SIDE EFFECTS OF SHOT PEENING ON FATIGUE CRACK INITIATION LIFE

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Abstract The beneficial effects of shot peening on fatigue life of mechanical components are well known. However, there are some reports in the literature that indicate inappropriate shot peening parameters tend to reduce the fatigue life. It is therefore, the purpose of this study to find a logical quantitative justification for these observations. Using finite element method, a dynamic elastic-plastic simulation of shot peening was presented. Effect of shot velocity and size on surface morphology after shot peening were examined. Fatigue crack initiation life calculation of shot peened specimens revealed that beneficial effect of shot peening significantly vanishes in the case of high velocities and bigger shots.

Keywords Shot Peening, Finite Element Method, Surface Roughness, Stress Concentration, Fatigue Crack Initiation Life

چکیده اثرات مفید ساچمه زنی بر عمر خستگی قطعات مکانیکی به خوبی شناخته شده است. اما گزارشات علمی وجود دارند که حاکی از کاهش عمر خستگی در اثر استفاده ناصحیح پارامترهای ساچمه زنی می باشد. بنابر این، هدف از این مقاله یافتن روشی کمی و منطقی برای توضیح این مشاهدات است. با استفاده از روش اجزاء محدود، شبیه سازی الاستو-پلاستیک دینامیک ساچمه زنی ارائه می گردد. اثر سرعت و اندازه ساچمه بر مورفولوژی سطح بررسی می شود. محاسبه عمر ایجاد ترک خستگی قطعه ساچمه زنی شده این مطلب را فاش نمود که اثر مفید ساچمه زنی در حالت استفاده از ساچمه های درشت و سرعت پاشش بالا، به طرز قابل توجهی از بین می رود.

1. INTRODUCTION

Shot peening is a cold working process in which small spherical shots with velocities of 20-100 m/s are fired against a target surface. Modifications produced in superficial layers of target surface by shot peening are strain hardening, compressive residual stresses and surface roughness [1]. There are many experimental works in the literature that show using shot penning can lead to increase fatigue life [1-9]. It is believed this improvement is mainly due to introduction of compressive residual stresses in surface and subsurface of treated parts. When impingement of shots and target occurs, a plastic zone surrounded by an elastic zone is created at the contact region. After rebounding shots, recovery of elastic zone beside resistance of plastic zone to further deformation, produces a distribution of compressive residual stresses in superficial layers.

Analyses presented by Al-Hassani [10] and Al-Obaid [11-12] were the first attempts to quantify depth of plastic zone and distribution of residual stress in shot peening. However, their analyses were highly simplified and mainly aimed at understanding the mechanics of shot peening. After the experimental study conducted to show differences between residual stress induced by static indentation and dynamic impact [13], and progress in numerical methods and power of computers, Meguid was the first researcher who applied finite element method to conduct dynamic elastic-plastic analysis of the process, using single shot [14]. When the mechanism of creation of residual stress and effect of shot peening parameters such as initial velocity and shot size on plastic deformation and residual stress are well established [15-20], attentions have been focused on studying complexities of the process such as strain rate [21] and multiplicity effects [22-24].

Review of the most of the work done in this area reveals that predicting residual stress has been the most interested issue. However, as mentioned above, shot peening also changes the surface morphology. By increasing surface roughness and thus producing points of stress concentration, shot peening may have detrimental effect on fatigue life. This occurs especially where the shot peening parameters are not well chosen (large shots, high velocities and over peening) [3,4,7]. Benediti utilized two different sizes of shot for shot peening of the same target [3,4]. His X-Ray diffraction measurement showed that the bigger shot would be more beneficial in terms of residual stress distribution. Nonetheless, fatigue tests did not indicate any improvement in life of the component. In addition, experiments carried out by Fathallah [7] revealed a noticeable deduction of fatigue life in the case of sever coverage of 1000% against the standard coverage of 100%.

Using verified finite element method, this study aims to examine the effect of shot velocity and shot size on stress concentration produced by shot peening and find out how fatigue life is affected by these parameters. A quantitative justification of reported fall in fatigue life of peened parts has been presented.

