

# SURFACE EFFECTS ON LOW CYCLE FATIGUE BEHAVIOR IN IN718 ALLOY

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## Abstract

Superalloys used in gas turbine engine rotating components require superior low cycle fatigue (LCF) properties, but often, the intrinsic LCF capability of the rotor, as determined by laboratory specimen tests, is limited by presence of fine particles such as carbides, borides and ceramic inclusions, as well as, pores, voids, and large grains in the alloy. Further, manufacturing processes such as turning, milling, and broaching can limit LCF life if they introduce surface damage and/or tensile residual stress. In IN718, prior studies have shown that fatigue initiation from MC carbides is promoted at lower test temperature and high stress, and the LCF life is significantly reduced. The present study investigates the effect of machining that can introduce carbide damage on LCF life, and a few post-machine processing methods for LCF recovery.

The IN718 material used in this study came from a gas turbine disk forging that was directly aged without the conventional solution heat-treatment. The microstructure was fine-grained with an average grain size of 11  $\mu\text{m}$ . Smooth and notched LCF properties were evaluated with machined and polished surfaces at test temperature and stress that promoted carbide initiation of fatigue cracks. Majority of the tests were performed at temperature of 560 K and at stresses of 1102 and 1240 MPa for smooth, and nominal stresses of 595 and 650 MPa for notched specimens. The min to max stress ratio (R) was 0.05. The cycles to failure were analyzed in terms of machining effect on surface carbides, and the fatigue initiation sites were studied by scanning electron microscopy (SEM). Smooth LCF specimens included as-machined (lathe-turned) and polished (600 grit SiC) surfaces and the notched LCF specimens included single-point bored (SPB) and media-polished notch surfaces. Lathe-turning and SPB cracked or damaged surface and subsurface carbides, considerably impacting the LCF life by factors of 3-15X (depending on test conditions). For a smooth lathe-turned surface, shot peening was effective in recovering LCF life by 5-10X at minimum over the as-machined surface. Some conventional post-machine processes for holes, such as mechanical honing, extrude hone and jig grinding and their influence on LCF life were studied as well.

## Introduction

Inconel 718 (IN718) is a Ni-based superalloy that is widely used to manufacture rotating components in gas turbine engines due to its high strength and good low cycle fatigue (LCF) resistance [1, 2]. This alloy is used most commonly in the solution heat treatment plus aged condition. Strength and LCF properties are critical in gas turbine applications, and in situations requiring enhanced properties, a 'direct aged' version without the solution treatment is used. The present study relates to the 'direct aged' version of the alloy. In this version, the gas turbine disk is typically produced by 'hot-die' forging followed by aging. Grain refinement during forging is critical in this process for improved LCF life of the disk [3, 4]. It is desirable that the fatigue critical

disks are produced with a fine grained microstructure in the range of 5-20  $\mu\text{m}$  to maximize fatigue benefits. However, prior studies have shown that crack initiation at carbides is promoted at high stress amplitude [5] and also, at lower test temperatures [6], and therefore, the carbides might limit the benefits from grain refinement under certain conditions. Further, the carbides at the surface of the part are sensitive to damage from surface machining [7, 8] or surface treatment processing, and in such cases, cracks may initiate early from carbides [9, 10]. The purpose of the present study is thus aimed at understanding the carbide damage produced during machining, and their effect on smooth and notched LCF life in 'direct aged' IN718 rotor material. Further, conventional post-machine processing of the surface was examined in terms on carbide damage and LCF life.

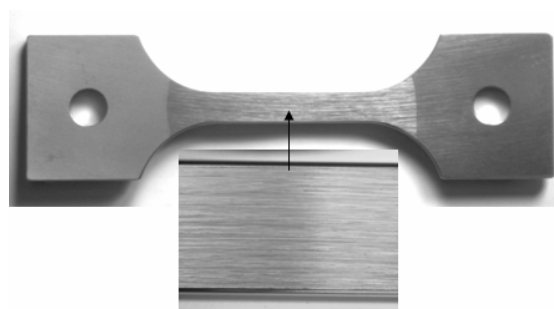
## Material and Experimental Procedure

Rotor grade 'direct aged' IN718 (DA718) disks were produced by commercial 'hot-die' forging practice into a contoured shape. The disk represented a forging shape for a large diameter but thin cross-section gas turbine engine with outer and inner (bore) diameters of 900 mm and 480 mm, respectively, and outer rim thickness of 63 mm. The input stock for the forgings was commercially available 250 mm diameter billet material produced from triple-melted (VIM+ESR+VAR) ingot. The wt. % chemistry of the billet was 18.0% Cr, 2.96% Mo, 1.0% Ti, 0.50% Al, 5.4% Nb+Ta (Ta<0.01), 17.95% Fe, 0.028% C, and balance Ni. The forging was given the standard IN718 aging cycle consisting of 990 K for 8 hours, followed by 895 K for 8 hours.

