 

# Influence of Cubic Boron Nitride Grinding on the Fatigue Strengths of Carbon Steels and a Nickel-Base Superalloy

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**The influence of cubic boron nitride (CBN) grinding on fatigue strength was investigated on an annealed carbon steel, a quenched and tempered carbon steel at room temperature, and a nickel-base superalloy, Inconel 718, at room temperature and 500 °C. The results were discussed from several viewpoints, including surface roughness, residual stress, and work hardening or softening due to CBN grinding. The fatigue strength increased upon CBN grinding at room temperature, primarily because of the generation of compressive residual stress in the surface region. However, in the case of Inconel 718, this marked increase in the fatigue strength tended to disappear at the elevated temperature due to the release of compressive residual stress and the decrease of crack growth resistance at an elevated temperature.**

**Keywords** alloy 718, cubic boron nitride, grinding, steel type 1042

## 1. Introduction

Recently, cubic boron nitride (CBN) grinding technology has been extensively applied in machining of high strength alloys, and many studies have indicated that a CBN wheel has superior performance to a general abrasive wheel in terms of machinability, grinding efficiency, and tool life, as well as surface integrity of the workpiece, which has a great effect on the fatigue property (Ref 1-3). Conversely, CBN grinding generally results in a compressive residual stress in a surface region, which is considered to contribute to the increase of fatigue strength, so that CBN grinding could be an excellent machining process even from the viewpoint of material strength. Nevertheless, the study of the influence of CBN grinding on the fatigue strength, especially the fatigue strength at an elevated temperature, has been reported less (Ref 4).

Inconel 718 is a precipitation strengthened nickel-base superalloy that is extensively used in critical components of aircraft engines and gas turbines for nuclear electricity generating stations due to its high thermal stability, good corrosion property at high temperatures, and other mechanical properties. However, Inconel 718 is extremely difficult to machine.

In this study, rotating bending fatigue tests were carried out on an annealed and a quenched and tempered carbon steel at room temperature and a nickel-base superalloy, Inconel 718, at both room temperature and 500 °C. The results of the CBN ground specimen were compared with those of an electropolished specimen and an emery paper polished specimen.

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**Table 1 Chemical compositions**

| Element | Composition, wt% | |
|---|---|---|
| | G10420 | Inconel 718 |
| C | 0.42 | 0.03 |
| Si | 0.27 | 0.05 |
| Mn | 0.81 | 0.06 |
| P | 0.013 | 0.008 |
| S | 0.016 | 0.002 |
| Ni | … | 52.26 |
| Cr | … | 18.5 |
| Mo | … | 3.08 |
| Co | … | 0.27 |
| Cu | … | 0.02 |
| Al | … | 0.55 |
| Ti | … | 0.96 |
| Fe | bal | 19.18 |
| B | … | 0.004 |
| Nb + Ta | … | 5.03 |

**Table 2 Mechanical properties**

| Material | Temperature, °C | Yield strength ($\sigma_{sl}$), MPa | 0.2% proof stress ($\sigma_{0.2}$), MPa | True breaking stress ($\sigma_B$), MPa | Tensile strength ($\sigma_T$), MPa | Reduction of area ($\psi$), % |
|---|---|---|---|---|---|---|
| G10420 A | RT | 377 | … | 659 | 1190 | 54 |
| G10420 QT | RT | … | 975 | 1112 | 1756 | 56 |
| Inconel 718 | RT | … | 1320 | 1461 | 2320 | 70 |
| | 500 | … | 1050 | 1254 | 1734 | 38 |

RT, room temperature

## 2. Materials and Experimental Procedures

The materials employed were a carbon steel, which corresponds to UNS number G10420 and is referred to as G10420 in this article, and a nickel-base superalloy, Inconel 718. Table 1 shows their chemical compositions in weight percent.

The carbon steel G10420 was heat treated by annealing at 840 °C for 1 h, which is referred to as G10420 A in this article; or it was treated by heating at 840 °C for 1 h and water quenching, then heating at 400 °C for 1 h followed by water cooling. The material in this condition is referred to as G10420 QT. The nickel-base superalloy, Inconel 718, was solid solution treated by heating at 982 °C for 1 h and water quenching, aging at 720 °C for 8 h, furnace cooling to 620 °C and heating at 620 °C for another 8 h, and finally by air cooling. Table 2 shows the mechanical properties of the materials after heat treatment.

