Performance of Solid SiAlON Milling Tools Doped With Different Rare Earth Elements on High Speed Milling of Inconel 718

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Abstract

Inconel 718 is a heat resistant superalloy used for manufacturing of critical components at the hot zone of an aircraft engine due to its outstanding high temperature mechanical and chemical properties. On the other hand, these superior properties as well as low thermal conductivity, high tendency to work hardening and built up edge (BUE) layer on the cutting face of the tool, make Inconel 718 one of the most difficult to cut metals. Therefore, there are limited number of tool materials which can be operated at aggressive cutting conditions during machining of superalloys. SiAlON based ceramics in the form of solid milling cutter were developed and utilized for high speed rough milling of superalloys, recently. The cutting performance of SiAlON based tools strongly depends on various material parameters such as α and β-SiAlON phase ratio, solubility of Al2O3 in β-SiAlON crystal structure (defined as z value), rare earth dopant type used in the composition, etc. In this study, an α/β-SiAlON, doped with four different rare earth (Y, Yb, Er and Ce) element was manufactured in the form of a solid milling cutter and tested on high speed milling of Inconel 718. It was observed that the main wear mechanism was the diffusion subsequent to adhesion and Y and Er doped SiAlON tools showed significantly better wear resistance in comparison to the other tools.

1. Introduction

Nickel based superalloys with outstanding high temperature mechanical and chemical resistance are used for manufacturing of the critical heat resistant parts of an aircraft engine. However, high shear strength, high tendency to work-hardening and to form built-up-edge (BUE) at the tool rake face during machining and low thermal conductivity make these materials difficult to machine [1]. Machining of Inconel 718, one of the most widely utilized superalloys, was reported 16, 6 and 4 times more difficult than machining of aluminum, low carbon steel and hardened steel, respectively [2]. Therefore, there is always a strong demand for a high wear resistant tool material which can be operated for machining of Inconel 718, successfully. Although WC-Co based cutting tools can be used for machining of Inconel 718 alloy up to a cutting speed of 50 m/min, motivation for manufacturing of the Inconel parts in shorter time by increasing the cutting speed hinders the application of these tools [3]. Zheng et al. [4] defined the machining at cutting speeds higher than 200 m/min. as ultra-high speed and there are limited tool materials can be operated under extreme cutting conditions which is the result of high cutting speed and pressure. α/β-SiAlON ceramic cutting tools with an optimum combination of hardness and fracture toughness, outstanding high temperature mechanical and chemical durability and high thermal shock resistance are one of the most suitable materials for these challenging application [5]. Altin et al. [6] investigated the wear of SiAlON turning inserts as a function of cutting speed and tool geometry. The authors stated that while flank and crater wear were dominant mechanisms for square inserts, flank and notch wear were mainly observed at the cutting edges of round inserts. In a similar investigation, Li et al. [7] tested SiAlON based inserts at different cutting speeds and observed the notch and flank wear as dominant wear mechanisms at low (120 m/min) and high (300 m/min) cutting speeds, respectively. Zheng et al. [8] also reported the adhesion and the abrasion as main wear mechanisms observed during turning of Inconel 718 at high cutting speeds.

In spite of their superior properties over carbide counterparts, the literature on the utilization of SiAlON inserts on high-speed milling of Inconel 718 is limited. Zheng et al. [4] manufactured and tested functionally graded SiAlON-TiCN inserts together with Al2O3-SiCw tools on high-speed milling of Inconel 718 alloy at various cutting speeds. They reported that the superior wear resistance of graded tool was observed at the cutting speeds between 700-900 m/min. Tian et al. [9] studied high-speed face milling of Inconel 718 with
SiAlON ceramic inserts under dry cutting conditions. They found the notch wear as dominant mechanism when the cutting speed is relatively low (600–1400 m/min.) and the adhesion wear at higher cutting speeds in the range of 1800–3000 m/min. Unlike to these studies, Çelik et al. [10] manufactured solid SiAlON based milling tools and investigated the comparative performance of these tools at high speed side milling experiments conducted at ~600 m/min, for the first time in the literature. A severe adhesion of work piece material to the cutting edge and a subsequent crater formation at the tool edge was reported under dry cutting conditions.

