ATLANTIS PRESS
Advances in Intelligent Systems Research, volume 154
6th International Conference on Measurement, Instrumentation and Automation (ICMIA 2017)

Numerical Optimisation of Shot Peening Process on a Steam Turbine Blade

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Keywords: Shot peening, Turbine blade, Numerical optimisation.

Abstract. This article provides a broad and extensive literature survey on optimisation of shot peening process that have been developed and applied in the past decades and summarises the knowledge that has been gained and then points out the shortages of the important investigations in optimisation of shot peening process. On this basis, optimisation function is formulated and genetic algorithm is chosen to conduct the optimisation. This optimisation screens out the influential parameters and provides the weights of different parameters in terms of their influence of shot peening outputs.

Introduction

Shot peening is an established cold working process and a surface finish treatment widely used to improve the fatigue life of metallic components [1, 2] in aero industry [3], power generation, automotive and biomedical [4] since it produces compressive residual stresses in top layer of the peened surface to delay initiation of fatigue failure and retard its propagation [4]. It is a process that one solid sphere impacts another solid surface [5]. Apart from the compression, shot peening also induces surface roughness and causes cold work to the peened component [4] both of which are detrimental to the fatigue life of components. All the three products are influenced by several continuous and discrete parameters [6, 7] which have a deterministic influence on the effectiveness of this shot peening [7]. Among some of these parameters, interactions exist between each other [8]. Most importantly the benefit, namely the potential to increase components' fatigue life, depends on a reasonable selection of those influential parameters [2].

In order to control the surface roughness and cold work under an acceptable level and take good advantage of the compression hereof, many researches tried to optimise shot peening process during the past decades. DOE was the most frequently used method. An early important investigation done by Baragetti [5] used Taguchi method to analyse the numerical simulation results of shot peening result in an optimisation of seven parameters. Later, Evans [9] derived mathematical expressions for the indentation of surfaces and proposed a procedure for optimisation. Rodopoulos, et al. [10] used the effects neutralisation model, besides design of experiment, to optimise the parameters of shot peening and efforts were made to define the optimum levels and tolerances. One important initiative is the stress relaxation which was used to examine the stability of compressive residual stresses. However, there was also only two levels for each parameter. George, et al. [11] used the Taguchi method to optimise process parameters of shot peening with two levels of each design variable from the selected four parameters and analysed interactions between parameters. Besides DOE, many other methods were used to optimisation of shot peening processes. Baragetti, et al. [12] proposed a numerical procedure (a software) which could predict shot peening effects through a non-dimensional function with which shot peening parameter levels could be chosen for a particular application. Petit-Renaud, et al. [13] established an empirical relationship between parameters of a typical shot

peening process and measures of residual stress, and based on this relationship they optimized the parameters with a single objective optimisation function. Miao, et al. [14] explored the relationship between parameters and residual stresses and surface roughness, and independently considered the surface integrity as the optimisation objective to optimise a shot peening process. Later, using the design and analysis of computer experiments method, Maximisation of residual compressive stress, minimisation of surface roughness and cold work were set as objectives of optimisation function by Bhuvaraghan, et al. [15]. They firstly considered friction between the shot and its corresponding surface and resulted in determination of the optimum area under compressive residual stress curve while keeping the cold work and roughness below the specification limits.

The shortages of these investigations include four points: (a) symmetric boundary conditions used which lead to non-balanced in-depth residual stress states according to Klemenz, et al. [16] and Klemenz, et al. [17], (b) rigid shot may increase the amplitude of compressive residual stresses, (c) the optimisation objective is only the compressive residual stresses and (d) most importantly the only two or three levels setting for each parameter might lead to losing fidelity of results. Additionally, all the investigations are not in consistent in terms of the parameter settings, which brings difficulties to comparisons and further academic uses for subsequent investigations. Either, none of those researchers has yet optimised this surface treatment systematically.