For the study of surface effects on LCF life, two types of conventional machining, namely, lathe-turning (LT) for flat surfaces and single point boring (SPB) for round holes, were used. Post-machine processing was used for round holes following SPB to determine its effect on LCF life. Processes evaluated were: mechanical honing with 400 grit SiC tools [11], extrude hone with 54 grit SiC abrasive media [12], and jig grinding with carbide tools [13]. Mechanical honing relies on simultaneous rotating and reciprocating motion of a stone or stick, made of bonded abrasive, to remove stock material in a low speed sizing operation. During an extrude-hone operation, a semisolid media embedded with abrasive grit is extruded between cylinders on either end of the work piece to remove stock material. Jig grinding is a form of internal grinding for finishing of the internal diameter of a part. For the flat surfaces, no such post-machine processing was applied, except that the effect of compressive residual stresses from 4A shot-peening was examined in terms of LCF effect.

Both flat and cylindrical test specimens were used for smooth LCF tests. The flat specimens had a rectangular gage section of nominal dimensions 50 mm x 12 mm x 5 mm, and the flat surfaces represented the lathe-turned surface of conventional IN718 disk machining. The edges of the specimen were polished and the grips shot-peened. An example of the flat specimen with lathe-turned surface is shown in Fig. 1A. Cylindrical specimens

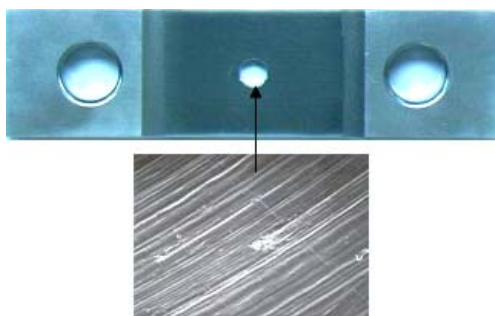
were used for reference LCF test with polished surface (per ASTM E606). An example of the specimen is shown in Fig. 1B. Approximately, 25 micron of surface material was removed using 400 and 600 grit SiC polishing. The nominal gage dimensions of the specimen were 25 mm long x 9.4 mm diameter. For notched LCF, the specimen was flat with a central and through thickness hole. The gage section was rectangular with nominal dimensions of 38 mm x 37 mm x 3.7 mm. The central hole produced a stress concentration ( $K_t$ ) of about 2.5 during axial LCF loading of the specimen. An example of the specimen is shown in Fig. 1C. The hole was machined by single-point boring (SPB) that left machining marks parallel to the stress axis. For reference tests, the same notched specimen was used but the central hole was ‘media-finished’. For media finishing, medium-sized-fused-cast  $Al_2O_3$  granules were used.



(A)



(B)



(C)

Figure 1. Example of smooth and notched LCF specimens with (A) lathe-turned gage section, (B) polished gage section, and (C) notched gage section with central hole (shown are machining marks left after single-point boring).

The LCF tests were carried out initially at several temperatures from 300 K to 880 K. It was determined that an intermediate temperature of 560 K adequately defined the LCF sensitivity to surface condition, and therefore, the majority of tests were carried out at 560K. Axial stresses of 1102 and 1240 MPa were used for smooth LCF tests, and 595 and 650 MPa nominal for notched LCF tests (1516 and 1656 MPa concentrated stresses at the notch

root, respectively). Tests were performed in a modified MTS servo-hydraulic machine using sinusoidal waveform and a min to max stress ratio ( $R$ ) of 0.05, and test frequency of 1 Hz. The LCF crack initiation sites of fractured specimens were studied by scanning electron microscopy (SEM) equipped with energy dispersive X-ray spectroscopy (EDS). It should be noted that in presenting the LCF lives in this paper, a relative scale was used, namely, in each Figure, the lowest LCF life of all data presented in this paper was indexed as 100, and all other lives were expressed as multiples of this lowest LCF life.

