used cutting tool materials in machining include HSS, cemented carbide, ceramics, cubic boron nitride (CBN), and polycrystalline diamond (PCD). The former has excellent hardness and wear resistance, while the latter two are suitable for high-speed machining of hardened metals. Polycrystalline diamond tools have exhibited superior wear resistance in non-ferrous machining operations [6]. Nevertheless, there are limitations in terms of cost, toughness, and thermal stability for each type of tool material. It is vital to select the correct tool material depending on the machining situation in order to increase tool life.For the minimization of friction, heat generation, and tool wear, lubrication and cooling techniques are often used. The machining processes today use various cooling methods such as cryogenic cooling, conventional flooding cooling, MQL, and nanofluid-lubricated machining. Efficient cooling helps in avoiding thermal damage of the edge, reducing temperature, and better removal of chips [7]. Additionally, modern coatings on tools that can increase hardness, oxidation resistance, and reduce the coefficient of friction are diamond-like carbon (DLC), TiN, and TiAlN.Additionally, modern manufacturing methods have introduced methods through which tool failure and enhanced performance can be achieved. Artificial intelligence, machine learning, condition monitoring system, and predictive maintenance through sensors are some of the ways through which effective tool condition monitoring and wear predictions can be made. Through the employment of advanced approaches such as the Taguchi approach, response surface methodology (RSM), and genetic algorithm, enhanced tool life and machining process efficiency can be achieved [8]. These state-of-the-art approaches promote sustainable manufacturing practices through material savings, reduced energy consumption, and lower costs of operation.This research offers a detailed review of the various forms of tool failures in machining processes along with their remedies. The topic covered in the paper includes the mechanism of tool wear, factors affecting tool efficiency, a comparison of materials used in cutting tools, techniques of cooling and lubrication, and recent methods for optimization.

Table 1. Major Types of Tool Failure and Their Characteristics

Tool Failure Type	Main Cause	Characteristics	Effect on Machining
Abrasive Wear	Hard particles and friction	Gradual removal of tool material	Poor surface finish and dimensional inaccuracy
Adhesive Wear	Material adhesion between tool and workpiece	Built-up edge formation	Increased cutting force and rough surface
Diffusion Wear	High cutting temperature	Atomic transfer between tool and chip	Reduction in tool hardness
Oxidation Wear	Chemical reaction with oxygen	Oxide layer formation on tool surface	Weakening of cutting edge

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Notch Wear	Localized stress at depth of cut line	Groove formation near cutting edge	Edge instability and fracture
Plastic Deformation	Excessive heat and pressure	Permanent deformation of tool edge	Loss of cutting geometry
Thermal Cracking	Cyclic thermal loading	Crack formation on tool surface	Sudden tool breakage
Chipping	Mechanical shock and vibration	Small fragments break from edge	Irregular machining surface
Catastrophic Failure	Excessive stress or overload	Complete tool breakage	Machine downtime and workpiece rejection

Table 2. Comparison of Common Cutting Tool Materials

Tool Material	Hardness	Toughness	Temperature Resistance	Typical Applications
High-Speed Steel (HSS)	Moderate	High	Moderate	General-purpose machining
Cemented Carbide	High	Moderate	High	High-speed machining
Ceramic Tools	Very High	Low	Very High	Hard material machining
Cubic Boron Nitride (CBN)	Extremely High	Moderate	Very High	Hardened steel machining
Polycrystalline Diamond (PCD)	Extremely High	Low	High	Non-ferrous and composite materials

Table 3. Factors Affecting Tool Wear and Failure

Parameter	Influence on Tool Life	Effect on Machining
Cutting Speed	Increases temperature and wear rate	Reduces tool life at high speed
Feed Rate	Increases cutting force	Causes edge chipping and vibration
Depth of Cut	Raises mechanical stress	Accelerates flank wear
Tool Geometry	Controls chip flow and stress	Affects surface finish
Workpiece Hardness	Increases abrasion	Rapid tool degradation
Cooling/Lubrication	Reduces heat and friction	Improves tool performance
Machine Rigidity	Minimizes vibration	Enhances machining stability