Figure 1 shows the shapes and dimensions of specimens. The notched specimen (Fig. 1a) was used to investigate the influence of CBN grinding on the fatigue strength. A dull circumferential notch of 5 mm radius was made at the center of the specimen. The notch was CBN ground or electropolished after machining. Cubic boron nitride grinding was performed at 31 m/s of wheel velocity and 0.1 m/s of table speed using a CBN wheel CB170N75VN5GP (CB, CBN abrasive; 170, mesh size; N, grade; 75, concentration; V, vitrified bond; N5GP, symbol of specific bond; manufactured by NORITAKE Co., Ltd, Nagoya, Japan) with an emulsion type coolant supplied. For some specimens, the notch was lightly scratched by two types of emery papers (No. 120 and 800) after electropolishing to assess the effect of surface roughness on the fatigue strength. The partially notched specimen (Fig. 1b) was used to observe the crack initiation and propagation behavior. Although the specimen was partially notched to localize the crack initiation site, the strength reduction factor was close to 1. Therefore, it can be considered a plain specimen. After machining,thepartiallynotchedspecimenwaselectropolished about 20 μm from the surface to remove the affected layer.

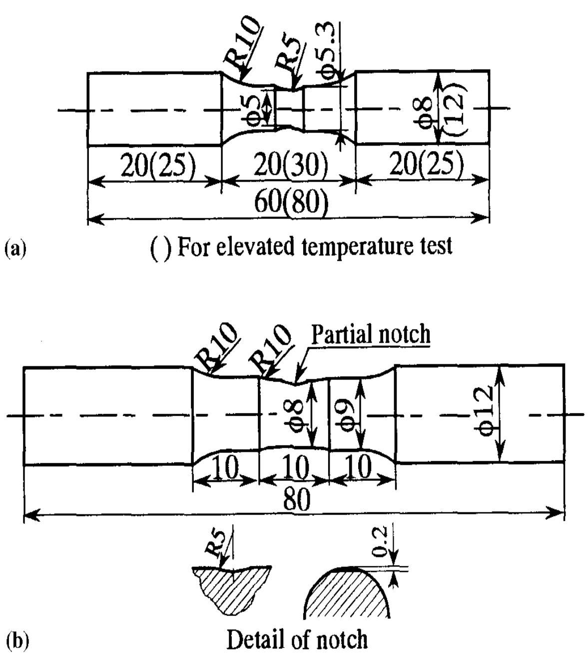



**Fig. 1** The shapes and dimensions (in mm) of specimens. (a) Notched specimen. (b) Partially notched specimen

The observation of fatigue damage in the CBN ground specimen was conducted directly, and the length of a crack in the electropolished specimen was measured using a plastic replication method under an optical microscope at a magnification of 400×. The crack length was defined as the length along the circumferential direction on the specimen surface. The residual stress was detected by an x-ray diffraction device (XRD-6000 SHIMADZU, Shimadzu Corporation, Kyoto, Japan), Cu-Kα ray, the wavelength $\lambda$ = 1.54178 Å, the angle of diffraction $2\theta$ = 155.6°, and the area of irradiation = 1 × 10 $mm^2$). The stress value referred to was the nominal stress amplitude at the minimum cross section, neglecting the partial notch in the partially notched specimen. The machines employed were the Ono-type rotating bending fatigue testers with a capacity of 15 N · m, operating at about 50 Hz for the tests at room temperature, and 100 N · m, operating at 55 Hz, at 500 °C.

## 3. Results and Discussion

### *3.1 Fatigue Strength at Room Temperature*

Figure 2 shows the stress amplitude and number of cycles (S-N) curves of electropolished and CBN ground specimens for all the materials at room temperature. The fatigue strength of the CBN ground specimen was much higher than that of electropolished specimen. Therefore, CBN grinding may be a superior machining process from the criteria of the excellent performance of CBN grinding and the high fatigue strength of CBN ground specimens at room temperature.

Figure 3 shows the crack growth curves in the partially notched specimens of G10420 A and Inconel 718 at the stress of each fatigue limit, which is defined as the stress amplitude for the specimen not to fracture after repetitions of $10^7$ cycles. Figure 4 shows the surface states after stress repetition of $10^7$ cycles for the specimens shown in Fig. 3. In both materials, nonpropagating cracks were observed. Figure 5 presents the