## Results and Discussion

### Microstructure and Tensile Properties

The microstructure of the forged and direct aged disk is shown in Fig. 2. The average gamma ( $\gamma$ ) grain size was 11  $\mu m$  (ASTM 10) with grain size varying from 5.6  $\mu m$  to 16  $\mu m$  (ASTM 9-12) depending on the location in the disk. Occasional grains with sizes as large as 20 to 30  $\mu m$  (ASTM 7-8) were also observed but they represented a small area fraction (<2%) in the microstructure. Further, the microstructure contained Nb/Ti-rich MC carbides, spheroidized delta-phase ( $\delta$ :  $Ni_3Nb$ ), and two strengthening phases:  $\gamma'$  and  $\gamma''$  precipitates [14]. The MC carbides were the most important constituents that reacted severely to tool tip cutting edges and produced surface damages. Therefore, maximum carbide size, the frequency of their occurrence and their clustering tendency are critical to the understanding of LCF capability. In the DA718 material studied here, the largest carbides were typically 20-25  $\mu m$  in equivalent diameter.

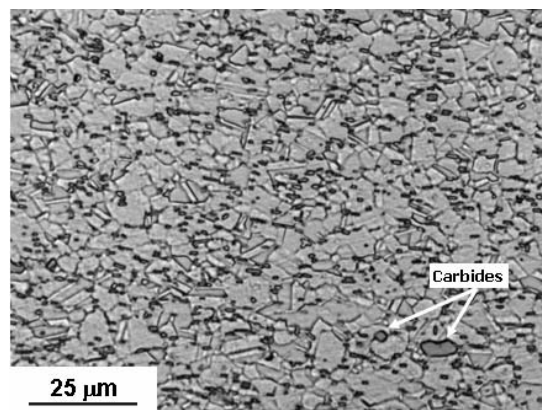


Figure 2. Example of microstructure. The carbides shown in the micrograph is of MC type.

The typical tensile properties of the disk forging are given in Table I. The ‘direct aged’ disk of the present study represented higher 0.2% yield strength (approximately, 15 %) relative to the conventional solution plus aged disk material.

Table I: Typical tensile properties of the disk forging

Temperature (K)	$\sigma_Y$ (MPa)	$\sigma_{UTS}$ (MPa)	$\epsilon_f$ (%)
298	1340	1550	15
561	1276	1375	16
811	1232	1366	16
921	1174	1316	23

### Surface Observations Following Conventional Machining and Effect on Low Cycle Fatigue Properties

As noted earlier, two types of conventional machining (lathe-turning and single point boring) were initially studied in terms of surface effects of LCF life. Fig. 3A and 3B show examples of surface appearances following lathe-turning of flat surfaces and single point boring of round holes, respectively. The critical damages on the surface, as shown in Fig. 3, were produced by the tool tip interacting with the MC carbides. The NbC was the most numerous of the MC carbides followed by Nb(Ti)C, and these carbides were cracked by the tool tip, and sometimes pulled out of the surface in fragments, and dragged along the surface in the direction of the tool tip motion.

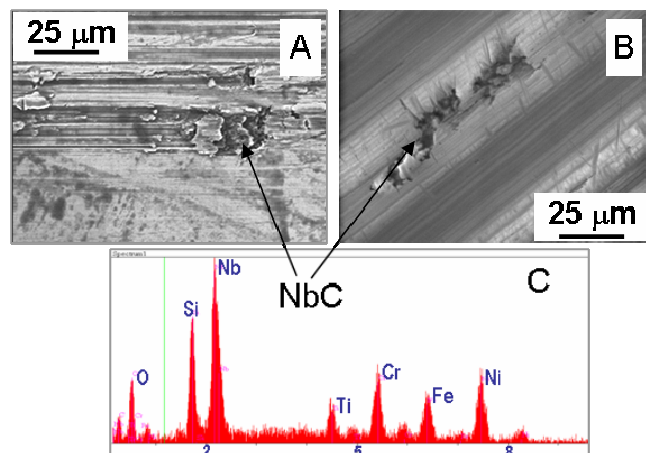


Figure 3. Examples of surface NbC carbide and surface damage during (A) lathe-turning (LT) of flat surface, and (B) single point boring (SPB) of round hole.

Cracking of MC carbides at the surface was further examined on unetched polished cross sections. Figure 4 shows evidence of carbide cracking at surface and subsurface locations typically within 25 μm of the machined surfaces. On the other hand, the post-machine polishing showed that the MC carbides generally remained uncracked, and only rare evidence of large carbides with light traces of cracking was observed. Examples of unetched cross sections through polished surfaces are shown in Figure 5.

