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A Review on Wear Behavior of Cutting Tools During Machining of Inconel, Nimonic, and Hastelloy

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Abstract

Objectives: Super-alloys are considered to be hard-to-machine materials; therefore, cutting tool is highly susceptible to be worn out during the machining operation. Because of that, the surface condition of the workpiece is very poor, and the machine is also likely to get damaged. Therefore, it is imperative to estimate the wear traces on the cutting tool along with the calculation of its useful life. **Methods/statistical analysis:** Various research conducted in this context has been reviewed and discussed in this study. For better understanding, the scope of this review is restricted to Ni-based super-alloys, especially Inconel, Nimonic, and Hastelloy. With regard to these super-alloys, tool wear (TW) mechanisms have been discussed. TW mechanism conferred in relation to various cutting speed (CS), feed rate (FR), and cut depth (CD) has also been compiled here in tabular form. **Findings:** From the review, it can be said that flank wear (FW) is one of the main reasons behind the cutting tool failure irrespective of machining environment, parameters, materials, etc. Along with FW, some conditions based wear mechanisms such as abrasion wear (AW), burr formation, chipping, adhesion wear (AdW), notch wear (NW), crater wear (CW), built-up-edge (BUE), diffusion wear (DW), etc. for TW were also operable in most of the situations. The wear of cutting tool was influenced severely by CS among the various machining parameters. **Application/ improvements:** Super-alloys are used primarily in the aviation industry because they have certain properties, such as high corrosion resistance, tremendous strength, excellent weldability, high fatigue and creep resistance, etc. High surface finish and precise dimensions of machined aerospace parts are very much needed for a high level of safety, which depends predominantly on the integrity of machining equipment.

Keywords: Super-alloy, Inconel, Nimonic, Hastelloy, Machining, Tool Wear

List of Abbreviations

TW	Tool wear
FW	Flank wear
AW	Abrasion wear
AdW	Adhesion wear
NW	Notch wear
CW	Crater wear
BUE	Built-up-edge
DW	Diffusion wear
MC	Microchipping
AW	Abrasive wear
NW	Nose wear
CS	Cut speed
FR	Feed rate
CD	Cut depth
WM	Wet machining
DM	Dry machining

1. Introduction

In manufacturing industries, machining operations are fundamental requisites. The main challenges in the metal-based industries are to ensure the high productivity and assured quality of machined parts. The use of a suitable machining operation helps to ensure the graded standards of the machined parts to a great extent. Because of this, the

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interest of researchers has increased in upgrading all aspects of machining operations. Among all machining processes, turning is a widely used machining process in metal-based industries, and a schematic diagram of turning operation is shown in Figure 1. The surface finish of any machined sample essentially depends on the selected machining parameters. The surface quality of a machined component is profoundly affected by the parameters such as CS, FR, CD, etc. Likewise, TW is also impacted by the chosen machining parameters as well. During the machining process, the cutting tool becomes blunt with time due to mutual friction between the tool and workpiece. The shape of the tool changes over time from its original design as a result of the progressive loss of tool material during operation. Therefore, TW is considered as a vital parameter in the machining operation and depends primarily on tool materials, workpiece materials, tool geometry, spindle speed, cut depth, cut length, feed rate, lubrication type, temperature, etc. These parameters need to be optimized not only for higher tool life but also for improved quality of the machined component. The worn tool requires more cutting force, more vibrations/noise is produced, and more temperature generates during friction, resulting in poor surface finish and poor dimensional accuracy. This also leads to high production cost, low quality, or subsided production efficiency.[1] In various studies, efforts have been made to optimize the parameters to enhance tool life in machining operation. These efforts are extensively based on the results obtained from experimental attempts and statistical/mathematical models.[2,3]

In this study, efforts have been made to compile various types of process optimization parameters in a sequential manner especially for Inconel, Hastelloy, and Nimonic. In the Turning Operation, the techniques used to enhance the tool life have also been reasonably presented.

