JMEPEG (2010) 19:1193–1198
DOI: 10.1007/s11665-009-9587-3

1059-9495/$19.00

Microscopic Observations on the Origin of Defects During Machining of Direct Aged (DA) Inconel 718 Superalloy

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(Submitted March 5, 2009; in revised form October 2, 2009)

Surface quality of advanced superalloys after machining is one of the major issues in the aerospace industry because it directly affects service characteristics of the machined part. Tool life of cemented carbide inserts with the TiAlN coating during machining of direct aged DA 718 alloys under roughing and finishing conditions has been under study. The defect origin on the surface of the machined part was investigated. Metallographic observations of the DA 718 were made using optical metallography and SEM/EDS. To find out the origins of surface defect formation, the morphology of machined parts and cross sections of the machined surfaces have been investigated. Two major categories of defects were detected on the surface of the machined part: cracks and tears. The origin of the cracks on the machined surface is related to shearing of the primary complex TiC/NbC carbide revealed in a structure of DA 718 alloy. At the same time, Nb-rich regions of the primary complex carbide interact with the environment (oxygen from air) during machining with further formation of low strength oxide layer on the surface, forming tears.

Keywords aerospace, coatings, failure analysis, machining, metallography

1. Introduction

Severe failures produced by fatigue, creep and stress corrosion cracking, invariably start at the surface of the components, and their origins depend to a great extent on the quality of the surface (Ref 1). Direct aged (DA) 718 alloy was developed from Inconel 718, a representative wrought superalloy for disc applications in gas turbines, a next generation of blade rotors. Application of this alloy has increased significantly in recent years due to its very high yield and ultimate tensile strength as well as excellent creep resistance up to 650 °C (Ref 2). DA differs from the standard processed Alloy 718 in forge practice and heat treatment. DA 718 receives larger forging reductions at lower temperatures; it is water quenched after forging, and then directly aged. As a result the very high room-temperature yield strength of 1350 MPa is reported for DA 718 (Ref 3, 4). One of the major characteristics of the machined parts for aerospace applications is their service properties, first of all—low-cycle fatigue strength. To ensure high-fatigue strength, the surface should be ideally defect-free after machining. This is a challenge for DA 718 due to its additional structural strengthening compared to Inconel 718 (Ref 5). In this case, surface integrity improvement of the Ni-based direct-aged alloy DA 718 requires a good understanding of the mechanism of defect formation during machining.

Due to low thermal conductivity, nickel-based alloys harden rapidly during machining and this affects the strain range within the cutting zone (Ref 6). The problem becomes even more complex when additional strengthening of aero-engine alloys leads to a more pronounced adverse effect on their machinability as well as surface quality. This is especially important for finishing operations where tolerances and requirement to surface finish are so tough that some machining parameters such as depth of cut and feed/rev lie within the work hardened zone (Ref 7).

DA 718 has grain sizes ranging from 2 to 10 μm. There are micrometer-sized, δ (Ni, Nb) particles distributed throughout the structure (Ref 4, 8). Isolated carbide, nitride, and oxide particles are also present. Strengthening in DA 718 alloy is produced mainly by intermetallic Ni, Nb (γ'') precipitates (20-40 nm diameter, 5 nm thick) with some contribution from Ni,(Al, Ti) γ' precipitates. Larger amount of precipitates in DA and carbides compared to Inconel 718 makes the alloy both stronger and more difficult to machine, thus increasing wear rate of cutting tools (Ref 2-4). Both tool life and surface integrity are two major issues for machining of DA 718 alloy. Surface integrity issues are primarily manifested with formation of tears and cracks on the surface of the machined part during cutting. They are most likely associated with large (5-15 μm) primary carbides that are contained in the structure of Inconel 718 superalloy. Primary carbides are complex TiC/NbC carbides (Ref 9, 10). They are hard and brittle and have a tendency to interact with the environment at elevated temperatures within the cutting zone (Ref 3, 11). Presence of hard abrasive particles (e.g., carbides, oxides) results in intense tool wear as well poor surface integrity.

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The goal of this paper is to investigate the relation between primary carbides in DA 718 alloys and defect (cracks, tears) formation of the surface directly after machining. This article is mainly focused on the mechanism of defect formation during machining of DA 718 alloy through understanding of nature of defects.

