Analytical fatigue life prediction of shot peened Inconel 718

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Introduction

Shot peening is commonly used on mechanical parts submitted to cyclic loads. During the process, compressive residual stresses and work hardening are introduced at the shot peened surface [1]. These two factors delay crack initiation and propagation and thus increase fatigue life. It is also reported that shot peening can modify the crack initiation mechanisms and relocate the crack initiation sites from the surface to the subsurface [2,3]. However, shot peening increases the surface roughness [4] which results in stress concentrations that can alter the fatigue life if the shot peening parameters are not carefully chosen [5,6].

In the aerospace industry, shot peening is usually not accounted for in the design stage but is rather considered as a safety margin. Understanding and modeling shot peening effects on crack initiation and propagation mechanisms would provide the essential grounds to account for the process beneficial effects at the design stage. This would lead to considerably lighter parts and would reduce the trials and errors required to define optimal peening parameters. This study aims at modeling crack initiation and propagation in shot peened Inconel 718 for different shot peening conditions and applied stress levels.

Objectives

The objectives are:

1) Observe and understand fatigue crack initiation and propagation mechanisms under high and low cycle fatigue on Inconel 718 for three shot peening conditions.
2) Model crack initiation and propagation by accounting for the shot peening conditions and the applied stress level.

Methodology

The tested material is the nickel based superalloy Inconel 718, commonly used for gas turbine engines parts submitted to high temperatures. 9.5 mm diameter cylindrical samples were axially tested at room temperature, in both high and low cycle fatigue (HCF and LCF), under a constant stress ratio of 0.1 at a frequency of 20Hz. Five different surface treatments were considered: 1) Polished, 2) as machined, 3) shot peened with steel cast shot S230 at 4A, 4) shot peened with cut wire CW14 at 4A and 5) shot peened with CW14 at 8A.

Shot peened specimens with rectangular cross sections and dimensions of 3.56 X 10.16 mm were also fatigue tested to study residual stresses and cold work redistribution.

Scanning Electron Microscopy observations were used to study crack initiation and propagation mechanisms and location. Residual stresses were measured with X-Ray diffraction.

A Navarro and de los Rios type model [7,8] (NR model) coupled with Chan's crack initiation model [9] was used to predict the experimental observations.

Results and analysis

In LCF (Fig. 1a), all cracks initiated at the surface for the cylindrical specimens, whether at a NbC carbide or at a feature causing a stress concentration. Fatigue life was highly dependent of the surface roughness.

In HCF (Fig. 1b), crack initiation mechanisms and locations were different for the three shot peening conditions. CW14 8A led to a 210 µm subsurface crack initiation and a 2 to 8 times fatigue life improvement when compared to polished samples. In the case of CW14 4A and S230 4A cylindrical samples, cracks initiated in the middle of the cross section at a grain larger than the average grain size which resulted in a 20 times improvement of the fatigue life.

