Effect of shot peening on the fatigue life and crack propagation prediction with experiments and Navarro-Rios Model

H.Y. Miao and M. Lévesque

CREPEC, Département de Génie Mécanique, École Polytechnique de Montréal, Canada

Abstract

Shot peening induces compressive residual stress in the top layer of a treated component. These stresses retard crack initiation and crack propagation. However, shot peening increases surface roughness which acts as stress concentrator and accelerates crack initiation. Therefore, the effect of shot peening depends on the balance of this beneficial effect (compressive residual stress) and detrimental effect (surface roughness). In this paper, a Navarro-Rios model has been developed based on the studies of De los Rios *et al*. [1] and Curits *et al* [2]. With this model, it is possible to study the propagation of the short crack of the peened component considering the residual stress and surface roughness after different peening intensities (0A, 2A, 4A, 6A, 8A and 10A). The predicted fatigue life limits are consistent with the experimental results from Michaud [3], especially for peened components under larger applied stress. In this studied case, both experimental and theoretical results show that peening intensity 2A produces best fatigue life improvement due to appropriate compressive residual stress and surface roughness.

Keywords Shot peening, Almen intensity, fatigue life, crack propagation, Navarro-Rios model.

Introduction

The effect of shot peening on the fatigue life can be explained by the combined effects of compressive residual stress and surface roughness. De Los Rios *et al*. [1] developed a model that incorporates the shot-peening effects on crack propagation laws and fatigue life predictions using microstructural fracture mechanics concepts. Residual stress and a work-hardened layer have been considered to predict the increase of the fatigue life. Curtis *et al*. [2] demonstrated that residual stress produced by shot peening induce a closure stress to prevent the propagation of the crack. However, surface roughness will accelerate the nucleation and early propagation of cracks. Therefore, the fatigue life after shot peening depends on the balance between its beneficial and detrimental effects. More recently, Xiang and Liu [4] introduced a mechanism modelling to explain the shot peening effect on fatigue life improvements on shot peened specimens. A crack growth-based life prediction methodology based on the equivalent initial flaw size (EIFS) concept has been applied. The effects of residual stress relaxation were proposed by a simplified effective residuals tress factor. The objective of this paper is to use the micro-mechanical notch sensitivity model based on the work of De Los Rios *et al*. [1] and Curtis *et al*. [2] to calculate fatigue limit of shot peened components and to study the influence of shot peneing intensity on fatigue life. Experimental residual stress and roughness results in [3] will be included into this model to obtain the influence of peening intensity on the fatigue improvement. Comparison with the experimental results from Michaud [3] shows that the N-R model can be used to predict fatigue limits of peened component under high applied loads and both calculation and experimental results show that 2A intensity produce the best fatigue life improvement in this studied case.

Experiments shot peening and fatigue life test

A series of Aluminum 7050-T7451 specimens, as shown in Figure 1, have been selected for shot peening and fatigue testing. Shot peening was performed at Aerospace Manufacture Technology Center (AMTC) of the National Research Council Canada (NRC) by Michaud [3]. Air pneumatic peening machine “BAIKER” with ceramic shots “Z425” were selected for shot peening at five Almen intensities: 2A, 4A, 6A, 8A and 10A, respectively.

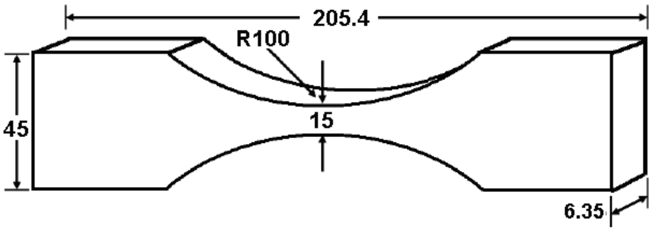

Figure 1. Dimensions (in mm) and design of the dogbone specimen [3]

Table 1 Five groups of shot peening parameters for shot peening [3]

