2005117

OPTIMISING SHOT PEENING PARAMETERS USING DoE

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Abstract

The control of residual stress is crucial in ensuring the integrity of engineering components and shot peening can be used to good effect to introduce the beneficial compressive residual stress levels required. It is, however, difficult to use normal shot peening control systems (e.g. Almen strips) to establish the ideal peening conditions that will result in the best component performance. This paper presents results from a study to optimise the peening parameters for a typical carburised steel used in high performance gearing by investigating how the main peening process parameters influence residual stress profiles measured using X-ray diffraction.

Statistical design of experiments (DoE) was used to limit the number of experiments required for optimisation to be possible. Using this technique and X-ray diffraction depth profiling methods for residual stress analysis, the maximum compressive residual stresses in carburised SAE8620 steel were measured for a range of peening conditions.

The results of the detailed process characterisation investigations have shown that, by using careful design of experiments, it is possible to fully optimise the shot peening process to obtain greater benefits than would be possible with traditional control processes.

Keywords: Shot peening; Compressive residual stress; Design of experiments; Optimised peening; Taguchi optimisation;

Introduction

Almen strips are commonly used to define all of the shot peening parameters in a single term. A thin strip of specific dimensions and material is exposed to a stream of shot and the curvature of the strip is measured to give the 'Almen intensity'. However, it is possible to achieve the same Almen strip curvature (arc height) using different peening parameters. In addition, the material from which the peened component is manufactured is likely to different from that used for the Almen strip. Therefore, this type of measurement does not give accurate information about the compressive residual stress levels present after shot peening as the use of different peening parameters and component materials may generate different residual stress profiles.

Shot peening can involve a wide range of process parameters, some of which may be critical and others which may have little or no effect on the level of compressive residual stress present after peening. Therefore, in order to optimise the peening process, it may be desirable to minimise the number of variables so that attention can be focused on controlling these variables within appropriate ranges. Screening experiments are an efficient way of determining the important factors with a minimal number of experiments and they may also be used as a first step to model a response with a response surface design. Once the primary variables that affect the responses of interest are known, a number of additional objectives may be pursued.

The shot peening process is known to behave in a non–linear manner as two different sets of peening parameters can achieve the same results and therefore, determination of the appropriate values that will achieve the maximum compressive stress at the greatest depth from the surface can appear to require extensive, if not prohibitive experimentation. This paper describes the application of a DoE approach to obtain the optimum peening parameters using a simple and inexpensive iterative process that could be used as a base for developing a tool to predict the optimum peening parameters for a wide range of component materials and geometries.

Experimental Methods

- **Material**

Eleven 30mm cubes were manufactured from SAE8620 (Ni, Cr, Mo steel) and carburised to give a case hardness of approximately 750Hv with a case depth of approximately 1mm. Carburising was followed by ground finishing to give consistent surface finish and residual stress.

- **Equipment**

The experimental peening work was carried out using a Ventus ATX peening cabinet and S230H conditioned steel shot provided by IPSC Surface Preparation Limited.

- **Measurements**

The residual stress measurements were carried out by X-ray diffraction using a Stresstech XSTRESS 3000 residual stress analyser. Near-surface depth profiles were generated using layer removal techniques with electrochemical polishing.

Experimental Design and Techniques

The objective of the study was to determine how an iterative DoE method could be used to systematically optimise (for maximum compressive residual stress) a shot peening process that has a range of parameters and associated responses.

Previous work (Petit-Renaud, 2000) identified the most influential factors as pressure, mass flow rate, angle of impact, distance from target and time of peening. The mass flow rate represents the mass flow exiting the nozzle in the peening cabinet and is measured in kg/min. The angle of impact is the relative angle of the nozzle and the specimen. The pressure is the air pressure used to deliver the stream of shot to the surface of the specimen and is directly related to the speed of the shot and hence, energy transfer from the shot to the surface of the specimen. These factors were included in both experimental designs as the interaction between them is the key to controlling the effectiveness of the peening process.

A modified Taguchi $L_8(2)^7$ array (Taguchi and Konishi, 1987) with two levels for each factor was chosen for the initial screening DoE (DoE (a)) in order to identify the effects of each individual factor. The $L_8(2)^7$ designation refers to the number of experiments (8), the number of levels for each factor (2) and the number of factors or interactions (in this case the array was modified to accommodate 5 instead of 7 factors). A full factorial design would require 128 experiments whereas the Taguchi experiment required only eight.