2. FINITE ELEMENT MODEL

2.1. Model Description A three dimensional model was used to simulate impingement of a single shot to a target workpiece using a finite element analysis package. The explicit integration scheme was used in this research to solve governing equations by numerical methods. The major advantage of the explicit solution scheme is its computation efficiency, because iterative calculation is not used and the tangent stiffness matrix is not formed [17].

Dimensions of workpiece were selected according to what proposed in the literature to establish the effect of the boundary [14, 16]. For impingement of a shot with radius *R*, the dimensions of target were considered as follow: width W=7R, height H=4R and breadth B=5R. Only a quarter of the shot and target were needed in this model due to their double symmetry with respect to the X-Y and Y-Z planes. The model mesh is shown in Figure 1. Eight noded brick finite elements were used to discrete the target and the shot. In addition to the boundary constraints along the planes of symmetry, the bottom surface of the target was fixed in all degrees of freedom.

An elastic-plasic material relationship was used to represent AISI 4340 steel with kinamatic hardening. Since shot-peening process involves very high-localised strain rates during impingement and rebounding of the jet stream [21], the Cowper-Symonds material model was employed for simulation of rate sensitivity of the material [22]. Despite many pervious researches [14-18, 21, 23] in which shot has been considers as a rigid body, in this work linear elastic material properties was introduced for shot which could be closer to reality. Therefore, the material properties of shot were: ρ (density) = 7800 Kg/m^3, E (elasticity modulus) = 210 GPa, υ (Poisson's ratio) = 0.3. The AISI 4340 steel target plate, as used by Majzoobi, et al [22], had the following particulars: ρ = 7800 kg/m^3, E = 210 GPa, υ = 0.3, σ_y (yield stress) = 1500MPa, H (plasticity modulus) =

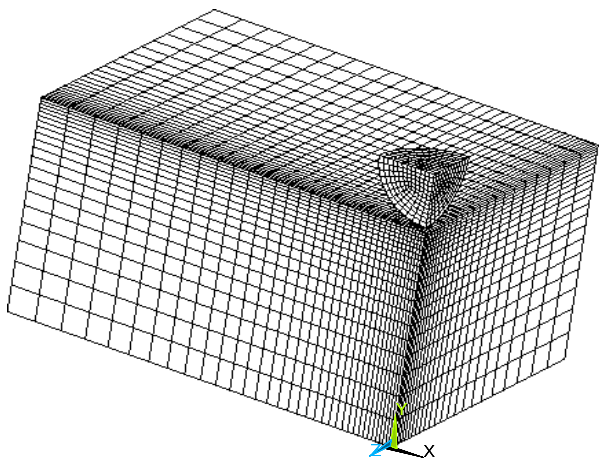

Figure 1. Finite element model.

1600MPa. Coefficients of Cowper-Symonds equation were also $c=2 \times 10^5$ and p=3.3.

To model the shot-target interface, contact nodes with friction coefficient of 0.1 were introduced on both top surface of the peened target and exterior curved surface of the shot. After exerting initial velocities on shot's nodes, model runs to allow impingement and rebounding occur. With performing trial runs, size and numbers of elements, especially in the region of contact were carefully determined to fulfill convergence criteria.

2.2. Verification of the Model For verification of the presented model, an experimental investigation carried out by Frija, et al [18], was simulated by the procedure described earlier. Shot diameter and velocity were 0.6 mm and 52 m/s, respectively. Residual stress in shot peened Ni-based super alloy Waspaloy was measured by X-ray diffraction method. Figure 2 shows the experimental results and those calculated from present study. There is a good agreement between the two sets of results, providing some validation for the accuracy of the present analysis.

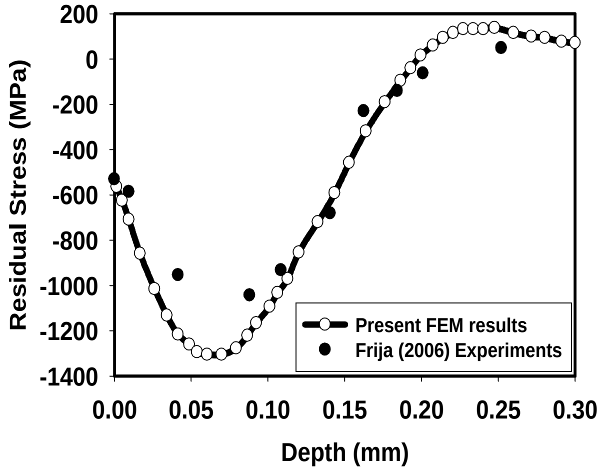

Figure 2. Verification of Finite Element Model.