Intensity	Pressure $[KPa]$	Mass flow $[kg/min]$	Angle $[Degree]$	Distance $[mm]$	Velocity of robot $[mm/s]$	Velocity of shots $[m/s]$
2A	37.9	1.6	90	25.4	10.4	12.7
4A	48.3	0.6	90	25.4	10.4	25.4
6A	68.9	0.4	90	25.4	10.4	38.1
8A	100.0	0.4	90	25.4	10.4	50.8
10A	155.1	0.4	90	25.4	10.4	63.2

Experimental Results

The measurements of roughness were carried out at École Polytechnique de Montréal with an electronic profilemeter “Mitutoyo SC/PRO/SJ”. Six groups of roughness were measured: specimens after shot peening (2A, 4A, 6A, 8A and 10A) and specimen without shot peening (0A). Table 2 presents the average roughness R_a, peak and valley roughness R_t as well as notch width RS_m for six groups of specimens.

Table 2 Roughness for six groups of specimens [3]

Parameters of roughness	Almen Intensity (A)					
	0	2	4	6	8	10
R_a $[\mu m]$	0.4	0.8	2.1	3.4	4.6	6.6
R_t $[\mu m]$ (α)	4.5	4.9	13.9	26.9	35.5	49.3
RS_m $[\mu m]$ (2β)	387	163	289	315	418	393

Residual stress profiles were measured by Proto Manufacturing Ltd. with X-Ray diffraction method for six groups of specimens. Figure 2 presents the measured residual stress profiles. It can be seen that with the increase of intensity, the depth of the maximum residual stress increases, while the maximum residual stress remains constant for 6A, 8A and 10A. In the N-R model, Robertson formula (1) is used for best fitting these residual stress profiles [5].

$$\sigma_{res} = A\exp\left[\frac{2(x-x_d)^2}{w^2}\right] + B \tag{1}$$

where σ_{res} is residual stress, x is the depth from surface, x_d, A, B, w and x_d are the fitting parameters. x_d can be related to the depth of the maximum compressive residual stress, $\mathrm{A} + \mathrm{B}$ represents the maximum compressive residual stress and w represents the width of the residual stress zone.

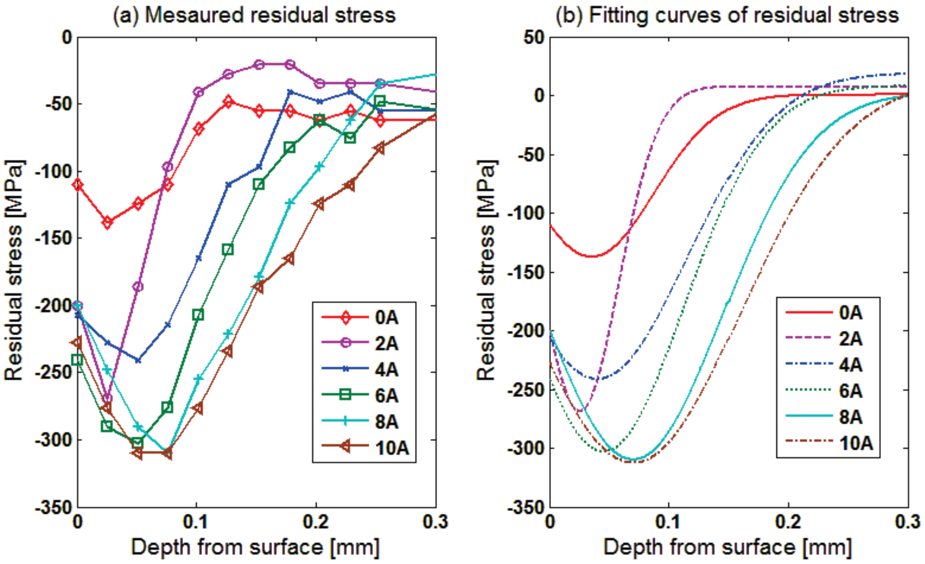

Figure 2 Residual stress for 6 groups of specimens: (a) measured [3] (b) Best fitting curves.

