FATIGUE LIMITS PREDICTION OF SHOT PEENED MATERIALS

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ABSTRACT

Shot peening is an effective method of improving the fatigue strength of components and structure. The change in surface layer properties caused by shot peening was evaluated by residual stress and cold work. The X-ray diffraction non-destructive method of measuring is used. In order to predict fatigue strength of metal components, it is necessary to apply a fatigue limit criterion that takes into consideration compressive residual stress and cold work. The theoretical model, gives a better approach of shot peening material fatigue behaviour. The model takes into account two essential beneficial effects that are: compressive residual stresses and the increase of cold work. It was demonstrated that the effect of cold work on fatigue strength is more important than that of residual stress. The fatigue limit criterion predicts that the crack origin is located into the region under the surface hardened layer. Comparison of predictions of this criterion against experimental fatigue limit data showed good agreement. The methodology followed to build this model could be adequately modified to derive models for other surface treatments.

KEYWORDS: Fatigue limit; Residual stress; Cold work; Surface treatment; Fatigue.

1. INTRODUCTION

Surface treatment is widely used as a method for improving the fatigue properties of engineering components, particularly in the aircraft industry. The principal surface treatment such as shot peening or nitriding have been carried out on many mechanical components before their delivery are aimed to differentiate the response of surface material properties. This occurs by inducing appropriate residual stress distribution. In fact, it is this appropriate induction which improves the fatigue life of shot peening material [1-3]. The modelling and simulation of the shot-peening process has received some attention from the scientific community [4-6].

Residual stress was measured by X-ray diffraction technique. The technique measures the residual stress from the determination of the shift in X-ray diffraction peak position ($°2\theta$), caused by the change of lattice spacing due to presence of residual elastic strain (stress). Simultaneously, the technique can measure the broadening of X-ray diffraction peaks to qualify the degree of cold work in the material [7]. During use, materials may cyclically harden or soften with repeated loading which may cause redistribution of any residual stresses present [8-9]. Therefore, cyclical relaxation of compressive residual stress reduces the benefit.

Frequently metallic components, when conceived for finite fatigue life, are designed to with stand many thousands, often even millions, of loading cycles. In order to predict fatigue strength of metal components, it is necessary to apply a fatigue limit criterion that takes compressive residual stress and cold work into consideration. A formula is proposed and comparisons with experimental results are provided.

2. MODEL

The dislocation movement is the most primary process of fatigue initiation. The proposed fatigue limit criterion is based on *Crossland*'s model and local approach. It takes into account the residual stress and cold work [4] which is given by the rate between the X-ray diffraction widths measurement of base material and shot peened one. Cold work C_w is defined as follows:

$$C_w = b/b_0 \tag{1}$$

Where b is the X-ray diffraction width of shot peened material, and b_0 is the X-ray diffraction width of base material. Based on the *Deperrois* model [10] the proposed criterion suggests the following relationship:

$$\sigma_{eq} + \alpha P_{max} \leq \beta \sqrt{C_W} \tag{2}$$

Where σ_{eq} is the maximum amplitude of the second invariant of stress deviator ($\sqrt{J_2(t)}$), P_{max} is the maximum value of the hydrostatic stress within a loading cycle. The hydrostatic stress P_{max} is equal to zero for a torsion test. The intensity of the applied torsion in our test is such that the specimen will just never be broken by fatigue. The parameter β is equal to fatigue limit in fully reserved torsion for base material. The second parameter α can be obtained from both fully reserved bending and torsion tests. Clearly the value of α is given by the formula:

$$\alpha = \frac{t_{-1} - f_{-1}/\sqrt{3}}{f_{-1}/3} \tag{3}$$

f_{-1} and t_{-1} are respectively fatigue limits in both fully reversed bending and torsion tests (at 10^7 cycles). Here, we have used the fatigue limits in both tests to determine these parameters, but any other two fatigue limits could be used as well. Equation (2) incorporates the benefits effects, i.e., compressive residual stresses and cold work, on fatigue strength. In this criterion, it is clear that the maximum value of the hydrostatic stress depends also on residual stresses as following:

$$P_{max} = (\sigma_{eq} + \sigma_m + \sigma_{xx}^R + \sigma_{yy}^R)/3 \tag{4}$$

Where σ_m is a mean stress, σ_{xx}^R is the longitudinal (axial) residual stress, and σ_{yy}^R is the transverse (circumferential) residual stress. Equation (2) is represented by the line with slope that separates the safe from the unsafe domain.

