The Optimization of Shot Peening Parameters in AISI403 Stainless Steel

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Abstract

Fatigue is a well-known failure problem for low-pressure end turbine blades, especially at the stress-concentration locations such as fir tree roots or dovetails. Shot peing is one of the most economical and effective approaches to enhance fatigue life by means of eliminating the oxidation layer and imposing a residual compressive stress layer on the surface. In this work, we present a systematic study on the correlation between the peening parameters with the surface morphology and residual stress. The typical blade material, AISI403 matensitic stainless steel, was employed for shot peing. The dominant parameters of peening pressure and coverage were varied with fixed peening distance, peening angles, shot grits, etc. The peening effects were evaluated by compressive residual stress and surface roughness. The optimized parameters were further analyzed by microhardness distribution underneath treated surface.

Keywords: shot peening; surface roughness; residual stress; air pressure

Introduction

The steam turbine blades play a critical role in safety concerns in both coal-fired and nuclear power plants. The fracture of blades often caused unplanned shutdown of power plants and consequently economy loss of billions. The blades are subjected to high centrifugal loading during long-term service. Thus combined with a wet steam environment, the blades are prone to failures such as high-cycle fatigue, stress corrosion cracking or corrosion fatigue, especially at stress-concentration sites like fir tree roots or dovetails [1, 2]. Shot peening has long been used as an effective means to relax stress concentration and produce a surface layer with compressive residual stress at such vulnerable locations. By shot peening the life of mechanic components like blades or gears can be extended 70-100% [3]. However, there are too many peening parameters such as air pressure, nozzle-workpiece distance, shot size, processing time, etc [4]. Unexpected surface microcracks may be even produced if these parameters are not well controlled [5]. Unfortunately peening parameters are often empirically designed. One typical example is that the peening effectiveness is conventionally examined in terms of peening intensity by Almen strip tests [6]. Peening intensity has no physical background or direct relation with the residual stress. Different parameters may produce similar Almen strip arc height while the residual stress is quite different in the workpiece. Therefore the effects by shot peening should be evaluated by more reliable methods. Besides compressive residual stress, which improves fatigue resistance, an adverse effect is the rougher surface after shot peening. Higher roughness means a higher probability for crack initiation. Normally both two factors will increase simultaneously. Thus the optimization of peening parameters is to obtain a good combination of the trade-off of the two factors.

In this study, we evaluated the residual stress together with surface roughness to approach an optimized combination of peening parameters. The dominant parameters in shot peening are the shot velocity and treat time. The former one is mainly controlled by peening pressure and the latter is manifested in terms of coverage. We varied peening air pressure and coverage with other fixed parameters like nozzle distance, shot size, peening angle etc.

Experimental

The used material was an AISI 403 martensitic stainless steel, which was a typical blade steel. The nominal chemical composition was 0.14C-0.31Mn-12.1Cr-0.50Si and balance of Fe, in wt%.

The steel was homogenization treated at 1050 °C for 1 h and then annealed at 700 °C. The hardness in the as-treated state was 2.4±0.2 GPa. The size of the peening samples was 40×40 mm^2 and thickness of 5 mm.

The shot peening was performed using an air pressure driven machine. The pressurized air was connected with an Atlas Copco air compressor. The shot peening intensity was tested by El Almen type-A strips and measured by El TSP-3 Almen gage. The diameter of the peening nozzle was 8 mm. The distance between nozzle and the workpiece was set as 220 mm. The peening grit was steel cut wire shot with diameter of 687±21 □m.

The surface roughness of peening samples was then characterized by Bruker NP-Flex white-light interferometry (WLI). The residual stress was measured by X-ray diffraction analysis using PANalytical X'Pert Pro system. The residual stress measurement is based on the well-know Bragg law and materials' elastic stress-strain relationship. Concisely it is calculated as, $\sigma = \frac{m}{d_0}(\frac{E}{1+\upsilon})$, where d_0 is the lattice spacing, *E* the elastic modulus, v the Poisson ratio, and *m* is a slope value of the lattice spacing varying with the diffraction angles.

Furthermore, a microhardness indent pattern was made from the cross-sectional view in the shot peened samples (Wilson Worlpert 402 MVD hardness tester) with load of 0.49 N. By measuring the hardness and corresponding distance from the treated surface, the relationship of hardness against the depth was plotted.