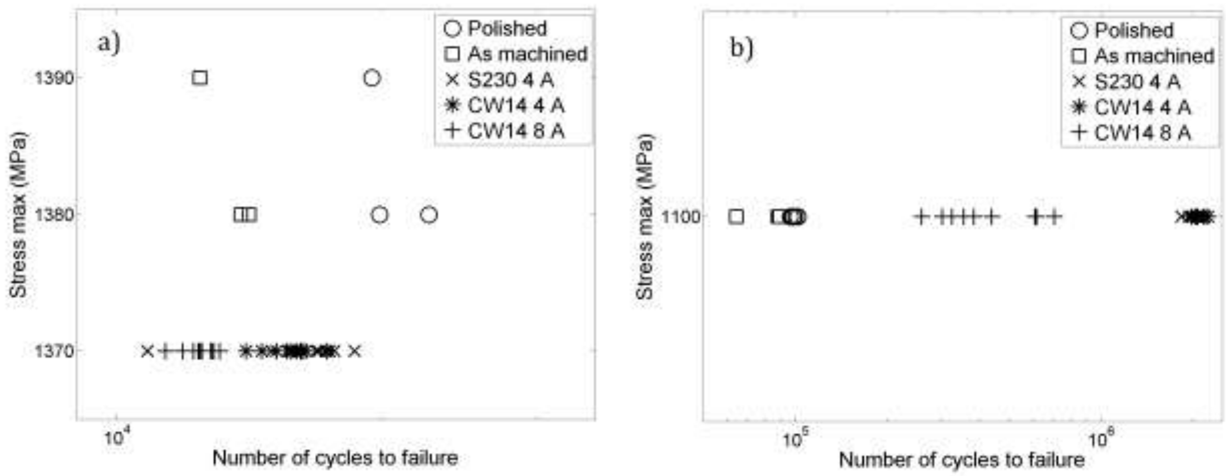

Figure 1: Fatigue tests results for a) low cycle fatigue and b) high cycle fatigue.

Cylindrical samples residual stresses and cold work profiles are presented in Fig. 2. Cold works was estimated using Prevéy's method [10] based on the XRD diffraction peak broadening. Residual stresses and cold work are negligible for polished specimens. As machined specimen showed lower and shallower compressive residual stresses when compared to the shot peened specimens. CW14 8A exhibited the deepest residual stresses and cold work effects. A tensile peak of approximately 175 MPa is observable at 230 µm under the surface. In accordance with previous surface roughness measurements, the surface cold work is higher for CW14 shot peened samples then for the S230 specimens. Cold work profile reach 0 before the end of the associated compressive residual stresses.

Residual stresses redistribution was measured on the rectangular specimens. The measurements were carried out in the 3.56 mm thick direction. The cold work was also calculated from these measurements. Results are presented in Fig. 3. The tensile residual stresses are higher than for the cylindrical samples since the thickness of rectangular samples is smaller than the cylindrical specimens' diameter. As already observed by Hoffmeister [11], residual stresses relax mostly during the first cycle. In LCF, compressive residual stresses become tensile. This is due to 1) the difference in yield strength between the surface and the bulk material; the surface being harder as a result of cold work and 2) the applied maximum stress which is harder than the bulk material yield strength. In LCF the roughness induced by shot peening is significant to fatigue.

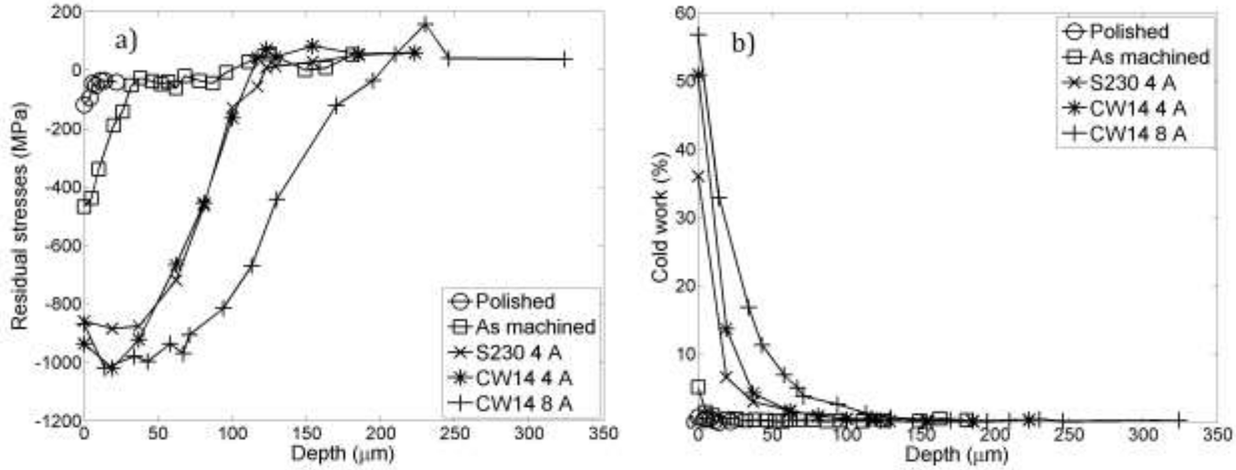

Figure 2: Cylindrical samples a) residual stresses and b) cold work profiles prior to test.