3. RESULTS AND DISCUSSION

3.1. Effect of Shot Velocity Seven different impact velocities were used: 25, 50, 75, 100, 150, 200 and 300 mm/s. in all analysis shot radius was considered 0.5 mm. Since deformation of path defined by Z=0 and Y=4R, after rebounding the shot is representative of surface morphology after shot peening, special attention was focused on Y-direction displacements of nodes along this path. By extracting these nodal values and plotting them along the path, shape and dimension of dent formed after impingement will be seen. Variations of surface morphology with shot velocity are shown in Figure 3. The result revealed, with increasing impact velocities, deeper and bigger dents form.

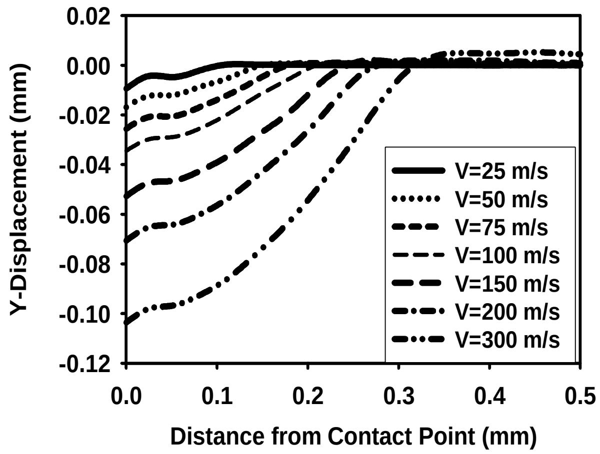

Figure 3. Effect of Shot velocity on dimple formed.

3.2. Effect of Shot Radius The influence of shot radius on the surface morphology of target workpiece was investigated next. This was done by fixing initial velocity at 100 m/s for four radiuses of shot: 0.25 mm, 0.5 mm, 1mm and 2 mm. Variations of surface morphology with shot radius are shown in Figure 4. This indicates, as expected, peening with a larger shot, keeping other parameters unchanged, results in deeper dents.

3.3. Effect of Shot Peening Parameters on Stress Concentration After presenting the surface roughness exerted by the shot peening, the nodal displacements were used to calculate peak to peak distance, D_p, and peak to valley height, R_t, of dents formed after shot peening. These values were used to estimate the stress concentration exerted by surface dimples according to the following expression proposed by [25]:

$$K_t = 1 + 4\left(\frac{R_t}{D_p}\right)^{1.3} \quad (1)$$

Variations of induced stress concentration with shot velocity and shot radius are shown in Figure 5 and Figure 6, respectively. Results show that increasing shot velocity and size increase stress concentration produced by shot peening. Growth of stress concentration is more pronounced in higher velocity and bigger shots.

3.4. Fatigue Crack Initiation Life Having in hand, the surface residual stress and local stress concentration one can easily calculate fatigue crack initiation life using the well-known SWT equation (Equation 2) and Neuber's rule (Equation 3) simultaneously. It has been assumed the equivalent strain would be the same as the first principal strain which is reasonable when a multi-axial state of stress presents in brittle materials [26].

$$\sigma_{\max}\frac{\Delta\varepsilon}{2}E = \left(\sigma_f'\right)^2\left(2N_f\right)^{2b} + \sigma_f'\varepsilon_f'E(2N_f)^{b+c} \quad (2)$$

$$\frac{\left(K_f\Delta S\right)^2}{E} = \Delta\sigma\Delta\varepsilon \quad (3)$$

Where S, σ, ε are nominal stress, local stress and strain respectively. E, Young modulus, σ'_f, fatigue strength coefficient, ε'_f, fatigue ductility coefficient, b, fatigue strength exponent, c, fatigue ductility exponent are material constants and K_f is the fatigue notch factor that can be expressed as following:

$$K_f = 1 + \left[\frac{K_t - 1}{1 + \frac{a}{r}}\right] \quad (4)$$

Where "a" is an empirically determined material constant, r is the notch root radius and K_t is the local stress concentration factor.

