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OPTIMISATION OF THE SHOT PEENING PROCESS IN TERMS OF FATIGUE RESISTANCE

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ABSTRACT

Shot peening is widely used to improve the fatigue properties of components and structures. Residual stresses, surface roughness and work-hardening can be identified as the main changes induced in the surface layers of the material, due to shot peening. The magnitude of these changes depends on the correct choice of the peening parameters. A thorough characterisation of the shots used, as well as the development of a method to obtain the peening intensity at saturation point, was undertaken. The effect of the shot peening variables on the surface changes of the 2024 aluminium alloy due to shot peening are examined experimentally. The development of a methodology to performed fatigue life predictions of the shot peened components is outlined in order to optimise the shot peening process and to determine the best levels of the process variables in terms of fatigue resistance.

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KEYWORDS

Shot peening; Aluminium 2024; Residual stress; DoE; Fatigue resistance.

1. INTRODUCTION

Engineering components and structures are regularly subjected to alternating loads, which made them prone to fatigue failures. It is a well known fact that almost all fatigue cracks form at surfaces due to a variety of surface stress concentration features, including grain boundaries, machining marks, surface breaking inclusions, and large notches [1]. Evidently, the control of surface initiation/growth of cracks is an effective means of enhancing the fatigue endurance of metallic components. The shot peening process is widely utilised for this purpose as it produces plastic deformation of the surface (Hertzian pressure and direct stretching [2]) leading to the creation of both surface work-hardening and high residual compressive stresses at, or just below the surface layer [3], which are effective in preventing or delaying crack growth [4].

The magnitude of the residual compressive stress and the depth to which it extends beneath the surface of the component must be controlled. It becomes immediately apparent that, for shot peening to be consistently effective and reproducible, a number of parameters must be closely controlled. Among these, the most important are [5]:

a) The peening media (shot),
b) the energy of the shot stream (intensity), and
c) the percentage of indentation of the part surface (coverage).

Many variables are involved in the peening process and an incorrect estimate of any of those variables may degrade rather than enhance the performance of components. For this reason, shot peening is a process frequently underestimated in design/ production through a lack of both understanding, and a clear definition of the optimum levels and tolerances of the process variables. Moreover, the beneficial effect of the process on fatigue resistance of ferrous materials is well established, whereas for aluminium materials it is less clear [6].

The object of this study is to ascertain the best peened properties of a component, including hardness, roughness, residual stress and fatigue life and strength; directly from the interaction of the process control parameters and initial component properties. Design of Experiments (DoE)/Robust Design methodology [7, 8] may be applied in this study to optimise the surface treatment parameters and to find their optimum levels. The use of this method avoids carrying out experiments on a trial and error basis, as in the past, and also gives indication of the direction of change of the variables that control the performance of the system, together with the relative role that variables have on determining the output [9].

2. EXPERIMENTAL DETAILS

2.1. Equipment and procedure

In this study, the experimental shot peening equipment utilised is of the direct-pressure air blast type. It consists of a standard blast cabinet, an electronically controlled feed valve system i.e., Magna Valve model No. 368, a media transfer valve, a pressure vessel, an oscillating nozzle mechanism, a turntable, and a fascia panel where are located the controls, as shown in Fig. 1-a,b.