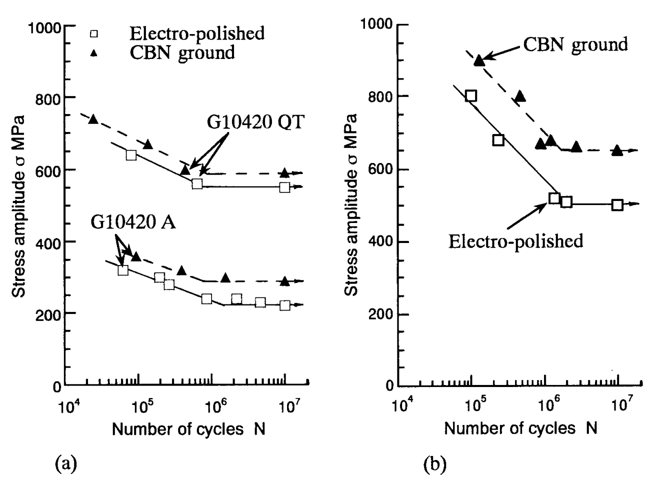



**Fig. 2** S-N curves at room temperature. (a)G10420 A and G10420 QT. (b) Inconel 718

surface states of CBN ground specimens for all of the materials after stress repetition of $10^7$ cycles at the stress of each fatigue limit. In all of the materials, nonpropagating cracks were recognized among the ground flaws. That is, the fatigue limit was determined by the limiting stress for crack growth in both electropolished and ground specimens. As for the emery paper polished specimen, it had already been reported by Nistani and Imai (Ref 5) that the nonpropagating crack was observed as well.

### 3.2 *Fatigue Strength at an Elevated Temperature*

Figure 6 shows the S-N curves of electropolished and CBN ground specimens for Inconel 718 at 500 °C. The fatigue strength of a CBN ground specimen is a little lower than that of the electropolished specimen through almost the entire region of stress levels except near the fatigue limit, where the fatigue limit of the CBN ground specimen was nearly equal to or a little higher than that of the electropolished specimen.

### 3.3 *Discussion*

Figure 7 shows typical profiles of a CBN ground surface around the notch root. In all of the materials, the values of maximum height roughness, $R_y$, were nearly the same, that is, approximately 1.5 μm.

Figure 8 shows the influence of surface roughness on the fatigue limit at room temperature, where *m* is the ratio of the fatigue limit of the emery paper polished specimen or the CBN ground specimen, $\sigma_w$, to that of the electropolished specimen, $\sigma_{wEP}$, meaning the relative fatigue limit. In the case of Inconel 718, the result at 500 °C is also plotted in Fig. 8. As seen from the results of the emery paper polished specimen, in which the influence of machining was almost eliminated except for the surface roughness, it is clear that the decrease of the fatigue limit caused by CBN grinding flaws can be nearly disregarded in all of the materials. Similar results were obtained at an elevated temperature for Inconel 718 as well, although the chemical composition differed a little from the alloy used in this study (Ref 6).

Figure 9 shows the distribution of the hardness (Vickers' hardness, or HV, under the load of 50 g) on the cross section beneath the notch root in both the CBN ground and the electropolished specimens. The ordinate is the ratio of the hardness measured in the grinding affected layer, *H′*, to that of the inner matrix, *H*, which was not affected by CBN grinding. The abscissa is the distance from the surface. The surface layer was work hardened through CBN grinding. This can be explained by the remarkable plastic deformation yielded in the ground layer (Ref 7). In the case of G10420 QT, however, it was work softened lightly. The hardened surface layer was

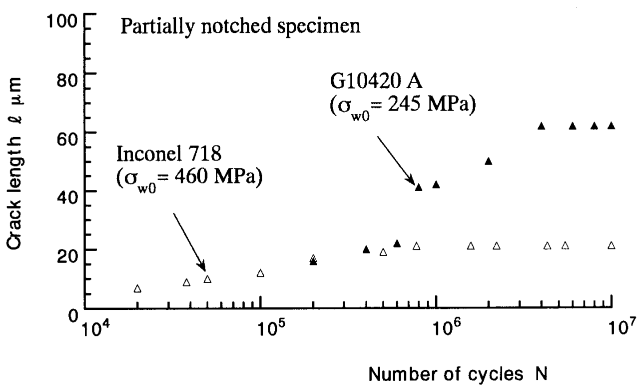



**Fig. 3** Crack growth curves at fatigue limit

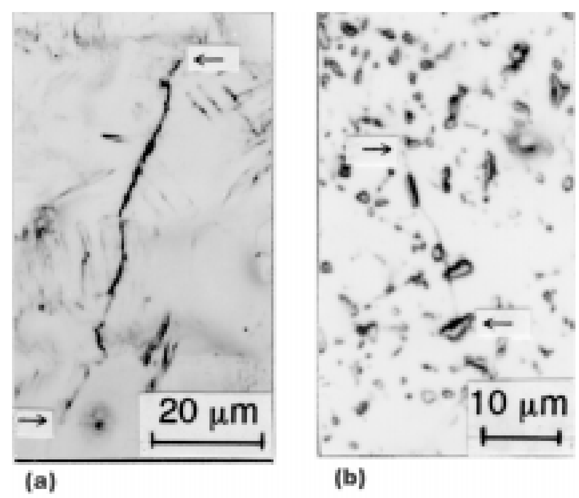



**Fig. 4** Nonpropagating cracks shown in Fig. 3. (a) G10420 A ($\sigma_{w0}$ = 245 MPa, *l* = 62 μm). (b) Inconel 718 ($\sigma_{w0}$ = 460 MPa, *l* = 21μm)