The factorial setup for DoE (a) is shown in Table 1. Two levels were selected for each factor resulting in an array of eight experiments. The levels for each parameter were chosen as the extreme values used in commercial shot peening. As the aim was to establish the range of the factors that would give the best results and use this work as a guideline for the more detailed DoE (b), not all of the interactions were investigated at this stage.

Table 1: Factor and level description for Taguchi DoE (a)

No.	A	B	C	D	E
1	-1	1	1	1	1
2	1	-1	1	1	-1
3	-1	1	1	-1	-1
4	1	1	-1	1	-1
5	-1	-1	-1	1	1
6	-1	-1	-1	-1	-1
7	1	-1	1	-1	1
8	1	1	-1	-1	1

		Level 1	Level 2
	Factors		
A	Time	5 sec	30 sec
B	Pressure	30 psi	60 psi
C	Mass	3 kg/min	11 kg/min
D	Distance	50 mm	150 mm
E	Angle	45 deg	90 deg

After the effects of each parameter had been calculated using the initial DoE screening, an inscribed Central Composite Design (CCDi) employing fifty experiments with three levels for each factor was chosen for the second DoE. Increasing the number of levels enabled response surfaces to be created that would further assist with identifying the most influential factors and provide further optimisation of the peening parameters. The inscribed CCD is a convenient way to generate a rotatable CCD that enables the full ranges of the experiment variables to be studied while excluding non-allowable operating conditions at one or more of the extremes of the design region.

The factors and levels for DoE (b) are shown in Table 2. Three levels were selected for each factor and two additional levels were added to allow estimation of the experimental error associated with the model. These levels were selected within the experimental range (inscribed CCD). The additional points are at different locations in the design space to those used in the model and are used in a "lack of fit" test for the model. In addition, nine replicated points were selected in order to estimate the experimental (pure) error expected in the response if the experiment is repeated. The centre point of the design was repeated four or more times and this gives an adequate estimate of the variation of the response and provides the number of degrees of freedom needed for an adequate statistical test of the model. In both experimental designs, the experiments were randomised within each group.

Table 2: Factor and level description for CCDI DoE (b)

		Level 1	Level 2	Level 3	Level 4	Level 5
	Factors					
A	Time	40 sec	55 sec	70 sec	85 sec	100 sec
B	Pressure	60 psi	68.75 psi	77.5 psi	86.25 psi	95 psi
C	Mass	5.5 kg/min	7.38 kg/min	9.25 kg/min	11.13 kg/min	13 kg/min
D	Distance	40 mm	50 mm	60 mm	70 mm	80 mm
E	Angle	35 deg	48.75 deg	62.5 deg	76.25 deg	90 deg

The specimens were shot peened using the peening cabinet and then electro-chemically polished to measure the near surface residual stress profiles using X-ray diffraction.

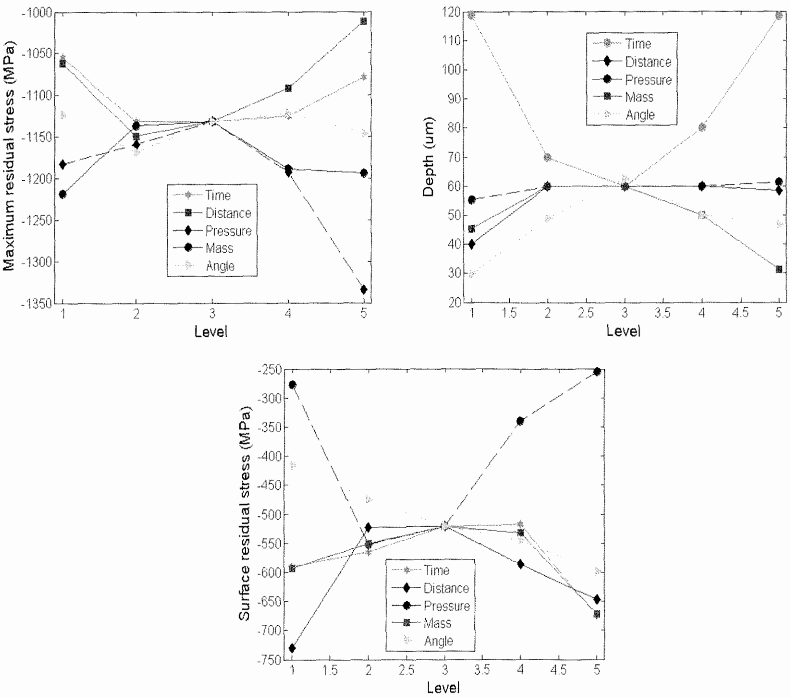

Figure 1: Response data for main factors of DoE (b). Pressure is the key factor for achieving high levels of surface and maximum residual stress. Depth is controlled mainly by the peening time while the distance from target has a very small effect ('prob. > F' > 0.5. In all three cases, results were obtained using cubic analysis).