The experiment was designed as two steps. First, at the coverage of 100%, three samples were peened at low, medium and high air pressures of 0.26 MPa, 0.40 MPa and 0.50 MPa, named as P026, P040 and P050, respectively. The peening pressure was selected based upon published paper on peening of the turbine blade []. Evaluated by surface roughness and residual stress, an optimized pressure was determined. Second, using the optimized air pressure, another two samples were peened under the coverage of 200% and 300%, named C200 and C300, respectively.

Results and discussion

Fig. 1a-c shows the three-dimensional images by WLI of P026, P040 and P050 samples. The surface roughness increases as the peening pressures increasing from 0.26 to 0.50 MPa. This can be evidently illustrated by cross-sectional outlines in Fig. 1d. By quantitative analysis from Figs. 1a-c, the surface roughness of the P026, P040 and P050 is 0.96±0.07 μm, 1.45±0.15 μm and 2.32±0.25 μm, respectively. These roughness values are however acceptable as compared to normal roughness value of 6 μm after normal machining. The measured residual stress of the three samples is summarized in Table 1. The compressive residual stress of P040 is 448 MPa, highest among the three samples. The residual stress of P050 is a bit smaller than that of P040. This can be probably attributed to the surface relief in the state of high peening pressure. It can thus be concluded that the peening pressure of 0.40 MPa produces a better combination of surface roughness and compressive residual stress.

Table 1 also shows that the peening intensity is very small at all the three peening pressures with coverage of 100%. This indicates that it has barely reached the saturation intensity under the three circumstances. Increasing the peening time can result in saturated intensity. The peening time is quantitatively determined by peening passes. Fig. 2 shows the saturation curve of the peening intensity under pressure of 0.40 MPa, with other parameters fixed. The intensity after 4 passes and 8 passes is 0.208 mm and 0.210 mm, respectively. The narrow difference gap indicates that the intensity is saturated after 4 passes, with a value of 0.21 mm.

Two samples with coverage of 200% and 300% under the peening pressure of 0.40 MPa were prepared. The measured peening intensities are 0.22 mm and 0.28 mm, respectively. Figs. 3a-b show the surface morphology by WLI. Fig.3c shows the comparison of the cross-sectional outlines. These figures indicate that the roughness of the two is quite close. Quantitative analysis from WLI images shows that the R_a values of the two are 3.27±0.61 mm and 3.83±0.34 mm, respectively. On the other hand, the residual compressive stress of C200 sample is 591±74 MPa, about 30% higher than that of C300 sample (455±80 MPa). The roughness and residual stress are compared in fig.3d.