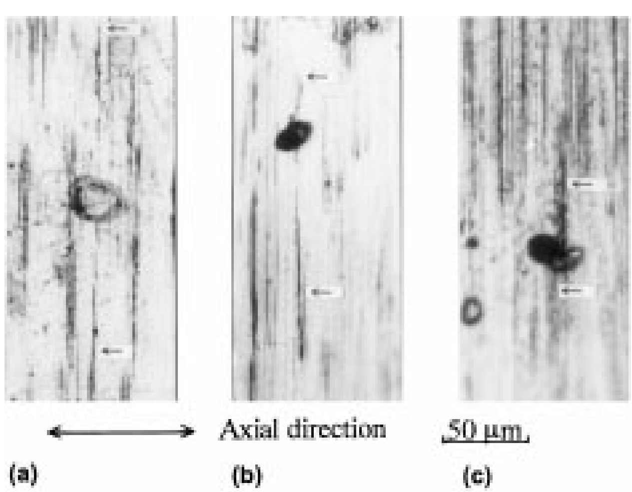



**Fig. 5** Nonpropagating cracks in a CBN ground specimen. (a) G10420 A. (b) G10420 QT. (c) Inconel 718

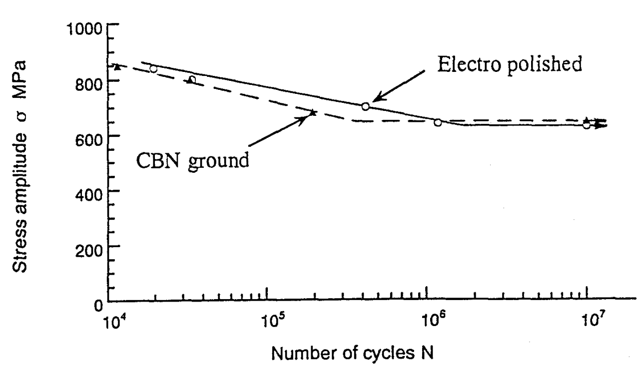



**Fig. 6** S-N curves at 500 °C (Inconel 718)

considered to contribute to the improvement of high cycle fatigue strength.

Figure 10 shows the microstructure of an affected layer on the cross section in the CBN ground specimens of two carbon steels. Marked plastic deformation was observed in G10420 A, while a thin fused layer that seemed to be a Beilby layer was observed in G10420 QT. These changes in microstructure corresponded in hardness to those shown in Fig. 9. The generation of the plastic deformed zone in the affected layer was reported for Inconel 718 also (Ref 7).

It is known that a tensile residual stress usually results in general abrasive grinding, while in CBN grinding, a compressive residual stress is usually generated in the ground layer (Ref 3, 4, 7).

Figure 11 shows the distribution of residual stress measured on the cross section beneath the notch root in the CBN ground specimen for each material. In the case of Inconel 718, the results before and after heating the specimen for 1 h at 500 °C under zero load condition are illustrated. The compressive residual stress was generated on and near the surface region in the CBN grinding process, but when heated, the compressive residual stresses were greatly reduced.

In general, it is considered that the influence of residual stress is equivalent to the effect of mean stress (Ref 8-10). The effect of mean stress can be recognized mainly in the propagation process of a crack (Ref 11,12.) Moreover, the crack propagation is important not merely in the finite life region but also