The cutting performance of SiAlON based tools strongly depends on various material parameters such as α and β-SiAlON phase ratio, solubility of Al₂O₃ in β-SiAlON crystal structure (z value), rare earth dopant type used in the composition, etc. While the effects of these variables on the performance of SiAlON cutting inserts used in high speed turning and milling of superalloys are substantially clear, the performance of solid SiAlON milling tools dependent on these parameters has not been investigated in detail, yet. The aim of this study is to investigate dopant-dependent milling performance of an α/β-SiAlON solid milling cutter prepared with four different rare earth (Y, Yb, Er and Ce) on high speed milling of Inconel 718.

2. Experimental Procedure
2.1. Manufacturing of SiAlON milling tools

An α/β-SiAlON composed of Y₂O₃ as main dopant and a small amount of Sm₂O₃ and CaO (in the form of CaCO₃) was used as the reference composition, the milling performance of which was previously investigated in [10]. While this composition was designated as S-Y, the other compositions derived from S-Y by replacing the main dopant with Yb, Er and Ce was labelled as S-Yb, S-Er and S-Ce, respectively.

α-Si₃N₄ (UBE-SN10), AlN (Tokuyama-E grade), Al₂O₃ (Sumitomo-HPA) and other rare-earth additive oxides (Y₂O₃ (Treibacher), Yb₂O₃ (Treibacher), Er₂O₃ (Treibacher), CeO₂ (Treibacher) and Sm₂O₃ (Treibacher)) were weighed in proper amounts and charged to an attritory mill in aqueous medium for the homogenization of the slurries. The slurries were then further mixed for one hour after the addition of organic pressing additives in the amount of 6 wt.% of the total solid loading. Then, SiAlON granules with an average diameter of 100 μm were obtained by the atomization of the SiAlON slurries in the chamber of a pilot-scale spray dryer. After this step, the granules were transferred to a cylindrical flexible polyurethane mold and compacted in an isostatic press (CIP) at 200 MPa in order to obtain green SiAlON rods. A binder burn-out heat treatment was conducted at 550°C for 1 hour prior to sintering of green SiAlON rods. After that, SiAlON rods were densified in a Gas Pressure Sintering (GPS) furnace (FCT-2200) at 1900°C and 100 bar N₂ gas pressure. After sintering, SiAlON rods were ground based on a six-flute milling tool geometry developed for SiAlON based solid milling tools by Davis et al. [11]. A representative picture of SiAlON milling tools was given in Figure 1.

2.2. High speed milling tests of SiAlON milling tools

High-speed milling tests were carried out with a 5 axis horizontal CNC machining center (Makino-GF8). A cylindrical Inconel 718 part with a diameter of 100 mm was used as work-piece materials in the tests. The elemental composition of Inconel 718 alloy is given in Table 1. An extreme cutting speed was selected as ~590 m/min. in order to increase cutting zone temperature over 1000°C. The radial (aₑ) and axial depth of cut (aₚ) were selected as 0.635 mm and 9.652 mm, respectively. The wear at the cutting edge of the tools was analyzed every two continuous cutting tests, one of which starts at d= 100 mm and ends d= 20 mm. The overall performance tests were stopped after the sixth continuous tests for each tool. The wear at the cutting edges of the tools were examined by a scanning electron microscope (SEM).

Table 1. Elemental composition of Inconel 718 alloy used in high-speed machining tests.

<table>
<thead>
<tr>
<th></th>
<th>Fe</th>
<th>Cr</th>
<th>Al</th>
<th>Nb</th>
<th>Mo</th>
<th>Ti</th>
<th>Ni</th>
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<td>wt.%</td>
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<td>15.26</td>
<td>4.42</td>
<td>3.60</td>
<td>2.35</td>
<td>0.76</td>
<td>Balance</td>
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3. Results and Discussion
3.1. Properties of SiAlON ceramics