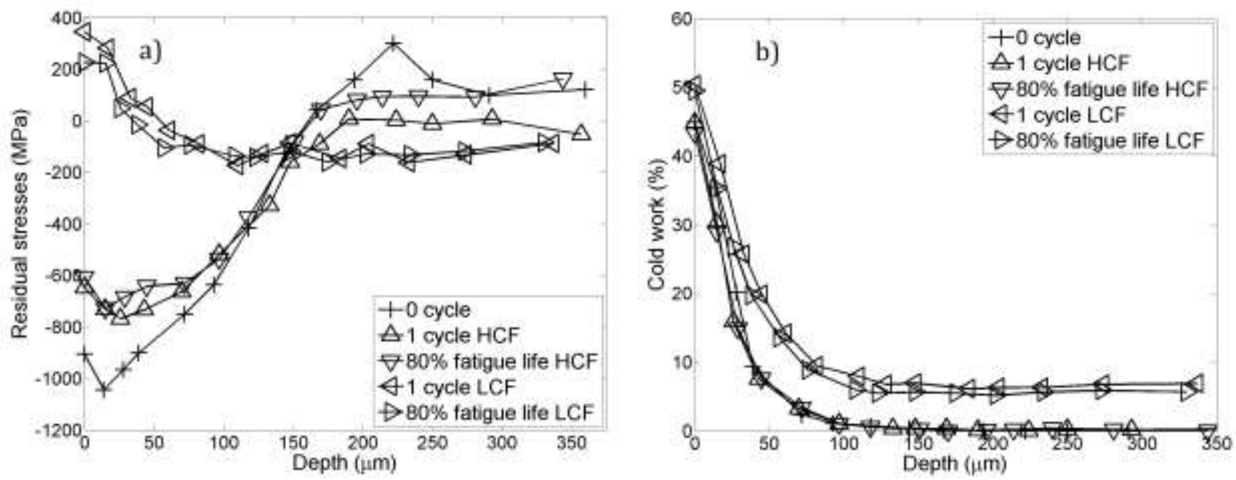

Figure 3: Rectangular samples relaxation a) residual stresses and b) cold work profiles under HCF and LCF conditions at 0 cycle, 1 cycle and 80 % of the fatigue life.

The NR model was successfully used to predict crack propagation and the fatigue life of the tested specimens. The surface roughness, cold work layer, residual stresses and carbides cracking were accounted for in the NR model. The number of cycles to subsurface initiation were estimated using Chan's model while for the surface crack initiations a pre-existing crack was considered. Residual stresses redistribution was calculated via a finite element model calibrated on the results presented in Fig. 3. The cold work was accounted for by a modification of the yield strength through depth. The predicted fatigue lives in LCF and HCF are respectively shown in Fig. 4(a) & (b).

For shot peened specimen tested in HCF, the model predicted that a crack could not propagate from the surface since its propagation is stopped at the first microstructural barrier under the effect of the compressive residual stresses and the resistance of the hardened surface layer. Considering all possible crack initiation scenarios and selecting the one leading to the shortest fatigue life, the model was able to predict the crack initiation location and the resulting fatigue life.