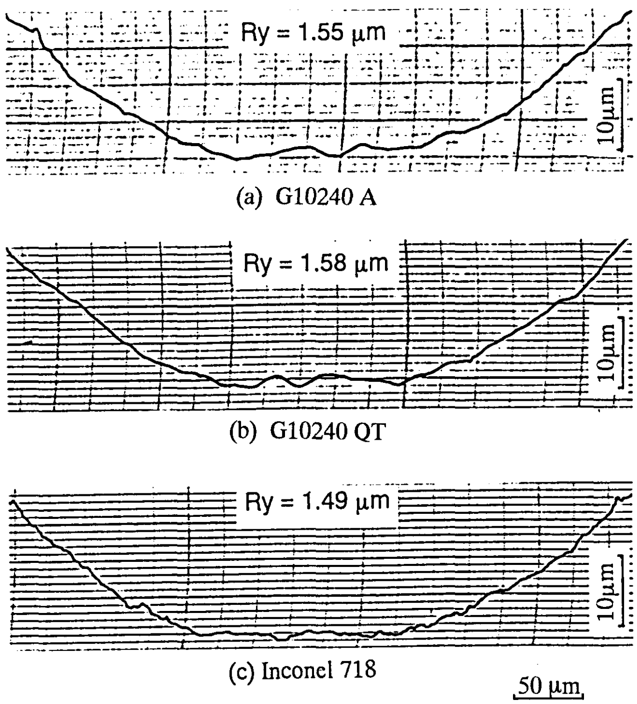



**Fig. 7** Profiles of CBN ground surface around the notch root

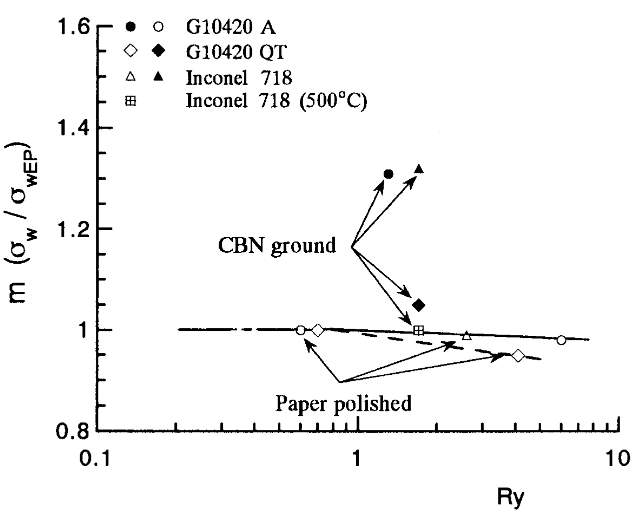



**Fig. 8** Effect of roughness on the fatigue limit

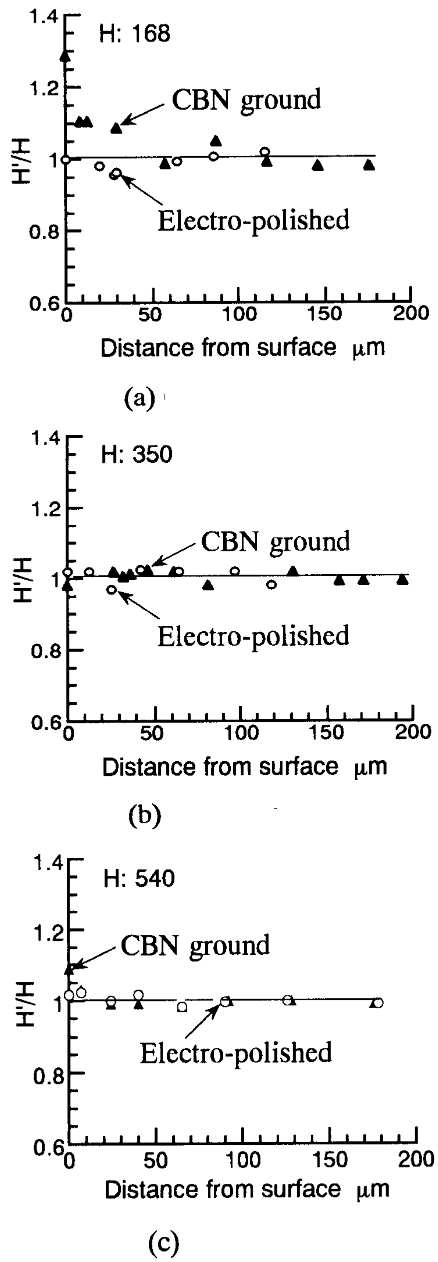
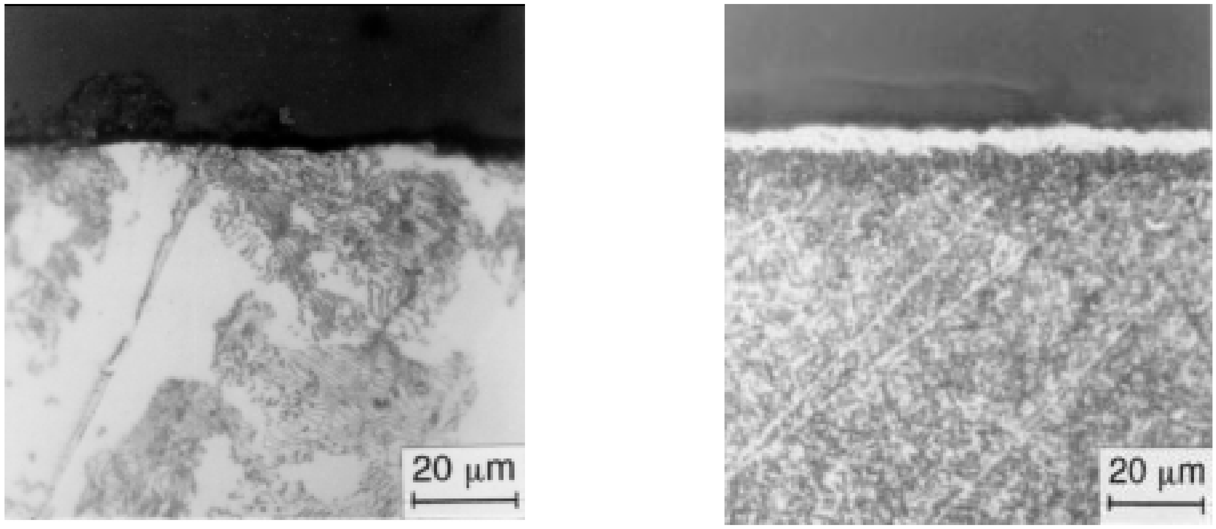