Formulation of optimisation

Objectives of Optimisation and Its Solution Methods. For the three effects of shot peening on the target material, residual stresses on the top layer is beneficial to improve the fatigue resistance of the material, hence it should be maximised. While, the material hardening may lead to stress relaxation of compressive residual stress on one hand [15]; and on the other hand surface roughness, more exactly the height of the cavities caused by impacts has a potential to weaken the benefits of compressive residual stresses and cause corrosive cracks [18]. Further, the material hardening could be calculate by the measurement of the material plastic strain at the yield point of the material and the cold work could be calculate by the measurement of the plastic strain of the peened surface [19]. Therefore, the applicable objectives of the model should be: (1) maximisation of the compressive residual stresses, (2) minimisation of material hardening and (3) minimisation of surface roughness.

Constraints of influential Parameter. For optimisation purpose, only those influential and also controllable parameters are taken into consideration in literature are summarised as following. Those parameters includes the initial velocity, diameter of the shot, incidence angle, moment of shot, exposure time, material of shot and plate and coverage. Each parameters hereof has its own variation range which is discussed as following. First, initial velocity could be set from 20m/s to 100m/s according to literature Frija, et al. [20] while Marsh [21] set it as 40m/s to 120 m/s. Although Soady [22] contended that it ranges from 40m/s to 70m/s, the range from 20m/s to 120m/s could be safe to cover the whole range from the industrial situation completely rather than partially in case. Second, the size/diameter of shots should be discrete values between 0.0450mm to 4.75mm [23] and the values are set in SAE J444 [23]. Note that most researchers such as Xie, et al. [24] set the values according to this range while 38mm was used for 3D by Klemenza, et al. [25]. Third, values of incidence angle could be set at a range of 45º to 90º [26] with respect to the target surface for it is energy-saving and also consistent with reality operation. Fourth, the time of shot peening could be set as pre-stressed or not, since pre-stressing techniques could increase the maximum compressive residual stress [28]. Fifth, the exposure time could be set as the peening times of the surface since the longer the exposure time, the more is the probabilistic peening times of the surface. Sixth, the material of shots could be set as the common materials are ceramic, steel and glass according to Champaigne [29] and Frija, et al. [20]. Last, the target material should be set according to which kind of components since different components have different common materials.

Optimisation of Shot Peening Process

Optimisation algorithm for the multiple-objective function. NSGAII is a non-dominated Sorting Genetic Algorithm and well-suited for highly non-linear design spaces and for discontinuous design spaces [30]. Based on the specific multiple optimization problem, the algorithm NSGA II was set as follows in Table 1 following the rules [31]. The population size controls the number of solutions generated at each iteration (generation) and its initial population is generated randomly or assigned from an external source. The number of generations controls the number of iterations that the algorithm will execute before termination and it was set as 100. Crossover Probability controls the probability with which parent solutions are recombined to generate the offspring solutions and its range is between 0.5 and 1.0. It was assigned a value as 0.9. Crossover distribution index is inversely proportional to the amount of perturbation in the design variables. Typically, the value of 10.0 was set as 20 to balance the premature and perturbation. Mutation distribution index is similar to crossover distribution index and was set as 100.

Table 1. Settings of the optimisation algorithm

Option	Value
Population size	12
Maximum generation No.	100
Crossover probability	0.9
Crossover distribution index	20
Mutation distribution index	100

Scaling factors and weights setting. Scaling factors and weights affect the optimum results are critical to multiple-objective optimisation problems. In this optimisation, the optimisation function is also modified by the scaling factors and weights so as to get desired optimum combination of parameters. This modification is implemented through the following function,

$$\text{minimise} \sum_{i=1}^{3} \frac{w_i}{SF_i} f_i(\text{P}) \tag{1}$$

where $f_i(P)$ is the $i-th$ sub-objective of the optimisation function, w_i and SF_i are the corresponding weights and Scaling factors respectively. In order to obtain proper optimisation results, it would be better to set the value of w_i / SF_i in the range at 0.1 to 10 [32]. Considering the range of the responses, namely the cold work, residual stress and the plastic strain, varies from one to another, the weights and scaling factors for these responses are set as following Table 2.

