On the potential application of a numerical optimization of fatigue life with DoE and FEM

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Abstract

Shot peening is a complicated and expensive process and many shot peening parameters have an influence on the improvement in fatigue performance. Design of Experiment (DoE) has become a very useful tool to optimize the process by considering the greatest amount of information. With the development of computer ability, the Finite Element Method (FEM) has been widely used to simulate this dynamic shot peening process. The Navarro-Rios model has been well developed for the prediction of the fatigue life after shot peening. Therefore, the objective of this work is to integrate these tools in order to establish a numerical OFDF system (Optimisation Fatigue life with DoE and FEM). With this system, it is possible to simulate the shot peening process, to predict the fatigue life of the shot peened component and to optimize the controlled shot peening process.

Keywords Shot peening, Almen intensity, fatigue life, DoE, N-R model, FEM

Introduction

Tufft [1] demonstrated the potential of shot peening to increase/reduce life by considering shot peening parameters (shot size, peening intensity, incidence angle and coverage) with a design of experiments (DoE) approach. Numerical simulation of the process was made possible with the development of the finite element method and the rapid development of computational power. Miao *et al.* [2] summarized existing FE models for the simulation of the shot peening process and developed a new 3D random FE shot peening model. Most of the shot peening parameters such as intensity, surface coverage and surface roughness and residual stress have been simulated. De los Rios *et al*. [3] and Curtis *et al* [4] developed a Navarro-Rios (N-R) model to predict the fatigue life of a peened component considering the residual stress and surface roughness after shot peening.

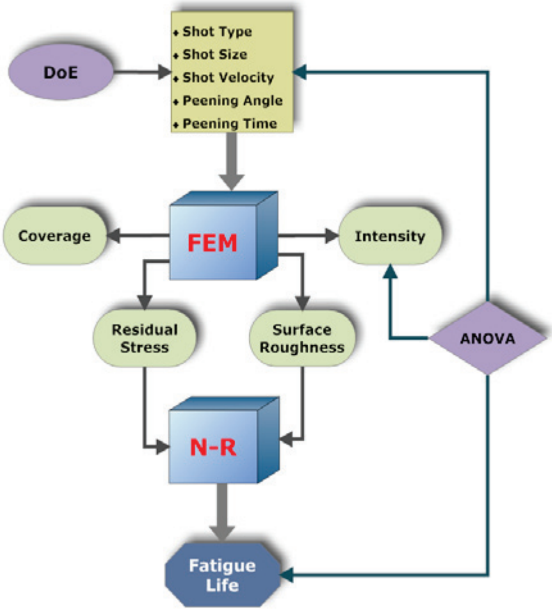

Figure 1 Schematic flow chart of the OFDF system

In this paper, a systematic optimization model combing DoE, FEM, N-R and ANOVA model will be introduced with a simple example. Figure 1 presents a schematic flow chart of the optimization of fatigue life based on Design of Experiment (DoE) and Finite Element Method (FEM). Five main parts of this system (DoE, FEM, N-R Model and ANOVA) have been combined in this system to optimize the fatigue life of the component after controlled shot peening.

Application of OFDF system

In this paper, an application of this OFDF system (Optimisation Fatigue life with DoE and FEM) has been performed to demonstrate the ability of this system. Two factors (Shot Size and Shot Velocity) with three levels have been considered to reduce the number of tests. Therefore, L_9 (3^2) tests were carried out to optimize the fatigue limit. An axisymmetric finite element model was developed to calculate the residual stress, roughness and intensity. With this axisymmetric FEM, the residual stress profile beneath one impact point is assumed to be uniformly distributed in the whole component. This assumption is acceptable for the study of intensity since it is in a state of saturation. However, for the prediction of the fatigue life, the residual stress and roughness depend on the peening time. In addition, the indentation profile obtained from one impact cannot represent the real surface roughness condition. Therefore, in order to simulate the real shot peening and predict the comparable fatigue life limit, a 3D random FEM introduced by Miao et al. [2] is necessary. Finally, ANOVA model is used to obtain quantitative relationship between the shot peing parameters and the fatigue life.