**Fig. 9** Distribution of the hardness beneath the notch root. (a) G10420 A. (b) G10420 QT (c) Inconel 718




(a) (b)

**Fig. 10** Microstructure on the cross section in a CBN ground specimen. (a) G10420 A. (b) G10420 QT

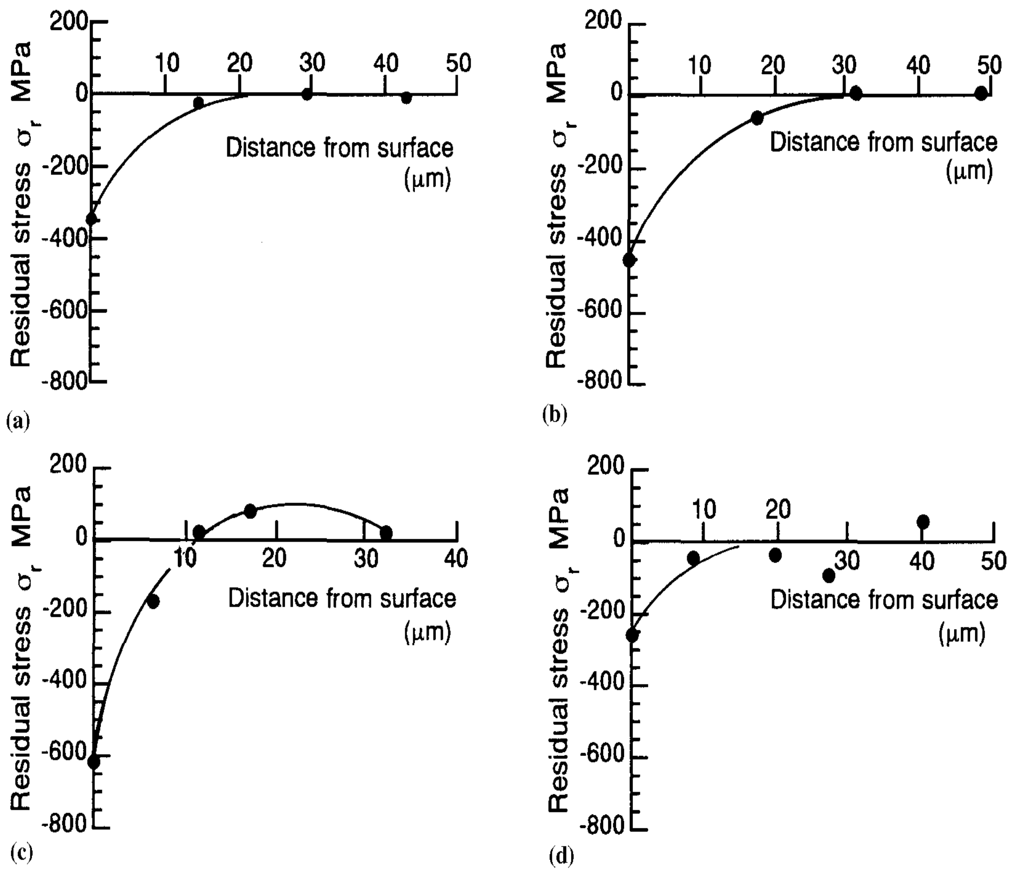



**Fig. 11** Distribution of the residual stress under the notch root. (a) G10420 A at room temperature. (b) G10420 QT at room temperature. (c) Inconel 718 before heating. (d) Inconel 718 after heating for 1 h at 500 °C

at the fatigue limit (Ref 13). Therefore, it can be concluded that (a) the main reason for the increase of fatigue strength in the CBN ground specimen at room temperature is because the crack propagation was effectively suppressed by the compressive residual stress induced by CBN grinding and (b) the big difference between the fatigue strengths of CBN ground specimen of Inconel 718 at the room temperature and the elevated temperature in the finite life region can be explained by