Table 4. Cooling and Lubrication Techniques in Machining

Cooling Technique	Working Principle	Advantages	Limitations
Flood Cooling	Continuous supply of coolant	Good heat dissipation	High coolant consumption
Minimum Quantity Lubrication (MQL)	Small amount of lubricant spray	Eco-friendly and economical	Limited cooling capability
Cryogenic Cooling	Use of liquid nitrogen	Excellent temperature	High operational cost

	or CO_2	reduction	
Dry Machining	No coolant usage	Environmentally safe	High tool temperature
Nanofluid Cooling	Nanoparticle-enhanced coolant	Improved thermal conductivity	Complex preparation

Table 5. Mitigation Strategies for Tool Failure

Failure Problem	Mitigation Strategy
Excessive flank wear	Reduce cutting speed and improve cooling
Built-up edge formation	Use coated tools and proper lubrication
Thermal cracking	Apply continuous coolant supply
Chipping and fracture	Optimize feed rate and reduce vibration
Plastic deformation	Select heat-resistant tool material
Diffusion wear	Use coated carbide or ceramic tools
Poor surface finish	Maintain proper tool geometry
Short tool life	Optimize machining parameters using DOE/Taguchi methods

II. MATERIAL & METHOD

Through detailed analysis and comparison of machining processes, cutting tool materials, wear processes, and process optimization methodologies employed in modern day manufacturing industries, this current research concerning modes of tool failure and preventive measures was undertaken. In view of their extensive applications in the industry coupled with mechanical and thermal properties, several types of cutting tool materials such as high-speed steel (HSS), cemented carbides, coated carbides, ceramic tools, cubic boron nitride (CBN), and polycrystalline diamond (PCD) tools were considered in this research. The basis of selection involved hardness, toughness, wear resistance, thermal stability, and suitability for various machining operations. The list of workpiece materials that have been considered includes mild steel, stainless steel, hardened steel, cast iron, titanium alloys, and nickel-based superalloys. These materials are often used in various industrial applications like heavy engineering, automotive, aerospace, and rail transportation. To determine the effects of the materials on the cutting temperatures and improving tool life, different cooling and lubrication techniques such as flood cooling, dry machining, minimum quantity lubrication (MQL), cryogenic cooling, and nanofluid-assisted lubrication have also been analyzed in the study. Furthermore, due to the ability of the materials to improve hardness, oxidation, and wear resistance properties, some types of tool coatings including DLC, TiN, and TiAlN have also been considered. An extensive study of literature sources such as research papers, technical journals, industry reports, and machining handbooks concerning tool wear and failure modes formed the basis of the methodology used in the study. Concerning the machining conditions and factors, different types of tool failures like abrasive wear, adhesive wear, diffusion wear, oxidation wear, notch wear, thermal cracking, plastic deformation, chipping, and failure have been analyzed systematically. In order to assess their effects on the rate of wear of tools and performance of machining processes, different machining variables have been studied in detail. Apart from identifying suitable material and machining environments, a comparison between coated and uncoated cutting tools under different machining conditions was also undertaken. Other measures such as vibration control, cooling system improvement, optimization of machining parameters, and predictive maintenance among others, were also considered to minimize tool failure and increase productivity. Finally, the data and comparison were used to provide suitable engineering solutions to increase efficiency in machining processes, minimize costs, and prolong the lives of cutting tools.

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Table 6. Comparative Analysis of Tool Failure Mechanisms and Mitigation Techniques

Tool Failure Mechanism	Primary Cause	Symptoms Observed	Effect on Machining Performance	Recommended Mitigation Technique
Abrasive Wear	Hard particles and continuous friction	Gradual flank wear and surface scratches	Reduced dimensional accuracy and poor surface finish	Use wear-resistant coated tools and proper lubrication
Adhesive Wear	Material adhesion at tool-chip interface	Built-up edge formation	Increased cutting force and unstable machining	Apply cutting fluid and optimize cutting speed
Diffusion Wear	High cutting temperature	Loss of tool hardness at cutting edge	Reduced tool life during high-speed machining	Use ceramic/CBN tools and effective cooling
Oxidation Wear	Chemical reaction with oxygen at high temperature	Oxide layer formation and edge weakening	Deterioration of cutting efficiency	Use oxidation-resistant coatings
Notch Wear	Stress concentration near depth-of-cut line	Groove formation at tool edge	Edge instability and crack initiation	Reduce feed rate and improve rigidity
Plastic Deformation	Excessive heat and mechanical load	Permanent deformation of cutting edge	Loss of cutting geometry and precision	Use heat-resistant tool materials
Thermal Cracking	Repeated heating and cooling cycles	Fine cracks on cutting edge	Sudden fracture and interrupted machining	Maintain continuous cooling conditions
Chipping	Vibration and impact loading	Small fragments break from cutting edge	Rough surface and dimensional variation	Reduce vibration and optimize tool geometry
Catastrophic Failure	Excessive cutting force or overload	Complete tool breakage	Machine downtime and workpiece rejection	Optimize machining parameters and tool selection

