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Short Communication

The effects of cutting speed on tool wear and tool life when machining Inconel 718 with ceramic tools

A. Altin [a], M. Nalbant [b], A. Taskesen [b,*]

[a] Yuzuncu Yil University, Technical High School, Van, Turkey
[b] Gazi University, Technical Education Faculty, Besevler, Ankara 06500, Turkey

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Abstract

In this study, the effects of cutting speed on tool wear and tool life when machining Inconel 718 nickel-based super alloy have been experimentally investigated. A series of tool life experiments has been carried out using silicon nitrite based and whisker reinforced ceramic tools which have two different geometries and three different ISO qualities with 10% water additive cutting fluid. The experiment results show that crater and flank wears are usually dominant wear types in ceramic square type (SNGN) inserts while flank and notch wear are dominant in round type (RNGN) inserts. Minimum flank wear is seen with SNGN tools at low cutting speeds while it is seen with RNGN tools at high cutting speeds.

1. Introduction

Inconel 718, which is a nickel based super alloy and different from other alloys, has been widely used in the aircraft and nuclear industry due to its exceptional thermal resistance and the ability to retain its mechanical properties at elevated temperatures over 700 °C [1–3]. Nickel based super alloys are classified as difficult to cut materials due to their high shear strength, work hardening tendency, highly abrasive carbide particles in the microstructure, strong tendency to weld and form a built-up edge and low thermal conductivity [4,5]. They have a strong tendency to maintain their strength at the high temperature that is generated during machining [6].

Short tool life and surface quality problems during machining of nickel based super alloys are main subjects that must be investigated. Residual stresses formed at work-piece surface during machining negatively affect the mechanical strain and corrosion properties of the work-piece [2,5].

The main factors that affect the performance of a cutting tool whilst machining super alloys are [6]: (i) high hardness, (ii) Wear resistance, (iii) chemical inertness and (iv) fracture toughness. Ceramic tools are suitable with regard to the first three properties even at high cutting speeds. With the introduction of sialon materials, Inconel 718 can be machined using whisker reinforced aluminum silicon carbide tools at more high cutting speeds.

The cutting speed is an important factor that influences the tool wear and tool life when cutting nickel based alloys. In this study, for the machining of Inconel 718 with ceramic inserts, cutting speed experiments of tool wear were carried out to investigate the effects of cutting speed on tool flank wear and tool life.

2. Experimental study

Machining experiments were carried out using OKUMA LB-45II type CNC turning machine having 60 kW DC motor in order to investigate the effects of cutting speed on tool wear. The chemical composition and mechanical properties of Inconel 718 work-piece materials used in the experiments are shown in Tables 1 and 2, respectively. The hardness of the work-piece material was measured and found to be 388 HBS. Boiling and melting points were 5660 °C and 3410 °C, respectively. Metallurgical structure of the work-piece was taken by using SEM device at the cutting speed of 60 m/min and it is shown in Fig. 1.

* Corresponding author. Tel.: +90 312 2126820/1843; fax: +90 312 2120059.
E-mail address: taskesen@gazi.edu.tr (A. Taskesen).

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Table 1
Chemical composition of Inconel 718 (wt%)

C	Mn	Si	P	S	Cr	Ni	Co	Mo	Nb + Ta	Ti
0.040	0.08	0.08	<0.015	0.002	18.37	53.37	0.23	3.04	5.34	0.98
Al	B	Ta	Cu	Fe	Ca	Mg	Pb	Bi	Se	Nb
0.50	0.004	0.005	0.04	17.80	<0.01	<0.01	0.0001	.00001	<.0001	5.33

Table 2
Mechanical properties of Inconel 718

Yield stress (MPa)	Tensile stress (MPa)	Strain (%)	Elastic modulus (GPa)	Thermal conductivity (W/m K)	Density (kg/m^3)
1110	1310	23.3	206	11.2	8470

The work-piece material used in the experiments was a cylinder with a diameter of 416 mm and a length of 52.8 mm. Diameter and volume of work-piece material Inconel 718 after the machining were measured as 408 mm and 273 cm^3, respectively.

Wear photographs of tool inserts were taken by zooming 30 times using JSM JOEL 6400 type electron scanning microscope. Nikon (Antifugungus NE akromat long barel type) optical microscope was used in order to determine the mean flank wear values (V_{BB}) of each insert.

Cutting tool inserts were chosen as square and round types that are widely used in manufacturing industry having two different geometries and three different ISO qualities. Materials and properties of cutting tools used are seen in Table 3.