2. Experimental

Microstructural studies of the direct aged (DA) 718 nickel-based superalloy have been performed using optical metallography and HR SEM/EDS techniques. Machining experiments have been performed using Nakamura SC450 turning Center. Tool life was studied under various cutting conditions. Turning experiments cutting parameters (finishing operation) are the following: cutting speed 30 m/min, depth of cut 0.125-1.5 mm, and feed 0.1225-0.2 mm/rev. Commercial cemented carbide inserts (K-grade) with TiAlN PVD coating commonly used for cutting of Inconel alloys were employed in this work. Cutting experiments have been performed under wet machining conditions. Machining was carried out on each workpiece with a fresh cutting edge for a radial length of 25 mm and the workpiece removed for metallographic observation. Five workpieces were prepared to evaluate the average number of surface microdefects (tears and cracks) per square centimeter of machined surface. After the surface morphology analyses, each workpiece was subjected for cross section sample preparation. Sections were hot mounted in Bakelite, ground using SiC paper and polished with diamond grit. After polishing, they were etched with acetic glycergia.

Microhardness measurements were conducted using a Knoop indenter at a load of 50 g for 15 s. Sections were hot mounted in Bakelite, ground using SiC paper and polished with diamond grit. After polishing, they were immersion etched in Kallings No. 2 reagent for approximately 10 s. To overcome hard particles sensitivity, a series of measurements were taken on a cross section and an average obtained.

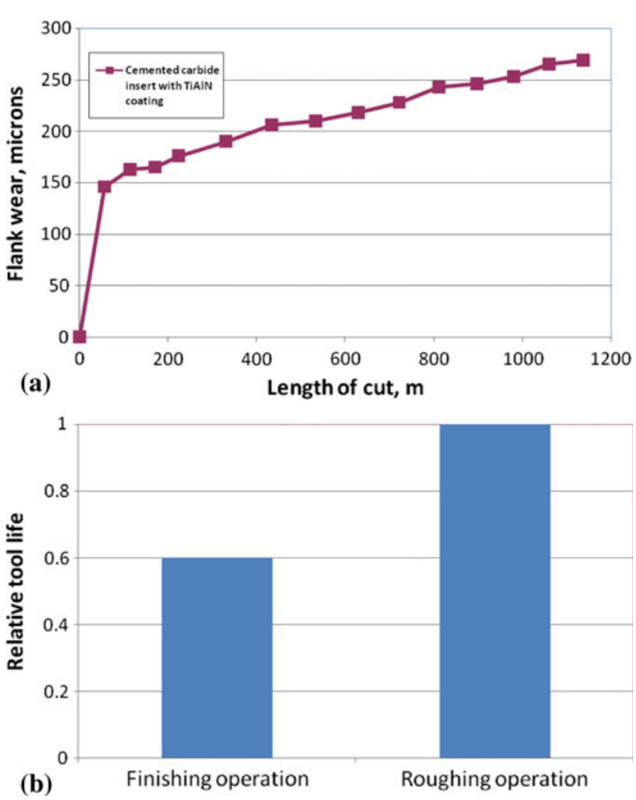

Fig. 1 Tool life for the coated cemented carbide inserts during machining of DA 718 alloy (cutting speed 30 m/min; depth of cut 0.7 mm): (a) roughing operation and (b) relative tool life during finishing and roughing operations

3. Results and Discussion

3.1 Tool Life Investigations

Figure 1(a) shows that tool life for the cemented carbide cutting inserts is quite sufficient during roughing operation. However, if the finishing operation is performed, tool life is reduced significantly (Fig. 1b) due to work hardening within the surface layer (Ref 7, 12, 13), along with higher general hardness of DA 718. To estimate work harden zone, microhardness tests were conducted. Figure 2 presents the microhardness depth profile of the DA and Inconel 718 workpiece surface from finishing operation. The Inconel 718 workpiece surface hardness was increased compared to bulk with a return to bulk values within the first 50 μm depth below the surface. The data obtained for the DA 718 indicate the effect of work hardening of the first 100 μm beneath the workpiece surface. The depth of the work-hardened layer is higher for DA 718 than for Inconel 718. Thus finishing operation is more challenging for the DA 718 alloy particularly in terms of complete elimination of the surface defects. Unfortunately, there is a lack of data on machining of advanced super alloys such as DA 718. Based on industrial practice tool life above 15 min is agreeable for machining of aerospace alloys. Recalculating the length of cut (m) into time (min) yields a tool life (Fig. 1a) greater than 40 min.