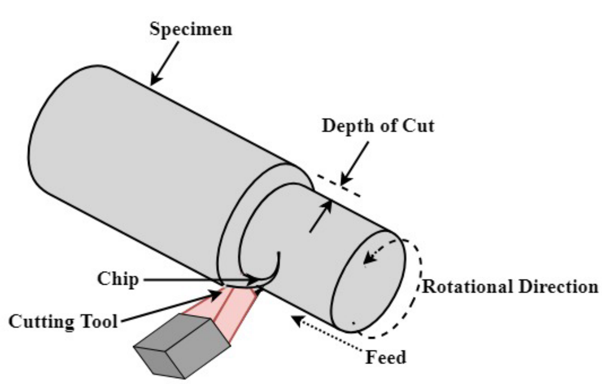

Figure 1. Schematic diagram of turning operation.

2. Tools Wear During Machining of Inconel

A super-alloy is a high performing alloy with outstanding chemical, physical, and mechanical features and primarily used in the aerospace industry. The aircraft components must be reliable, precise, and durable. Therefore, the manufacturer needs to produce precise and high-quality parts on a consistent basis. Even a minor deviation from the standards is a reason for rejection more often. Therefore, it is mandatory to standardise the machining process with utmost precision at any circumstances. Super-alloys are not only expensive but also difficult-to-cut alloys. However, machining of super-alloy needs to be conducted in such a way that the alloy should not be wasted and at the same time, the component should not be rejected too. Ni-based super-alloys are extensively used in the aviation industry especially for static or rotating parts of the hottest portions of aero engines.

Inconel is a Ni–Cr-based super-alloy and frequently used in many aerospace components. Inconel is a hard material and considered as one of the hard to machine metals. Owing to that the cutting tool usually gets worn out during the machining of Inconel. Thakur et al.[4] performed the high-speed turning on Inconel 718 using cemented WC tool insert. They found that flank wear (FW) and microchipping (MC) were the primary mode of tool failure. Altin et al.[5] examined the impact of speed of cut on TW in the machining of Inconel 718. They stated that the square-shaped ceramic inserts were dominantly worn out via CW and FW mechanism. On the other hand, the round-shaped ceramic inserts were predominantly suffered by FW and NW. At low CS, square-shaped inserts were exhibited lowest FW. However, round-shaped inserts exhibited considerable resistance against FW at high CS. Costes et al.[6] observed that tool coated with low cubic boron nitride content exhibited better tool life and the observed wear mechanism was predominantly AdW and DW. Devillez et al.[7] analyzed the efficacy of the various coatings in enhancing the carbide tool life. As per their investigation, AlTiN coating showed best tribological behaviour. This coating has successfully limited the BUE phenomena and abrasive wear (AW) of the tool. Jawaid et al.[8] performed wet machining (WM) of Inconel 718 using PVD TiN-coated WC inserts. They found that coated tools exhibited slightly better tool life than the uncoated one at high speed turning. The mechanisms of tool failure for all the specimens were chipping and FW. Khan et al.[9] used polycrystalline cubic boron nitride inserts (round and C-type) tool for turning of Inconel 718. At slow CS, round-shaped insert exhibited five times better wear resistance than the C-type insert. However, severe grooving and BUE were reported for both. With the escalation of CS, grooving and BUE were reduced. At very high speed of cut, they reported catastrophic insert fracture resulted in poor tool life.

The experimental approach for TW study is not only costly but also time-consuming. Therefore, Lotfi et al.[10] proposed a 3D finite element model to envisage TW during the machining of Inconel 625. The experimental and simulation results were correlated and they found an excellent agreement between the two. For experimental and simulation purpose, the tools used for machining purpose were PVD-TiAlN carbide and ceramic inserts. In the simulation, they found that FW was propagated rapidly with the increase in CD. However, the FR has almost no effect on the FW. Jahanbakhsh et al.[11] evaluated the TW of whisker ceramic insert in the machining of Inconel 625. They developed a mathematical model using response surface method. Their analysis iterated that TW was mainly affected by the CD; however, FR had limited influence. Antonialli et al.[12] performed a taper turning operation on Inconel 625 and studied the tool life. As per their results, tool life is short when taper turning was performed on the super-alloy. They found rapidly evolved and wider FW on the tool. MC was also severe with the escalation in FR.

From the review, it can be quoted that FW is the primary mechanism for TW irrespective of machining condition and coating material used. The shape of the tool inserts also plays a crucial role on the FW. It was reported that at high CS, round-shaped inserts provide a considerable resistance against FW. Similarly, at low speeds, FW mechanism is not that severe even the square-shaped inserts were used. A detailed description of TW at various machining conditions and parameters is provided in Table 1. Apart from FW, some other types of wear mechanism were reported in the literature such as chipping, AW, NW, AdW, DW, BUE, etc. at different conditions. Taguchi method is often used to optimize the machining parameters to obtain smooth surface finish and minimum TW at particular operating conditions.