3. Results and discussion

Generally, cutting tool materials are exposed to high mechanical stresses and thermal disturbances when machining nickel based super alloys resulting in cutting tool wear and short tool life. The most known tool wear type while cutting the Inconel 718 is notch wear formed at the depth of cut due to high thermal combinations, high work hardness, high strength of the work-piece and abrasive particles [2,5,7,8]. Excessive notch wear is seen at low cutting speeds when machining nickel based super alloys. Furthermore; flank wear, chipping and severe damages are the causes of tool wear. Wear rate of ceramic tools at high cutting speeds is smaller than those cutting tools at low cutting speeds [9,10]. In some literature studies, whisker reinforced aluminum oxide cutting tools are suitable

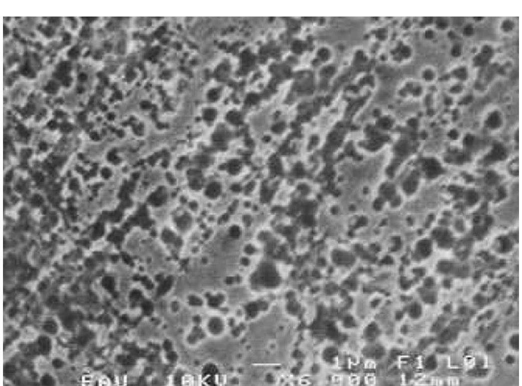

Fig. 1. Typical metallurgical structure of the machined work-piece material.

for the machining of Inconel 718 at the cutting speeds between 200 m/min and 750 m/min [1,2,8,11]. In this study, wear values, wear types and chip types at different cutting speeds were determined for the machining of Inconel 718.

Silicon nitrite based and whisker reinforced aluminum oxide ($Al_2O_3 + SiC_w$) ceramic inserts having two different geometries (square and round type) were used in order to examine wear properties of Inconel 718. Geometry and material properties of these inserts are shown in Table 1. These inserts were tested by cutting Inconel 718 under constant feed rate 0.20 mm/rev, constant depth of cut 2 mm and different cutting speeds between 150 m/min and 300 m/min taking into consideration of ISO 3685 and manufacturer's recommendations. For each experiment, 273 cm^3 work-piece material was cut and mean flank wear values were measured. These values and wear types are shown in Fig. 2 and Table 4, respectively.

Reference flank wear value $V_{BB} = 0.3$ mm is chosen as wear criterion according to International Standard Organisation (ISO 3685). A cutting tool was rejected and further machining was stopped based on one or a combination of the following rejection criteria in relation to ISO Standard 3685 for tool life testing:

- Average flank wear $\geqslant 0.3$ mm.
- Maximum flank wear $\geqslant 0.4$ mm.
- Nose wear $\geqslant 0.5$ mm.
- Notching at the depth of cut line $\geqslant 0.6$ mm.
- Excessive chipping (flaking) or catastrophic fracture of the cutting edge.

Whisker reinforced aluminum insert ($Al_2O_3 + SiC_w$) KYON 4300 SNGN and silicon nitrite based ceramic KYON 2100 SNGN insert remained below the reference value at 150 m/min as seen in Fig. 1. The other round type two inserts exceeded the reference case and they are not suitable for cutting Inconel 718 at this cutting speed. Silicon nitrite based ceramic insert KYON 2000 RNGN weared out even more rapidly at this speed. Wear types and values that were seen at cutting inserts at all cutting speeds are shown in Table 4.

From Fig. 2, it can be seen that round type cutting inserts were worn out more quickly than that of squared

Table 3
Geometry and material of the cutting tool inserts

Material	Grade	Catalog no.	Rake angle
Sialon ceramic	KYON 2000	RNGN 12 07 00 T01020	−7
Sialon ceramic	KYON 2100	SNGN 12 07 12 T01020	+5
Whisker-reinforced ($Al_2O_3 + SiC_w$)	KYON 4300	SNGN 12 07 12 T01020	+5
Whisker-reinforced ($Al_2O_3 + SiC_w$)	KYON 4300	RNGN 12 07 00 T01020	−7

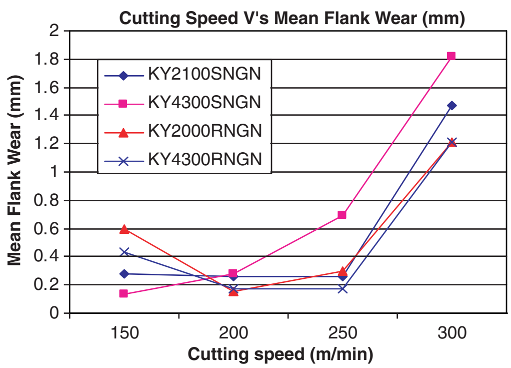

Fig. 2. Relationship between the mean flank wear (V_{BB}) and cutting speed (V) while machining of Inconel 718 ($f = 0.2$ mm/rev, $d = 2$ mm).

type inserts at low cutting speeds. This case can be attributed to the tool geometry. When increasing the cutting speed, tool wear value decreased. Generally good agreement is observed between these experimental results and the existing literature studies.