Table 1 lists Taguchi's L_9 (3^2) array for the arrangement of the shot peening parameters Ceramic shot with three shot diameters: 0.4mm, 0.7mm and 1mm as well as three shot velocities: 20 m/s, 60 m/s and 100 m/s have been defined.

Table 1 Taguchi's L_9 (3^2) Array

Run No.	1	2	3	4	5	6	7	8	9
Diameter $[mm]$	0.4	0.4	0.4	0.7	0.7	0.7	1.0	1.0	1.0
Velocity $[m/s]$	20	60	100	20	60	100	20	60	100

Axisymmetric finite element model method

The axisymmetric finite element model of Figure 2 was developed to simulate the shot peening results such as intensity, residual stress and roughness. Ls-Dyna explicit software was applied to simulate the impact between one rigid shot and the target component.

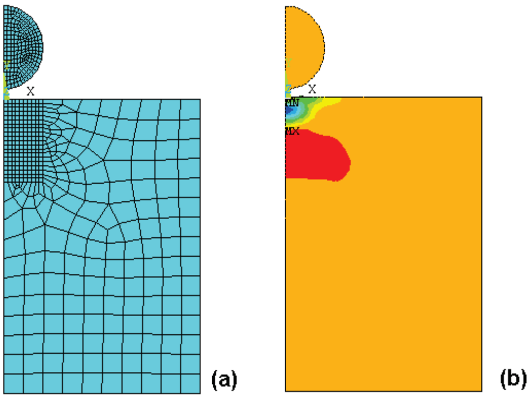

Figure 2 Finite element models: (a) Axisymmetric model; (b) SX residual stress contour.

Table 2 Material properties in FE models

	Young Modulus (GPa)	Poisson ratio	Density (Kg/m^3)	Yield stress (MPa)	Tangent Modulus (GPa)
Ceramic shot	300	0.27	3850	--	--
Almen strip (A)	201	0.33	7830	1120	1.6
AA 7050-T754	71	0.33	2830	460	15

Table 2 lists material properties used in the FE models for the simulation of the ceramic shots impacting Almen strips and aluminium components. Ceramic shot was assumed to be rigid in the FE model. SAE 1070 spring steel Almen strips (Type A thickness = 1.27 mm) have been used for the Almen intensity test. Material properties of Almen strip were taken from [5].

Nine numerical simulations with ceramic shots impacting Aluminum 7050-T7451 were performed to calculate residual stress profiles and surface indentations. Material properties of ceramic shot and aluminium components were listed in Table 2. Material properties of Aluminium 7050-T7451 were taken from [6]. The induced stress profile beneath the impact point and the indentation profile near one impact were considered as residual stress and roughness value in the following N-R model. More realistic simulation of the shot peening process should be performed with the 3D random model developed by Miao *et al.* [2] in order to obtain more reliable residual stress and surface roughness results.

Figure 3 illustrates three residual stress profiles beneath the impact point after the first three runs. It is noted that at certain shot diameter, with the increase of shot velocity, the depth of maximum residual stress and the depth where the residual stress change from compressive to tensile increase greatly. Figure 3(b) plots the three fitting residual stress profiles with Equation (2) [3]. Compared with the simulated curves in Figure 3(a), these curves describe well the compressive part of the residual stress. However, they ignore the tensile part of the residual stress. Further study on the fitting equation is suggested in order to best fit the real residual stress profile.

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

where σ_{res} is residual stress, x is the depth from surface, x_d is the depth of the maximum compressive residual stress, $A + B$ is the maximum compressive residual stress and w is the width of the compressive residual stress curve.