As-Machined Surface Effect on LCF. The effect of the as-machined surface on smooth LCF life is shown in Fig. 6 in relation to reference LCF specimens that had a polished surface. The abscissa axis is a relative scale for LCF lives, and data are shown for tests at low and high stresses (1102 and 1240 MPa) for a test temperature of 560 K. A significant drop in LCF life, approximately, 15X at 1102 MPa and 3X at 1240 MPa, was evident from the machined surfaces relative to the polished surfaces. Similar observations were also made with the notched LCF specimens for tests at the same temperature, and nominal stresses of 595 and 650 MPa. Figure 7 shows test results, and a drop in LCF life by about 6X at 595 MPa and 4X at 650 MPa was evident due to the machined surfaces relative to the polished surfaces. Methods of removing stock material (i.e. polishing) without damaging the surface carbides were demonstrated to be effective at improving the LCF life compared to conventionally machined surfaces.

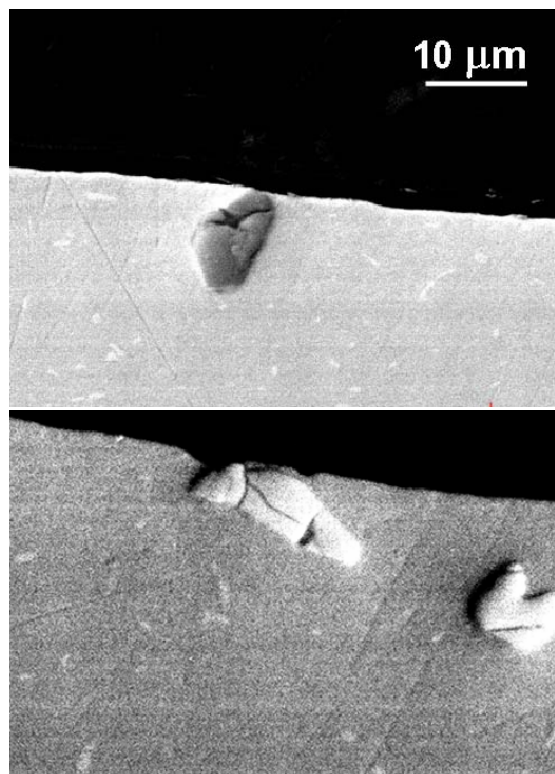


Figure 4. Unetched micrograph from section through machined surface illustrating cracked carbides at surface and subsurface locations.

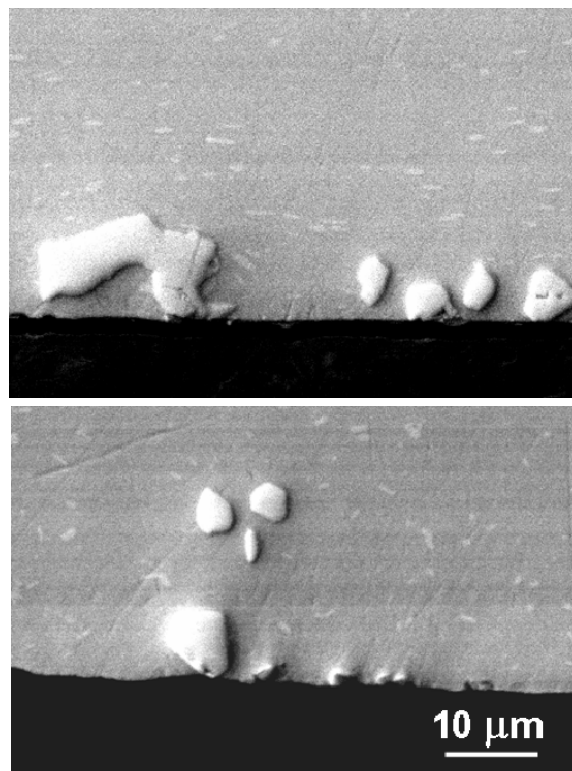


Figure 5. Unetched micrograph from section through post-machine polished surface illustrating predominantly undamaged carbides at surface and subsurface locations.