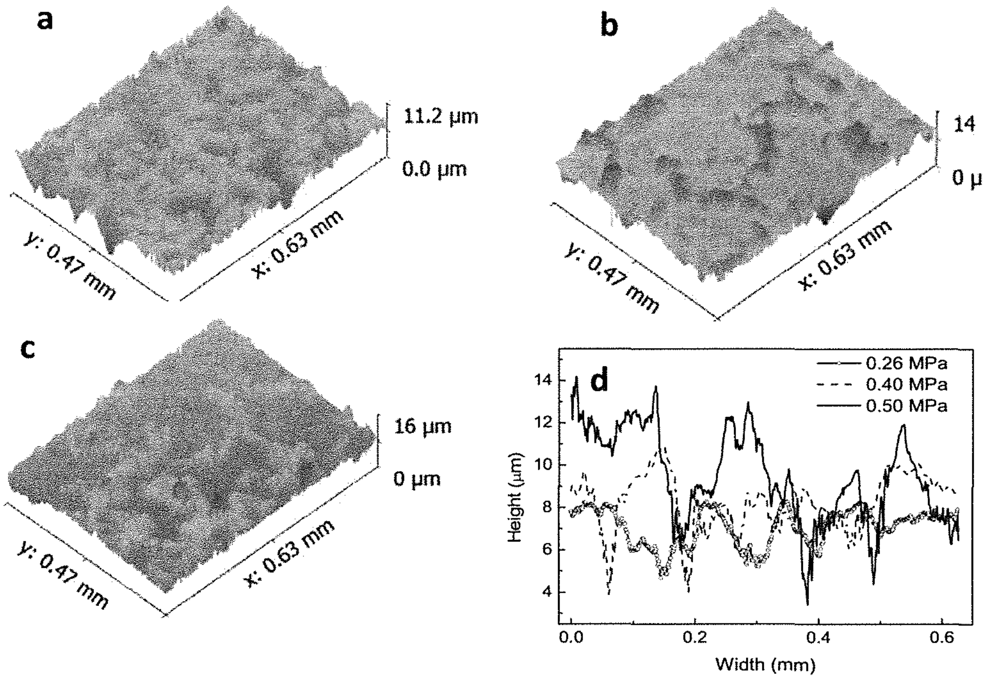

Fig. 1 The three-dimensional imaging by WLI under the air pressure of (a) 0.26 MPa, (b) 0.40 MPa and (c) 0.50 MPa; (d) the comparison of the cross-sectional outlines of the three samples

Table 1 The surface roughness and residual stress varying with peening pressure.

Peening pressure (MPa)	Peening intensity (mm)	Surface roughness (µm)	Residual stress (MPa)
0.26	0.110	0.96±0.07	-316.4 ± 61.9
0.40	0.136	1.45±0.15	-448.0 ± 34.8
0.50	0.158	2.32±0.25	-422.0 ± 38.7

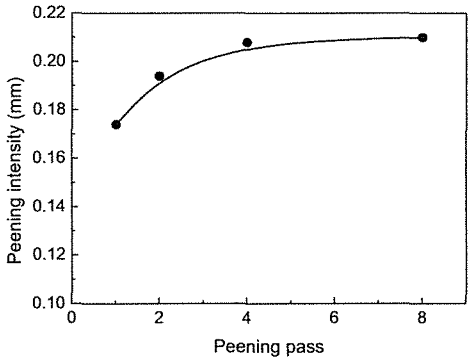

Fig. 2 The saturation curve of peening intensity under pressure 0.40 MPa

The decrease in residual stress of the C300 sample can be understood by the difference of elastic and plastic deformation during shot peeing. Besides heat release, the shock energy is absorbed by elastic as well as plastic deformation. At the early stage of shot peening, both stored energy in the material increases with processing time. At a critical time the elastic energy is saturated while further plastic deformation contributes more to work hardening, which results in a higher hardness in the surface than in the substrate. Fig. 4 compares the hardness distribution of the two samples along distance away from the peened surface. The average hardness in the top 50 μm depth of the 200% and 300% coverage samples are 3.3±0.3 GPa and 3.7±0.2 GPa, respectively. It can be also seen that the plastic deformation affected depth in the two samples are very similar, about 300 μm. The longer peening time in the 300% sample results in a higher surface hardness. This higher hardness is originated from contribution of work-hardening by plastic deformation during shot peening. With excessive plastic deformation, the elastic stress may be relaxed, resulting in a lower compressive residual stress. Here it concludes that the combination of 0.40 MPa with 200% coverage produces an optimized peening result in terms of surface roughness and residual compressive stress for the present AISI 403 martensitic steel.