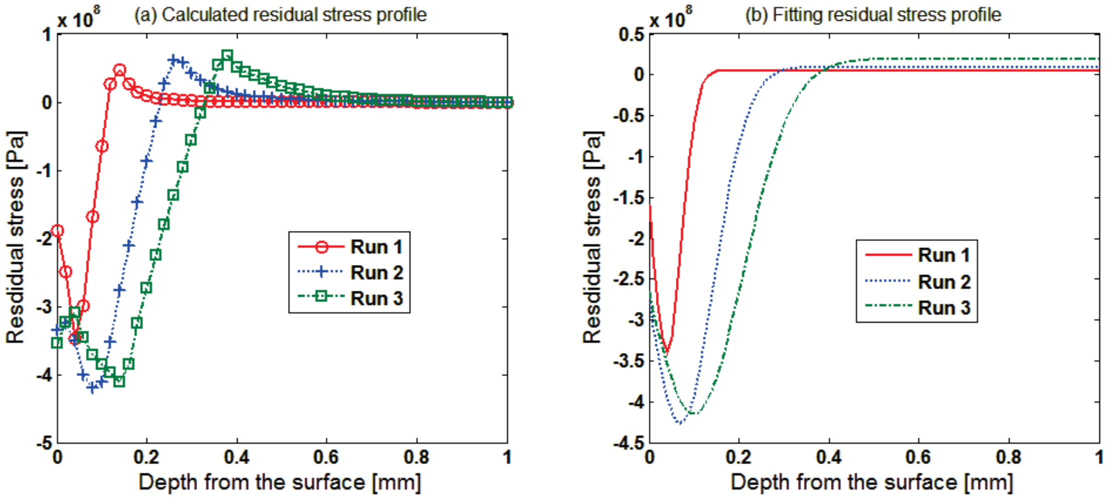

Figure 3 Calculated and Fitting curves of residual stress profiles for the first three runs.

Table 5 Intensities calculated from FEM for nine tests

Test No.	1	2	3	4	5	6	7	8	9
Depth R_t ($\times 10^{-6}m$)	3.15	10	16	6	18.65	28.7	7.3	24.5	40
Half width RS_m ($\times 10^{-6}m$)	66.7	117	150	117	200	250	150	233	300

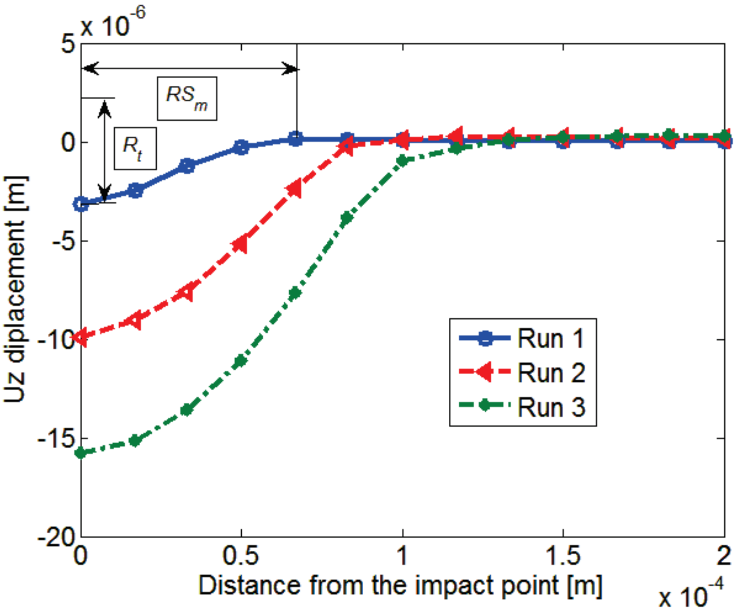

Figure 4 Plastic indentations for the first three runs.

Figure 4 shows the FE calculated plastic indentation profiles for the first three runs. From this figure, the depths R_t and half widths RS_m of the plastic indentation can obtained. Table 5 lists the depths R_t and half widths RS_m after nine runs respectively. These results can be used as surface roughness in the N-R model for the fatigue life calculation. It is worth noting that, the depth has been regarded as R_t and half width has been regarded as RS_m only as an example. These depth value and half width value cannot represent accurately the real roughness after shot peening. Further study with 3D random model is strongly suggested to simulate the real shot peening process to obtain this roughness information. From Table 5, it can be found that R_t and RS_m increase with the increase of diameter and velocity simultaneously.