The calculation of the hydrostatic stress requires the determination of the residual stresses. In the frame with axes (P_{max}, σ_{eq}), the loading way moves to the negative axis of hydrostatic stress P_{max}, of an equal value to:

$$C = (\sigma_{xx}^R + \sigma_{yy}^R)/3 \tag{5}$$

meanwhile the line of the criterion moves to the positive axis of maximum amplitude of the second invariant of stress deviator σ_{eq}. Figure 1 shows schematically the proposed fatigue limit criterion compared with *Crossland's* one.

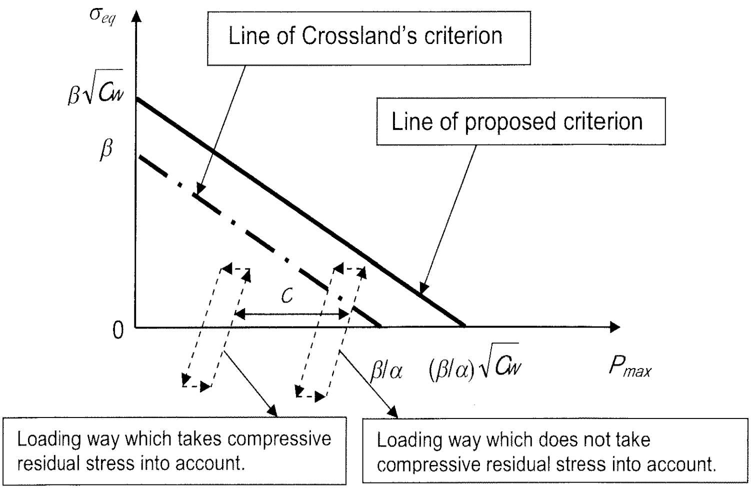

Fig. 1. Comparison between Croosland's criterion and the proposed one

However, residual stresses are relaxed by repeated loading during fatigue. Despite considerable research [11-14], the technical challenge of understanding and accurately quantifying residual stress relaxation and redistribution under cyclic mechanical and thermal load remains. On the contrary, the undertaken researches proved that the X-ray diffraction width does not change appreciably by varying the number of cycles and/or applied stress [15-16]. Thus, we adopt the hypothesis that the X-ray diffraction width is independent from fatigue loading.
To use this criterion, it is necessary to know:

- residual stresses and cold work distributions;
- the applied load;
- fatigue limits in bending and torsion of the base material.

The complexity of the relaxation of compressive stresses and the variation of the X-ray diffraction width in depth allows us to test the criterion at every cycle N and every depth z. Therefore, the fatigue limit criterion is represented in a diagram (P_{max}, z, σ_{eq}), and has to be checked according to the following relation:

$$\sigma_{eq} + \alpha P_{max}(z, N) \leq \beta(N)\sqrt{C_W}(z) \tag{6}$$

If the criterion is fulfilled to all cycles, one can note that the loading falls inside the criterion safe domain. If the criterion is not been fulfilled, the fatigue crack is initiated. Hence, one can deduce that the residual stresses and the cold work introduced by shot peening are not sufficient. Therefore, it is necessary to modify both the residual stresses profile and the X-ray diffraction width one by varying shot peening parameters or by changing the nature of the material. The model can also determine the positions of the fatigue crack.