Figure 2 (a)-(d) shows the back-scattered electron (BE) images and (e) shows the x-ray diffraction (XRD) patterns of the SiAlON compositions after sintering. The microstructure of the SiAlON compositions is formed by the dark gray needle-like β-SiAlON grains.
and equiaxed α-SiAlON grains which appear more brighter due to partial solubility of high atomic number rare earth atoms in α-Si3N4 crystal lattice. The white islands in sub-micron size distributed throughout the microstructure are the oxynitride phase. It is seen in Figure 2 (a)-(c) that the microstructural characteristics of S-Y, S-Yb and S-Er samples were quite similar to each other in terms of grain shape, size and amount of α and β-SiAlON phases. On the other hand, α-SiAlON grains were not detected in the microstructure of Ce-doped sample (Figure 2 (d)), proving that the stabilization of α-SiAlON phase was not achieved by Ce in comparison to the other rare earth elements. This was also confirmed by XRD analysis given in Fig. 2 (e). According to Ekstrom [12], the largest rare-earth cation to be able to enter the α-SiAlON structure alone is Nd³⁺, with an ionic radius of 0.98 Å. The larger cations such as La³⁺ (r= 1.03 Å) and Ce²⁺ (r= 1.01 Å) are considered unable to occupy alone the interstitial sites in α-SiAlON crystal structure. In this study, 5 mole % of Sm³⁺ and Ca²⁺ (with a radius of 0.958 and 1 Å, respectively) were used together with Ce³⁺; however, stabilization of α-phase was not achieved because of their insufficient amounts in the composition. A considerable crystallization of grain boundary phase in the form of melilite (a nitrogen-rich refractory phase) with a general formula of $\text{Ln}_2\text{Si}_{3-x}\text{Al}_x\text{O}_{3+x}\text{N}_{4-x}$ was also detected in XRD patterns.

3.2 High speed milling performance of SiAlON tools

Figure 3 shows the worn flank faces of the SiAlON tools after 2nd, 4th and 6th tests. A uniform adhesion of the work-piece material to the cutting surfaces of the tools occurred due to extreme temperature at the cutting zone above softening point of Inconel 718, which was reported by Çelik et al. [10] as ~1060°C. After the 2nd test, a characteristic accumulation of Inconel 718 alloy at the tip of the cutting edges was also observed. The amount of accumulated Inconel 718 at these regions for S-Y and S-Er tools was considerably lower than that of S-Yb and S-Ce tools. This is probably the result of different wetting characteristics of the SiAlON tools, which was probably affected by the type of rare-earth elements used in the composition. After 4th and 6th tests, the amount of accumulated Inconel 718 layers at the tool tips increased due to progressive wear of the milling tools. In case of Yb-doped composition, a crater with ~100 μm width and ~500 μm length formed by the instantaneous removal of this adhered Inconel 718 was observed after the 4th test. The formation of these relatively huge craters indicates that the strength of S-Yb-diffusion layer interface was not enough to protect the surface integrity of the tool. The thermal expansion mismatch between SiAlON and diffusion products plays an important role on the strength of this interface and therefore formation of crates [10]. Since the wear occurred as the consequence of the instantaneous removal of the adhered Inconel 718 layer together with the fragments of the tool material from the flank face, it became impossible to express the comparative wear behavior of the milling tools quantitatively. However, it is obvious in Figure 3 that the chemical wear resistance of Y and Er-doped SiAlON milling tools were much higher than that of Yb and Ce-doped counterparts.
In order to reveal the chemical composition of the diffusion products, the worn surface of S-Yb tool after 6th test was investigated in detail by EDX analysis which is given in Figure 4. It is clear in Figure 4 that the diffusion layer at the tool tip composed mainly of Al, Cr and O as well as Ti. The Al-rich diffusion products at the Si₃N₄ based ceramic cutting tools was also reported by Tian et al. [9]. According to these elements distributed throughout the diffusion scale, (Al, Cr)₂TiO₅ crystallization on the tool face was expected. Since the thermal expansion coefficient of this phase (~0.68×10⁻⁶ K⁻¹) is much lower than that of Si₃Al₂ON substrate (~3×10⁻⁶ K⁻¹), a quick removal of the diffusion scale from the cutting edge due to the formation of large number of thermal cracks was expected. Consequently, compatibility of diffusion products with the Si₃Al₂ON substrate as well as wetting behavior of the substrate were strongly dependent on the type of rare-earth used in the starting composition, which determines the machining performance of solid Si₃Al₂ON milling tools.

4. Conclusion

In this study, high speed machining performance of solid Si₃Al₂ON ceramics doped with different rare-earth elements was investigated. Although comparative wear behavior of the milling tools was not obtained quantitatively due to instantaneous removal of the adhered Inconel 718 layer together with the fragments of the tool material from the flank face, it was obvious that superior wear resistance of Y and Er doped Si₃Al₂ON tools was determined. Moreover, a diffusion scale composed of Al, Cr, Ti and O elements was formed at the tool tip. The type of the rare-earth dopants was expected to affect the compatibility of this scale and therefore chemical wear resistance of the tool.

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References