3. Tools Wear During the Machining of Nimonic

Nimonic is another member of Ni-based super-alloys with excellent fatigue and creep resistance properties. It is also resistant to high corrosive or oxidative environment.[20] It is frequently found in those areas of aerospace, automobile, and other industries where high creep resistance is required such as combustion chamber of aircraft engine, gas turbine, power generators, heat exchangers parts, etc.[21] As already discussed in the previous section, most of the super-alloys are considered as hard to machine alloys. Nimonic is also no exception. In Table 2, an attempt has been made to compile the reported tool wear mechanisms as a result of Nimonic machining in different machining environments/conditions.

Kumar et al.[22] studied the TW of PVD-coated carbide insert tool during the machining of Nimonic C-263 using acoustic emission sensors. Tool condition monitoring using acoustic signals is apparently a powerful technique and provides quite reliable data. They found TW progression is majorly dependent on CS. The tool life is essentially hampered by AW, MC, and plastic deformation (PD). Ezilarasan and Velayudham[21] developed an empirical model to predict the TW and other parameters during machining of Nimonic C-263 using whisker-reinforced ceramic inserts tool via response surface methodology. Taguchi method was used to design the experiment. Whisker-reinforced ceramic insert provided considerable tolerance against TW at higher CS. Velmurugan et al.[23] employed the Taguchi method to design the machining operation on Nimonic C-263 using PVD and CVD coated inserts. They found PVD-coated AilTiN insert showed the remarkably low wear rate. At lower CS, PVD-coated tools exhibited lower FW whereas, same was true for CVD-coated tools at high CS.

Chetan et al.[24] performed machining operation on Nimonic 90 and investigated the wear characteristics of the carbide cutting tools coated with TiN using PVD. They conducted experiments on dry as well as minimum quantity lubrication conditions. Intense nose wear (NW) on cutting inserts was observed by them. Apart from NW, AW and catastrophic failure were also reported for Nimonic 90 super-alloy.

Chavan et al.[25] studied the TW mechanism of alumina-based ceramic inserts in the machining of Nimonic 80A super-alloy. They found CS has a profound effect on TW. Tool failure was mainly governed by AdW and

Table 1. Reported tools wear mechanism in the literature during the machining of Inconel super alloy at various machining conditions

S. no.	Inconel grade	Machining operation	Tool material	Parameters	Outcomes	Ref.
1.	718	DM	Si_3N_4& Al_2O_3+TiC	CS: 30–500 m/min FR: 0.19 mm/rev CD: 0.5 mm	Tools were severely worn out. AW, thermally activated wear.	13
2.	718	DM	Cemented WC insert tool	CS: 40–55 m/min FR: 0.05–2.0 mm/rev CD: 0.5 and 1 mm	FW and MC	4
3.	718	DM	WC insert	CS: 20–200 m/min FR: 0.1 and 0.2 mm/rev CD: 0.75 mm	AlTiN coating was reported as best coating	7
4.	718	DM	Si_3N_4 & whisker reinforced Al_2O_3 + SiC_w ceramic inserts	CS: 150–300 m/min FR: 0.2 mm/rev CD: 2 mm	Square geometry tool: CW and FW Round geometry tool: FW and NW Optimum CS: 250 m/min At low CS: square type tool is better	5
5.	718	DM	F7030-coated carbide insert	CS: 30–45 m/min FR: 0.03 mm/rev CD: 1.2 mm	FW	14
6.	718	WM	Cubic boron nitride (CBN) insert with TiN binder	CS: 50–500 m/min FR: 0.2 mm/rev CD: 0.3 mm	AdW and DW	6
7.	718	DM	Carbide tool	CS: 15–35 m/min FR: 0.101 mm/rev CD: 1.5 mm	DW (at CS 35 m/min)	15
8.	718	WM	Carbide (CVD)-coated insert	CS: 60–255 m/min FR: 0.1 mm/rev CD: 0.5 mm	At low speeds: peeling of coating At high speeds:heavy NW, burn marks	16
9.	718	WM	Heat isolating TiAlN/ AlTiN-coated tool	CS: 65–125 m/min FR: 0.1 mm/rev CD: 0.25 mm	AW, NW, catastrophic type damage and BUE	17
10.	718	WM	PVD TiN-coated WC tools	CS: 25–100 m/min FR: 0.08–0.14 mm/ tooth CD: 1.0 mm	Chipping and FW	8
11.	718	WM	Polycrystalline CBN inserts	CS: 150–450 m/min FR: 0.05–0.20 mm/rev CD: 0.2 mm	AdW and AW	9
12.	718	DM	TiAl/TiAlN-coated carbide tools	CS: 150–300 m/min FR: 0.2 mm/rev CD: 2 mm	FW, BUE, Chipping, NW	18
13.	625	DM	PVD AlTiN-coated carbide inserts	CS: 65.91–234.09 m/ min FR: 0.07–0.23 mm/rev CD: 0.46–1.64 mm	Chipping, FW	11
14.	625	DM	Al_2O_3/TiCN/TiN/ TiAlN-coated inserts	CS: 32.96–117.04 m/ min FR: 0.1–0.3 mm/rev CD: 0.32–2.68 mm	FW, Best wear coating was TiCN	19

