Influence of Shot Peening and Deep Rolling on High Temperature Fatigue of the Ni-Superalloy Udimet 720 LI

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1 Abstract

The Ni-superalloy Udimet 720 LI is typically used for application as turbine disc material for gas turbines. The present investigation was undertaken to determine if the elevated temperature fatigue strength can be improved by mechanical surface treatments. Shot peening and deep rolling were performed on circumferentially notched (k_t = 2.3 and 3.5) specimens. Axial fatigue tests were performed at T = 650 °C using a stress ratio of R = 0.1. The fatigue performance will be compared with electrolytically polished references.

2 Introduction

Udimet 720 LI is a nickel-based superalloy with reduced chromium, carbon and boron content as compared to the original Udimet 720. Typical property requirements are good LCF and HCF strengths at elevated temperatures, creep strength and damage tolerance. Considerable work has been undertaken to optimize these properties by thermal and thermomechanical treatments resulting in microstructural modifications regarding, e. g., grain size, γ' size and distribution, carbide- and boride-phase content, and grain boundary morphology [1–3]. The present investigation was performed to determine if the elevated temperature notch fatigue performance of Udimet 720 LI can be improved by mechanical surface treatments such as shot peening and deep rolling.

3 Experimental

Cylindrical blanks (∅ 12 × 60 mm) were prepared by wire-guided electrical discharge machining from a fully heat treated turbine disc having a homogeneous fine grained microstructure as shown in Figure 1. Tensile specimens were machined from the blanks with gage diameters and lengths of 4 and 20 mm, respectively. Tensile tests were performed at ambient and elevated (650 °C) temperatures. The initial strain rate was 8.3×10^{-4} s^{-1}. Tensile results are given in Table 1.

Table 1: Tensile properties of Udimet 720 LI

test temperature	E [GPa]	$\sigma_{0.2}$ [MPa]	UTS [MPa]	El [%]	$\varepsilon_F = \ln A_0/A_F$
RT	220	1120	1535	14	0.13
650 °C	180	1050	1280	32	0.33

