Effect Tool Wear during End Milling on the Surface Integrity and Fatigue Life of Inconel 718

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Abstract

Inconel 718 is known to be among the most difficult-to-cut materials due to its high strength even at high temperatures, low thermal conductivity, and especially rapid work hardening. Machining Inconel 718 is a challenging task since tool wear adversely affects surface integrity and product performance of machined components. In this paper, the effect of tool wear on surface integrity and its impact on fatigue performance of Inconel 718 alloy (45 ± 1 HRC) by end milling using PVD coated tools are studied. The evolutions of surface integrity including surface roughness, microstructure, and microhardness were characterized at three levels of tool flank wear (VB = 0, 0.1 mm, 0.2 mm). At each level of tool flank wear, the effects of cutting speed, feed, and radial depth-of-cut on surface integrity were investigated respectively. End milling can produce surface finish between 0.1 μm and 0.3 μm under most of the conditions. Roughness is generally higher in step-over direction than feed direction. No obvious white layer is observed in subsurface microstructure. The machined surface is significantly work-hardened due to the dominant mechanical loading. Four-point bending fatigue test shows that none of the milled samples failed within four million cycles. Fatigue endurance limits of the machined samples at different reliability levels were calculated and correlated with the experimentally determined fatigue life.

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Keywords: Surface integrity; Inconel alloy, milling; wear; fatigue

1. Introduction

Inconel 718 is one of the most commonly used nickel-based alloys in aerospace industry. It is known to be among the most difficult-to-cut materials due to its high strength even at high temperatures, low thermal conductivity, and especially rapid work hardening. Tool wear is an unavoidable and complicated phenomenon occurring in machining process. It is of great interests to machining industry to investigate the inherent relationship among tool flank wear, surface integrity, and fatigue performance of machined components.

In this research, the effects of tool flank wear on surface integrity and fatigue life of components by end milling of Inconel 718 was studied. The variation of surface integrity at different levels of tool flank wear and diverse combinations of process parameters was investigated. Tool wear values were measured and determined by an on-line optical tool inspection and measurement system. Surface integrity was characterized and four-point bending fatigue testing was used to determine the fatigue life of milled Inconel 718 specimens. By correlating tool flank wear, surface integrity, and fatigue performance of the machined components, a process space with acceptable tool flank wear can be determined for designed fatigue life with controlled variance.

2. Background on milling of Inconel 718

The main problems encountered when machining Inconel 718 are short tool life and thermal damage [1]. Aspinwall et al. [2] found that compressive surface residual stress in milling of IN 718 was produced when a horizontal upwards cutter orientation was used, while a tensile stress was produced using a horizontal downwards operation. Krain et al. [3] showed a specific combination of tool material and
geometries. Kortabarria et al. [4] compared the residual stress profiles induced by different dry face turning conditions. Devillez et al. [5] found that all residual stress profiles present a thin layer exhibiting tensile residual stresses near the machined surface with a maximum tensile stress at the surface in turning IN 718. This layer is followed by a zone with compressive stresses, several times thicker than the tensile layer. Kenda et al. [6] found that cryogenic turning of IN 718 generates high compressive residual stresses, and prevail at deep depth in the subsurface.

Alauddin et al. [7] found that cutting speed influences the tool life significantly in full-immersion end milling and down milling provides longer tool life than up milling in half-immersion end milling of IN 718. Sharman et al. [1] showed that tool coating was the main factor affecting tool life, followed by cutting speed and workpiece angle in end milling IN 718. They also found that the primary tool wear mechanism was adhesive and a “built-up edge” was seen on the tool. Kim et al. [8] observed that before reaching the maximum flank wear of 0.3 mm, almost similar cutting lengths were reached under the three different environmental conditions at higher cutting speed in milling IN 718. Jawaid et al. [9] found that wear rate increases with increased cutting speed for each fixed feed. Coated tools performed better than uncoated tools at most of the cutting conditions, which can be attributed to the high wear resistance and low thermal conductivity of TiN coating layer. Li et al. [10] developed an online optical system to inspect tool wear conditions during end milling of IN 718. Guo et al. [11] conducted a review of experimental study on surface integrity characterization after machining of hardened and difficult-to-cut alloys.