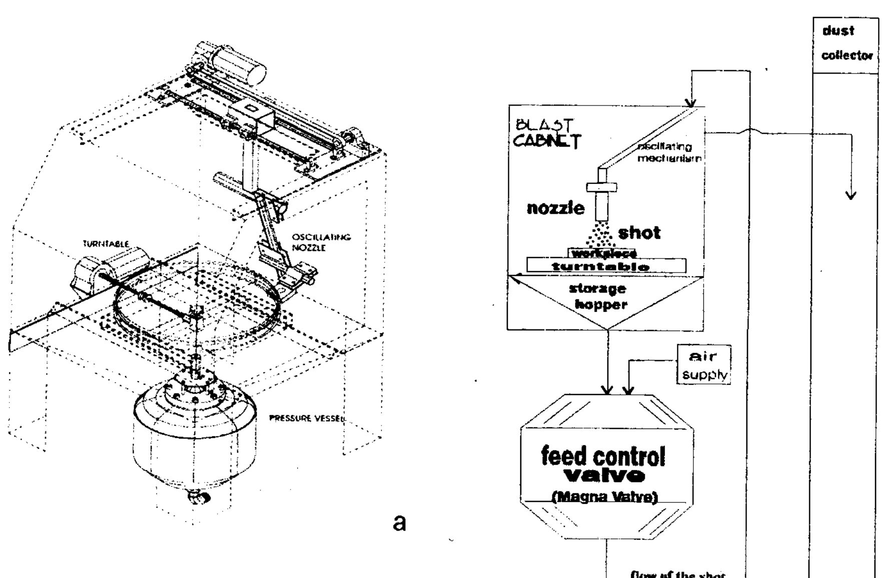

Figure 1 Air-blast peening equipment: a) main components, and b) flow diagram of the media

Compressed air is controlled via a remote pressure regulating valve. A pressure transducer is fitted to the air line down stream of the regulator. The pressure monitored by the transducer is indicated on a digital display in the control enclosure. This display is used, in conjunction with the pressure regulating valve, to accurately set the blast air pressure. The compressed air enters through the Precifeed pressure vessel, which is at the bottom of the cabinet storage hopper. Inside this pressure vessel, there are both compressed air and shot media. There is also a new system for accurate control of the media feed rate, namely, the Magna Valve, which uses a magnetic effect to restrain and prevent ferrous media falling through the bore of the valve. This ensures an exceptional level of repeatability when compared with conventional machines. The combined media/air flow then passes through the boost hose to the nozzle oscillating mechanism mounted at the top of the cabinet, which directs the shot to impact the workpiece to be peened. The shot drops to the storage hopper of the cabinet while the supplied air is drawn off to a dust collector. Fig. 1-b shows schematically the general arrangement of the shot flow in the equipment.

The procedures for operating the shot-peening machine are briefly described below:

a) Peening a sample attached to the rotating table with the nozzle oscillating mechanism stationary under automatic control.
b) Peening a sample attached to a stationary turntable and with the nozzle oscillating over the target under automatic control. This procedure is employed in the present investigation.

A trial run of the machine gave the results listed in table 1. The Almen intensity was selected according to specifications for this material. Equally, the shot size S230 was selected because it is widely used in industry.

Table 1. Details of the peening parameters

Shot	Air pressure	Stand-off distance	Duration (passes) At saturation point	Nozzle size	Almen intensity
S230	60 psi	6 in	8 sec. And 100% coverage	¼ in	17A

2.2. Shot media and its characterisation

Details of the spherical cast steel and spherically conditioned cut wire steel peening media used in this study are illustrated in table 2.

Table 2. Specifications of the shot peening media.

SHOT PEENING MEDIA			
Shot Characteristic	Designation SAE J 441/827/2175	Nominal diameter Inches/mm	Specification Hardness
Spherical Cast steel	S330	0.0330/0.838	56-58 Rc (615-668 Hv)
	S230	0.0230/0.584	56-58 Rc (615-668 Hv)
	S170	0.0170/0.432	45-52 Rc (410.5-548.5 Hv)
	S110	0.0110/0.279	45-52 Rc (410.5-548.5 Hv)
Spherically conditioned steel	SCCW 20	0.0196/0.5	610-670 Hv
	SCCW 23	0.0236/0.6	610-670 Hv

To determine the size and shape distributions of each type of shot, Image Analysis techniques were employed. For such distributions, samples of shots were selected at random by repeat subdivision of a tray of shots until approximately 100 remained as a non-biased sample. An image analyser Olympus CH-2 LECO was used. Distributions of the size (diameter), shape factor (roundness) and aspect ratio (major length by minor length) of the S230 shot are shown in Fig. 2 a-c.

Results show that roundness and aspect ratio values are consistent with those required by specifications (MIL-S-13165C and SAE-HS84). Conversely, the average measured shot size is larger than the specified nominal diameter, but it is still within the upper tolerances. It is worth pointing out that variable tolerances within specifications are not at all clear. Significant differences between specifications are reported in the technical literature.