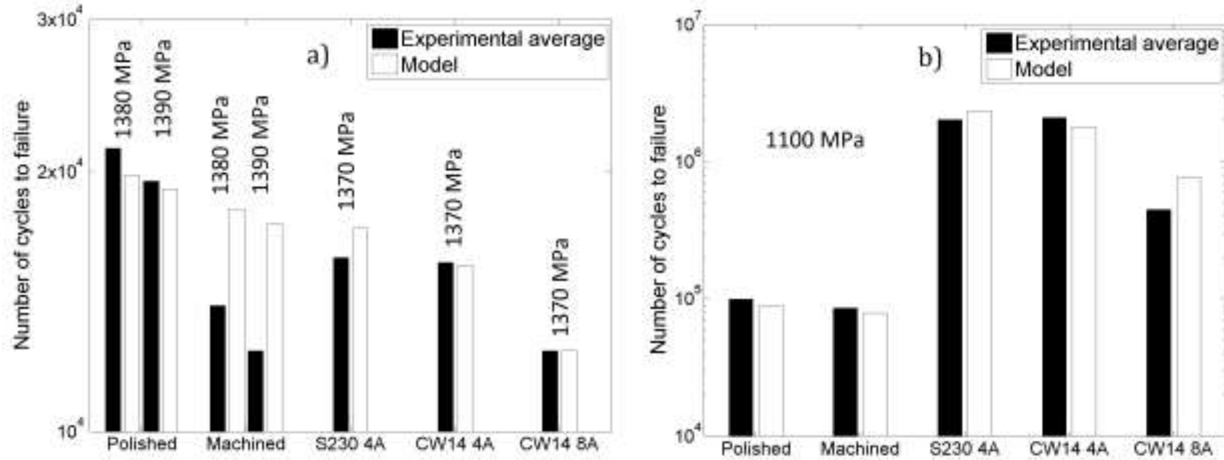

Figure 4: Model predictions compared to experimental average values in a) LCF and b) HCF.

Conclusions

Inconel 718 specimens with different shot peening conditions were fatigue tested at room temperature in LCF and HCF. Different crack initiation mechanisms and locations were observed. Shot peening can improve fatigue life up to 20 times in HCF but can also be detrimental in LCF. To take full benefits from the process, shot peening parameters should be carefully chosen since they directly influence the fatigue life. A NR model type coupled with Chan's crack initiation model was successfully used to predict the crack initiation location and the resulting fatigue life for all cases.

References

[1] E.R. de los Rios, A. Walley, M.T. Milan, G. Hammersley, Fatigue crack initiation and propagation on shot-peened surfaces in A316 stainless steel, International Journal of Fatigue 17(7) (1995) 493-499.

[2] J.T. Cammett, P.S. Prevéy, N. Jayaraman, The effect of shot peening coverage on residual stress, cold work, and fatigue in a nickel-based superalloy, Tech. rep., DTIC Document (2005).

[3] M.A.S. Torres, H.J.C. Voorwald, An evaluation of shot peening, residual stress and stress relaxation on the fatigue life of AISI 4340 steel, International Journal of Fatigue 24 (8) (2002) 877-886.

[4] J.K. Li, Y. Mei, W. Duo, W. Renzhi, An analysis of stress concentrations caused by shot peening and its application in predicting fatigue strength, Fatigue & Fracture of Engineering Materials & Structures 15 (12) (1992) 1271-1279.

[5] D. Novovic, R.C. Dewes, D.K. Aspinwall, W. Voice, P. Bowen, The effect of machined topography and integrity on fatigue life, International Journal of Machine Tools and Manufacture 44 (2) (2004) 125-134.

[6] L. Wagner, Mechanical surface treatment on titanium, aluminium and magnesium alloys, Materials Science and Engineering: A 2363 (2) (1999) 210-216.

[7] A. Navarro, E.R. de los Rios, Short and long fatigue crack growth: a unified model, Philosophical Magazine A 57 (1) (1988) 15-36.

[8] A. Navarro, E.R. de los Rios, An alternative model of the blocking of dislocations at grain boundaries, Philosophical Magazine A 57 (1) (1988) 37-42.

[9] K.S. Chan, A microstructure-based fatigue-crack-initiation model, Metallurgical and materials Transactions, A 34 (1), 43-58.

[10] P.S. Prevéy, The measurement of subsurface residual stress and cold work distributions in nickel base alloys, Residual Stress in Design, Process and Materials Selection, WB Young, ed., ASME, Metals Park, OH (1987) 11-19.

[11] J. Hoffmeister, V. Schulze, R. Hessert, G. Koenig, Residual stresses under quasi-static and cyclic loading in shot peened Inconel 718, International Journal of Materials Research 103 (1) (2012) 66-72.