Compared with sharp tools, worn tools will negatively affect surface integrity and fatigue performance of the machined components. Koster and Field [12] suggested that the main mechanical property affected by machining is high cycle fatigue strength and the actual endurance limit depends on the particular process used and the severity of operation. Koster [13] found that the endurance limit of steel was dependent on surface roughness while nickel and titanium alloys were not. Machining induced residual stress has been recognized as one of the main factors which will significantly affect fatigue life [13,14]. It has been shown that the presence of a white layer associated with high tensile residual stress by a worn tool is very detrimental for rolling contact fatigue performance [15]. Guo et al. [17-19] concluded that the nature of surface residual stress and the depth of maximum compressive residual stress in the subsurface are important for fatigue damage. Matsumoto et al. [20] found that the average fatigue life of the turned AISI 4340 samples was higher than those ground ones. Denkena’s [21] showed that the turned samples using fresh tools exhibit higher fatigue strength than the ground ones. Only when a massive tool wear (VB = 0.2 mm used for each cutting condition) occurs, the fatigue strength of the turned samples drops below the fatigue strength of the ground ones.

Jeelani and Collins [22] showed that fatigue lives of the EDMed IN 718 specimens decreased slightly compared with those of the parent metal specimens, but remained unchanged with variations in cutting speed. Bentley, et al. [23] found the fatigue strength of gamma titanium aluminide intermetallic alloy was substantially increased by HSM compared to grinding since HSM may produce compressive residual stress in the subsurface. Li, et al. [24,25] found that the number of fatigue cycles generally decreased when increasing cutting tool flank wear in milling AISI H13 steel.

3. Tool wear vs. surface integrity experiment

End milling of Inconel 718 experiments were carried out with flood coolant on a 3-axis CINCINNATI Arrow 500 CNC vertical machining center. Tool flank wear was monitored and measured by an on-line optical tool monitoring system integrated with the CNC machine, see Fig. 1.

Fig. 1 On-line optical tool monitoring system for end milling.

3.1. Work material and cutting tool

The Inconel 718 work samples used in up milling experiments were 25 mm × 21 mm × 13 mm rectangular blocks. They were thoroughly hardened and tempered to 45 ± 1 HRC. Before milling tests, the top and bottom sample surfaces were face milled to remove the heat treatment induced surface defects and ensure flatness to eliminate machining errors.

The cutting tool (XOEX 120408R-M07, F40M) used in the milling tests was a 20 mm diameter end milling cutter with one PVD (Ti, Al) N/TiN-coated carbide inserts. The tool holder and the PVD-coated inserts were made by SECO Tool Company.

3.2. Experimental design

Table 1 lists the process conditions for the milling experiments. To investigate the effects of tool flank wear and typical process parameter values on surface integrity, totally twenty-one cutting tests (7 different cutting conditions, with three levels of initial tool flank wear: VB = 0, VB = 0.1 mm, and VB = 0.2 mm used for each cutting condition, see Fig. 2) were planned in the experiment.
### Table 1. End milling experiment plan to characterize surface integrity.

| Sample # | VB (mm) | Cutting condition # | Cutting speed [m/min] | Feed per tooth [mm/tooth] | Radial DOC [mm] | Axial DOC [mm] |
|----------|---------|---------------------|-----------------------|---------------------------|----------------|---------------|
| 1        | 0       | 1                   | 40                    | 0.15                      | 0.5            | 0.5           |
| 2        | 0.1     | 2                   | 60                    | 0.15                      | 0.5            | 0.5           |
| 3        | 0.2     |                     |                       |                           |                |               |
| 4        | 0       |                     |                       |                           |                |               |
| 5        | 0.1     | 2                   | 60                    | 0.15                      | 0.5            | 0.5           |
| 6        | 0.2     |                     |                       |                           |                |               |
| 7        | 0       |                     |                       |                           |                |               |
| 8        | 0.1     | 3                   | 80                    | 0.15                      | 0.5            | 0.5           |
| 9        | 0.2     |                     |                       |                           |                |               |
| 10       | 0       |                     |                       |                           |                |               |
| 11       | 0.1     | 4                   | 60                    | 0.1                       | 0.5            | 0.5           |
| 12       | 0.2     |                     |                       |                           |                |               |
| 13       | 0       |                     |                       |                           |                |               |
| 14       | 0.1     | 5                   | 60                    | 0.2                       | 0.5            | 0.5           |
| 15       | 0.2     |                     |                       |                           |                |               |
| 16       | 0       |                     |                       |                           |                |               |
| 17       | 0.1     | 6                   | 60                    | 0.15                      | 0.3            | 0.5           |
| 18       | 0.2     |                     |                       |                           |                |               |
| 19       | 0       |                     |                       |                           |                |               |
| 20       | 0.1     | 7                   | 60                    | 0.15                      | 0.4            | 0.5           |
| 21       | 0.2     |                     |                       |                           |                |               |