3.2 Investigation of Machined Part: Structure of Workpiece Material and Surface Morphology After Machining

First, the microstructure of workpiece material (DA 718 alloy) was compared to regular Inconel 718 alloys before machining using high-resolution SEM microscopy (Fig. 3a and b). There is a big difference in microstructure: the precipitates form at the grain boundaries and then in grain interior creating strengthening as well as harsh machining environment for the

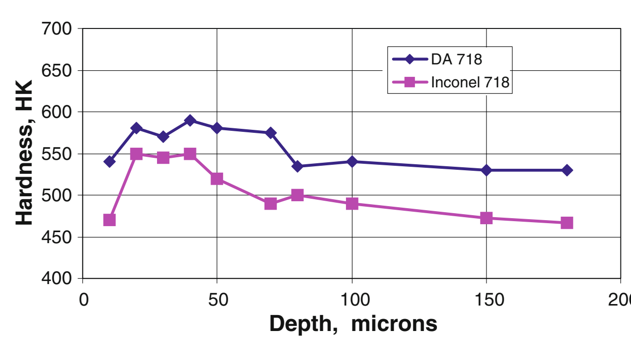

Fig. 2 Microhardness depth profile of the DA and Inconel 718 workpiece surface after the finishing operation

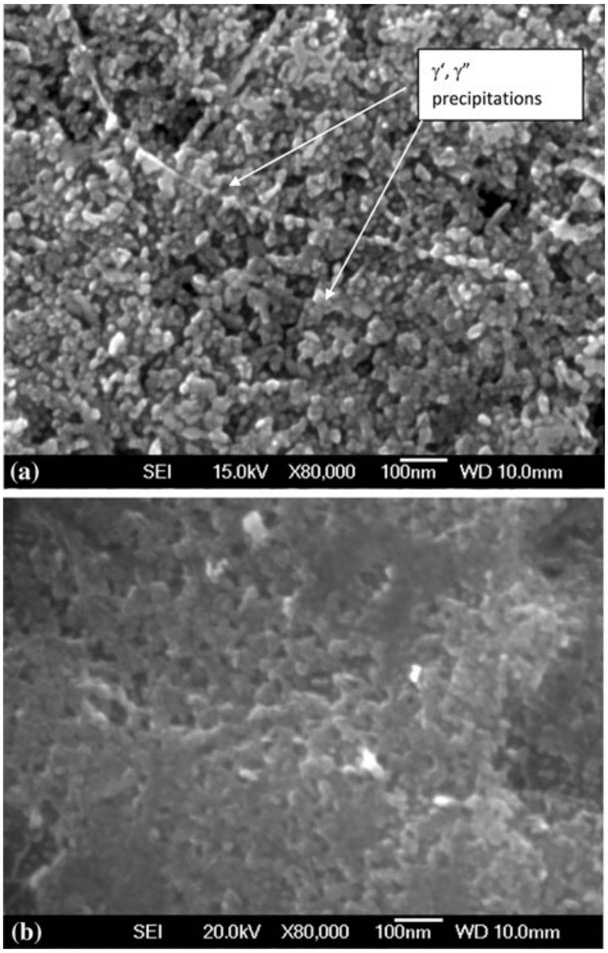

Fig. 3 Microstructure of studied workpiece materials: (a) DA 718 and (b) Inconel 718 alloys (HR SEM, magnification 80,000×)

DA 718 (Fig. 3a). As a result, the average microhardness values of both alloys are different: HK 467 (HRC 46) for the Inconel 718 and HK 533(HRC 51) for the DA 718.

Optical studies of the DA 718 alloy microstructure indicate the presence of large primary carbides (Fig. 4a). These primary carbides, as SEM/EDS data show, are mostly complex TiC/NbC carbides (Fig. 4b, d, and e). The carbides were distributed randomly, with a size of 1-15 μm.

Investigation of surface morphology of the machined surface was made after finishing and the average number of surface microdefects was three to four defects per square centimeter. There are two typical defects on the surface of DA 718 after machining: (1) cracks (Fig. 5a) and (2) tears (Fig. 5c). Cracks on the machined surface are associated with both types of carbides: TiC and NbC. Surface morphology observation revealed that microcracks are preferably forming on TiC or Ti-rich regions of the complex Ti/NbC particles (Fig. 5a and b). In contrast, the tears (Fig. 5c) are related to the oxidation of NbC (Fig. 5d).

