Finite element simulation of shot peened residual stress relaxation under low and high cycle fatigue loadings

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Introduction

Shot peening is widely used in automobile and aerospace industries to improve fatigue properties of metallic materials. Shot peening results in: (1) Surface compressive residual stresses beneficial to fatigue resistance by preventing crack initiation and delaying crack propagation; (2) Surface plastic deformation which results in dislocation at the surface; (3) Surface hardening which increases local yield strength and therefore increases the resistance for further plastic deformation from mechanical loading; (4) Surface roughness which acts as stress concentrator and produces crack initiation. The compressive residual stress is one of the key factor for fatigue life improvement. However, residual stresses may relax during fatigue loading and therefore greatly reduce the benefit of shot peening. McClung [1] provided a broad and extensive literature review of the stability of residual stress. The redistribution and relaxation of residual stresses under static mechanical loading, cyclic loading, thermal exposure and crack extension have been investigated. Prevéy [2] revealed a strong dependence of the amount of relaxation on the degree of the cold working induced during surface treatment. Cold work is cumulative and increases with the intensity and coverage of shot peening. Conventional shot peening produces 10% to 50% cold work. In addition, different shot type may introduce different cold work and the depth of cold work increases with the increase of intensity [3].

Most of the residual stress relaxation studies were based on experimental investigation by X-ray diffraction (XRD). Many experimental studies showed that most of the relaxation occurred on the first cycle. Analytical analyses and empirical relationships have been obtained to describe the residual stress relaxation. Zhuang [4] explained that the cyclic relaxation is caused mainly by: (1) Shot peening results: initial residual stress and cold work profiles, (2) Loading conditions: fatigue stress amplitude, mean stress, stress ratio and number of cycles, and (3) Material properties: cyclic stress-strain response and degree of hardening/softening. Zhuang has developed an analytical and Finite Element Models (FEM) to calculate the surface residual stress relaxation with respect to fatigue cycles at different stress amplitude. Meguid [5] has developed a FEM incorporating shot peening process and residual stress relaxation in IN718 under mechanical and thermal loadings. FEM simulated results showed that the combined thermomechanical loadings were capable to fully relax the residual stresses within the first cycle. Buchanan and John developed FEMs to simulate the residual stresses relaxation under one cycle mechanical loading and thermal loading in IN100[6]. Both experimental and simulated results showed that surface compressive residual stresses change to tensile under larger mechanical loading.

The objective of this study was to simulate the shot peening induced residual stress and cold work redistribution during mechanical loadings at different stress levels. Finite element models were developed to simulate the residual stress relaxation and the predictions were compared with X-Ray Diffraction (XRD) measurements.

Table 1 Inconel 718 monotonic tensile properties in agreement with ASTM E8M-13a standard.

E (GPa)	ν	$\sigma_{y0.2\%}$(MPa)	σ_u(MPa)	El. (%)	AR. (%)
205	0.32	1156	1413	23	33

Table 2 Inconel 718 chemical composition obtained by optical spectrometry (weight %).

Elements	Ni	Cr	Nb	Mo	Ti	Al	Co	Mn	Si	Cu
Composition	Bal.	17.84	5.02	3.07	1.16	0.64	0.35	0.16	0.06	0.06

Experimental procedure

The tensile properties and chemical compositions of Nickel alloy IN718 are listed in Table 1 and Table 2, respectively. Conventional shot peening was performed according to the standard specification using Conditionned Cut Wire (CW14) with density ρ_s=7800kg/m^3, nominal diameter D_s =0.3556mm. Almen intensity of 8A and 100% coverage were selected in the shot peening process. The stand-off distance was 300mm and the nozzle diameter was 12.7mm. A mass flow rate m_s= 6.8kg/min was controlled by MagnaValves provided from Electronics Inc. Shot velocity v_s= 75m/s was measured by a Shot Meter provided from Progressive Technology.