#### 3.3. Sample preparation

The machined samples were degreased by ultrasonic cleaning in acetone and then rinsed with DI-water before surface integrity characterization. Then, the samples were cross-sectioned with an abrasive cut-off saw at gentle cutting conditions to avoid excessive modification of surface integrity of the milled workpieces. After being mounted in cold setting epoxy, the samples were gently polished to a mirror-like finish. The samples were then etched with waterless Kalling’s reagent, rinsed in cold water, and dried by air.

#### 3.4. Surface integrity characterization

After end milling test, surface integrity factors including: surface roughness, microstructure, and microhardness were characterized in this study.

#### 3.4.1. Surface roughness

Surface roughness along feed direction and step-over direction was measured by Mahr stylus (PGK 120 with 90° and 2 μm radius tip). In order to get statistical stable data, three measurements along each direction were made at different locations when tracing on the machined surfaces. Fig. 3 shows the machined surface texture. The measured results of surface roughness along two directions were shown in Fig. 4.

It shows that fifteen of all the twenty-one milled surface had much higher roughness along step-over direction than along feed direction under the milling conditions listed in Table 1. Only three out of the twenty-one milled surfaces have surface roughness value of 0.3 μm < \( R_a \) < 0.4 μm in step-over direction and the remaining samples have surface roughness between 0.1 μm and 0.3 μm in both directions. In step-over direction, surface roughness increases with the increase of cutting speed at VB = 0 and VB = 0.1 mm. In feed direction, surface roughness generally increases when tool flank wear increases at each cutting speed level. The effect of feed per tooth can also be seen that \( f_z = 0.15 \) mm/tooth generally produces smaller surface roughness in both directions compared with \( f_z = 0.10 \) mm/tooth and \( f_z = 0.20 \) mm/tooth.
3.4.2. Subsurface microstructure

Although the chips carry away the majority of heat generated in milling process, a certain percentage of heat still dissipates into the machined surface. At abrasive milling conditions (high cutting speed, small feed rate, and large tool wear), it is possible that sufficient heat will conduct into the workpiece and induce phase transformation to form a white layer on the machined surface. However, optical images of the subsurface microstructure of twelve of the twenty-one samples do not show a noticeable white layer (Fig. 5). The possible reason is that the periodic tool/work contact reduces the amount of heat dissipated into the machined surface. Compared with the continuous tool/work contact in turning and grinding processes, milling would have less chance to induce thermal white layer at the same level of tool wear. This may explain why a white layer could be generated much more easily in turning and grinding.

3.4.3. Surface and subsurface microhardness

Microhardness on the surface and in the subsurface was measured at a load of 50 g for 10 s using a Knoop indenter. Microhardness of the machined surfaces was measured in two orientations: parallel and perpendicular to the feed direction. Three measurements were performed in each direction and an average of six measured values was used as surface microhardness. In the subsurface, microhardness measurements were taken at about 10 μm intervals between successive readings up to 100 μm. Similarly, three measurements were made at the same depths in the subsurface. Fig. 6 illustrates the representative microhardness profiles when tool wear increases.

Since the surface material experienced both mechanical and thermal loading, surface properties depend on the coupling effects of the two loadings. As thermal loading in milling has the characteristics of discontinuity and short time duration, while mechanical loading would be the predominant factor determining the surface properties. Based on the measured microhardness data for all the samples, the work-hardening resulted from mechanical loading on the machined surface would be dominant since much higher average microhardness occurred on the surface than the subsurface. The low microhardness at approximately 5 μm into the subsurface is likely induced by the edge effect of micro-indenter rather than thermal effect. The reason for the measured low hardness was explained in [26].