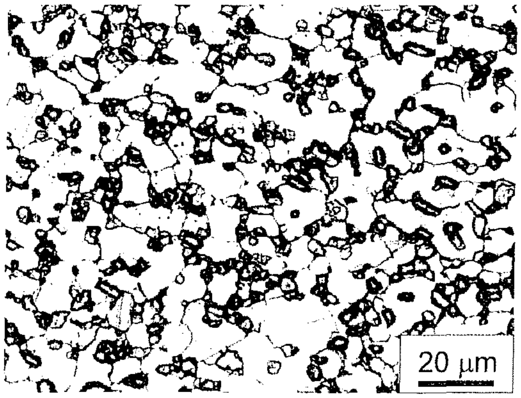

Figure 1: Microstructure of Udimet 720 LI

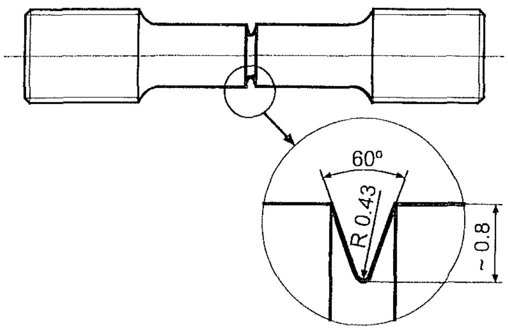

Figure 2: Geometry of the notched fatigue specimens

Fatigue specimens were machined having a circumferential 60° V-notch as illustrated in Figure 2. The notch root radius was either 0.43 or 0.30 mm. Part of the specimens was electrolytically polished (EP) to serve as a reference. Others were shot peened. Shot peening was performed using an injector type machine and spherically conditioned cut wire (SCCW 14) with an average shot size of 0.36 mm. Specimens were peened to an Almen intensity of 0.24 mmA. Furthermore, some specimens were deep rolled using a hydraulically driven three-roll device operating in a lathe. Deep rolling (DR) was performed on specimens having a notch root radius of 0.43 mm. 55° rolls with a tip radius of 0.3 mm were used. Thus, during deep rolling, the notch root radius of the specimens was reduced from 0.43 to roughly 0.3 mm. After these mechanical surface treatments, the surface layer properties were characterized by measurements of surface roughness through profilometry and X-ray measurements of half width breadths and residual macrostresses. Measurements were taken from the (311) planes. Surface layers were subsequently removed by electropolishing to enable the determination of depth profiles. Fatigue tests were performed in axial loading at $R = 0.1$ using a servohydraulic testing machine. Tests were done at 650 °C at a frequency of about 60 Hz. Specimens were heated by means of a 3-zone electric resistance furnace. Fracture surfaces were studied by SEM.

3 Results and Discussion

The microstructure of the fully heat treated Udimet 720 LI material is shown in Figure 1. The average γ grain size is about 15 µm. Typical surface layer properties caused by shot peening are illustrated in Figure 3. In addition, measurements are shown for material shot peened and an-

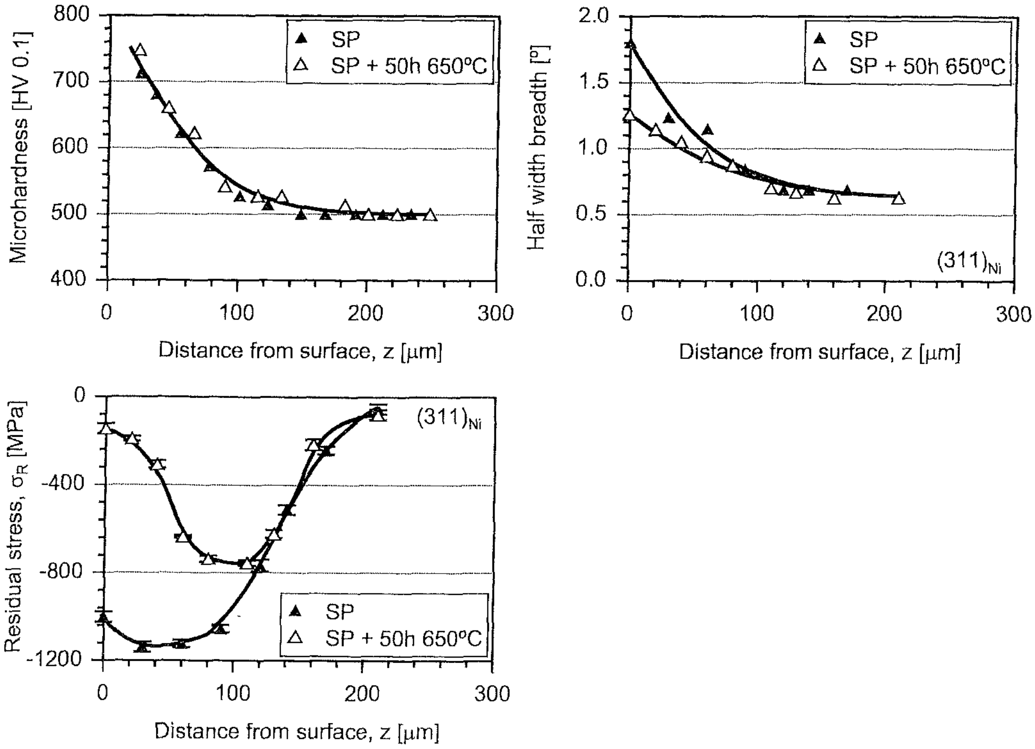

Figure 3: Shot peening induced surface layer properties (SP: SCCW 14, 0.24 mmA)

nealed at 650 °C for 50h. This annealing treatment corresponds to the heat cycle that 10^7 cycles run-out specimens in the elevated temperature (650 °C) tests will see.