A rectangular cross section specimen with width of 10.16mm and thickness of 3.56mm has been studied in this paper. Shot peening was performed on 4 flat surfaces of the rectangular cross section. Uniaxial tensile and compressive mechanical test was performed at room temperature under a 20 Hz on a MTS machine. Two stress levels (σ_{max} =1100MPa, 1370Mpa) and with stress ratio $R = {}^{\sigma_{min}}/_{\sigma_{max}} = 0.1$ were selected. The stress level σ_{max}=1100MPa leads to high cycle fatigue (HCF) and σ_{max}=1370MPa leads to low cycle fatigue (LCF).

Residual stress after shot peening and after mechanical loading were measured by XRD technique. Pulstec μ-X360n apparatus equipped with a Cr tube was used to perform XRD measurements. Measurements were done on {311} planes family using Kβ lines. X-ray elastic constant, used for residual stress calculation, was measured on a flat tensile micro-specimen made of the same material, having the same grain size and microstructure. A Kammrath & Weiss GmbH micro-tensile machine was used for this purpose. The same machine was used to perform cold work measurement calibration. The micro-specimen was plastically deformed by increments and corresponding diffraction peaks broadenings were recorded via Full Width at Half the Maximum (FWHM) values. The relation between FWHM and plastic deformation was approximated by the relation proposed by Prévey in [7] in order to assess high values of cold work. Electropolishing was applied to remove layer of material to obtain the in-depth residual stress and cold work profiles. Relaxation and redistribution of stress due to the layer removal process were corrected by Moore & Evans correction.

Experimental XRD measurements

Figure 1(a) and (b) present the measured residual stress and cold work profiles at different fatigue loading conditions, respectively. The initial values (after shot peening and 0 cycle fatigue loading), 1 cyclic fatigue loading and at 80% of the fatigue life are presented. It can be seen that for both HCF loading (σ_{max}=1100MPa) and LCF loading (σ_{max}=1370MPa), compressive residual stresses relax significantly after 1 cycle and remain constant up to 80% of the fatigue life. For σ_{max}=1100MPa, both surface and maximum compressive residual stresses relax to 300MPa. However, when σ_{max}=1370MPa, the compressive residual stresses reverses to tensile stresses at the surface and compressive stresses in the bulk. Similar results have been obtained by Buchanan and John for IN100 [6].

Figure 1 (b) shows that shot peening produces significant cold work (45-50%) on the surface of the sample. Cold work has maximum value on the top surface of the sample and decreases to 0 at the a depth of 0.15mm. For HCF loading (σ_{max}=1100MPa), cold work keeps the same value as 0 cycle fatigue loading. While in the case of LCF loading (σ_{max}=1370MPa) at 1 cycle and 80% fatigue life cycles, cold work increases in both surface and bulk material compared to the value at 0 cycle. This increase of cold work is due to plastic deformation during mechanical loading which is higher than the yield stress of material.