Table 2: The scale factors and weights for each response

Responses	Scaling factor (SF)	Weight (w)
Cold work	100	1
Residual stress	1000	1
Plastic strain	0.001	1

Robustness analysis. The robustness of the optimisation was analysed and its robustness is shown in Six Sigma graphs, Figure 1 (a), (b) and (c), respectively corresponding to each response, namely residual stress, cold work, and plastic strain. These graphs display a normal distributions for selected responses respectively. This distribution is generated using the calculated mean and standard deviation values for the response and displays the lower and upper bound values, the number of standard deviations between the bounds and the mean value, and the total quality level.

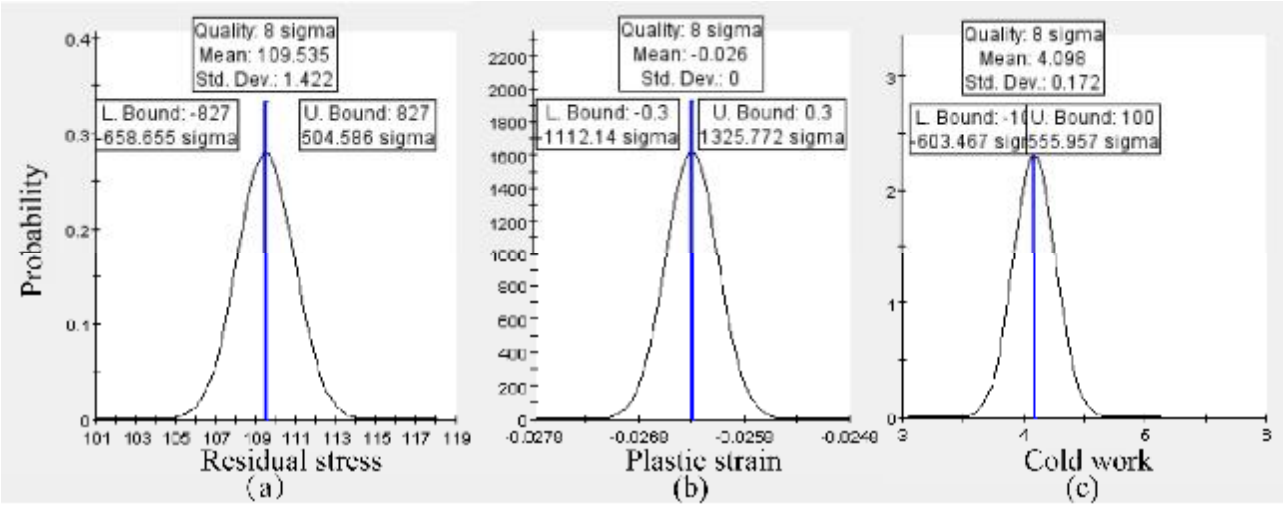

Figure 1. Six sigma graph of residual stress (a), plastic strain (b) and cold work (c)

As shown in Figure 1 that the values of residual stress are all in the range from -827 to 827, which is bounded according to material properties. The sigma level is 8 which is higher than the level 6. The level 6 shows that the percent variation is 99.9999998, which is a percentage of success. This greater value signifies that the reliability of residual stress is high and the optimisation of residual stress is reliable. Similarly, the sigma level of either plastic strain or cold work is also greater than the level 6. Likewise, their reliability are high and the corresponding optimisations are reliable.

Results of the optimisation

The linear Pearson Correlation method was used for the correlation calculation of parameter X and Y through the equation (2) as follows,

$$r_{xy} = \frac{\sum_{i=1}^{N}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{N}(X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{N}(Y_i - \bar{Y})^2}} \tag{2}$$

where, the X_i and $\bar{X}$ are the i_{th} value of parameter X and the mean value of X; likewise, Y_i and $\bar{Y}$ are the i_{th} value of parameter Y and the mean value of Y; N is the number of each parameter, namely X, Y; r_{xy} is the correlation value between the two parameters, X and Y. Through the above calculation, a correlation table is obtained as a patch chart that uses colour to represent the correlation value between selected output parameters and selected input parameters. This table provides a quick look at the most influential/influenced parameters from the selected parameters.