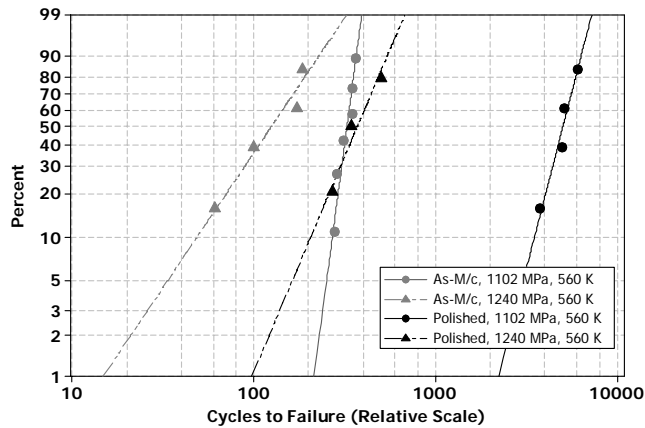


Figure 6. Weibull plot showing effect of as-machined surface on smooth LCF life relative to polished surface. Test temperature 560 K, and applied stresses 1102 and 1240 MPa.

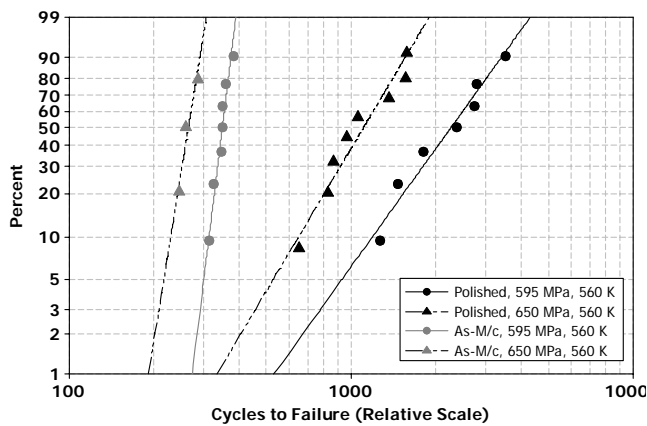


Figure 7. Weibull plot showing effect of as-machined surface (SPB) on notched LCF life relative to media-polished surface. Test temperature 560 K, and applied nominal stresses 595 and 650 MPa.

**LCF Initiation Sites.** The carbides were most life limiting for the 560 K tests. The LCF failure in the as-machined specimens always initiated from surface MC carbides (primarily NbC) due to frequent cracking of these carbides from the machining operation. Figure 8 shows SEM micrographs illustrating a damaged NbC on the machined surface, and the LCF initiation from such carbides in smooth LCF specimens. The typical size of the carbide at the initiation site ranged from 15 to 25  $\mu\text{m}$  and corresponded to the large carbides in the size distribution. Many secondary cracks were present on the specimen surface, and were always associated with carbides as shown in Fig. 8A. These micro-cracks formed early in life [6] especially under conditions of high stress amplitude. Their presence suggests that the carbides, when damaged or cracked by the insert tip during machining, caused early LCF initiation and led to significant life reduction relative to polished specimens. In the polished LCF specimens, the 560 K tests included both carbide and grain initiations, which were located at both surface and subsurface locations. Figure 9 shows SEM fractographs of LCF initiation from an as-machined (SPB) notched LCF specimen. LCF failure always initiated from surface carbide that was damaged or cracked by the tool tip. In the notched specimen, the highest stress occurred only at the notch

root, and secondary cracks were thus infrequent and limited to the notch root vicinity only.

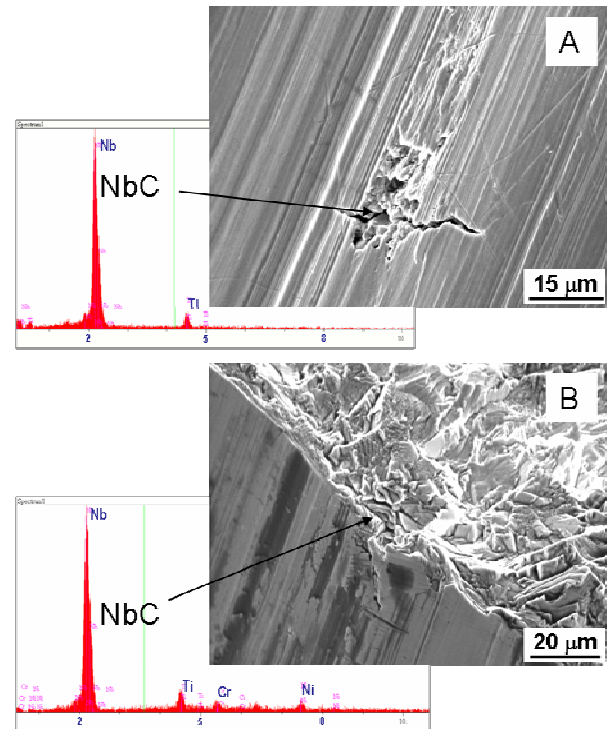


Figure 8. SEM of as-machined smooth LCF failure: (A) Example of secondary crack initiation, (B) Typical fracture initiation from NbC (560 K/1102 MPa).