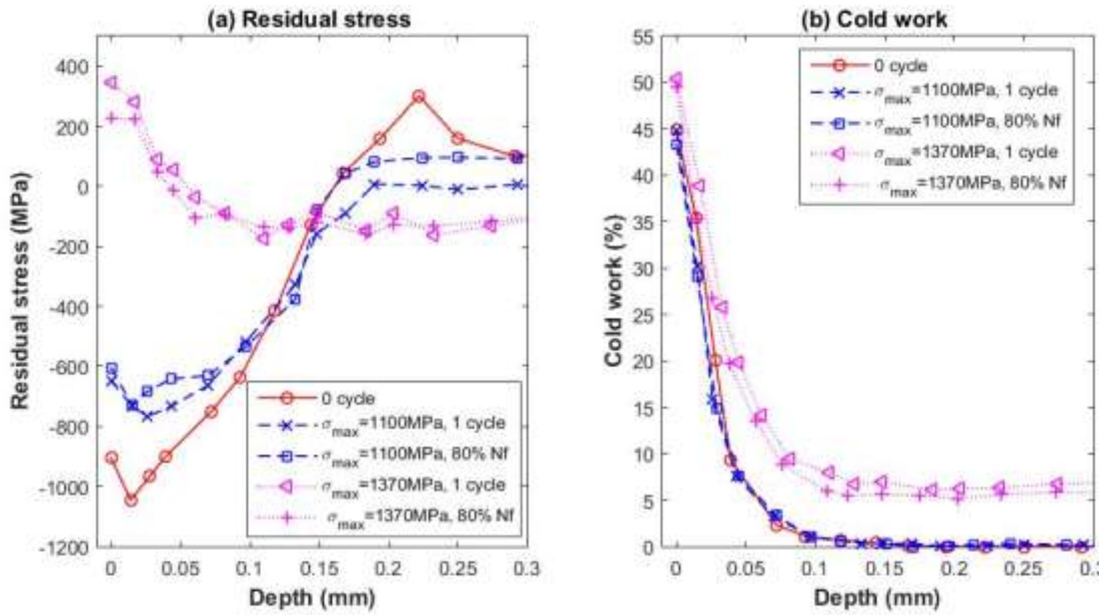

Figure 1 Residual stress and cold work (plastic strain) after different mechanical loadings.

Finite element simulation

The residual stress relaxation FE model was developed in ANSYS using solid element SOLID185. The FE model assumed that 1) the residual stress field was equi-bi-axial and balanced by tensile residual stresses in the bulk material; 2) a cold work (plastic strain) layer caused by extensive plastic deformation was present; and 3) the hardening of the surface increased the yield strength [6]. The residual stress field was assumed to obey:

$$\sigma_{res} = A \times e^{\frac{-2(x-x_d)^2}{W^2}} + B + C \times e^{\frac{-(x-x_e)^2}{2G}} \quad (1)$$

While the cold work was assumed to obey

$$CW = ae^{bx} \quad (2)$$

where A, x_d, W, B, C, x_e and G are fitting parameters for residual stress and a and b are fitting parameters for cold work and x is the depth of the profiles. The residual stress and cold work profiles were input into the FE model as initial state.

Chaboche's constitutive material properties as shown in Figure 2 was used to describe the IN718 material in the FE model. It was obtained from experimental results as described using [3, 8]:

$$\sigma = a_1 \times \left(1 - e^{C_1 \varepsilon_p}\right) + a_2 \times \left(1 - e^{C_2 \varepsilon_p}\right) + \sigma_y \quad (3)$$

where a_1=147.5MPa, a_2=651.996MPa, C_1=324.278 and C_2=6.974 and σ_y=1074MPa. Yield stress at 0.05% plastic strain was obtained as IN718 bulk yield strength $\sigma_0 = 1074$MPa in the finite element simulation. Experimental residual stress profile relaxation measurement in Figure 1(a) shows that the residual stress relaxed mainly after first loading. Therefore, in this paper, the residual stress relaxation after only one load cycle was simulated.