It has been assumed that various shot peened specimens are subjected to cyclic load of 800 MPa maximum stress and 0 stress ratio. The calculated crack initiation life is shown in Figure 7 for different shot velocities and in Figure 8 for

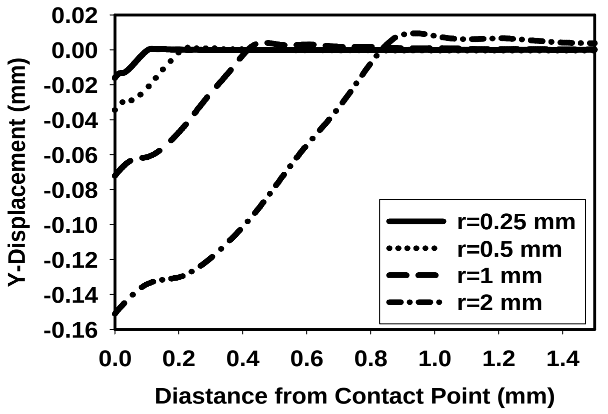

Figure 4. Effect of shot radius on dimple formed.

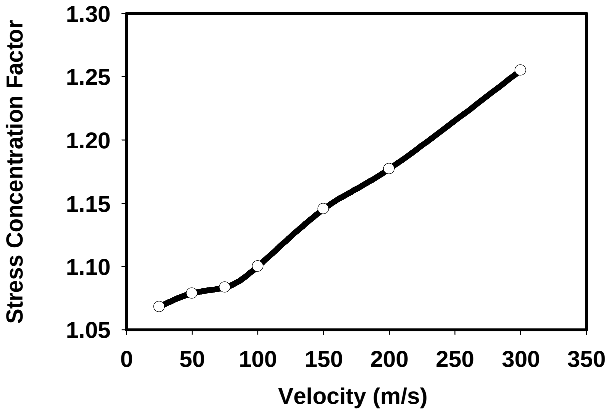

Figure 5. Effect of shot velocity on stress concentration induced by shot peening.

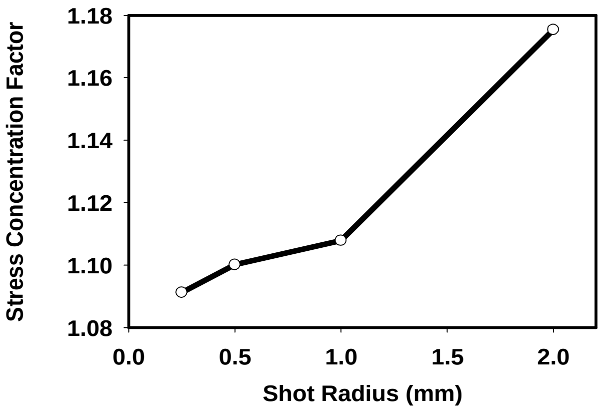

Figure 6. Effect of shot radius on stress concentration induced by shot peening.

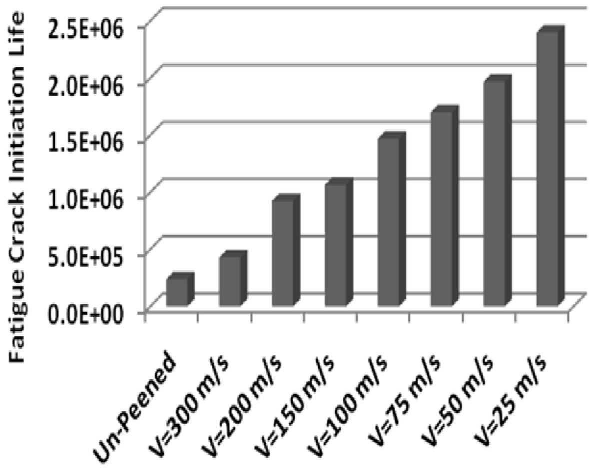

Figure 7. Effect of Shot Velocity on Fatigue Crack Initiation Life.