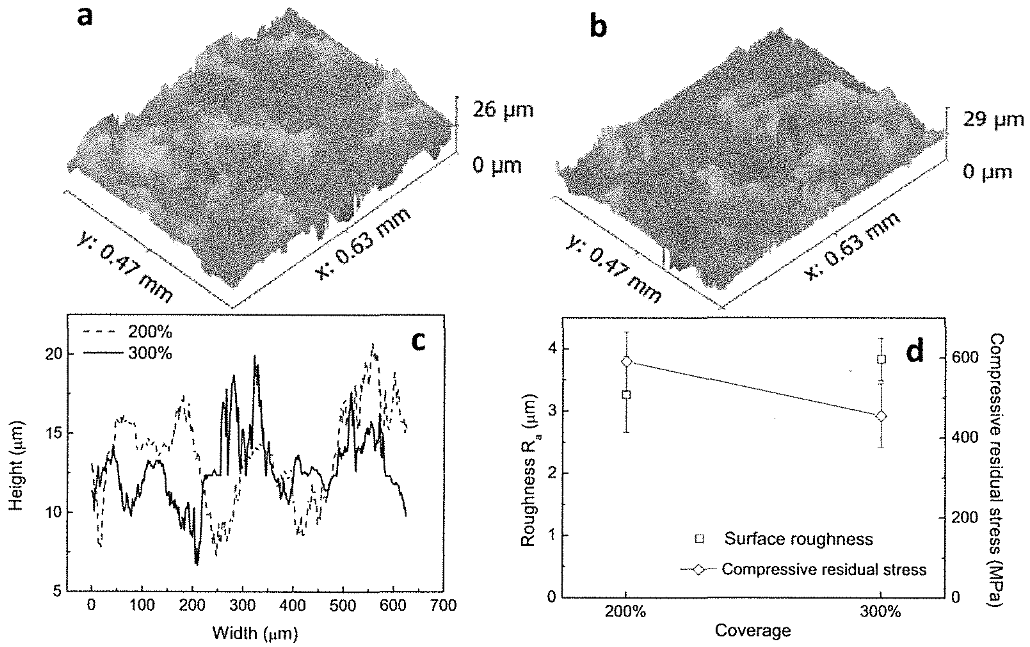

Fig. 3 surface roughness of peened surface at pressure of 0.40 MPa with coverage of (a) 200% and (b) 300%; (c) the comparison of cross-sectional outlines from (a) and (b); and (d) comparison of roughness and compressive residual stress at the two coverage.

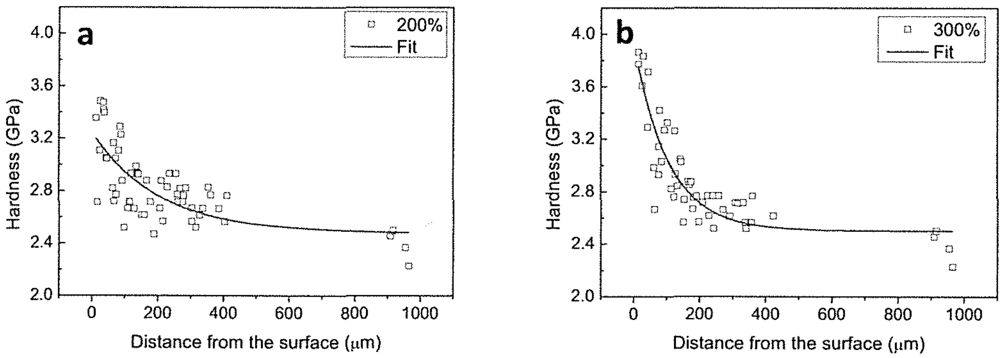

Fig. 4 The hardness distribution away from the peened surface with (a) 200% and (b) 300% coverage.

Conclusions

With varied the predominant shot peening parameters, we studied the effects of peening pressure and coverage on compressive residual stress and surface roughness. The roughness increases with peening pressure and time. The compressive residual stress is highest in this study at peening pressure of 0.40 MPa and coverage of 200%. The stress relaxation by excessive plastic deformation results in a decreasing residual stress at peening pressure of 0.50 MPa or 300% coverage. The combination of 0.40 MPa peening pressure and 200% coverage approaches an optimized peening condition for AISI 403 martensitic steel.

References

[1] M. James, M. Newby, D. Hattingh, A. Steuwer. *Shot-peening of steam turbine blades: Residual stresses and their modification by fatigue cycling.* Procedia Engineering, 2010, Vol. 2(1), pp. 441-451.
[2] C. Verpoort, C. Gerdes. *Influence of shot peening on material properties and the controlled shot peening of turbine blades.* Metal Behaviour & Surface Engineering, Curioni, S. et al.(eds), IITT International, 1989, Vol., pp. 97-155.
[3] M.A.S. Torres, H.J.C. Voorwald. *An evaluation of shot peening, residual stress and stress relaxation on the fatigue life of AISI 4340 steel.* International Journal of Fatigue, 2002, Vol. 24(8), pp. 877-886.
[4] T. Seno, H. Horiuchi, T. Naito. *Effect of various peening parameters on compressive residual stress for carburized steel.* ICSP-3 Proceedings, pp. 505-512.
[5] S. Bagherifard, I. Fernandez-Pariente, R. Ghelichi, M. Guagliano. *Effect of severe shot peening on microstructure and fatigue strength of cast iron.* International Journal of Fatigue, Vol. 65, pp. 64-70.
[6] H.Y. Miao, S. Larose, C. Perron, M. Lévesque. *An analytical approach to relate shot peening parameters to Almen intensity.* Surface and Coatings Technology, 2010, Vol. 205(7), pp. 2055-2066.