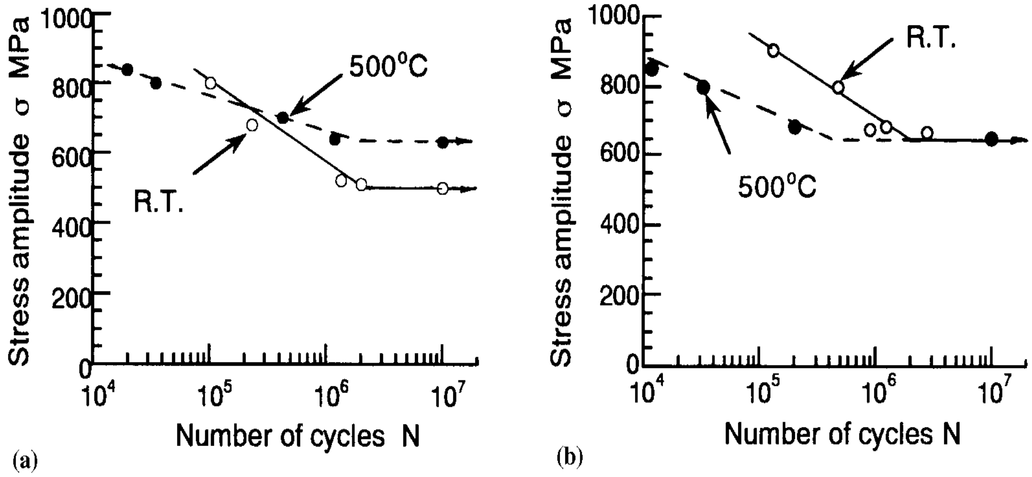



**Fig. 12** S-N curves (Inconel 718) (a) Electropolished specimen. (b) CBN ground specimen

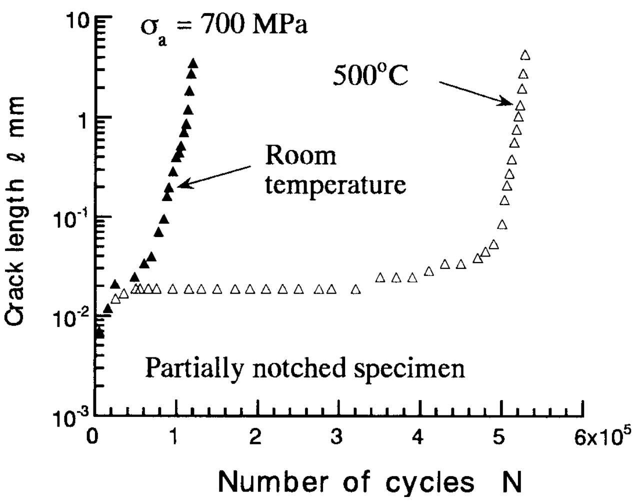



**Fig. 13** Crack growth curves (Inconel 718)

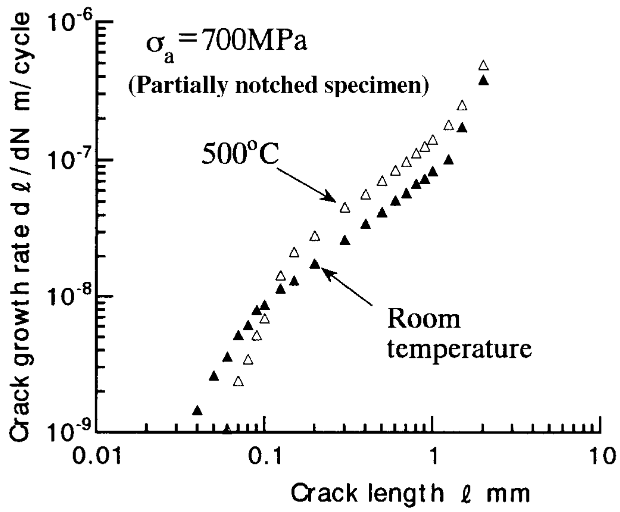



**Fig. 14** *dl*/*dN* vs. *l* (Inconel 718)

the decrease of both the compressive residual stress and the crack growth resistance at the elevated temperature (Ref 14).