The proposed criterion can determine fatigue life. We make the hypothesis that α is independent from number of cycles. Let us assume that S-N curve of base material in fully reversed torsion is described by the relationship:

$$\sigma_\tau = [\frac{t_{-1}}{1-\kappa N^{-\lambda}}] \qquad (7)$$

where σ_τ is the amplitude of applied shear stress. The coefficient $\kappa > 0$ and exponent $-\lambda<0$ are two material parameters. Once the fatigue limit t_{-1} is determined, parameters κ and λ can be easily identified from S-N curve [17]. Obviously, it is clear that the parameter β of a given number of cycles N is written as:

$$\beta(N) = \sigma_\tau(N) \qquad (8)$$

By introducing in the equation (6), the value of β in equations (8) and (7), the fatigue limit criterion achieves the form:

$$\sigma_{eq} + \alpha\, P_{max}(z, N) \le [\frac{t_{-1}}{1-\kappa N^{-\lambda}}]\sqrt{C_W(z)} \qquad (9)$$

Equation (9) is a fatigue life prediction formula of fatigue life criterion.

3. MATERIAL AND EXPERIMENTAL PROCEDURES

Residual stresses and cold work (X-ray diffraction width) were determined by using X-ray diffraction method. The present research has been conducted with low alloy known as steel 35NiCrMo16 (with two different ultimate tensile strength of R_m). The chemical composition of this material is shown in table 1 and the mechanical properties are shown in Table 2.

Table 1
Chemical compositions of the materials tested

Material	C(%)	Ni(%)	Cr(%)	Mo(%)	Mn(%)	Va(%)	Si(%)
35NiCrMo16	0,37	4,5	1.8	0,51	0,4	-	0,29
32CrMoVa13	0,32	0,3	3,3	1,2	0,7	0,35	0.4

Table 2
Mechanical properties of materials tested

Material	R_m (MPa)	t_{-1} (MPa)	f_{-1} (MPa)	b_0 (°2θ)
35NiCrMo16	1200	320	555	2
35NiCrMo16	1100	310	525	2
32CrMoVa13	1200	380	660	2.5

The material was quenched in oil and tempered. The ultimate tensile strength resulting from heat treatment is equal to 1100 MPa. The cylindrical specimens were first shot peened, and then fatigue tested. Shot peening treatment was carried out by injection using steel shot S 230 of 0.57 mm of diameter, an *Almen intensity* of 0.30 – 0.35 mm A, and coverage of 200%. The data used are found in *Bignonnet* [18]. Three experimental fatigue tests that were carried out on standardized specimen:

torsion, rotary bending and tension-compression, allowed to determine the fatigue limit of the material. The residual stresses of the shot peened and cyclically loaded specimen were measured. The relaxation of residual stresses occurs essentially during the first cycle, which corresponds to the rearrangement of the residual stress caused by plastic strain. The residual stress becomes stable when the superposition of the stress stays below the cyclic yield stress. Up to 10^3 cycles, residual stress measurement showed no significant relaxation. For this reason 10^3 cycles is sufficient to determine the stabilized residual stress state after fatigue. Plots of axial and circumferential residual stresses with stress ratio R= -1, after 10^3 cycles, for the three fatigue tests are given in Fig. 2a, 2b and 2c.