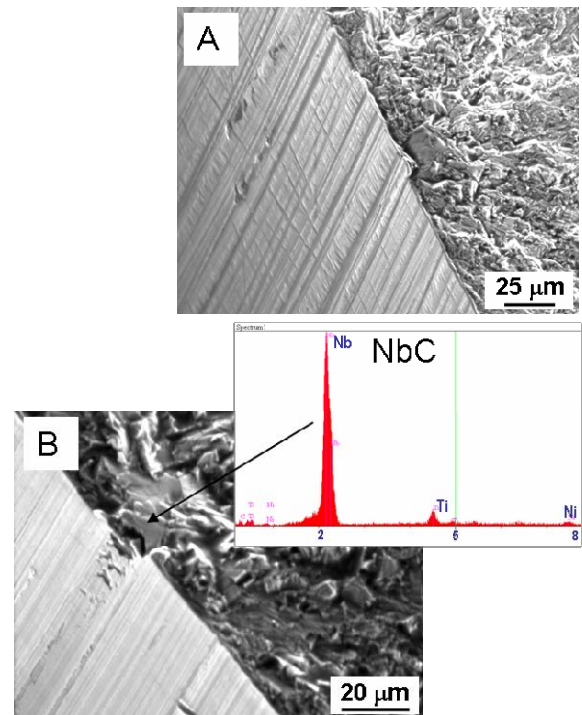


Figure 9. SEM of as-machined notched LCF failure: (A) Specimen surface near crack initiation site, and (B) Fracture initiation from surface NbC (560 K/595 MPa).

### Surface Observations Following Post-machine Processing and Effect on Low Cycle Fatigue Properties

Post-machine processing was examined, as noted before, for machined round holes only because there were a number of commercially available processes that could be easily utilized to process the SPB surface of the hole. The processes utilized were mechanical honing, extrude-hone, and jig-grinding per conditions stated earlier, and Fig. 10 illustrates the surface appearances from these processes. Note that all these processes removed material by

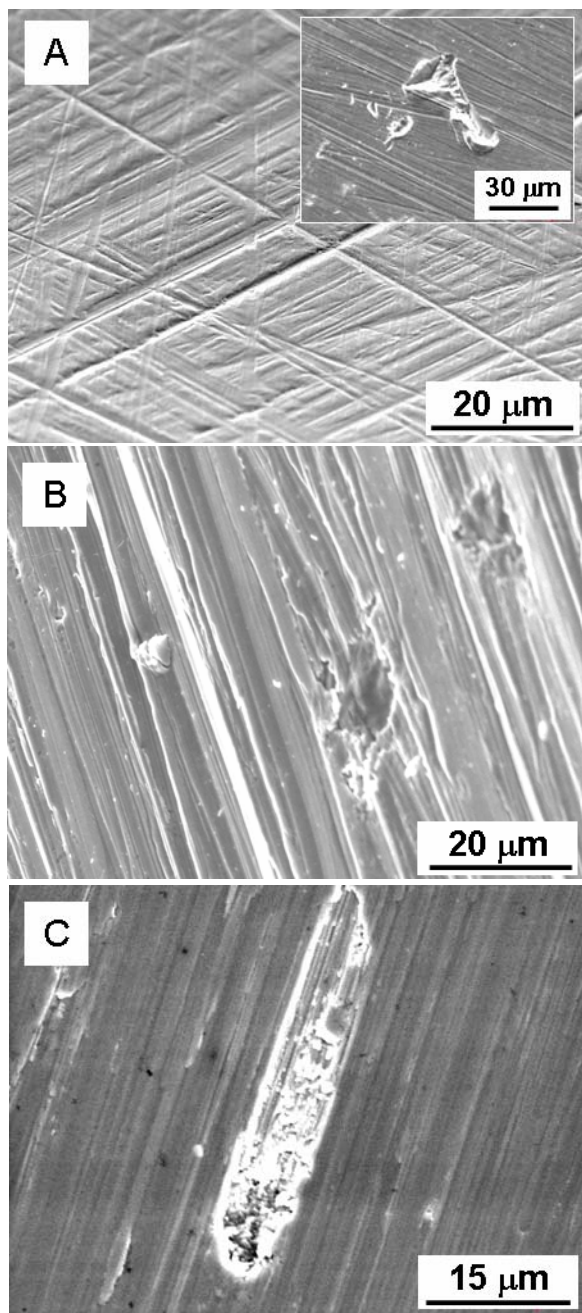


Figure 10. Examples of surface and NbC appearances after post-machine processing of round holes: (A) Mechanical honing, (B) Extrude honing, and (C) Jig grinding.