After shot peening to an Almen intensity of 0.24 mmA, the microhardness (Fig. 3a) drastically increases from around 500 in the bulk to values above 750 HV 0.1 at the surface owing to the marked work-hardening capacity of the material at ambient temperature (Table 1). Interestingly, this shot peening-induced microhardness profile is not changed by the annealing at 650 °C for 50 h (Fig. 3a). Obviously, the high dislocation density being responsible for this strengthening effect is stable at 650 °C. On the other hand, the shot peening-induced half width breadth which depth profile is very similar to that of the microhardness is somewhat more affected by the anneal (Fig. 3b). It is argued that the contribution of residual microstresses to the interference line broadening may be responsible for this difference in thermal stability between microhardness and half width breadth (compare Figs. 3b with 3a). Residual microstresses may partially relax without significant losses in dislocation density. Apparently, residual macrostresses are even more affected by the anneal (Fig. 3c). Particularly, near surface residual compressive stresses are markedly reduced presumably, owing to free surface effects while stresses at depths greater than 100 μm are hardly affected.

The S-N curves at 650 °C are shown in Figure 4 comparing shot peened with electrolytically polished conditions. The 10^7 cycles fatigue strength is increased by shot peening from 690 to 780 MPa while no fatigue life improvement is seen in the finite life regime (Fig. 4). In order to determine if this poor fatigue performance of shot peened specimens tested at high maximum stresses where residual stresses will cyclically relax is related to roughness-induced early microcrack growth, the shot peened notch root was mechanically polished to remove all peening-induced microcracks, dents and overlaps. As seen in Figure 5, the roughness in the as-peened condition (SP) was markedly reduced by polishing (SP + MP) and almost as low as in the electropolished reference (EP). However, only slight life improvements in the high stress regime were found after polishing shot peened specimens (Fig. 6). Presumably, crack nucleation is quite early at these high maximum stresses irrespective of near-surface high dislocation densities at smooth surfaces.

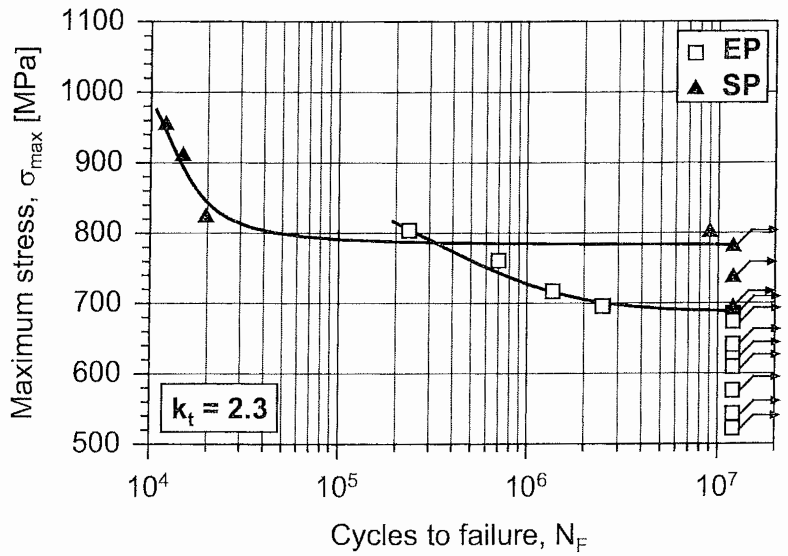

Figure 4: S-N curves of notched specimens ($R = 0.1$, $k_t = 2.3$, $T = 650$ °C, $f = 60$ s^{-1}, air)

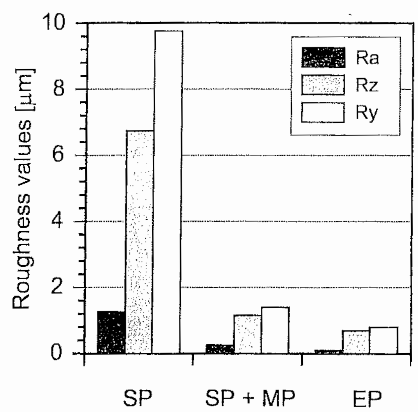

Figure 5: Surface roughness values of the notch root after various mechanical surface treatments