Cross sections of different spots of the machined surface show crack-progression and surface flow formation in a zone with large carbide concentrations (Fig. 6 and 7). High temperatures, around 600-800 °C, are generated on the tool/workpiece interface during machining of Ni-based super-alloys (Ref 12). At these temperatures, intensive oxidation of the machined surface is taking place even under intensive coolant flow (Ref 13). It was shown elsewhere that NbC intensively oxidizes at temperatures above 400 °C (Ref 11, 14). The EDS spectrum in Fig. 5(b) indicates that TiC oxidizes as well but more slowly (Ref 10). Figure 6(a and d) is related to Fig. 5(a and b) and shows that cracks on the outer surface of DA 718 are a result of shearing while cutting carbide particles, mostly TiC. Nb oxides layers form on the NbC-metal matrix interface of the Ni-based superalloy during high-temperature oxidation. Niobium oxide formation on the machined surface is confirmed by EDS data

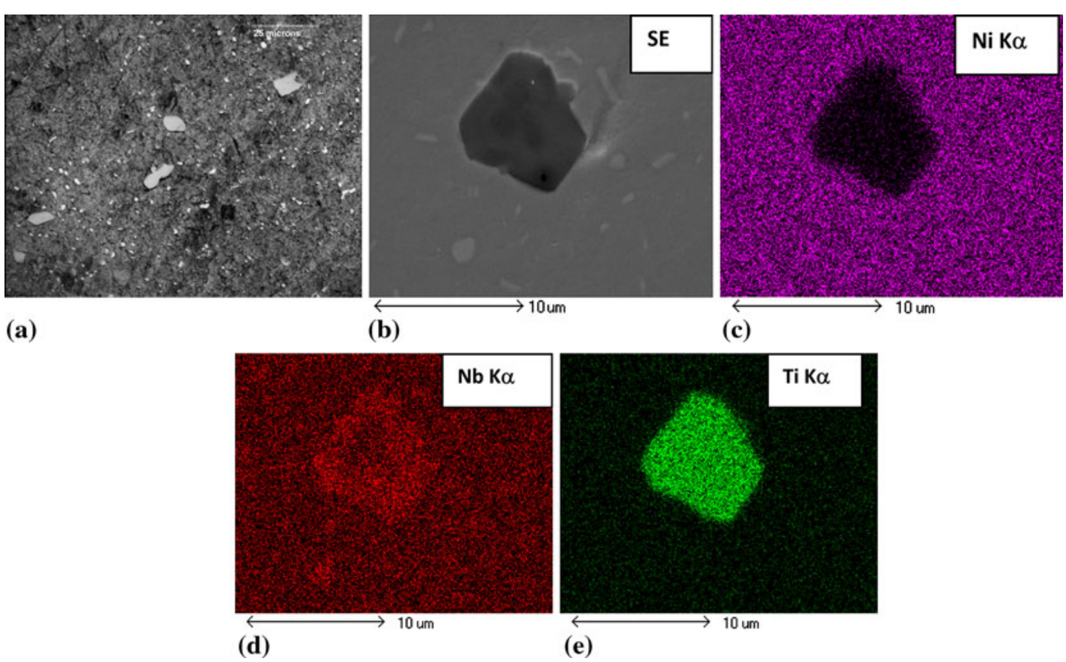

Fig. 4 Optical microphotograph: (a) large primary carbides (magnification 1000×); EDS elemental maps (magnification 5000×): (b, c, d, e) complex TiC/NbC carbides on the machined part of DA 718 alloy