a minimum amount of 25  $\mu\text{m}$  and thereby, removed the damaged layer on the surface from the SPB operation. Among these processes, the mechanical honing showed the least severe damage to the machined carbide. For example, the carbide in the inset of Fig. 10A was among the largest carbides (about 25  $\mu\text{m}$ ) but it was not as severely damaged or dragged as seen in other processes.

The notched LCF life with the central hole reconditioned by the above three processes is illustrated in Fig. 11. The LCF lives from the as-machined (SPB) notched specimens are included for comparison. All specimen failures initiated from carbides in these tests, and SEM micrographs illustrating these initiation sites are shown in Fig. 12. Referring to Fig. 11, the mechanical honing showed best LCF lives and all mechanically honed LCF tests exceeded SPB life. On a typical basis live improved by roughly 3X. This was consistent with above surface observations in that mechanical honing probably caused least carbide damage and reduced the probability of badly damaged carbide. Nevertheless, this possibly resulted in the high scatter in data as seen in Fig. 11. The extrude-hone process showed improvement over SPB on a typical basis, and the jig grinding was essentially the same as SPB in terms of LCF life. It should be noted that the SPB machining yields the best LCF capability on a probabilistic approach because of the tight scatter in the data, despite its lower typical life. However, the data in Fig. 11 clearly illustrated the potential of mechanical honing and extrude-hone processes in removing SPB damaged surface layer. Further effort is required to optimize the process parameters (such as feed rate and depth of cut) to reduce the scatter in the data. No such investigation was made in the present study.

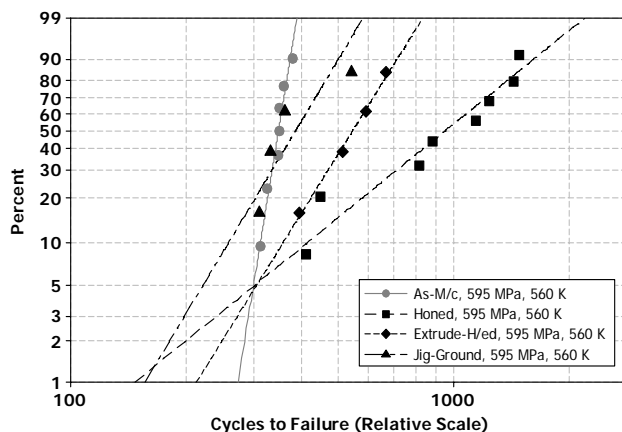


Figure 11. Weibull plot of notched LCF lives after post-machine processing in relation to as-machined (SPB) notched surface.

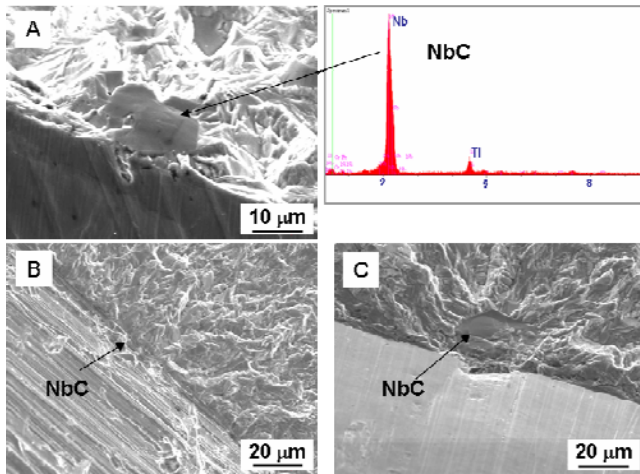


Figure 12. SEM of Notched LCF specimens following post-machine processing: (A) Mechanical honing, (B) Extrude honing, (C) Jig-grinding.