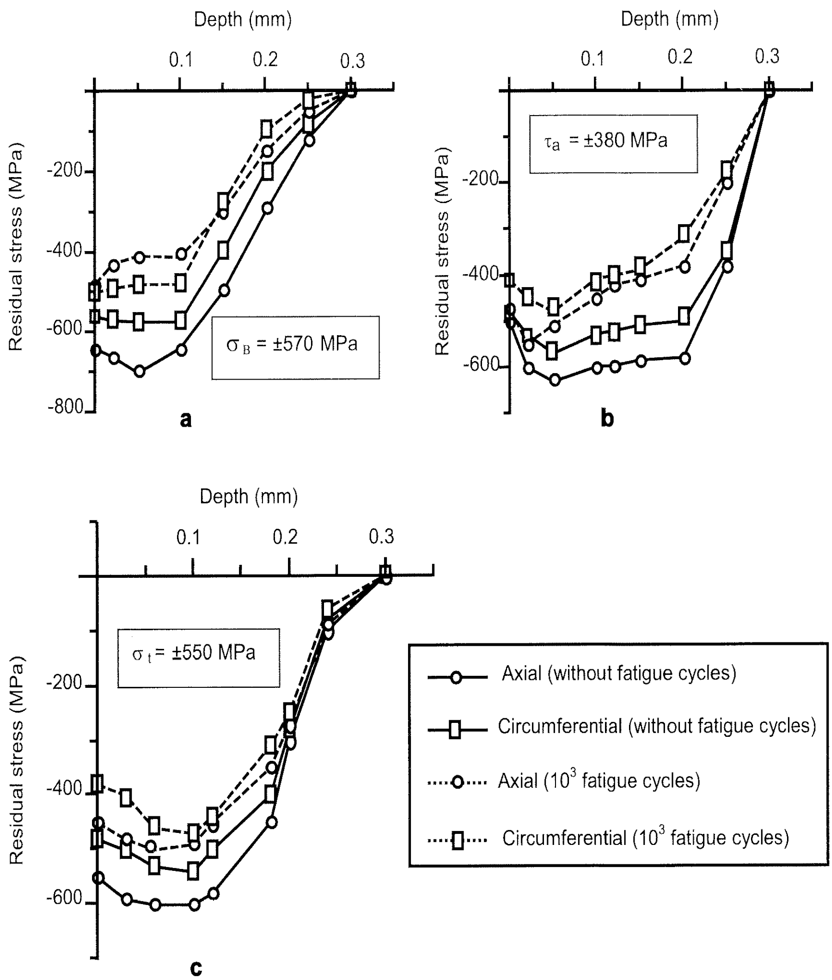

Fig. 2. Axial and circumferential residual stress profiles of 35NiCrMo16 as function of applied cyclic stress amplitude: a- rotary bending (σ_B), b- torsion (τ_a), c- tension-compression (σ_t)

From these figures, we can see that the initial residual stress was released and redistributed. As it is apparent, the residual stress relaxation is depending on the amplitude and the direction of the applied load. For all specimens, the peened layer is equal to 0.3 mm. The figure 3 shows the X-Ray diffraction width profile for a peened material. It can be noticed that the X-ray diffraction width decrease with increasing depth into the material.

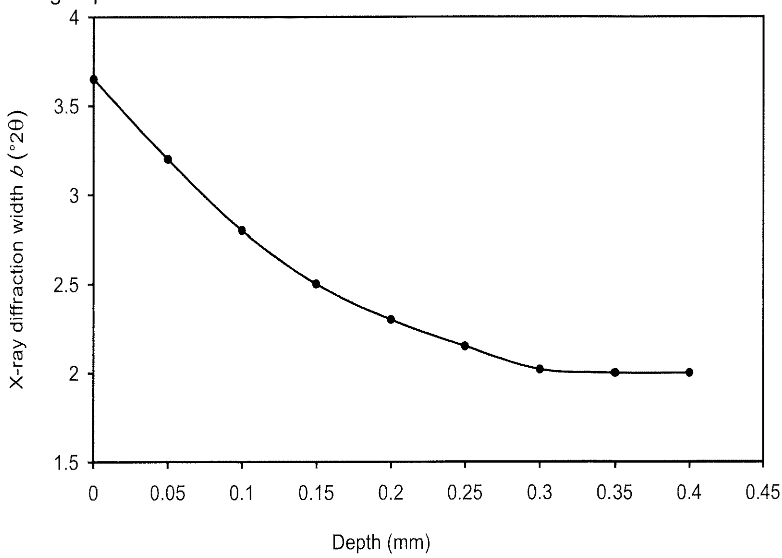

Fig. 3. X-ray diffraction width-depth distribution of 35NiCrMo16

4. APPLICATION OF THE MODEL

The Table 3 shows the fatigue limits given by the proposed model and experimental results.