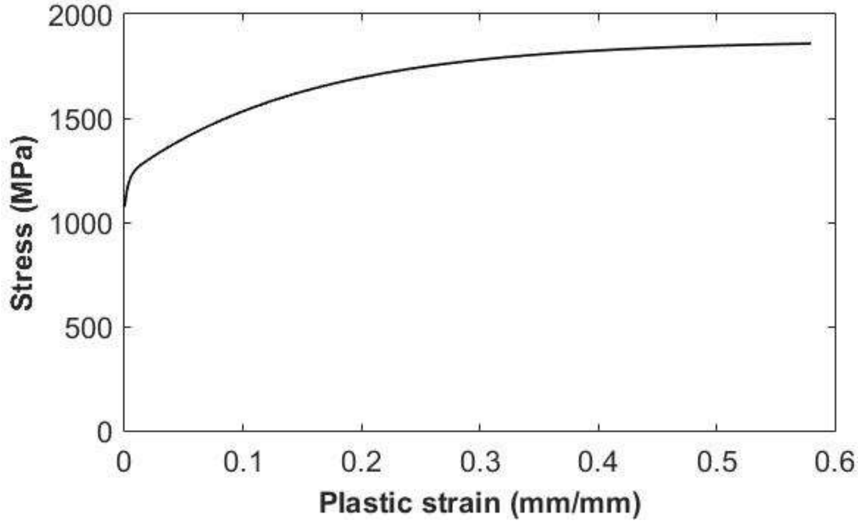

Figure 2 IN718 material true stress and plastic strain curve

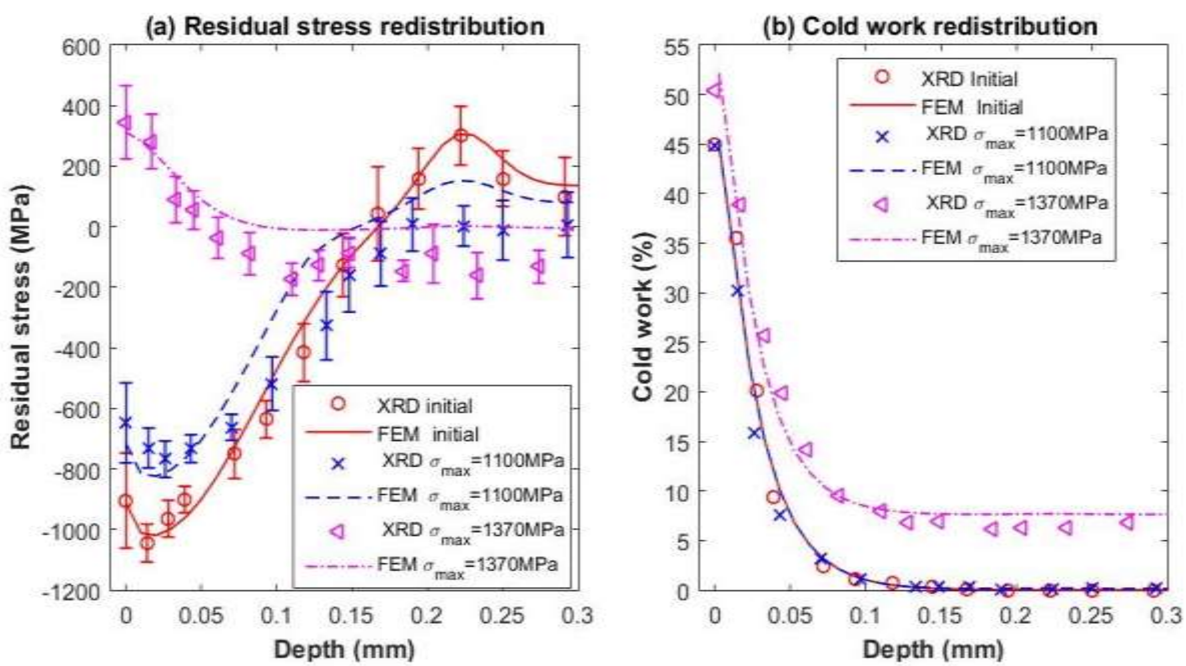

Figure 3 Comparison between FEM simulated and experimental measured residual stress and cold work redistributions (a) residual stress redistribution; (b) cold work redistribution.

Results and analysis

Figure 3 compares FEM simulated residual stress and cold work redistributions under two mechanical loadings (σ_{max}=1100MPa, 1370Mpa) with experimental XRD measurements. It can be seen that simulated residual stress and cold work redistributions at two loading conditions are both consistent with the experimental measurements. Therefore, the developed FEM model is validated to able to simulate the residual stress and cold work relaxation under 1 cycle fatigue loading.