AW mechanisms. They also developed a cutting force model for the same and the results obtained were closely matched with the experimental one.

As per the reviewed articles, the primary mechanism of TW in the machining of Nimonic alloys is FW (just like in Inconel) irrespective of grades and machining conditions. Other TW mechanisms are AW, burr formation, chipping, AdW, NW, CW, BUE, and DW. These mechanisms may occur at different operating conditions and also dependent on the selection of machining parameters. The coating process also has a significant role on wear behaviour of coated tools. It was reported that tools coated by CVD process are exhibited slightly better wear resistance than the PVD-coated one. Some other types of equipment like acoustic emission sensors were also used to observe the tool conditions. Response surface methodology was also used in several papers to develop an empirical modal for depicting tool conditions. Taguchi method was also used by various authors to design the machining experiment for minimal TW.

4. Tools Wear During the Machining of Hastelloy

Hastelloy (C-22HS) is another nickel-based super-alloy with FCC crystal structure and possess excellent corrosion resistance. It is extensively used in the fabrication of rocket clamshell. In Table 3, reported tool wear mechanisms at different cutting environments have been compiled during the machining of Hastelloy. As super-alloys are difficult to cut materials, Akıncıoğlu et al.[29] used the Taguchi method to determine the optimum parameters for machining and cryo-treatment of cutting tool to protect it against wear. They found shallow as well as deep cryogenic treatment of WC tool is helpful in preventing the unwanted TW during turning. At the same time, better surface finish and low manufacturing cost could be achieved by efficiently utilizing the Taguchi approach. In the turning of Hastelloy C-22HS, Kadirgama et al.[30] studied the TW mechanism and estimated tool life of coated carbide tools. For the investigation, PVD-coated TiAlN; TiN/TiCN/

Table 2. Reported tools wear mechanism in literature during the machining of Nimonic super-alloy at various conditions

S. no.	Nimonic	Machining operation	Tool material	Parameters	Outcomes	Ref.
1.	C-263	DM	PVD-coated carbide insert	CS: 22, 33, 54 m/min FR: 0.102 and 0.143 mm/rev CD: 0.75 mm	AW, MC, and PD. The magnitude of wear depends on the cut speed.	22
2.	C-263	DM	Carbide-coated tool inserts	CS: 42–68 m/min FR: 0.127 mm/rev CD: 1.25–1.27 mm	FW, NW, burr formation, chipping	26
3.	C-263	DM	PVD-coated carbide inserts	CS: 22, 33, 54 m/min FR: 0.051–0.143 mm/rev CD: 0.5–1.0 mm	FW	27
4.	C-263	DM	CVD multilayer-coated inserts	CS: 51 and 84 m/min FR: 0.2 mm/rev CD: 1 mm	FW, AdW, DW. CVD multilayer coated inserts performed well within the range of CS	28
5.	C-263	DM	PVD/CVD-coated carbide inserts	CS: 60–150 m/min FR: 0.05–0.25 mm/rev CD: 0.2–0.5 mm	FW, CW, edge chipping	23
6.	90	DM and MQL	PVD (TiN)-coated carbide inserts	CS: 60 and 120 m/min FR: 0.15 and 0.25 mm/rev CD: 0.5 mm	NW, AW, and Catastrophic failure	24
7.	80A	DM	alumina-based ceramic inserts	CS: 100–400 m/min FR: 0.12–0.22 mm/rev CD: 0.75–1.1 mm	FW, BUE, DW, NW	25