When increasing the cutting speed from 150 m/min to 200 m/min, a decrease was observed in tool wear except for KYON 4300 SNGN (Fig. 2). But, flank wear values of all inserts (V_{BB}) remained below reference case at this cutting speed.

Previous investigations on nickel based machining confirmed that ($Al_2O_3 + TiC$) ceramic inserts have better performance than carbide inserts and that whisker reinforced aluminum oxide ceramic inserts ($Al_2O_3 + SiC_w$) have good performance for cutting of nickel based super alloys [12–15]. The results of this study are in good agreement with the existing experimental data in the literature.

If the cutting speed is increased to 250 m/min, whisker reinforced aluminum oxide insert ($Al_2O_3 + SiC_w$) KYON 4300 SNGN was worn out to excess but the other three inserts remained below reference case. At this cutting speed, the types of tool wear are seen in Table 4.

All inserts were worn out beyond the reference value at 300 m/min cutting speed. At this speed, round type cutting inserts showed better performance than squared type tools.

As a result, KYON 4300 SNGN insert resisted only at low cutting speeds. At high cutting speeds both KYON 4300 RNGN and KYON 2000 RNGN inserts showed good performance compared to the other inserts. The recommendation for tool inserts for the cutting of Inconel 718 were KYON 4300 square type at low cutting speeds and KYON 2000 round type at high cutting speeds. KYON4300 SNGN insert was not suitable for cutting Inconel at high speed.

In this study, flank wear and excessive notch wear, which are important problems reducing tool life, are mainly observed in the machining experiments with ceramic tools (see Figs. 3 and 4). It is considered that the tools having negative and larger clearance angle must be used in order to solve notch wear problem. Moreover, notch wear can be prevented or minimized by applying conical turning techniques [1,2,4,5,10]. Some literature studies also state that machining of Inconel 718 with whisker reinforced ceramic tool gives better performance in terms of tool life under high-pressure coolant supplies up to 15 MPa com-

Table 4
Wear types and flank wear values

Tool material	$V = 150$ m/min		$V = 200$ m/min		$V = 250$ m/min		$V = 300$ m/min	
	V_{BB} (mm)	Wear type	V_{BB} (mm)	Wear type	V_{BB} (mm)	Wear type	V_{BB} (mm)	Wear type
Sialon ceramic KY2000 RNGN	0.60	Flank wear Plastic deformation	0.15	Flank wear Notch Wear	0.30	Flank wear	1.21	Flank Edge def.
Sialon ceramic KY2100 SNGN	0.28	Flank wear Notch Wear Thermal cracks	0.26	Flank wear Adhesion Built up edge	0.26	Crater Flank	1.47	Flank Notch Adhesion
Whisker-reinforced $Al_2O_3 + SiC_w$ KY4300 SNGN	0.13	Flank wear Edge wear	0.28	Crater wear Flank wear Plastic Def.	0.69	Crater Flank Thermal Plastic Def.	1.82	Nose crack
Whisker-reinforced $Al_2O_3 + SiC_w$ KY4300 RNGN	0.43	Crater wear Flank wear Thermal cracks	0.17	Flank wear Notch wear	0.17	Flank Notch	1.21	Flank wear Notch wear