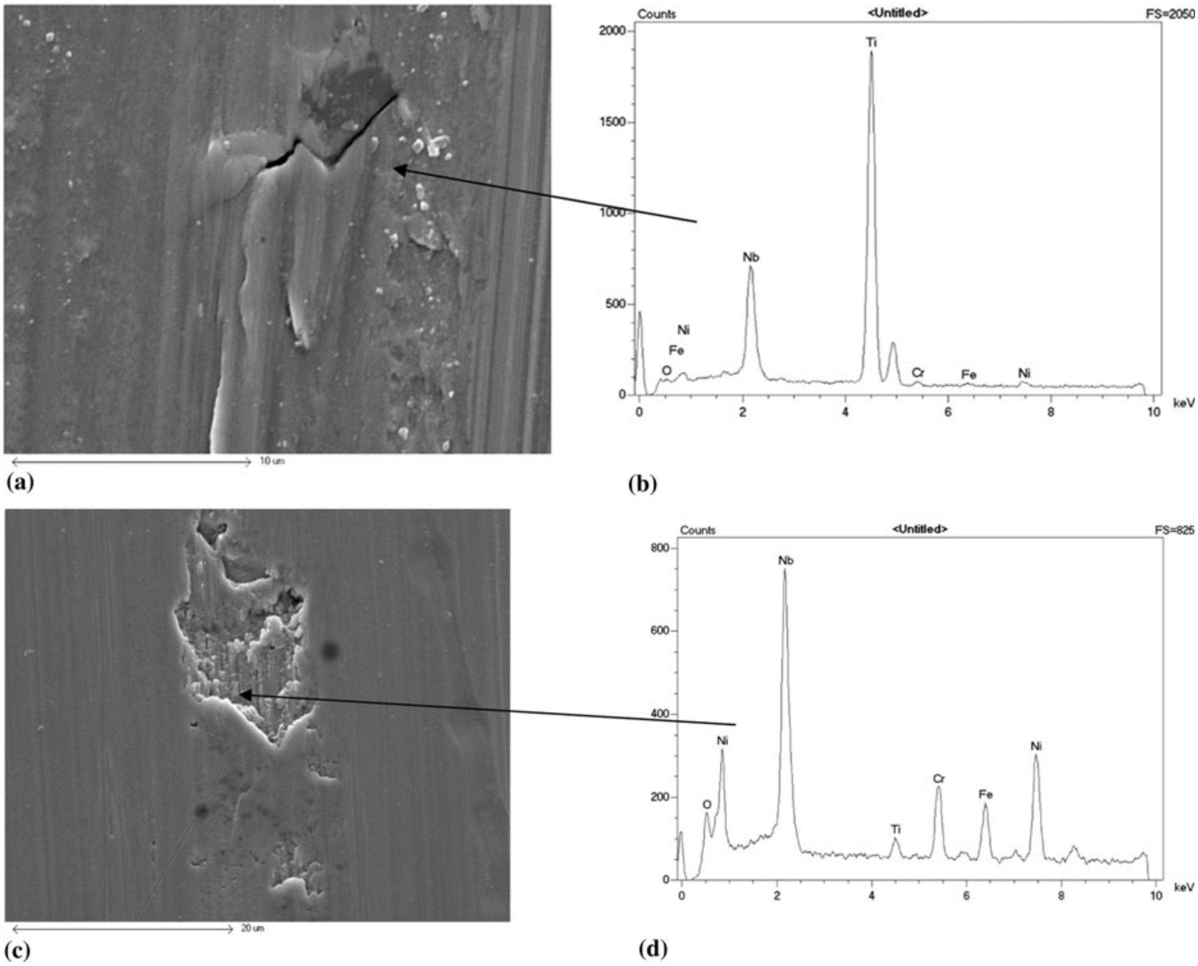

Fig. 5 SEM EDS data on surface morphology and defects formation on the machined surface of DA 718 alloy: (a, b) cracks and (c, d) tears