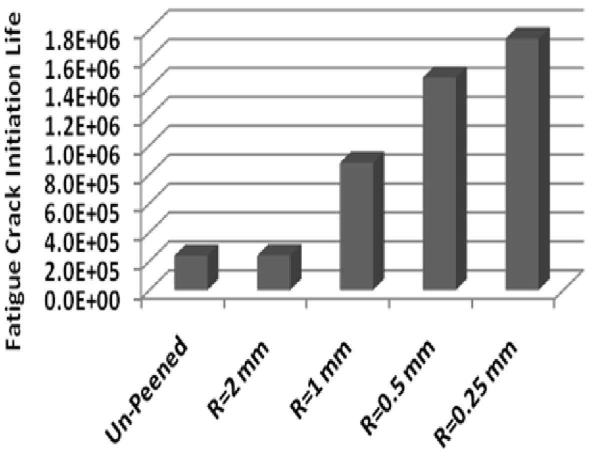

Figure 8. Effect of Shot Radius on Fatigue Crack Initiation Life.

different shot radiuses. It can be concluded from these results that conducting shot peening process with larger velocities and bigger shots occasion a significant reduction in fatigue crack initiation life. All beneficial effects of shot peening have disappeared in the case of 2 mm shots. It is because of bigger dents and high stress concentration that was formed by that size. Although bigger shots and larger velocities cause deeper compressed layers and some percentage of this reduction would recover in the propagation phase of life, as far as crack initiation life is the main concern, which is the case in this study, larger velocities and bigger shots have detrimental effects on fatigue life.

4. CONCLUDING REMARKS

Finite element analysis was conducted to simulate shot peening process. Special attention has been focused on surface roughness producing after shot peening. Variations of surface morphology and induced stress concentration with shot velocity and shot size indicated using high velocities and big shots generate detrimental surface roughness that deteriorate beneficial effects of shot peening. These detrimental effects would be very noticeable in the crack initiation phase and must be seriously considered when crack initiation is the main design criterion. Calculated fatigue crack initiation life indicated using big shots could completely offset expected fatigue life improvement of shot peening. High velocities could also terminate about 80% improvement of smaller shot velocities.

5. REFERENCES

1. Farrahi, G. H., Lebrun, J.L. and Couratin, D., "Effect of shot peening on residual stress and fatigue life of spring steel", ***Fatigue and Fracture of Engineering Materials and Structures***, Vol. 18, No. 2, (1995), 211-220.
2. Farrahi, G. H. and Ghadbeigi, H., "An investigation into the effect of various surface treatments on fatigue life of a tool steel", ***Journal of Materials Processing Technology***, Vol. 174, No. 1-3, (2006), 318-324.
3. Benedetti, M., Bortolamedi, T., Fontanari, V. and Frendo, F., "Bending fatigue behaviour of differently shot peened Al 6082 T5 alloy", ***International Journal of Fatigue***, Vol. 26, No. 8, (2004), 889-897.
4. Benedetti, M., Fontanari, V., Scardi, P., Ricardo, C.L.A. and Bandini, M., "Reverse bending fatigue of shot peened 7075-T651 aluminium alloy: The role of residual stress relaxation", ***International Journal of Fatigue***, Vol. 31, No. 8-9, (2009), 1225-1236.
5. Hatamleh, O., Lyons, J. and Forman, R., "Laser and shot peening effects on fatigue crack growth in friction stir welded 7075-T7351 aluminum alloy joints", ***International Journal of Fatigue***, Vol. 29, No. 3, (2007), 421-434.
6. Hatamleh, O. and DeWald, A., "An investigation of the peening effects on the residual stresses in friction stir welded 2195 and 7075 aluminum alloy joints", ***Journal***

of Materials Processing Technology, Vol. 209, No. 10, (2009), 4822-4829.

