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A Theoretical and Experimental Investigation into the Development of Coverage in Shot Peening

Saravannan Karuppanan*, Jose Solis Romero+, Eduardo R. de los Rios+, Chris Rodopoulos+ and Andrew Levers#
*Universiti Teknologi Petronas, Bandar Seri Iskandar, Perak Darul Ridzuan, Malaysia
+SIRIUS, Department of Mechanical Engineering, University of Sheffield, S1 3JD Sheffield, UK
#Airbus UK Chester Road, Broughton, Chester CH4 0DR, UK

1 Introduction

Shot peening is a mechanical pre-stressing surface treatment that substantially improves the strength of metals if the process is carefully controlled. The earliest record of mechanical pre-stressing probably predates 2700 BC, when hammered gold helmets were found during the Crusades, as reported in reference [1].

Peening was a well-accepted technology in the early 1920's when hand-peening with specific hammers was used in the race-car industry [2]. However, shot peening as a process of the cold working of metal surfaces, was only realised in the middle of 1920's, as a consequence of the accidental observation that the parts which were sand-blasted for cleaning purposes showed an increased fatigue life.

Since the 1960's, the understanding of the shot peening process has increased significantly, especially in the area of fatigue life improvement. The use of shot peening to improve component fatigue life has also been standardised [3]. However, shot peening process parameters are still selected by means of empirical considerations or by experience. Determining the peening schedules required for optimum shot peening is still a grey area.

In most shot peening applications, uniform residual compressive stress in the surface zone is the sole desired effect, as the stresses will resist the formation of fatigue cracks within the component during service, thereby improving significantly the life of the peened component. A few examples of the type of part which have shown a good response to shot peening, include crankshafts (900% life increase), gears (1500% life increase) and connecting rods (1000% life increase) [4].

Although the mechanism of shot peening is a simple concept, the process is complex. The effectiveness of the shot peening process is dependent upon the uniformity of the induced compressive residual stresses and the energy transfer that occurs during the impact of the shots with the target surface. In practice, the process efficiency is established by means of coverage, intensity and saturation.

The scope of this study is to investigate the development of coverage and its relationship to intensity and saturation peening. Within this scope, the objectives of this research are: (i) to compare coverage results obtained experimentally with theoretical models of coverage development, (ii) to establish a relationship between coverage and intensity and (iii) to obtain an empirical relationship to predict coverage.

2 Coverage

Coverage is defined as a measure of the area fraction of a component surface that has been impacted in a given peening time, usually expressed as a percentage. It is a measure of the interaction between neighbouring indentations, and hence the uniformity of the residual stresses within the surface layers of the shot peened component.

Complete visual coverage, (100 % coverage), is reached when the entire surface of a reference area has been indented. At this point, the residual stresses are assumed to be uniform in the surface layers of the component. Coverage of less than 100% is ineffective because of the unpeened surface which contributes to uneven distribution of residual stresses in the surface layers of the component. Coverage above 100 % is achieved by using multiples of the exposure time to 100 % coverage.

Indentations are most likely to occur without overlap in the early stages of the shot peening process so that the coverage increases linearly with time. The rate of coverage decreases with time because the probability of overlap increases. The probability that an uncovered area be covered by a new indentation becomes smaller and smaller with time. Hence the approach to 100 % coverage is exponential. In practice, 100 % coverage can neither be accurately measured nor achieved with certainty after a definite exposure time. Hence, complete coverage is assumed to occur when the observed coverage reaches 98 % [5,6].

Coverage can be assessed qualitatively by visual inspection of the reference area with a magnifying glass, or quantitatively by image analysis or by the dyescan tracers technique. Theoretical models have been developed to predict the development of coverage. In this project, the development of coverage will be determined experimentally with the use of an image analysis technique. Two theoretical models, the Avrami equation and the Holdgate model, will also be used to predict the development of coverage.

2.1 The Avrami Equation

A theoretical model reported by Kirk et.al.[7] considers shot size indentation, peening rate and exposure time for the prediction of coverage. This model was based on the earlier work by Avrami and therefore is called the Avrami Equation.