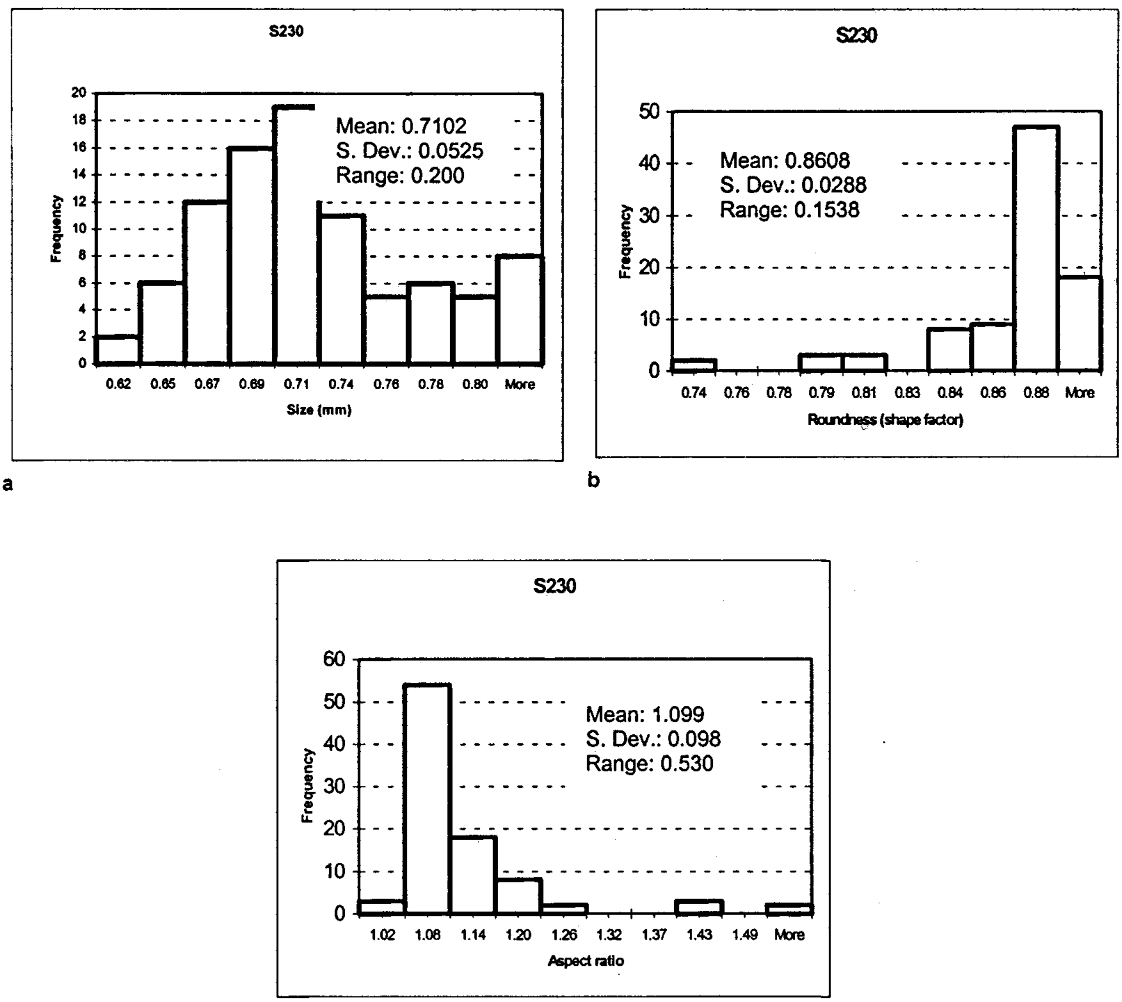

Figure 2. Histogram showing the shot S230 distribution of: a) Size (diameter), b) shape factor, and c) aspect ratio.

Hardness and density were also determined in accordance with specification procedures. Results of hardness are summarised in table 3. Density measurement gave constant values of 7.63 g/cm^3 . Both hardness and density met the requirements.