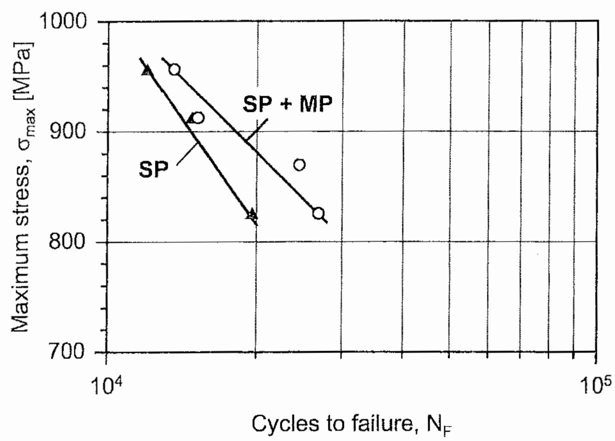

Figure 6: Effect of polishing on LCF-fatigue performance of shot peened specimens ($R = 0.1$, $k_t = 2.3$, $T = 650$ °C, $f = 60$ s^{-1}, air)

As opposed to shot peening, much greater depths of plastic deformation can be induced by deep rolling (Fig. 7). However, microhardness values close to the surface of deep rolled specimens are lower than after shot peening. Presumably, the size of the shot being much smaller than the size of the rolls leads to higher near-surface deformation degrees. As seen in Figure 8, deep rolling can drastically improve the fatigue life of the electropolished reference even at very high nominal maximum stresses of σ_{max} = 800 MPa where the life improvement due to shot peening is rather small.

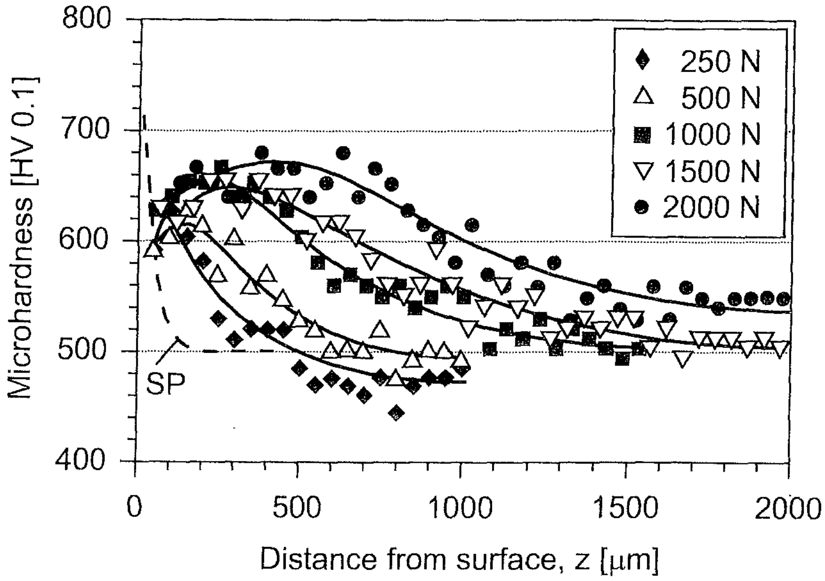

Figure 7: Microhardness profiles after deep rolling with various rolling forces compared to shot peening (SP: 0.24 mmA)

While the process window is quite wide with regard to suitable rolling forces which lead to life improvements of more than three orders of magnitude (Fig. 8), some loss in fatigue life was observed at the highest rolling force used. Metallographic observation of the deep rolled notch roots showed process-induced microcracks (Fig. 9), which could easily act as crack starters during subsequent fatigue testing. As often observed on fatigue fracture surfaces of deep rolled specimens, the stage of early crack growth in residual compressive stress fields where cracks may significantly be hindered to propagate can easily be identified by a shiny zone [4]. It is argued that the width of this zone corresponds to the crack depth where the local stress intensity range as controlled by applied and residual stresses had overcome the threshold value ΔK_{th} (Fig. 10).