Fatigue limit optimization with N-R model and ANOVA method

With the help of the residual stress profiles (Figure 3 shows example results for three runs) and roughness results (Table 5) at nine FEM simulations, it is possible to calculate the fatigue limit of the shot peened material using N-R model developed by De los Rios *et al*. [3] and Curtis *et al* [4]. A Matlab program of the N-R model using equations in [3] and [4] was developed to calculate the fatigue life of shot peened component. Same material parameters and component configuration listed in Miao et al. [7] were used in this N-R model. Properties of Aluminum 7050-T7451 were taken from studies of Michaud [6]. Different from the studies in [7], FE simulated residuals stress and roughness profiles replaced experimentally measured residual stress and roughness profiles in [7].

Figure 5 presents the relationship between crack length and the cycle of fatigue test using the N-R model. Table 6 lists the calculated fatigue limits for nine runs with an example of the input parameters. It can be found that runs 8 and 5 produce larger fatigue limits.

Table 6 Predicted fatigue life for nine runs

Run No.	1	2	3	4	5	6	7	8	9
Fatigue limit ($\times 10^5$ Cycle)	2.86	8.53	8.47	3.29	9.85	7.48	3.18	10.82	5.28

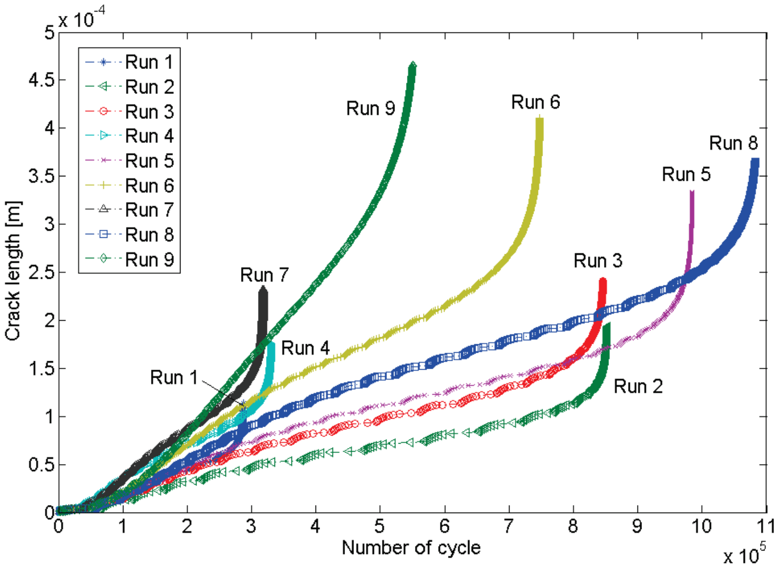

Figure 5 Relationship between crack length and number of cycle for nine runs

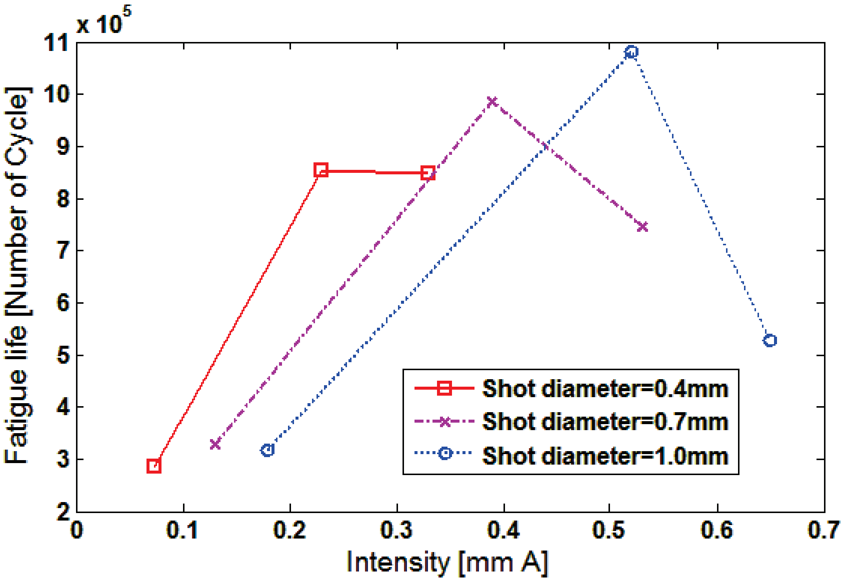

Figure 6 Relationship between intensity vs. fatigue limit

Figure 6 presents the relationship between intensity and fatigue limit from results in Table 1, 3 and 6. For each curve, three different intensities correspond to three velocities. It can be found that fatigue life increases with the increase of the intensity firstly, and then decreases with the further increase of the intensity. In addition, same intensity produced by different shot size and velocity can produce different fatigue life improvement.

Similar to Equation (1), a regression Equation (3) with a squared multiple correlation coefficient $\mathrm{R}^2 = 0.93728$ can be obtained with ANOVA model by Software STATISTICA.

$$Y_F = -819518 + 949176 \times X_D - 386756 \times X_D^2 + 44876 \times X_V - 290 \times X_V^2 - 7324 \times X_D \times X_V \quad (3)$$

Conclusions