Table 3 Fatigue lives for six groups of specimens under two cyclic loads [3]

Maximum stress $[MPa]$	Fatigue life (cycles)					
	0A	2A	4A	6A	8A	10A
345	36 854	324 754	275 245	116 545	103 389	98 092
	44 147	279 667	250 353	116 138	96 289	113 212
	39 711	268 734	162 419	170 359	120 815	78 730
379	24 377	100 981	.....	63769	73 065	64 811
	24 012	62 043	86 632	69 934	68 205	60 224
	23 652	111 931	81 740	79 554	60 048	56 850

Table 3 presents the fatigue lives of the shot peened component under two different applied stresses $\sigma_{max} = 345$ and $379MPa,$ respectively with load ratio $R = 0.05$. For each applied stress value, three tests were performed. From Table 3, it can be found that shot peening with 2A intensity produces the best fatigue life improvement effect. The performance of the shot peening on the fatigue limits decreases gradually when intensity increases from 2A to 10A.

Navarro-Rios model for the fatigue life prediction

A Matlab program was developed to calculate the fatigue life of a shot peened component considering surface roughness and residual stress profiles according to the work described by De los Rios et al. [1] and Curits et al. [2]. In this section, only the main steps, parameters and the equations used in the program are presented.

Figure 3 presents the relationship between crack length and number of cycle for six intensities with maximum applied stress (a) $\sigma_{max} = 345MPa$ and (b) $\sigma_{max} = 379MPa$, respectively. Figure 3 shows that for both cases, intensity 2A produces largest fatigue limits. Then from 4A to 10A, fatigue limits decrease with the increase of peening intensity.

Table 4 Parameters for the N-R model for the calculation of fatigue life of Al 7050-T7451

1. Loads	
Maximum applied stress (σ_{max})	345 and 379 MPa
Factor of geometric stress concentration (K_t)	1.045
Factor of geometric stress concentration caused by shot peening (K_{trug}.)	Equation $K_{trug} = 1 + 1.05\frac{\alpha}{\beta}$
Load ratio (R)	0.05
2. Mechanical properties of Al7050-T7451	
Cyclic yield stress (S_{Ycyc})	$460\ MPa$
Fatigue limit	$160\ MPa$
Poisson's ratio (ν)	0.33
Shear modulus (G)	$27\ GPa$
3. Microstructure properties of material	
Grain diameter (D)	$0.01\ mm$
Width of the grain boundary (r_0)	0.0
4. Crack propagation properties of material	
Mode of propagation	Mode I
Coefficient of law of Paris (A_1)	$1.61E^{-10}(m/cycle, MPa \cdot m^{1/2})$
Exponent of law of Paris (m_1)	$3.12\ (m/cycle, MPa \cdot m^{1/2})$
Coefficient (A_2)	$0.28\ (m/cycle, m)$
Coefficient (m_2)	$1.30\ (m/cycle, m)$ for $\sigma_{max} = 379MPa$
	$1.34\ (m/cycle, m)$ for $\sigma_{max} = 345MPa$
5. Dimension of specimen (Figure 1)	
Length	$15.0\ mm$
Thickness	$6.35\ mm$
6. Surface roughness	
Roughness parameter (R_t)	Table 2
Roughness parameter (RS_m)	Table 2
7. Residual stress profile	
Residual stress (A, x_d, W and B)	Fitting values of residual stress profiles in Figure 2 with Equation (1)