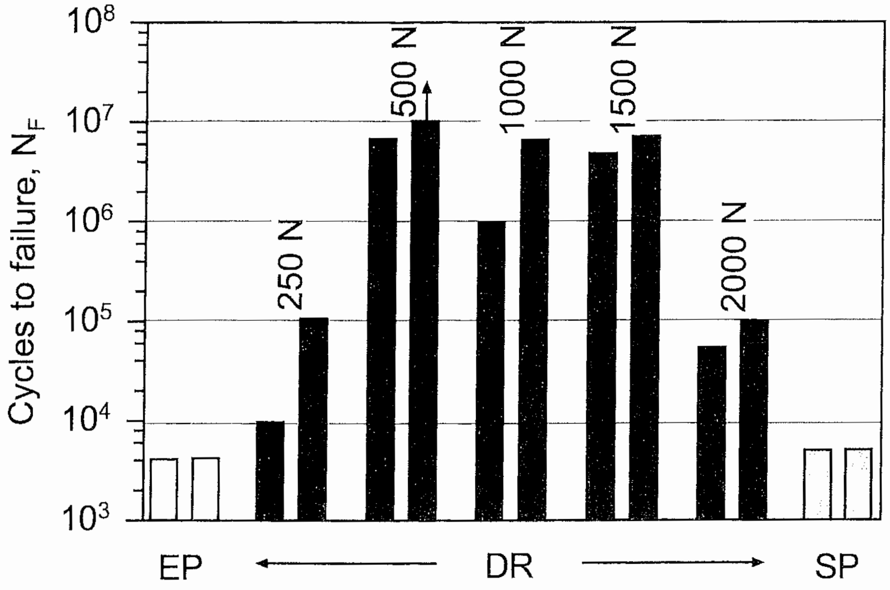

Figure 8: Fatigue life ($R = 0.1$, $\sigma_{max} = 800$ MPa, $k_t = 3.5$, T = 650 °C, $f = 60\ s^{-1}$, air) of the various conditions

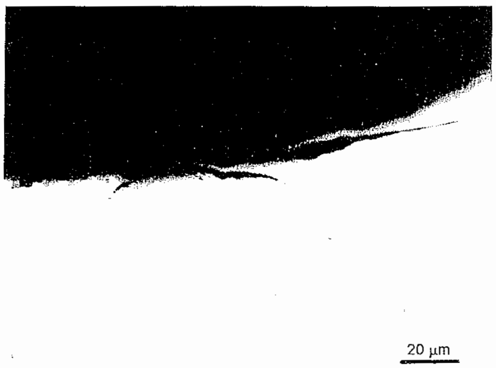

Figure 9: Process-induced microcracks in the notch root after deep rolling with a rolling force of 2000 N

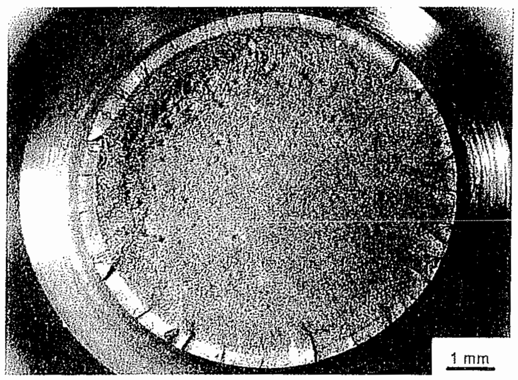

Figure 10: Typical HT-fatigue fracture surface after deep rolling with an optimum rolling force ($F = 500$ N, $R = 0.1$, $k_t = 3.5$, $T = 650$ °C, air, $f = 60\ s^{-1}$, $\sigma_{max} = 800$ MPa, $N_F = 6.65 \cdot 10^6$)

4 Acknowledgements

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5 References

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