Table 3. Reported tools wear mechanism in the literature during the machining of Hastelloy super alloy at various conditions

S. no.	Hastelloy	Machining operation	Tool material	Parameters	Outcomes	Ref.
1.	C-22HS	WM	Kennametal ((KC725M, KC520M, KC915M and KC930M))	CS: 100–180 m/min FR: 0.1–0.2 mm/rev CD: 1–2 mm	FW, NW, chipping, plastic lowering at cutting edge, BUE attrition/adhesion, and oxidation	30,33
2.	C-22HS	DM	Cryo-treated WC tool	CS: 30–90 m/min FR: 0.1–0.3 mm/rev CD: 1 mm	Cryogenic treatment increased wear resistance of WC tool	29
3.	276	DM	Ceramic inserts	CS: 150–250 m/min FR: 0.15–0.25 mm/rev CD: 0.5–1.5 mm	FW, chipping, BUE	31
4.	C-2000	WM	Uncoated and PVD-coated carbide with TiAlN	CS: 15–31 mm/min FR: 0.1–0.2 mm/rev CD: 0.4–1.0 mm	AdW and DW mechanisms	34

TiN and CVD-coated TiN/TiCN/Al_2O_3; TiN/TiCN/TiN tools were used by them. Irrespective of coating used, the tools were worn out by the following phenomena i.e., FW, NW, chipping and plastic lowering at cutting edge. In addition, the prominent wear mechanisms for all the tools were attrition/adhesion, oxidation, and BUE.

Khidhir and Mohamed[31] studied the ceramic TW characteristics while machining of Hastelloy-276. They found that FW, chipping, and BUE are the main wear mechanism. TW was predominantly influenced by the values of CS and CD. Razak et al.[32] developed a mathematical model for studying the machining operation of Hastelloy C-2000. With the help of this mathematical model, an experimental study was designed. They observed that the tool was worn out by the combination of multiple wear mechanism such as galling, chipping, plucking, and abrasion.

Likewise, FW is the primary mechanism of TW in the machining of Hastelloy. However, the parameters and conditions specific wear tendencies reported in the literature are AdW, DW, BUE, chipping, NW, etc. Some empirical models were also proposed to mimic the machining of Hastelloy where special attention was paid to TW characteristics. The use of Taguchi method for process optimization is generally observed in the literature. Apart from coatings, cryogenic treatment on coated and uncoated inserts was also employed for increasing the wear resistance of the cutting tool. The method was found adequate for improving the wear resistance of the WC tool.

5. Conclusions

In this article, the failure trends of cutting tools in the machining of Inconel, Nimonic, and Hastelloy and the mechanism behind failure disposition are reviewed. This review has been organised in the context of various tool materials, tool coatings, machining parameters, machining environments, etc. In this study, it was found that FW is one of the primary causes for the wear of cutting tools in almost every kind of situation. FW is not the only vital failure mechanism for cutting tool failure during machining of Inconel, Nimonic, and Hastelloy but other types of mechanisms also play a role in making the cutting tool unusable. Except for FW, other types of failure mechanisms are condition dependent. These wear mechanisms were AW, burr formation, chipping, AdW, NW, CW, BUE, DW, etc. and predominantly dependent on tool materials, tool coatings, machining environment, machining parameters, and machined materials. More often two or more than two wear mechanisms were contributed to cutting tool wear in the machining operations of the three super-alloys referenced here. In more generalized language it can be said that AdW on slow cutting speed (CS), AdW, attrition and BUE on medium CS and PD, chipping and DW on high CS along with FW were the main wear mechanisms reported behind the cutting tool failure in most of the cases. There is a high likelihood of having NW in the cutting tool at a higher cut depth. Optimum cutting conditions and parameters for every cutting tool material with respect to machined alloy were different, so it was nearly impossible to generalize the optimum cutting conditions and parameters. In comparison to other parameters, the CS was found to have a maximum impact on TW.

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