Table 3. Microhardness Vickers (Hv, 0.05) of each type of shot.

Standard dev.	38.223	42.635	30.520	34.513	47.902	23.229
Mean	615	484	491	724	650	652
Shot	S230	S110	S170	SCCW-20	SCCW-23	S330

2.3. Target material properties

The material tested was, aluminium 2024-T351. The chemical composition and the monotonic mechanical properties for the as received material are shown in tables 4 and 5 respectively.

Table 4. Chemical composition of the Al 2024-T351 (weight percentage).

Si	Fe	Cu	Mn	Mg	Cr	Zn
0.5	0.5	3.8-4.9	0.3-0.9	1.2-1.8	0.1	0.25

This material is used extensively in the aircraft industry for structural applications.

Table 5. Details of the mechanical properties of the tested material.

Material Property	Units	Al 2024
Density	g/cm^3	2.77
Poisson's ratio	-	0.33
E	GPa	72.4
Hardness	HB	120
Yield strength	MPa	345
UTS	MPa	470

2.4. Specimen design and preparation

Two different specimen profiles were employed for the assessment of the final peened material properties and axial fatigue test, as shown in Figs. 3 and 4. A coupon specimen was used for determining the residual stresses, hardness gradient and roughness. In contrast, an hourglass type specimen was used for the axial fatigue test. All specimens were machined from a large plate with either a T-S centre line or T-L surface orientations, which are illustrated in Fig.

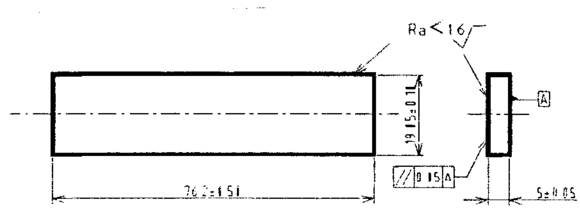

Figure 3. Geometry of the coupon used for evaluating the effects of the shot peening process (dimensions in mm).

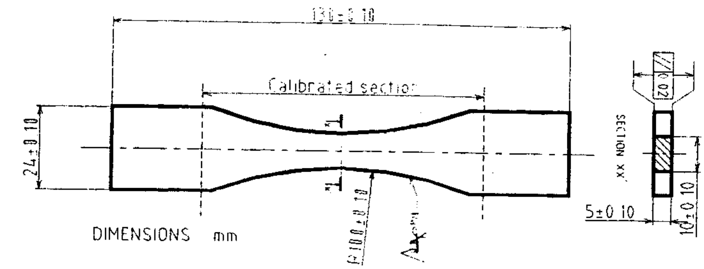

Figure 4. **Geometry of the hourglass shape specimen for axial fatigue tests**

In order to minimise the machining effects and ensure repeatability, manufacturing of the specimens was done using CNC machines.

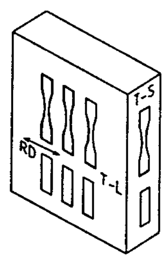

Figure 5 **Schematic diagram of the specimens' orientation in the sheet.**

2.5. Measuring techniques used

a) Arc height or intensity. After shot peening, arc heights or Almen intensities were monitored using a standard digital type Almen gauge, with digital accuracy to 0.0002" (0.0051 mm)[10].

b) Saturation point. The basic concept of the Almen Saturation Intensity is to determine the time at which a surface is impinged over the whole of the desired area. Saturation point is, therefore, defined as the exposure time where doubling the exposure time will achieve an increase in arc height of not greater than 10%. An algorithm, developed by one of the authors (AL) for determining the saturation point by means of full regression analysis, has been used in this study. An equation of the form

$$\text{Arc\_Height} = \frac{A}{(\text{Time} + b)^P} - \frac{A}{b^P}$$

has been adopted for the solution form having boundary conditions such that:

1. At time =0, Arc height = 0 (imposed directly by the equation).
2. As time approaches infinity arc height approaches a saturation value.
3. Each data point has equal weighting.

Where A, b, and p are fitting parameters.

A full regression analysis to provide the minimum sum of differences from the input data points is used.