A procedure of an OFDF (Optimization Fatigue strength with DoE and FEM) system has been developed and illustrated using a simple example. The simulated results presented in this paper show that it is possible to establish a numerical optimization system before the real expensive and time-costing shot peening and fatigue test. The simulated results show the potential application of this system. However, several further studies should be performed to improve this system and make it more practical. More shot peening parameters such as surface coverage, peening angle etc., which have influence on the shot peening results should be considered thoroughly with previously developed 3D random model. A more reliable equation should be selected to describe the residual stress profile considering the tensile part of the residual stress profile. The relaxation of the residual stress profile (closure stress) during the high cyclic fatigue test should be considered in the N-R model to make it more realistic. However, the difficulty with this is that much of the stress relaxation is actually due to fatigue crack growth. Further measurements of the residual stress after different number of cycles during fatigue test could be carried out for including this phenomenon into the N-R model.

References

[1] M.Tufft, *Shot peen impact on life, part 1: designed experiment using René 88DT*, Proceedings of the 7th International Conference on Shot Peening, (1999), pp. 244–253.

[2] H.Y. Miao, S. Larose, C. Perron and M. Lévesque, *On the potential applications of a 3D random finite element model for the simulation of shot peening*. Advances in Engineering Software, Vol. 40, (2009), pp.1023-1038.

[3] E. R. De los Rios, M. Trull and A. Levers, Modeling Fatigue Crack Growth in Shot-Peened Components of Al 2024-T351, Fatigue fracture and engineering material structure, Vol. 23 (2000), pp. 709-716.

[4] S. Curtis, E. R. de los Rios, C. A. Rodopoulos and A. Levers, Analysis of the Effect of Controlled Shot Peening on Fatigue Damage of High Strength Aluminum Alloys, International journal of fatigue, Vol. 25 (2003), pp. 59-66.

[5] M. Guagliano, Relating Almen intensity to residual stress induced by shot peening : a numerical approach, journal of materials processing technology, Vol. 110 (3001), pp. 277-286.

[6] S. Michaud April, *Influence du grenaillage sur la vie en fatigue d'un alliage d'aluminium,* Master thesis, (2007), École Polytechnique de Montréal.

[7] H.Y. Miao and M. Lévesque, Effect of shot peening on the fatigue life and crack propagation prediction with experiments and Navarro-Rios Model, 11th International conference of shot peening, (2011). South Bend, USA.