Table 3: Correlation table of parameters

Output variable	Angle	Diameter	Time	Velocity
Residual stress	0.53	-0.7	-0.37	0.64
Plastic strain	-0.55	0.59	0.41	-0.61
Cold work	-0.5	0.73	0.31	-0.63

Input variable

This correlation table uses different shades such as blue, green, yellow, and red to indicate the relationship between parameters. The greater the absolute value of a correlation coefficient, the stronger the relationship is between the parameters. The strongest relationship is indicated by a correlation coefficient of –1 or 1, and the patch is shaded dark blue (–1), dark red (1) red. The weakest

relationship is indicated by a correlation coefficient of 0, and the patch is shaded green. Coefficient values between 0 and –1 or 1 are shaded a continuum of blue to green to yellow to red. According to this rule and the values in Table 3, diameter, velocity, angle and time have descending effects on the residual stress. Regarding the plastic strain, velocity has the highest effect, followed by diameter and then angle; time has the lowest effect. While, the effects of the parameters to cold work is slightly different from their effects to plastic strain and residual stress. Diameter has the highest effect to cold work, followed by velocity and then angle, the lowest effect from time.

Summary and Conclusion

This paper reviewed the definition of a shot peening process and summarised its influential parameters. Then analysed the important investigations in optimisation of shot peening process. Accordingly, influential parameters were identified and optimisation function including objective function and corresponding constraints was formulated to carry out the optimisation. Finally, the shot peening process was optimised and the robustness of the optimisation was verified through reliability analysis. As a result, the study showed that velocity is the most influential parameters in terms of its effect on the responses followed by the impact angle, diameter of shots and the shot peening time, in this order.

Acknowledgement

This research was financially supported by the Eskom. They authors would like to express their appreciation to Dr. Mitchell for his technical supports.

Literature References

[1] B. Bhuvaraghan, et al., Shot peening simulation using discrete and finite element methods. Adv. in Eng. Soft., Vol. 41 (2010), p. 1266-1276.
[2] S. Bagherifard, R. Ghelichi, and M. Guagliano, A numerical model of severe shot peening (SSP) to predict the generation of a nanostructured surface layer of material. Surf. & Coat. Technol., Vol. 204 (2010), p. 4081-4090.
[3] H. Y. Miao, et al., Experimental study of shot peening and stress peen forming. J. of Mater. Proces. Techol., Vol. 210 (2010), p. 2089-2102.
[4] Y. M. Xing and J. Lu, An experimental study of residual stress induced by ultrasonic shot peening. J. Mater. Process. Technol., Vol. 152 (2004), p. 56-61.
[5] S. Baragetti, Shot peening optimisation by means of 'DoE', Numerical simulation and choice of treatment parameters. Int. J. Mater. & Product Technol., Vol. 12 (1997), p. 83-109.
[6] T. Chaise, et al., Modelling of multiple impacts for the prediction of distortions and residual stresses induced by ultrasonic shot peening (USP). J. Mater. Process. Technol., Vol. 212 (2012), p. 2080-2090.
[7] H. Y. Miao, et al., On the potential applications of a 3D random finite element model for the simulation of shot peening. Advances in Engineering Software, 2009. 40(10), p. 1023-1038.
[8] K. Schiffner and C. Droste gen. Helling, Simulation of residual stresses by shot peening. Computers & Structures, Vol. 72 (1999), p. 329-340.
[9] R. W. Evans, Shot peening process, modelling, verification, and optimisation. Mater. Sci. Technol., Vol. 18 (2002), p. 831-839.
[10] C. A. Rodopoulos, et al., Optimisation of the fatigue resistance of 2024-T351 aluminium alloys by controlled shot peening - methodology, results and analysis. Int. J. Fatigue, Vol. 26 (2004), p. 849-856.
[11] P. M. George, N. Pillai, and N. Shah, Optimization of shot peening parameters using Taguchi technique. J. Mater. Process. Technol., Vol. 153 (2004), p. 925-930.