Data integrity: The normal industrial criteria applied for input data suggests that;

1. Successive arc height increments reduce in magnitude.
2. Time intervals should progressively double (i.e. 2, 4, 8, ...).
3. Successive tangents reduce and show a smooth trend.

Output: Saturation point (time and arc height) if contained within the data range (program extrapolation outside the input data range is not to be allowed). The result of one saturation point determination using the algorithm described above, is shown in Fig. 6.

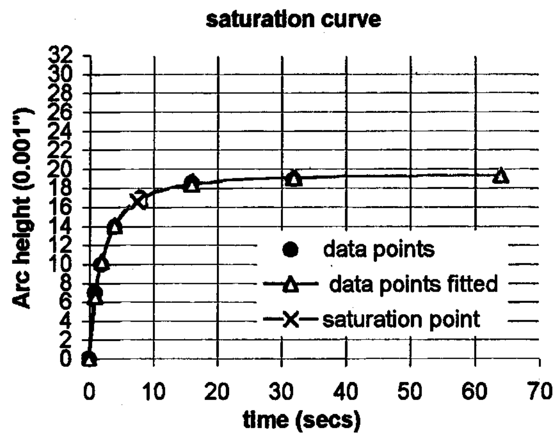

Figure 6. **Saturation curve of S230 shot, 60 psi, 6 in stand-off distance, and as it can be seen 17A at 8 sec. and therefore 100% coverage.**

c) Residual stress measurements. The Hole drilling technique will be used in the course of this research for measuring the residual stress. [11].

With strain sensors judiciously placed before dissecting the part, the sensors respond to the deformation produced by relaxation of the stress with material removal. The initial residual stress can then be inferred from the measured strains by elasticity considerations.

X-ray diffraction strain measurement, which does not require stress relaxation, offers a non-destructive alternative to the hole drilling method, but has its own severe limitations. Aside from the usual bulk and complexity of the equipment, which can preclude field application, the technique is limited to strain measurements in only very shallow surface layers. Although other non-destructive techniques (e.g., ultrasonic, electromagnetic Eddy current) have been developed for the same purposes, these have yet to achieve wide acceptance as standardised methods of residual stress analysis [12].

3 RESULTS AND DISCUSSION

Results of the three main effects of shot peening carried out on 2024 aluminium in according to the conditions listed in table 1, are as follows:

a) Microhardness gradient

The creation of the highly distorted surface layer because of the intense plastic deformation induced by shot impacts provokes work hardening. This is quantified by taking sub-surface hardness measurements. The results of those measurements are given in Fig. 7.

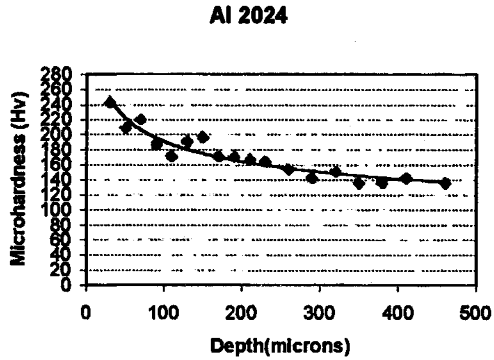

Figure 7. In-depth microhardness profile of the Al-2024 peened coupon. Measurements were obtained starting at 30 μm from the surface.

b) Roughness

The average of ten measurements gave a value of Ra = 9.4 μm. The peened surface roughness is considerably higher than for an unpeened coupon which registered only 1-3 μm.

c) Residual stresses

Fig. 8. shows that the through thickness depth distribution of residual stresses decreases parabolically from the surface. It can also be seen that shot peening gave compressive residual stresses at the surface (-138 MPa) with the maximum stresses occurring below the peened surface (-448 MPa at 0.076 mm). The unpeened CNC machined coupon shows shallow tensile residual stresses on the surface.

An equation reported by Robertson [13], was used to plot the calculated curve in Fig. 8. Correlation coefficients were higher than 0.92.