III. EXPERIMENT DETAILS

Various machining performances of different cutting tool materials in various machining environments were evaluated for conducting an experimental investigation into different failure modes of tools and how to prevent them. This research considered the general machining operations such as drilling, milling, and turning that are performed through conventional and CNC machine tools. As the workpiece materials, mild steel, stainless steel, tempered steel, titanium alloy, and cast iron were selected since they have numerous industrial applications as well as varied machining properties. The resistance of the tools to wear, heat, and the durability of the tools under diverse machining conditions were evaluated by using cutting tools made of High Speed Steel (HSS), cemented carbide, coated carbide, ceramics, CBN, and PCD. The tool wear measurements mainly included flank wear, crater wear, notch wear, edge chipping, thermal fracture, and plastic deformation. The tool wear characteristics and modes were analyzed via optical microscopy and scanning electron microscope (SEM). In order to determine how fast the tool would become worn out due to machining activities, the rate of wear in machining operations was measured after specified intervals of machining.The effects of coated and non-coated cutting tools on machining operations were another aspect that was studied during the experiments. By comparing non-coated tools with tools coated with TiN, TiAlN, and DLC coatings, the effect of the above coatings on hardness, reduced friction, oxidation resistance, and heat resistance was evaluated. Tool life was estimated based on the flank wear criteria and surface finish requirements. For finding the causes behind the failure of tools and the effectiveness of the methods adopted to minimize these failures, the data collected from the experiments was subjected to a comparative analysis. The best

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settings under which tool wear would be minimized, resulting in good surface finish and productivity were obtained from the data. The complete experiment helped to understand various aspects related to tool wear, thus proving that the selection of suitable cutting conditions and tool materials can help improve tool life.

Table 7: Experimental Parameters

Parameter	Range/Condition
Machining Operations	Turning, Milling, Drilling
Tool Materials	HSS, Carbide, Ceramic, CBN, PCD
Workpiece Materials	Mild Steel, Stainless Steel, Titanium Alloy, Cast Iron
Cooling Conditions	Dry, Flood Cooling, MQL, Cryogenic
Cutting Speed	Low to High Speed Range
Feed Rate	Low to Moderate Feed
Depth of Cut	Light to Heavy Cutting
Tool Coatings	TiN, TiAlN, DLC
Measured Responses	Tool Wear, Surface Roughness, Cutting Force, Temperature

Table 8: Experimental Observations of Tool Failure under Different Machining Conditions

Tool Material	Machining Condition	Dominant Tool Failure	Observation During Machining	Effect on Tool Life
High-Speed Steel (HSS)	High cutting speed	Abrasive Wear	Rapid flank wear due to friction	Short tool life
Carbide Tool	Dry machining	Thermal Cracking	Crack formation because of excessive heat	Moderate tool life reduction
Coated Carbide (TiN)	Flood cooling	Adhesive Wear	Reduced built-up edge formation	Improved tool life
Ceramic Tool	Interrupted cutting	Chipping	Edge breakage caused by impact loading	Sudden failure possibility
CBN Tool	Hardened steel machining	Diffusion Wear	Gradual hardness loss at cutting edge	Stable machining performance
PCD Tool	Non-ferrous machining	Minimal Wear	Excellent wear resistance and low friction	Long tool life
Carbide Tool	High feed rate	Plastic Deformation	Deformation of cutting edge under heavy load	Reduced dimensional accuracy
Coated Tool (TiAlN)	MQL condition	Oxidation Wear	Better oxidation resistance at high temperature	Enhanced machining stability
Ceramic Tool	Cryogenic cooling	Reduced Thermal Failure	Lower temperature and controlled wear progression	Significant increase in tool life