7. Fathallah, R., Laamouri, A., Sidhom, H. and Braham, C., "High cycle fatigue behavior prediction of shot-peened parts", ***International Journal of Fatigue***, Vol. 26, No. 10, (2004), 1053-1067.
8. Sidhom, N., Laamouri, A., Fathallah, R., Braham, C. and Lieurade, H. P., "Fatigue strength improvement of 5083 H11 Al-alloy T-welded joints by shot peening: experimental characterization and predictive approach", ***International Journal of Fatigue***, Vol. 27, No. 7, (2005), 729-745.
9. Wang, S., Li, Y., Yao, M. and Wang, R., "Fatigue limits of shot-peened metals" ***Journal of Materials Processing Technology***, Vol. 73, No. 1-3, (1998), 57-63.
10. Al-Hassani, S.T.S., "Mechanical aspect of residual stress development in shot peening", ***1st International Conference on Shot-Peening***, Paris, France, (Sept 1981), 583_602.
11. Al-Obaid, Y.F., "A rudimentary analysis of improving fatigue life of metals by shot-peening", ***Journal of Applied Mechanics***, Vol. 57, (1990), 307_312.
12. Al-Obaid, Y.F., "Shot peening mechanics: experimental and theoretical analysis", ***Mechanics of Materials***, Vol. 19, (1995), 251-260.
13. Kobayashi, M., Matsui, T. and Murakami, Y., "Mechanism of creation of compressive residual stress by shot peening", ***International Journal of Fatigue***, Vol. 20, No. 5, (1998), 351-357.
14. Meguid, S.A., Shagal, G. and Stranart, J.C., "Finite element modeling of shot-peening residual stresses", ***Journal of Materials Processing Technology***, Vol. 92-93, (1999), 401-404.
15. Meo, M. and Vignjevic, R., "Finite element analysis of residual stress induced by shot peening process", ***Advances in Engineering Software***, Vol. 34, No. 9, (2003), 569-575.
16. Meguid, S.A., Shagal, G., Stranart, J.C., and Daly, J., "Three-dimensional dynamic finite element analysis of shot-peening induced residual stresses", ***Finite Elements in Analysis and Design***, Vol. 31, No. 3, (1999), 179-191.
17. Guagliano, M., "Relating Almen intensity to residual stresses induced by shot peening: a numerical approach", ***Journal of Materials Processing Technology***, Vol. 110, No. 3, (2001), 277-286.
18. Frija, M., Hassine, T., Fathallah, R., Bouraoui, C. and Dogui, A., "Finite element modelling of shot peening process: Prediction of the compressive residual stresses, the plastic deformations and the surface integrity", ***Materials Science and Engineering: A***, Vol. 426, No. 1-2, (2006), 173-180.
19. Hong, T., Ooi, J.Y. and Shaw, B., "A numerical simulation to relate the shot peening parameters to the induced residual stresses", ***Engineering Failure Analysis***, Vol. 15, No. 8, (2008), 1097-1110.
20. Hong, T., Ooi, J.Y. and Shaw, B.A., "A numerical study of the residual stress pattern from single shot impacting on a metallic component", ***Advances in Engineering Software***, Vol. 39, No. 9, (2008), 743-756.
21. Meguid, S.A., Shagal, G. and Stranart, J.C., "3D FE analysis of peening of strain-rate sensitive materials using multiple impingement model", ***International Journal of Impact Engineering***, Vol. 27, No. 2, (2002), 119-134.
22. Majzoobi, G.H., Azizi, R. and Alavi Nia, A., "A three-dimensional simulation of shot peening process using multiple shot impacts", ***Journal of Materials Processing Technology***, Vol. 164-165, (2005), 1226-1234.
23. Meguid, S.A., Shagal, G. and Stranart, J.C., "Development and validation of novel FE models for 3D analysis of peening of strain-rate sensitive materials", ***Journal of Engineering Materials and Technology***, Vol. 129, (2007), 271_283.
24. Kim, T., Lee, J.H., Lee, H. and Cheong, S.K., "An area-average approach to peening residual stress under multi-impacts using a 3D symmetry-cell FE model with plastic shots", ***Materials and Design***, Vol. 31, (2010), 50-59.
25. Li, J.K., Mei, Y., Duo, W. and Renzhi, W., "An analysis of stress concentrations caused by shot peening and its application in predicting fatigue strength", ***Fatigue Fract Engng Mater Struct***, Vol. 15, No. 12, (1992), 1271-1279.
26. Stephens, R.I., Fatemi, A., Stephens, R.R. and Fuchs, H.O., "Metal Fatigue in Engineering", 2nd ed., Wiley-interscience, (Chapter 10), (2000).