4. Fatigue performance

4.1. Fatigue sample preparation

The Inconel 718 rectangular blocks used for fatigue testing were of dimensions: 200 mm × 21 mm × 12 mm. Before end milling tests, the blocks were also face milled on top and bottom surfaces to remove the heat treatment induced surface defects and ensure flatness to eliminate errors that may affect experimental results. The cutting tool used in the machining tests was a 20 mm diameter end milling cutter with one PVD (Ti, Al) N/TiN-coated carbide insert. The tool holder and the PVD-coated inserts were all made by SECO Tool Company. Four rectangular Inconel 718 blocks were sequentially end milled by the same cutting tools. So the milled blocks are categorized as specimens machined by tools with different flank wears. Both top and bottom of the blocks were machined using the same cutting parameters, see Table 2. Flood coolant was applied throughout the tests. In order to assign the flank wear value ranges into four specimens without causing tool failure, each side of the specimens was equally divided into three zones and three individual inserts were used to mill one surface which greatly shortened the cutting time for each tool (about 13 minutes in each zone), see Fig. 7. Three fresh tools were first applied to mill on the top
surface of one workpiece and then sequentially on the other
top surfaces of the three remaining specimens. Following the
same procedure, the bottom surfaces of the four specimens
were prepared using another three fresh tools. In this way, the
top and bottom surfaces of the end milled specimens were of
the similar surface conditions. Representative images of tool
wear evolution on flank face can be seen in Fig. 8 (tool #2
milling in zone #2 of the four samples). Before fatigue test,
the specimens’ edges were polished to eliminate the effects of
burs and sharp-edges on fatigue life.

| Table 2. End milling parameters to prepare fatigue samples. |
|-----------------------------------------------------------|
| Cutting speed | Axial depth of cut \( a_p \) (mm) | Feed rate \( v \) (mm/min) | Radial depth of cut \( a_e \) (mm) | Rotational speed \( n \) (rpm) |
|----------------|---------------------------------|-----------------|------------------------------|-----------------|
| 90             | 0.5                             | 215             | 0.5                          | 1433            |

Fig. 7 Divided zones on top and bottom surfaces of the workpiece.

4.2. Fatigue testing setup

Four-point bending fatigue tests were run at room
temperature on a MTS 810 Test System (Fig. 9). The MTS
810 test system consists of a servo-hydraulic fatigue testing
machine, a Flextest SE digital controller, and the
MultiPurpose TestWare Software (MPT). The test specimen
sits on the loading fixture which is bolted to the oscillating
piston. The oscillating piston moves up and down with the
loading fixture at a certain frequency. The supporting fixture
is fixed at supporting end to keep the loading direction
constant.

A cyclic load was applied at a frequency of 10 Hz and with
a sinusoidal waveform. The nominal stress can be calculated
by the beam theory:

\[
\sigma = \frac{3Pa}{wh^2}
\]

where specimen width \( w = 21 \text{ mm} \), height \( h = 12 \text{ mm} \), \( a = \frac{1}{2} b = 38.1 \text{ mm} \) (Fig. 10).

The maximum tensile stress \( \sigma_{\text{max}} \) at the bottom of test
samples was set to be 800 MPa, which is larger than 50% of
the UTS (1435 MPa) of IN 718. As shown in Fig. 10, the
load-span \( b \) was set to 76.2 mm, support-span = \( 2a + b = 152.4 \text{ mm} \), and the stress amplitude ratio \( R = 0.1 \). The fatigue
testing conditions are listed in Table 3.

| Table 3. Four-point bending fatigue testing condition. |
|-------------------------------------------------------|
| Max stress \( \sigma_{\text{max}} \) (MPa) | 800 |
| Min stress \( \sigma_{\text{min}} \) (MPa) | 80 |
| Stress ratio \( R (\sigma_{\text{min}}/\sigma_{\text{max}}) \) | 0.1 |

4.3. Fatigue life

Fatigue life management of machined components under
the progression of tool wear is concerned from the viewpoint of
product performance. Fatigue test was terminated when the
failure of the specimen occurred or the upper limit of loading
cycles, which was preselected as 4 million cycles (in
consideration of testing time, cost, facility capability, etc.)
was reached. However, none of the four samples failed within
4 \( \times \) 10^6 cycles, see Fig. 11.
5. Conclusions

This work focused on the basic relationships between tool wear, surface integrity, and fatigue in end milling of Inconel 718. The key results may be summarized as follows:

- All the milled surfaces had roughness of less than 0.4 μm, and the majority surface roughness less than 0.25 μm. Higher tool wear produced less surface roughness.
- Thermal-induced white layers were not observed for the concerned tool wear levels, which may be explained by the improved cooling effect from the periodic tool/work contact in milling compared to constant tool/work contact in turning and grinding.
- The machined surface has been work-hardened due to the dominant mechanical loading which can be seen by relatively higher microhardness at milled surface.
- No fatigue occurred within four million cycles for all the machined samples up to tool wear VB 0.2 mm. Tool wear within a certain range doesn’t necessarily affect the fatigue life.

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