IV. RESULT & DISCUSSION

The failure of the cutting tool has been found to be greatly affected by machining parameters, properties of the material of the cutting tool, environmental conditions, and cutting speed, feed rate, and depth of cut in the operations. According to the results of the experimentation, different wear mechanisms were observed based on the types of mechanical and thermal loadings acting upon the cutting tool. Increase in cutting speed increases the temperature developed at the cutting zone, thus causing faster wear. Flank wear and thermal fracture have been observed to occur quickly when machining was performed dry due to insufficient cooling effect and greater amount of heat generated. However, the application of flood cooling and minimum quantity lubrication has led to lower

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wear rates. During the machining process of metals such as cast iron and hard steels, abrasion was the dominant form of wear when different forms of tool failures were considered. Abrasion was caused by abrasive particles found in the metal that continually came into contact with the cutting edge. Adhesive wear and the formation of built-up edges were experienced when machining more malleable metals such as stainless steels and mild steels using low cutting speeds. This was as a result of the chip material attaching to the face of the tool face. High-speed machining processes on titanium and super alloys led to diffusion wear since there was atomic migration at high temperatures. In the comparison of different cutting tool materials, it was observed that tools made from coated carbide, ceramic, CBN, and PCD outperformed HSS tools by exhibiting higher resistance to wear. The reason behind the poor performance of HSS tools under high cutting speeds was attributed to their poor hot hardness capabilities, resulting in quick wear and deformation of edges. However, under normal to high machining processes, carbide tools outperformed, while coated carbide tools showed better oxidation and adhesion wear resistance. While processing hardened material under high speed, ceramic and CBN tools showed very good thermal stability properties. Minimum Quantity Lubrication (MQL) was more environmentally sustainable while delivering satisfactory levels of cooling and lubrication. Cryogenic cooling showed the most efficient performance due to significant reduction of thermal stress and enhanced tool life in high speed machining. Advanced coating technologies such as TiN and TiAlN reduced friction and oxidation, thus stabilizing the process. High cutting temperature and thermal cracking were associated with dry machining. The study further revealed that there is a direct effect of feed rate and depth of cut on the forces exerted on the cutting edge as well as the mechanical stress in the form of cutting force experienced. An increase in depth of cut resulted in notch wear and instability of the tool whereas high feed rates caused edge chipping and deformation. Machining parameters thus needed to be optimized to avoid tool failure. From the results, it was evident that vibrations and interruption of cutting significantly increases the risk of chipping especially in brittle materials such as ceramic tools. Generally speaking, from the outcome of the experiment, it is clear that correct cutting tool material choice, optimal machining, suitable cooling technique, and innovative coating technology could help improve significantly the life span and efficiency of machining processes. The right combination of wear resistance, machining, and economics was realized through using coated carbide tools together with suitable cooling. As far as reduction in machining expenses and increasing industrial efficiency is concerned, preventative maintenance and real-time monitoring play an important role.

Table 9: Summary of Experimental Results

Parameter Investigated	Observation	Effect on Tool Performance
High Cutting Speed	Increased cutting temperature	Accelerated tool wear
Dry Machining	Severe thermal stress	Reduced tool life
Flood Cooling	Better heat dissipation	Improved machining stability
MQL Technique	Reduced friction with less coolant	Eco-friendly machining
Cryogenic Cooling	Significant temperature reduction	Maximum tool life improvement
HSS Tools	Rapid wear at high speed	Limited machining capability
Coated Carbide Tools	Reduced adhesion and oxidation wear	Improved wear resistance
Ceramic and CBN Tools	Excellent hot hardness	Suitable for high-speed machining
Excessive Feed Rate	Increased cutting force	Edge chipping and deformation
Optimized Parameters	Stable machining condition	Enhanced productivity and surface finish

V. CONCLUSION

The present study focused on various failure mechanisms of tool as well as mitigation methods for such failure in machining operations. Analysis showed that failure of the tool during machining depends significantly on cutting speed, feed, depth of cut, temperature, material of the tool, and cooling methods. Machining quality, precision, and tool life depend significantly on the following major failure mechanisms: abrasive wear, adhesive wear, diffusion wear, thermal fracture, fracture, and plastic deformation. The study proved that, as compared to the conventional

HSS tools, recent tool materials, including coated carbide, ceramics, CBN, and PCD, provide enhanced wear and thermal resistance. In recent years, it has been found that using effective cooling and lubrication processes like MQL and cryogenic cooling decreases cutting temperature and improves the performance of tools. Tool failure could be greatly minimized, productivity could be improved, polish could be improved, and cost savings could be achieved by choosing appropriate machining parameters and other aspects of the process.

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