Wear mechanisms of silicon carbide-whisker-reinforced alumina ($\text{Al}_2\text{O}_3$–$\text{SiC}_w$) cutting tools when high-speed machining aged Alloy 718

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Abstract The paper is aimed at the identification and characterization of wear mechanisms of SiC whisker-reinforced alumina when turning aged Alloy 718 under different cutting conditions and when machining dry and with coolant. Secondary and backscatter electron microscopy accompanied by focus ion beam milling and EDX techniques were used for analysis of worn-out tools. Notch wear on the major cutting edge was found to consist of two notches: depth-of-cut notch and secondary notch located outside the chip area. The last was found to be governed by adhesion and attrition associated with adverse chip flow conditions. Formation of a minor notch was related to attrition by the defects found on the machined surface. Diffusion of Ni, Fe, and Cr into SiC whiskers was found to degrade them and facilitate adhesion. Chemical wear mechanisms were found to be responsible for degradation and decomposition of whiskers and formation of tribolayer on tool surfaces, which in turn was related to the reduced adhesion of Alloy 718 on the tool. Cracking on the tool rake and localized plastic deformation were found to further accelerate tool deterioration.

Keywords Alloy 718 · Whisker-reinforced alumina · Notch wear · Diffusion · Chemical wear

1 Introduction

Tool wear and associated tool life is a key criterion of performance of a tool material in question. Recognized importance draws extensive attention of researchers [1–3] where the investigated aspects can be grouped into studies of morphology of worn-out tools, chemical stability of tool materials, aspects of strength, etc. Severity of tool wear as a whole depends on the intensity of individual wear mechanisms or their combinations.

Alloy 718 is a heat-resistant superalloy which retains mechanical strength at temperatures up to 650 °C and fracture toughness down to −40 °C, and possesses high oxidation and corrosion resistance [4]. Low thermal conductivity, adhesiveness, chemical affinity to many tool materials as well as highly abrasive and work-hardenable microstructure lead to short tool life and low production efficiency of machining operations. Application of ceramic tools offers a significant increase in production efficiency [1], yet new issues related to tool wear arise. Notch wear is the dominant wear mechanism which limits tool life of pure alumina ceramics and often leads to tool failure [5]. While application of SiC whisker-reinforced or silicon nitride-based ceramics may reduce notching, new issues of adhesion [6], diffusion [2], and chemical wear [7] arise.

Two principal areas of notch formation are observed when machining Alloy 718: depth-of-cut (DOC) notch on the major cutting edge and notch on the minor cutting edge [2]. DOC notch is typically used as the tool life criterion since its large values may result in tool fracture [8], while minor notch controls generated surface quality [9]. Formation of the DOC notch is considered to be determined by a high gradient of thermal and mechanical stresses [10]. Other
mechanisms involve adhesive wear associated with micro welds accompanied by tool material pluck out [11] and attrition wear, both by work-hardened edges of chips [12] and burrs formed at DOC line [13]. Minor notch is also an inherent wear mode when turning Alloy 718 with pure and whisker-reinforced alumina [8], mixed alumina, and Si3N4-based ceramics [1]. Brandt et al. [2] found that intensity of minor notch is speed dependent and suggested chemical wear as notch formation mechanism. High temperatures of above 1,200–1,400 °C were required for chemical reactions in the Al2O3–SiC system [14]. Significantly lower temperatures on the tool flank [1] especially in the surface formation region [15] suggest that chemical wear is not the dominant contribu-
tor to the wear mechanisms in the minor notch.

Several types of chemical wear of ceramic tools are recognized: reactions of the workpiece material or environment with alumina matrix (Al2O3) and reactions with strengthening phases (TiC, SiC, Si3N4, TiB2, etc.). Alumina cutting tools when machining steels are known to react with formation of iron-based spinels of Fe2O3–Al2O3 [16] and Fe–Al2O3 [17]. Extensive use of magnesia as deoxidizer in steels and Alloy 718 [2] can lead to formation of MgO–Al2O3 or more complex spinel of Fe–Mg–Al–O system [18]. Most of the reaction products become either plastic or liquefy under the cutting temperature thus forming tribolayer on the tool surfaces. An advantage of the tribolayer is that in liquid state, it suppresses tool/workpiece adhesion and reduces friction coefficient [19]. Use of SiC whisker reinforcement in ceramics is expected to additionally intensify the formation of tribolayer through oxidation of whiskers. Silica is known to form on the Al2O3 and SiC interface [20]. Liquid at cutting temperatures SiO2 phase may react with alumina and form either aluminosilicate glass or crystalline mullite [21].

Diffusion on the contrary to tribolayer leads to intensification of adhesion processes as well as reduces tool life by changing tool material properties. Brandt et al. [2] identified intensive counterdiffusion of Ni, Fe, and Cr into silicon-containing phases and diffusion of Si into the workpiece material when high-speed machining with Al2O3–SiCw and Si3N4 tools. Similar processes with replacement of silicon by chromium were observed by Narutaki et al. [9] when machining Alloy 718 with Si3N4 composite.

Besides notching, diffusional, and chemical wear, other issues of cracking, plastic deformation, tool fracture, etc. require detailed study and understanding of their formation mechanisms. The objective of the present investigation is to identify wear mechanisms intrinsic to high-speed turning of aged Alloy 718 with whisker-reinforced alumina (Al2O3–SiCw) tools and to characterize their formation mechanisms. Intensity and specifics of the detected wear mechanisms were analyzed in view of the effect from cutting conditions and coolant application.

### 2 Experimental details

Machining tests were run on a 70-mm-diameter bar work-piece of Alloy 718 supplied in solution annealed and aged (precipitation hardened) conditions (HRC, 45 ± 1). The chemical composition is listed in Table 1. Longitudinal turning operation was performed on a 70-kW SMT 500 CNC lathe with up to 4,000 rpm spindle speed. All tests employed CC670 whisker-reinforced alumina (Al2O3–SiCw) DGN150712T0120 inserts with 1.2-mm nose radius and 0.1×20° chamfer. When installed on the CDJNL3025P11 toolholder, they provided −6° back and −6° side rake angles and 93° major cutting edge angle. Two series of tests (see Table 2) were run in order to evaluate tool wear/life of the ceramics under variation of feed, depth of cut, and cutting speed, where the conditions were selected based upon recommendations from the industry. The third series investigated influence of speed and coolant application (Table 2) on tool life and wear mechanisms. If otherwise not stated, tests were run under application of 5 % semi-synthetic coolant at 5 bar and 40 l/min. Size of flank wear land (VB) was used as the criterion of tool life due to intensive notching of the tools and large variation of its magnitude. All other types of wear were observed upon reaching the criteria value of VBmax≈0.3 mm.

Initial observation and measurements of worn-out inserts were performed with a Leica MZ16 optical stereomicroscope. HRSEM LEO/Zeiss 1560 was used in backscatter electron mode for detailed observations of worn tools. HRSEM FEI Nova NanoLab 600 was used for secondary electron imaging and focused ion beam (FIB) cross sectioning and lamella preparation. EDX quantitative analysis was done on an ISIS 300 Microanalysis System.

### 3 Results and discussion

Irrespective of cutting conditions or coolant application, the morphology of the worn-out tools comprises (see Fig. 1) of a notch on the major cutting edge (hereinafter major notch),

<table>
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<th>Table 1</th>
<th>Chemical composition of Alloy 718 in weight percent</th>
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<tr>
<td>Elem</td>
<td>Ni</td>
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<tr>
<td>Min</td>
<td>50.0</td>
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<td>Max</td>
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