[12] S. Baragetti, P. d. Milano, and P. L. d. Vinci, A numerical procedure for shot peening optimization by means of non-dimensional. Int. J. .Mater. Product Technol., Vol. 15(2000), p. 91-103.
[13] F. Petit-Renaud, et al., Optimization of a shot peening process. Proceedings of the Institution of Mechanical Engineers Part L-Journal of Materials-Design and Applications, Vol. 222 (2008), p. 277-289.
[14] H. Miao, et al., Effect of optimization of shot peening parameters on surface integrity of nak80. Functional Manufacturing Technologies and Ceeusro I, D.W. Zuo, et al., Editors. (2010). p. 537-539.
[15] B. Bhuvaraghan, et al., Constrained probabilistic multi-objective optimization of shot peening process. Engineering Optimization, Vol. 43 (2011), p. 657-673.
[16] M. Klemenz, et al. Finite element simulation of the residual stress states after shot peening. in Mater. Sci. forum. 2006.
[17] M. Klemenz, et al., Numerical prediction of the residual stress state after shot peening, in High Performance Computing in Science and Engineering', (2007), p. 437-448.
[18] M. Taro, T. Chaise, and D. Nélias, A methodology to predict the Roughness of Shot Peened Surfaces. J. Mater. Process. Technol., (2014).
[19] G. I. Mylonas and G. Labeas, Numerical modelling of shot peening process and corresponding products, Residual stress, surface roughness and cold work prediction. Surf. & Coat. Technol., Vol. 205 (2011), p. 4480-4494.
[20] M. Frija, et al., Finite element modelling of shot peening process, Prediction of the compressive residual stresses, the plastic deformations and the surface integrity. Mat. Sci. Eng. a-struct., Vol. 426 (2006), p. 173-180.
[21] K. J. Marsh, Shot peening: techniques and applications. Engineering Materials Advisory Service Ltd. (United Kingdom), (1993), p. 320.
[22] K. A. Soady, Life assessment methodologies incoroporating shot peening process effects, mechanistic consideration of residual stresses and strain hardening Part 1 - effect of shot peening on fatigue resistance. Mater. Sci. Technol., Vol. 29 (2013), p. 637-651.
[23] T. E. S. f. A. M. L. S. A. A. Space, SAE J444 Standard Surface Vehichle Recommended Practice. (1993).
[24] L. Xie, et al., Investigation on experiments and numerical modelling of the residual stress distribution in deformed surface layer of Ti-6Al-4V after shot peening. Mater. & Design, Vol. 41 (2012), p. 314-318.
[25] M. Klemenza, et al., Application of the FEM for the prediction of the surface layer characteristics after shot peening. J. Mater. Process. Technol., Vol. 209 (2009), p. 4093-4102.
[26] T. Kim, et al., Effects of Rayleigh damping, friction and rate-dependency on 3D residual stress simulation of angled shot peening. Mater. & Design, Vol. 46 (2013), p. 26-37.
[27] R. Shivpuri, X. Cheng, and Y. Mao, Elasto-plastic pseudo-dynamic numerical model for the design of shot peening process parameters. Mater. & Design, Vol. 30 (2009), p. 3112-3120.
[28] C. Barrett and R. Todd. Investigation of the effects of elastic pres-stressing technique on magnitude of compressive residual stress induced by shot peen forming of thick aluminum plates. in Proceedings of the 2nd international conference on shot peening. (1984).
[29] J. Champaigne, Shot Peening Overview. 2001, Metal Improvement Company.
[30] A. Seshadri, A Fast Elitist Multiobjective Genetic Algorithm, NSGA-II.
[31] Isight 5.9 User's Guide. 2014, Rhode Island, USA., Dassault Systèmes Simulia Corp.
[32] Information on http://blog.sina.com.cn/s/blog_68d0921b0102vac7.html.