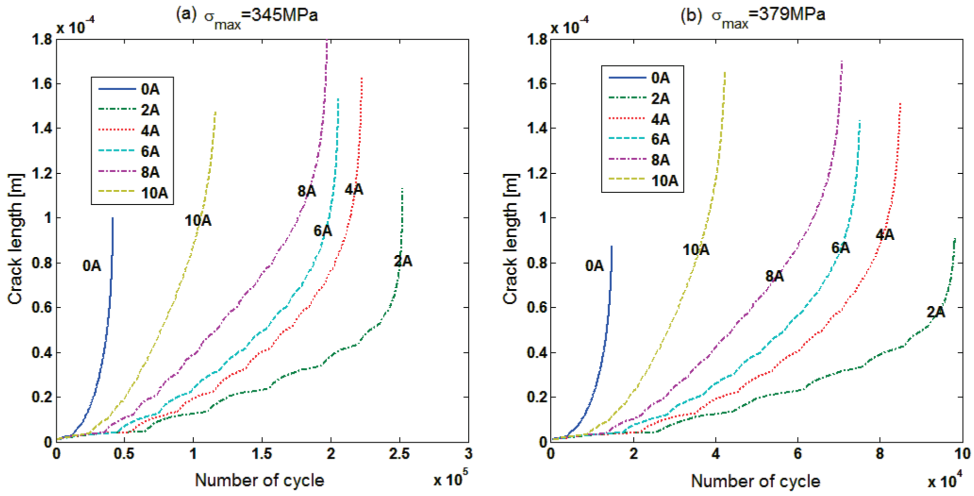

Figure 3 Relationship between crack length and number of cycle for five Intensities

Figure 4 compares the calculated values and the experimental results with maximum applied stress $\sigma_{max} = 345$ and $379MPa$. It can be seen that in the case of $\sigma_{max} = 379MPa$, the calculated results are more consistent to the experimental results than in the case of

$\sigma_{max} = 345MPa$. In addition, larger variance occurred for three tests with the same conditions in the in the case of $\sigma_{max} = 345MPa$ than in the case of $\sigma_{max} = 379MPa$.

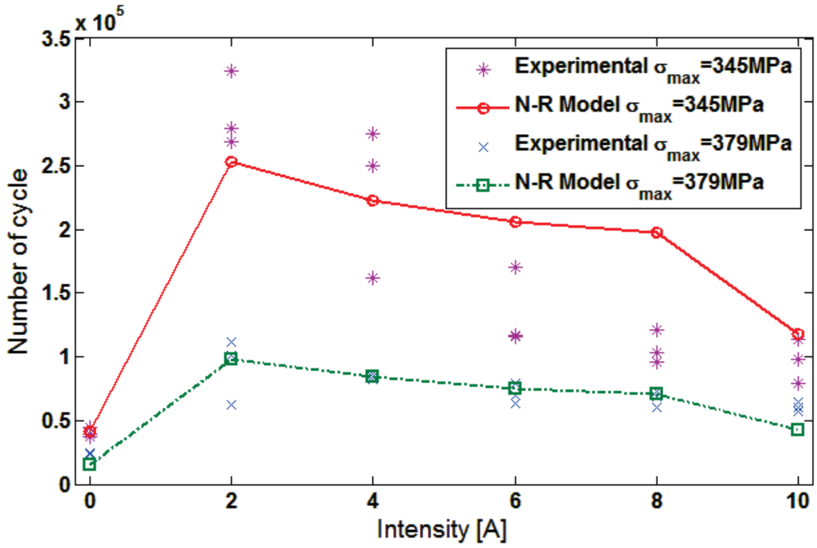

Figure 4 Relationship between number of cycle and intensity for two Maximum applied stresses

Discussion and Conclusions

The contributions of this study are as follows:

1. The N-R model proposed by De los Rios *et al*. and Curits *et al* was further studied with the help of experimental residual stress and roughness results.
2. The tendency of the theoretical calculated fatigue improvement effects under different peening intensity is consistent well with the experimental results.
3. Both calculated and experimental results show that well controlled shot peening condition such as 2A in this studied case can produce best fatigue life improvement.

The relaxation of the residual stress has been ignored in this developed N-R model. Further study considering this effect should be performed to obtain more reliable results. In addition, the N-R model developed in this paper is a basic study for another paper to establish a numerical OFDF system (Optimisation Fatigue life with DoE and FEM) [6].

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