Results and Discussion

The results obtained for the first and second experiments are shown in Table 4 and Table 5. The results shown in Table 4 for DoE(a) indicate that the angle of impact and mass flow rate have the most influence on surface residual stress (SRS) and the distance from target has the least effect. Peening time and pressure have the most influence on maximum residual stress (MRS) and pressure appears to have the most influence on the depth of the maximum residual stress. The pressure and the distance from target are also significant factors in terms of surface residual stress and depth but not maximum residual stress. A higher maximum residual stress is achieved using a combination of higher pressure and lower mass flow rate and a maximum compressive residual stress of 1.28GPa was achieved at a depth of 110μm using a combination of higher pressure and low mass flow rate combined with a shorter distance and a high angle of impact. As the stream of shot is leaner when the pressure-mass ratio is high, there is little interaction between the shot in the stream. This has an influence on the other parameters and the peening time has to be set at its maximum level. Although the experimental surface is flat and no geometrical constraints are present in this work, duplex peening will typically result in a maximum residual stress of approximately -1.36GPa in carburised gears.

The results of DoE (b) indicate a strong interaction between most of the parameters studied in this investigation (see Figure 1). Pressure and distance play an important role on both maximum residual stress and surface residual stress. Pressure and mass flow rate are also significant with "prob. > F" value of 0.002 (values less than 0.05 indicate that the terms are significant). The same applies for the interaction between mass flow rate and distance ("prob. > F" 0.0378) where the shot stream has to be lean enough to allow quick drainage. A good starting value for pressure/mass flow rate ratio was approximately 15. (i.e. mass flow rate of 5 kg/min would equate to 75 psi). The peening time depends on all of the parameters that were analysed in this investigation but in general, either short or long periods of peening will achieve good results (Figure 2).The maximum level of residual stress is achieved for short periods of peening as the effect of drainage will dominate after a certain period of time, thus minimising the energy transfer. In single shot analyses, it can be found that incoming shot will decrease the level of residual stress at the point of impact (Guagliano 2001, Meguid et. al 2002). The interaction between angle of impact and mass flow rate is shown in Figure 3. A cubic equation to describe the system was derived from the analysis of variance (ANOVA) for DoE (b). The confidence in the model is very high and theoretical results acquired using the cubic equation are compared with experimental values in Table 5. The maximum error is 13% and taking account of other sub-processes that have an error of ±5%, the experimental and predicted results are in very good agreement.

Table 4: Experimental results for DoE (a)

Experiment	SRS	MRS	Depth
A1	-743.7	-1225.5	80
A2	-574.5	-1257.6	40
A3	-641.2	-1244.9	80
A4	-490.3	-1286.3	80
A5	-782.5	-1204.1	110
A6	-606.1	-1240	40
A7	-788.4	-1261.5	40
A8	-660.3	-1289	110

Conclusions

The DoE approach has enabled prediction of residual stress states for given processing conditions with a high degree of confidence and has enabled optimisation of the process to maximise compressive residual stress.

The work described here has been for ideal flat samples. Work is continuing to explore geometry effects leading to interactions with the shot stream.

Table 5: Theoretical calculation of response using cubic analysis compared with experimental results (absolute error varies from 0.11% to 12.77).

Theoretical			Experimental			Error		
SRS [MPa]	MRS [MPa]	Depth [um]	SRS [MPa]	MRS [MPa]	Depth [um]	SRS [%]	MRS [%]	Depth [%]
-858.51	-1477.84	83.57	-892	-1475	80	-3.75	+0.19	+4.46
-550.54	-1118.5	79.9	-584	-1167	80	-5.73	-4.16	-0.12
-747.53	-971.66	99.89	-739	-980	100	-0.85	+1.15	-0.11
-616.43	-1183.66	26.17	-634	-1145	30	-2.71	+3.38	-12.77