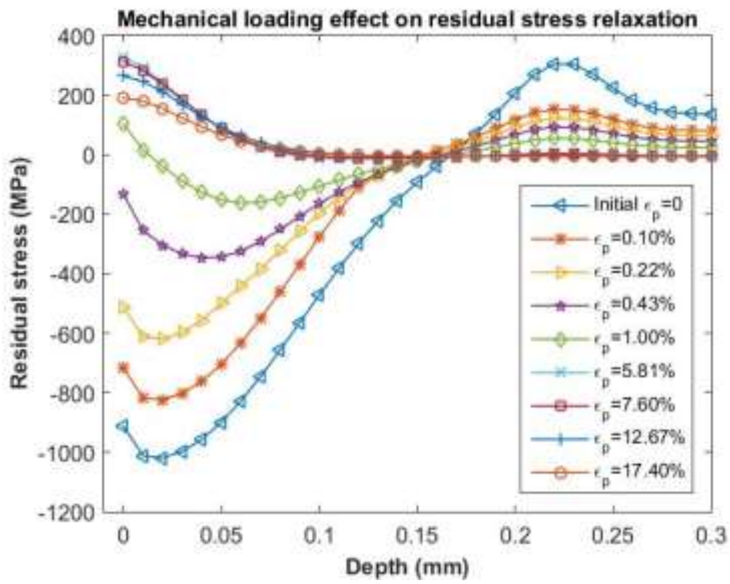

Figure 4 The effect of applied loading σ_{max} on the residual stress relaxation.

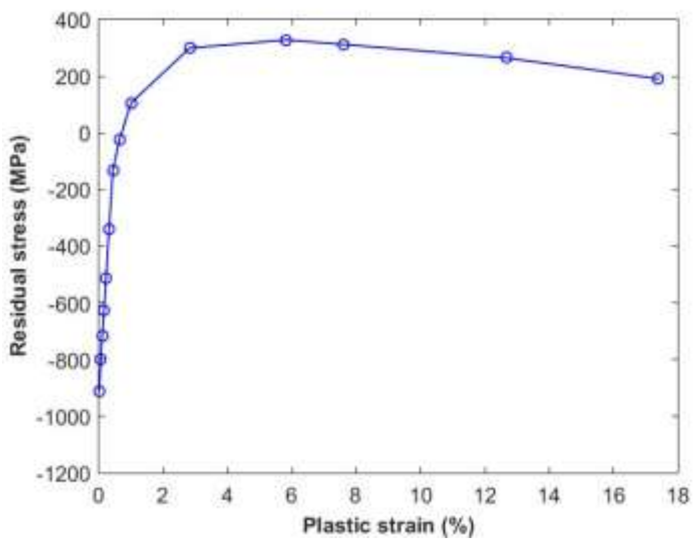

Figure 5 Relationship between surface residual stress and applied plastic strain.

Figure 4 presents the residual stress relaxation under 8 different fatigue loading levels (plastic strain ϵ_p from 0.1% to 17.4%). It can be seen with the increase of the loading level, the surface compressive residual stress gradually increases to tensile value. Figure 5 shows the relationship between the applied plastic strain and surface residual stress after relaxation. It can be seen that for small plastic strain, surface residual stress increases rapidly into tensile and then with the increase of plastic strain, the surface residual stress reaches maximum and decreases gradually.

FE simulated results show that in the case of ϵ_p=0.67% (σ_{max}=1225MPa), the surface residual stress changes sign from compressive to tensile. In the case of ε_p = 5.81 % (σ_{max}=1350MPa), relaxed surface stress reach maximum σ_{sur}=328MPa. Similar tendencies have been presented by Kirk on different shot peened materials such as copper, nickel and steel using experimental studies [9].

Conclusions

A FEM was developed to simulate the residual stress relaxation under mechanical fatigue loadings. The residual stress, cold work profiles and the hardening effect on the yield strength of the material have been taken into account in the FE model. The simulated results were validated with the experimental XRD measurement. Both simulation and experimental measurement show that for IN718, when the applied stress loading σ_{max} is larger than material yield stress, the compressive residual stress start to relax. With the increase of the applied loading, the relaxation of the compressive residual stress increases. At certain stress (σ_{max} =1225MPa) or plastic strain (ϵ_p=0.66%) loading, surface compressive residual stress changes to tensile. Then at certain stress (σ_{max}=1350MPa) or plastic strain (ϵ_p=5.81 %,) loading, the relaxed surface residual stress reach the maximum tensile value and started to decrease with the increase of the applied loading.

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