Table 3
Comparison between fatigue limits (experimental and predicted)

Fatigue test	Experimental fatigue limit (MPa)		Predicted fatigue limits (MPa)
	Base material	Shot peened material	
Torsion	310	380	326
Rotary bending	525	570	596
Tension-compression	490	550	553

The shot peening for the studied conditions represents an enhancement of fatigue limit from 8% to 22%, when comparing to the base material. The value of α is equal to 0.022. Therefore, the effect of residual stress on fatigue strength is negligible. The improvement of the fatigue limit is essentially due to the cold work.

Comparison of the predicted and the experimentally observed fatigue limit is done in Fig.4. The abscissa is the experimental value of the fatigue limit, and the ordinate is the predicted value of the fatigue limit. The diagonal of the box shown in Fig.4 represents a complete agreement between predicted and experimental fatigue limits.

The two dashed lines, above and below the diagonal correspond to an error on the fatigue limit of $\pm 6\%$ factor.

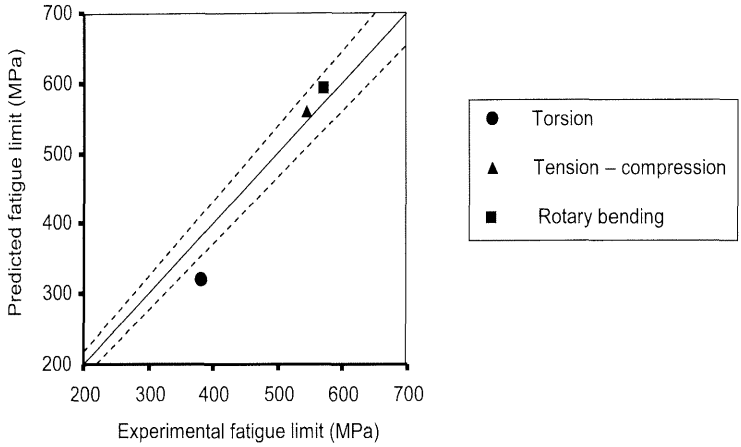

Fig. 4. Comparison between experimental and predicted fatigue limits

Except for torsion test, the predicted fatigue limits are in good agreement with experimental values. Because the model supposes that initiation of the fatigue crack in the material grain takes place before the failure of the specimen, the predicted fatigue limit, in the case of torsion test, is lower that of the measured one.

In the case of the rotary bending, the predicted fatigue limit is higher than the measured one. It was assumed that the greater affected depths in shot peening can only be realized with a concomitant surface degradation, which drastically reduces fatigue life [19]. The model determines the position of the crack source at the depth equal to 0.3 mm, corresponding to the thickness of the peened layer. However, the fatigue limit criterion predicts that the crack origin is located into the region under the surface hardened layer.

5. CONCLUSION

The fatigue limit prediction methodology for cyclical loading has been developed in this work by material state investigation. Stress gradient and topography effects are not induced in this analysis. The theoretical model gives a local approach of the shot peened material fatigue behaviour. The model takes into account two essential beneficial effects that are: compressive residual stresses and cold work. It was demonstrated here, that the effect of cold work on fatigue strength is more important than the one of residual stress. This model permits to predict the fatigue limit of shot peened material. On the other hand, the fatigue limit criterion predicts that the crack origin is located into the region under the surface hardened layer. The model can determine fatigue live of metallic components by using S-N curves. Comparison of the predictions of this criterion against experimental fatigue limit data showed good agreement. The model predicted the initiation of the fatigue crack in sub layer. This goes in concordance with experimental observations [20]. The initiation and the propagation of the fatigue crack from the surface are probably due to the surface roughness which is not taken into account. Though shot peening results in work-hardening and beneficial compressive residual stress at surface, it, however, also damage the surface causing shot peening folds [21]. Because in this model fatigue source is formed inside the weak grains before the failure of the specimen, predicted fatigue limits are generally slightly lower that those measured ones. Another important property of this model is that it can be used to optimize the shot peening parameters and to choose the suitable material. Methodology followed to build this model could be adequately modified to derive models for other surface treatments.

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