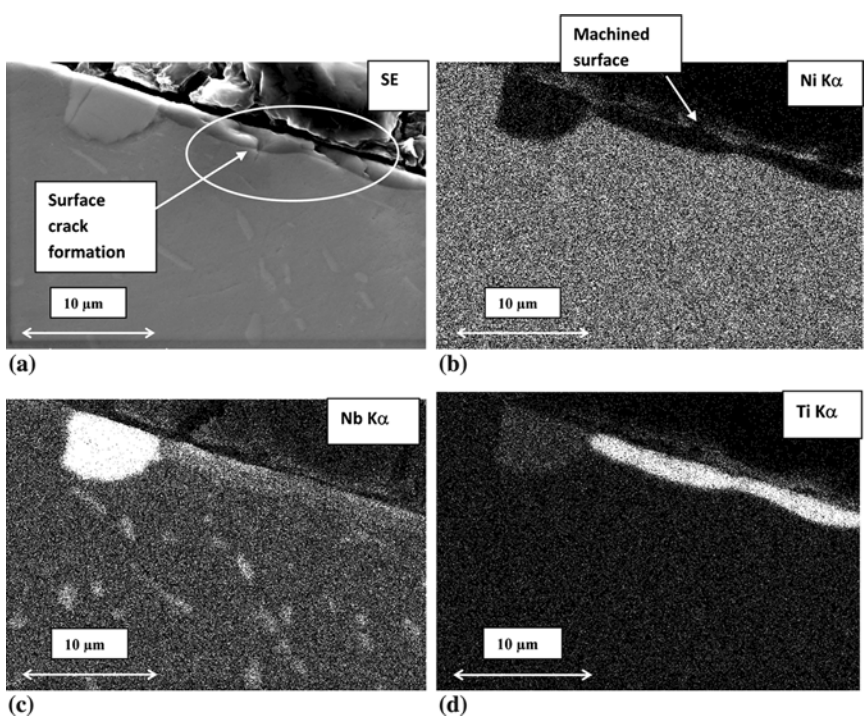

Fig. 6 SEM/EDS elemental map of the cross section of the machined surface of DA 718 alloy with surface and interior microcrack formation (magnification 5000×)

(Fig. 5d) as well as by elemental mapping of the carbides concentration area (Fig. 7c and e). These oxides are not strong enough to sustain large strains generated on the tool/workpiece interface, in particular during machining of DA 718 superalloy (Ref 15, 16). As a result, the tears form (Fig. 6a and c).

Origin of tears is a more complex combination of the shearing mechanism of primary carbides combined with environmental interaction (oxidation from air). Eruption occurred mainly at NbC dominating carbides due to NbC being oxidized more readily because of its lower Gibbs free energy compared to TiC (Ref 17). The following question could arise: would the tearing be indicative of a more ductile failure, than cracking failure; or, is the area around an NbC particle likely to be tougher than the material surrounding a TiC particle?

The Pilling-Bedworth ratio (Ref 11, 16) influences the eruption of oxides. If the value of the PB ratio were over 2.3, eruption of the oxide would occur as a result of compressive stress. In the case of NbC, eruption occurred readily because the PB ratio is 2.61. However, the eruption of titanium oxides is rare because of its low PB ratio (1.95 value).

Figure 7(a and c) shows flow formation and crack propagation into the interior of the carbide when the outer surface of the two-phase carbide contains a relative abundance of Nb. Figure 6(a) also confirms that sheared NbC carbide is susceptible to have interiorly propagating microcracks (Ref 11).

Based on the data obtained, a conclusion could be made that it is still a challenge to achieve simultaneous high productivity without adverse effect on the defect formation during machining of direct aged 718 superalloy. Since DA 718 was discovered, there are no reports regarding the machining of this advanced superalloy. Thus, some directions of future research could be outlined:

– Machining under aggressive cutting conditions (turning, finishing operation) could be made using ceramic inserts.