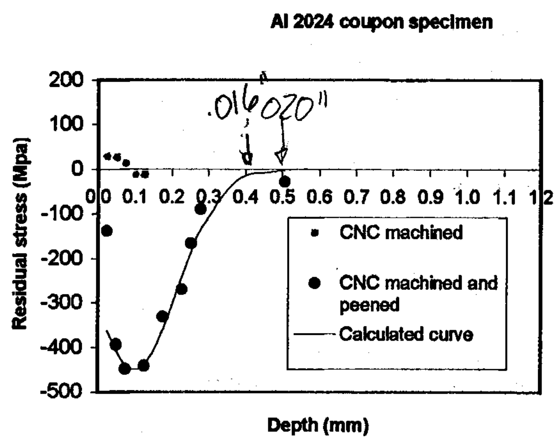

Figure 8 In-depth measurements of the longitudinal residual stress obtained by means of the hole drilling method

d) Effect of shot peening on fatigue

Results of axial loading fatigue tests, carried out using the specimens shown in Fig. 4 of 2024 T351 aluminium alloy, and peened using two different peening conditions, (i) Coarse shot: S330, intensity 19.2A; (ii) fine shot: S110, intensity 6.8A, showed that the fatigue properties obtained using conditions (i) are significantly better than those obtained using (ii). In fact, the fatigue properties given by condition (ii) are no better even than the unpeened base material properties, see Fig 9. These results underpin the need of an optimisation of the shot peening process in terms of fatigue resistance.

There is also a need for modelling the effect of shot peening in metal fatigue to enable the prediction of fatigue life in shot peened components. As indicated earlier, the changes to the material within the peened depth are mainly the development of a compressive residual stress, work hardening and a distortion of the grain structure. These effects have to be incorporated into fatigue crack propagation laws in order to develop a methodology for predicting the fatigue behaviour of shot peened components. The approach to follow in this research programme is based on Microstructural Fracture Mechanics principles. A suitable adaptation of the Navarro-Rios model [14] will be used for crack analysis and life prediction. This method incorporates variables such as microstructure, initial flaw size, residual stresses, surface topography, work hardened layer, etc. within the system equations. Because the effect of these variables is not linear, a numerical approach will be used to solve the equations. A computer program will be developed to carry out life prediction calculations. The input variables will be (i) traditional fatigue data for the base material (e.g. long crack da/dU vs ΔK), (ii) initial flaw size (e.g. dimple size, surface damage due to overpeening), (iii) profile of residual stress, (iv) hardness of the work hardened layer, (v) surface topography.

The residual stress is included as a closure stress at the crack (resistance to the opening of the crack), while the material distortion in the shot peened layer is included as a work hardening term within the resistance to plastic deformation at the crack tip. The closure stress is obtained by calculating the mean value of the function describing the residual stress distribution between x=0 and x=a (a: crack depth) over the portion of the crack contained within the shot peened layer (see Fig. 9). Similarly, the resistance to plastic deformation within the plastic zone is obtained by calculating the mean value of the function describing the work hardened flow stress ahead of the crack tip in the plastic zone (see Fig. 7).

The results will be in the form of either cycles to failure for a given applied stress or the S-N curve of the shot-peened material and a fatigue map showing the crack arrest line and the crack instability line. The designer and maintenance engineer to perform safe-life calculations or damage tolerance predictions will use this information.

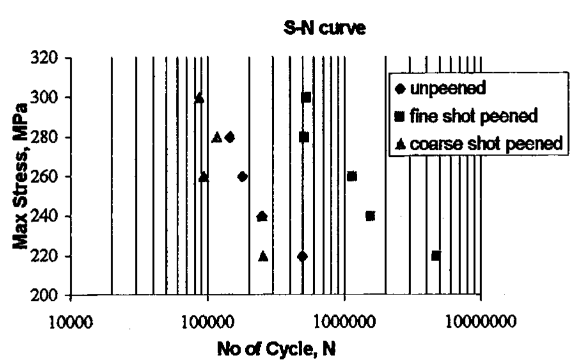

Fig. 9.- Fatigue properties of 2024 T351 with three different surface treatments: unpeened, peened (coarse S330 shot, 19.2A intensity) and peened (fine S110 shot, 6.8A intensity)

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