Figure 12 shows the effect of elevated temperature on the fatigue strengths of (a) an electropolished specimen and (b) a CBN ground specimen in Inconel 718. In the case of the electropolished specimen, although the fatigue strength at the high stress level is lower at 500 °C than at room temperature, the fatigue limit is much higher at 500 °C than at room temperature. In the case of the CBN ground specimen, the fatigue strength decreases through almost the entire stress level due to the elevated temperature, but the fatigue limits at both temperatures are nearly the same. This means that the improvement of fatigue strength by CBN grinding cannot be expected at an elevated temperature. Moreover the nickel-base superalloy was mainly used at elevated temperatures so that it was not useful to apply the CBN grinding technique for the improvement of the fatigue strength of a nickel-base superalloy at an elevated temperature, though the CBN grinding dose improved the surface integrity and the grinding efficiency.

Figure 13 shows the crack growth curves of a partially notched specimen at both temperatures for Inconel 718. Figure 14 shows the relationship between the crack growth rate and the crack length. The growth of a crack smaller than approximately 20 μm was extremely suppressed, while that over 20 μm was accelerated by the elevated temperature.

Figure 15 shows the variation of the HV (50 g) at the surface region and inner matrix with the heating time at 500 °C under zero load condition. The surface region was hardened rapidly, and a peak was reached after heating for approximately 7 min, whereas the inner matrix was softened lightly. After heating for approximately 15 min, the softening tended to saturate. But a big difference in the hardness existed between the surface region and the inner matrix; that is, the surface region was considerably hardened at elevated temperature.

Figure 16 shows the scanning electron micrographs of surface state around the initiated crack at both temperatures. The marked oxidation was observed at an elevated temperature. This suggests that the oxide films formed in the surface region may be the main contributor to the hardening of the surface re-

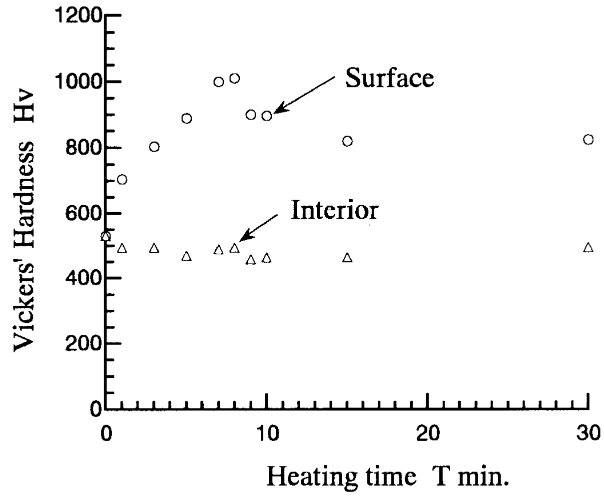



**Fig. 15** Variation of the hardness with heating time (Inconel 718)

gion and were correlated to the suppression of crack growth through the oxide induced crack closure phenomenon at an elevated temperature.

## 4. Conclusions

Through CBN grinding, the fatigue strength was increased considerably at room temperature because the crack propagation was effectively suppressed by the compressive residual stress generated in the CBN grinding process. However, the similar improvement was not recognized at an elevated temperature because both the compressive residual stress near the ground layer and the resistance to crack propagation were decreased at the elevated temperature. The effect of surface roughness on the fatigue strength can be neglected within the range of this study.

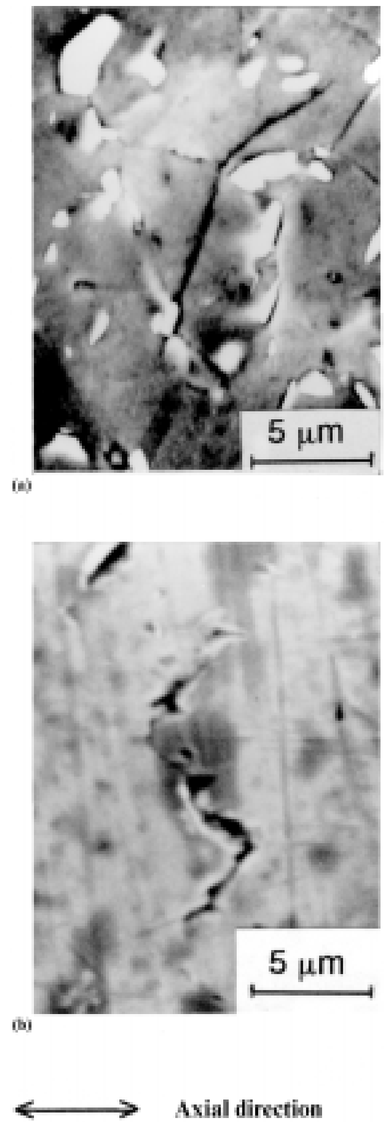



**Fig. 16** Scanning electron micrographs of surface state near an initiated crack (Inconel 718). (a) At room temperature. (b) At 500 °C

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