#### Surface Observations Following Introduction of Surface Residual Stresses and Effect on LCF Life

Surface residual stresses were introduced through shot-peening to an intensity of 4A on the as-machined (i.e., lathe-turned) flat surfaces of smooth LCF specimens. Figure 13 shows the residual stress profile with depth in the LCF specimen. A cross-section through the peened surface is also included in this figure. The shot peened surface essentially retained all surface carbides, including those previously cracked or damaged by the lathe turning operation. Following shot peening, the large carbides, as shown in Fig. 13, appeared highly fragmented.

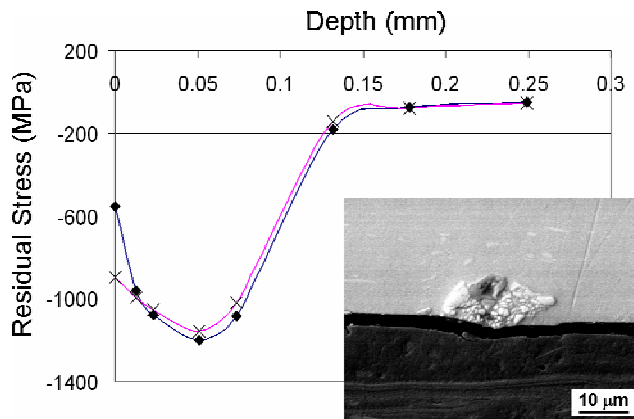


Figure 13. Residual stress pattern introduced by shot-peening and example of large carbide appearance at the surface following shot-peening.

Figure 14 shows smooth LCF life after shot-peening in relation to the as-machined specimens. The LCF life was recovered in these shot-peened specimens, and this can be attributed to the compressive residual stress at the surface that extended to 100  $\mu\text{m}$  with -600 MPa or more in magnitude. The compressive residual stress, therefore, protected the specimen from the machine-damaged layer. All shot peened LCF lives were shown with an

arrow to the right in Fig. 14 to indicate that these flat LCF specimens (see Fig. 1A) fractured at the specimen shoulder and outside the gage section. The two groups of test data, A and B, were due to failures from surface carbides or internal grain facets, respectively, at the shoulder location.

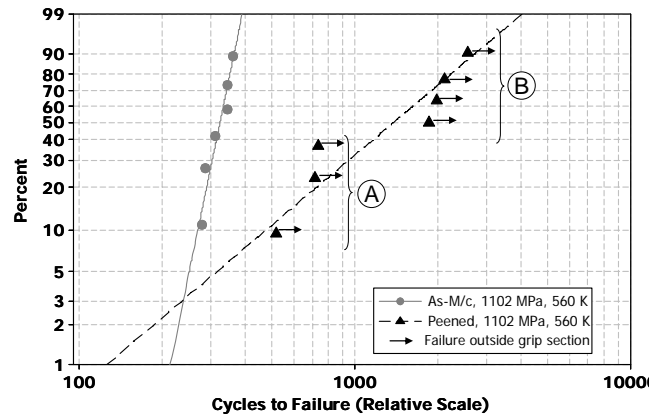


Figure 14. Weibull plot of smooth LCF lives after shot peening (4A) in relation to as-machined (lathe-turned) smooth surface. 'A' and 'B' refer to failures outside the specimen gage section, and from carbide and internal grain, respectively.

#### Summary and Conclusions

(1) The role of machining methods and their impact on surface integrity, smooth and notched LCF life of 'direct aged' IN718 forged disk was studied. Conventional machining practices, such as lathe-turning of surfaces and single point boring of holes, cracked or damaged the surface carbides considerably to impact the LCF life by factors of 3-15X depending on the test conditions. Cracked carbides were observed at both surface and subsurface levels, and were often restricted to a surface layer of 25  $\mu\text{m}$  or less.

(2) Full LCF life was possible in smooth specimens given a fine 400 and 600 grit polishing or media finishing where the damaged surface layer was removed. Some conventional post-machine processes for holes, such as mechanical honing, extrude hone and jig grinding, were studied. Mechanical honing and extrude-hone showed potential as finishing processes to improve LCF life over as-machined surfaces, but will require future study with the process parameters optimized to prevent carbide damage. The statistically estimated minimum LCF capability of as-machined notched features is greater than post-machine treated notch features due to the tight scatter in the data.

(3) For flat, as-machined (lathe-turned) surfaces, shot peening was effective in protecting the surface layers containing cracked carbides under a deep compressive residual stress, and therefore, effectively recover LCF life 5-10X at minimum relative to an as-machined surface.

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