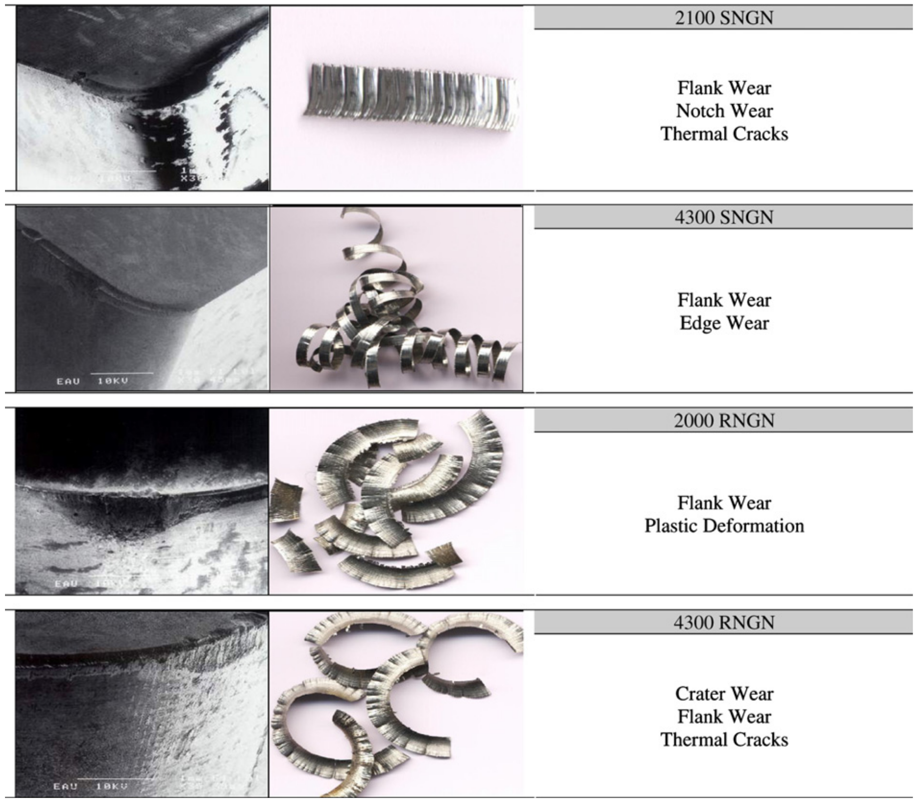

Fig. 3. Wear types and chip formation at $V = 150$ m/min according to the insert type.

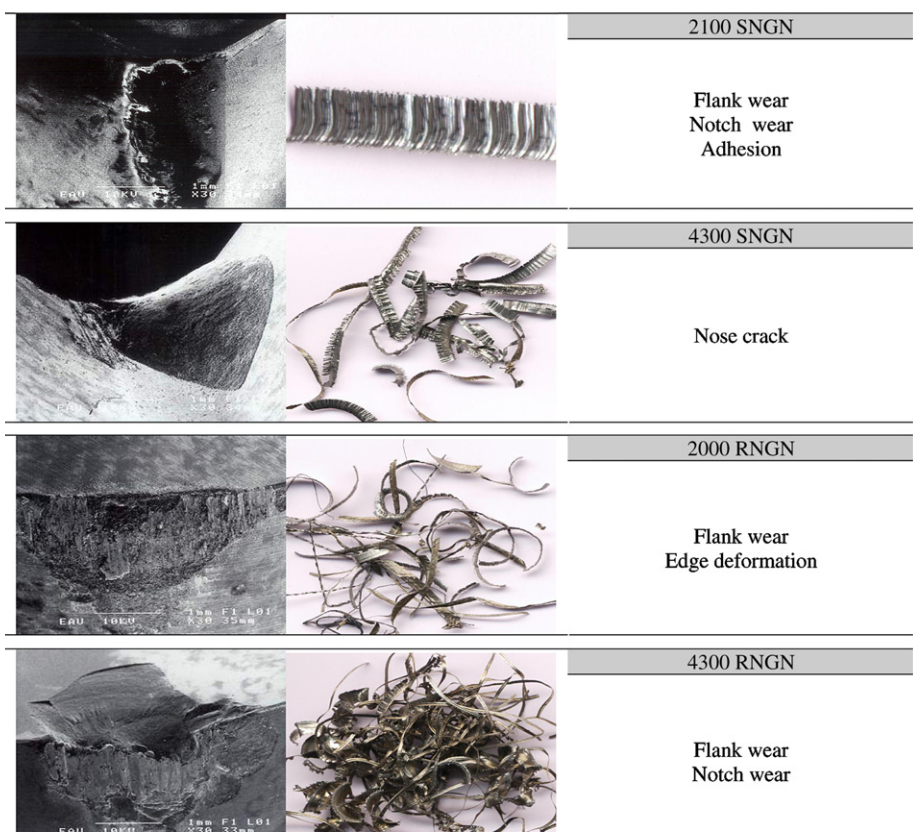

Fig. 4. Wear types and chip formation at $V = 300$ m/min according to the insert type.

pared to conventional coolant supplies. The use of 15 MPa coolant supply pressure tends to suppress notching during machining thus improving tool life, while the use of higher coolant supply pressure of 20.3 MPa did not show improvement in tool life probably due to accelerated notch wear caused by water jet impingement erosion. Cutting forces decreased with increasing coolant supply pressure [16].

4. Conclusions

The conclusions drawn from the turning of Inconel 718 with silicon nitride based ceramic and whisker reinforced ($Al_2O_3 + SiC_w$) aluminum inserts are as follows:

1. Generally, flank wear, crater, notching and plastic deformation are the wear mechanisms observed with ceramic inserts. The dominant wear mechanisms seen at round type inserts are flank and notch wear while flank wear and crater are the major wear types of square type inserts.
2. Based on experimental results, the optimum cutting speed can be deduced as 250 m/min and the tool life is affected negatively above this speed.
3. Square type inserts showed good performance compared to round type inserts at low cutting speeds. The recommendation for tool inserts for the machining of Inconel 718 were square type KYON 4300 insert at low cutting speeds whilst round type KYON 4300 insert was recommended at high cutting speeds.

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