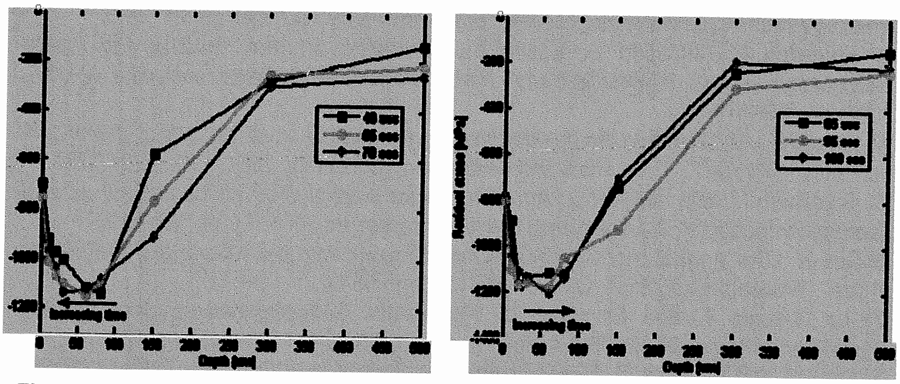

Figure 2: Residual stress profiles for different peening time periods. Increasing time will begin decreasing the depth of the maximum residual stress in early stages of peening. Continuation of the peening operation will increase both the magnitude and depth of the maximum residual stress. The effect is still under investigation.

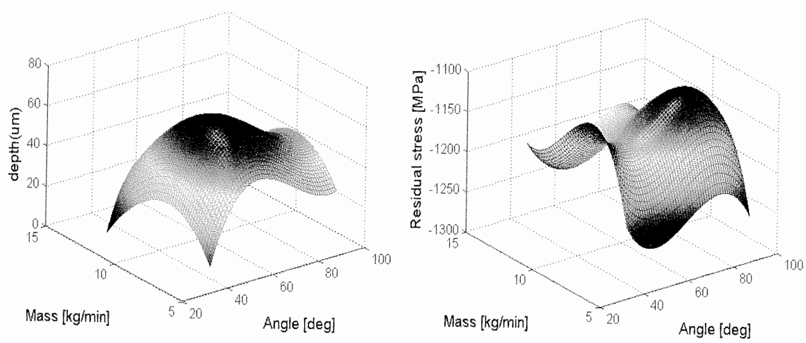

Figure 3: Interaction between angle of impact and mass flow rate on depth and MRS. A higher impact angle typically will generate larger depths of compressive residual stress. This can be enhanced by choosing an angle that will provide the best energy transfer and drainage.

Acknowledgements

EPSRC are gratefully acknowledged for supporting this research work through the Structural Integrity managed programme. USF Vacublast are also thanked for their generous support and for providing the Newcastle Shot Peening research facility.

References

[1] Al-Hassani S.T.S., Kormi K., Webb K.D.C. *"Numerical Simulation of Multiple Shot Impact"*. Proceedings ICSP-7, Warshaw, Poland, 1999; pp. 217-227.
[2] Deslaef D., Emmanuelle R., Rasouli Y. S., *"3D Finite Element Models of Shot Peening Process"*. J. Materials Science Forum 2000, Vols 347-349; pp. 241-246.
[3] Fathallah R., Inglebert G. Castex L., *"Modelling of Shot Peening and Plastic Deformation Induced in Metallic Parts"*. Proceedings ICSP-6, San Francisco, CA, USA, 1996; pp. 464-473.
[4] Guagliano M. *"Relating the Almen intensity to residual stresses in shot peening: A numerical approach"*. J. Materials and Processing Technology 2001; 110; pp 277-286.
[5] Guagliano M. and Vergani L. *"An approach for prediction of fatigue strength of shot peened components"*. J. Engineering Fracture Mechanics 2004; 71; pp 501-512.
[6] Iida K. *"The Analyses of the Shot Velocity thrown from the Nozzle and the Bladed Wheel"*. Proceedings ICSP-5, Oxford, UK; 1993; pp 55-60.
[7] Le Guernic Y. and Eckersley J. *"Peenstress Software Selects Shot Peening Parameters"*. Proceedings ICSP-6, San Francisco, CA, USA, 1996; pp. 481-492.
[8] Meo M. and Vignjevic R. *"Finite element analysis of residual stress induced by shot peening process"*. J. Advances in Engineering Software 2003; 34; pp. 569-575.
[9] Meguid S. A., Shagal G. and Stranart J. C. *"3D FE analysis of peening of strain-rate sensitive materials using multiple impingement model"*. Inter. J. of Impact Engineering 2002; 27; pp. 119-134
[10] Nadkarni V. S. and Sharma M. C. *"Some Aspects of Mass Flow Control of Shots in Pneumatic System"*. Proceedings ICSP-5 Oxford, UK; 1993; pp 49-54.
[11] Petit-Renaud F. *"Optimisation of the Shot Peening Parameters"*. M. Phil. Thesis, University of Newcastle upon Tyne, Sep. 2000.
[12] Taguchi G. and Konishi S., *"Taguchi Methods Orthogonal Arrays and Linear Graphs: Tools for Quality Engineering"*. Amer Supplier Inst, April 1987.