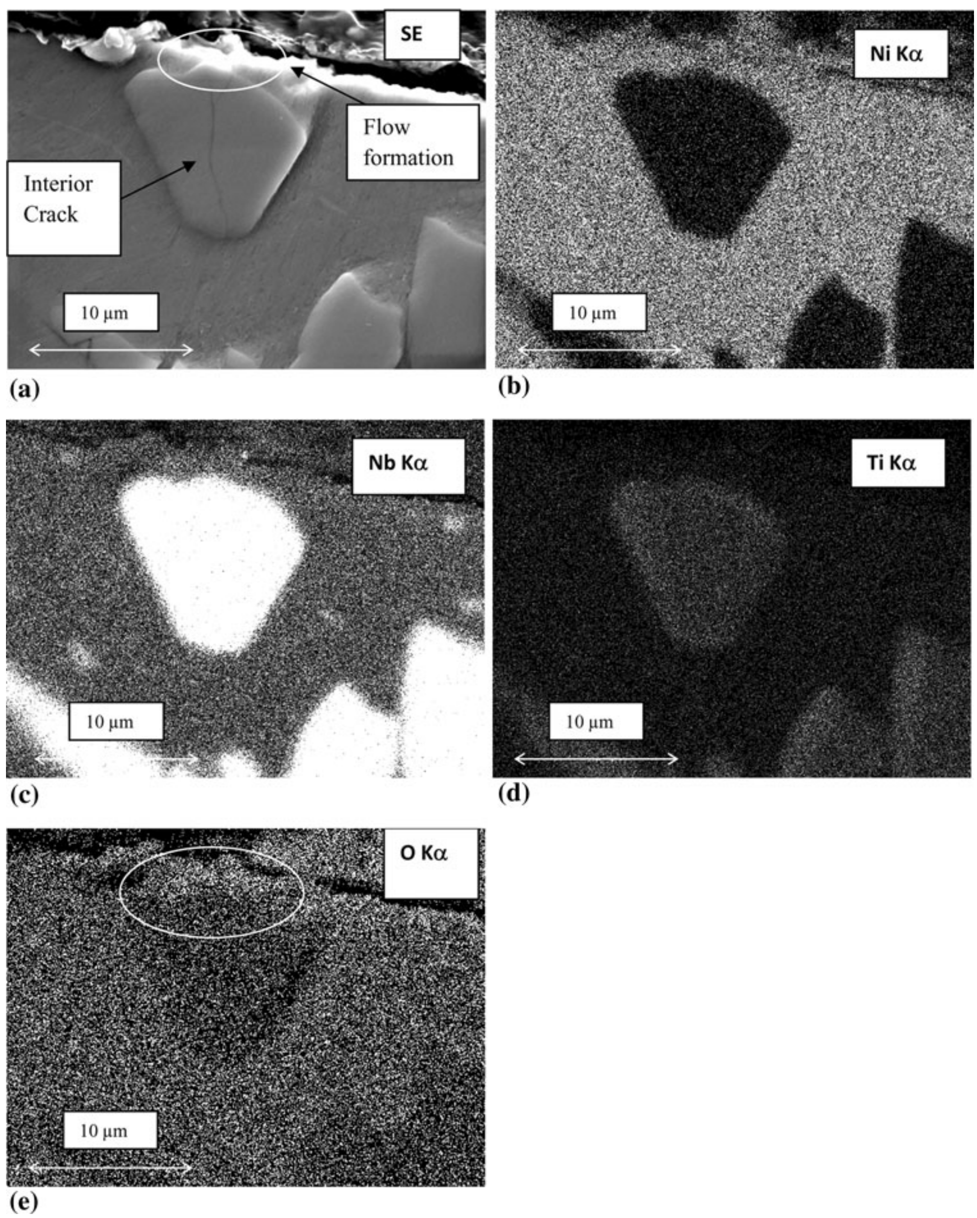

Fig. 7 SEM/EDS elemental map of the cross section of the machined surface of DA 718 alloy with flow formation (magnification 5000×)

However, it is highly questionable whether it is possible to achieve economical tool life and simultaneously prevent defect formation due to additional strengthening of the material as well as high temperature at the tool/workpiece interface (Ref 16).

– Machining under more moderate conditions could be made by coated CC inserts. However, the expectation has to be realistic because temperature of NbC stability against oxidation is below 400 °C (Ref 9, 11). Reducing temperature down to this level during machining of DA 718 is a difficult task.

4. Conclusions

Achieving simultaneously high productivity and improved surface integrity (preventing surface defect formation) during machining of direct aged 718 superalloy remains a challenging task.

Application of CC inserts with TiAlN PVD coating results in high tool life during rough turning of DA 718. However, during the finishing operation, tool life is significantly diminished due to higher average hardness values of the workpiece material and thus work hardening.

To find out the origin of defect formation, surface morphology of the machined parts as well as cross sections of the machined surfaces were investigated in detail. Two major categories of defects were detected on the surface of the machined part: crack and tears. The origin of the microcracks, visible on the surface after machining, is related to the Ti-rich regions of the complex Ti/NbC carbide particles present in a structure of DA 718 alloy. The oxidation of NbC dominating carbides starts at the outer surface of the carbide and matrix interface, propagates into the interior of the carbide, finally causing eruption. It was found from the study of the cross section that the surface layer was broken from eruption of NbC on the surface with tear formation. However, in the case of TiC, oxidation and eruption occurred only at the outer surface of the carbide, and did not progress toward the inside during machining.

Acknowledgment

Research is supported by Pratt & Whitney Canada.

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