This equation is based on the assumption that each shot particle makes the same size of indentation and that the shot particles arrive at the surface in a statistically random manner, but at a rate which is uniform over a significant period of time. In this respect, the Avrami equation in terms of the parameters that are readily determined for a particular peening system, is written as follows:

$$C(t) = 100\left\{1 - \exp\left(-\frac{3r^2\dot{m}t}{4A\bar{r}^3\rho}\right)\right\} \qquad (1)$$

$C(t)$ is the coverage at any particular time
r is the average radius of the indentations
A is the area of shot spread
t is the time during which the indentations were being created

$\dot{m}$ is the mass flow rate of shots
ρ is the density of the shot
$\bar{r}$ is the average radius of the shots

2.2 The Holdgate Model

N.M.D Holdgate [8] extended existing models for describing the development of coverage, to one applicable to a general peening system involving multiple peen sources. The proposed model states that if the overall coverage C of a reference area S is known at time t, the overall coverage after the interval δt is approximately given by:

$$C(t+\delta t) = 1 - \left[1 - C(t)\right] \prod_{j=1}^{n_s} \left[1 - \frac{a_j}{S}\right]^{\delta N_j} \tag{2}$$

n_S is the number of peen sources
a_j is the total area of indentation caused by the peens from the j-th peen source at time δt
δN_j is the number of peens from the j-th peen source expected to impact the reference area in an interval of time δt

This model can be simplified for a single peen source as:

$$C(t+\delta t) = 1 - \left[1 - C(t)\right] \left[1 - \frac{a}{S}\right] \tag{3}$$

2.3 Intensity and Saturation

Intensity correlates the amount of energy transferred during the impact of a typical shot with the work piece and is related to the kinetic energy of the blast stream [9]. The Almen strip test, which was originally proposed by J.O.Almen, is used to quantify the intensity level [10].

Saturation refers to the number, uniformity and relative position of the impingements caused by the shot striking the work piece during the exposure time. Saturation is a measure of the effectiveness of the shot peening process. Almen strips can be used to measure the saturation point which is defined as the earliest point on the curve of arc height versus peening time, where doubling the exposure time produces no more than a 10 % increase in arc height.

An algorithm developed by one of the authors, for determining the saturation point by means of full regression analysis, has been used in this study. An equation in the following form has been adopted for the solution.

$$Arc \quad Hight = \frac{A}{(time \; + \; b)^p} - \frac{A}{b^p} \tag{4}$$

Where A, b and p are fitting parameters. Figure 1 show the implementation of equation (4).

3 Experimental Details

3.1 The Shot Peening Machine, Media and Target Material

The shot peening machine used in the experiments was a direct-pressure air-blast type, where compressed air at a desired pressure is supplied to the pressure vessel. The pressure of the air is monitored by a pressure transducer and is indicated on a digital display in the facia control. The combined air-media flow then passes through the boost hose into the nozzle mounted at the top of the cabinet. The nozzle directs the shot to the work piece to be peened and can be set to remain stationary or move at a selected speed. An electronically controlled feed valve system (MagnaValve), located at the bottom of the pressure vessel, controls the feed rate of the shot.

The shot peening media used in the experiments were S110, SCCW20, S230 and S330, and were projected at impingement angles of 30^o, 45^o and 90^o.

Aluminium 2024-T351 and aluminium 7150-T651 were used for the coverage investigation and A type Almen test strips (cold rolled spring steel SAE 1070) were used for intensity determinations.

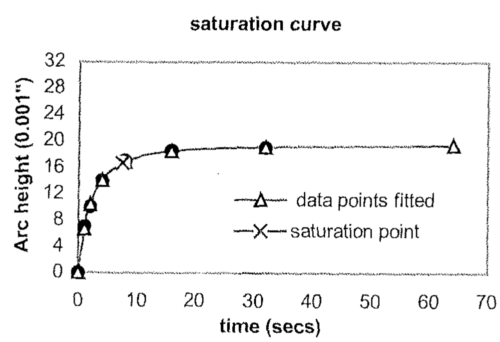
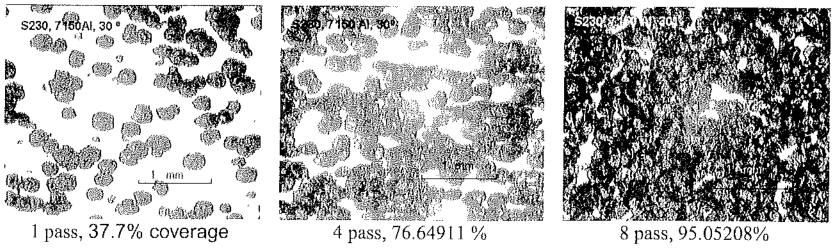


Figure 1: Saturation curve for S230 shot, the saturation point is at 17A and 8 sec

3.2 Experimental Determination of Coverage

Dimensions of the specimens used for the coverage experiments were 25 mm × 19 mm × (5~7) mm. The surface of the specimens was polished to 1mm finish before peening. A microscope with magnification ×32 was used to capture images of the specimen after each shot peening pass and an image analysis program (SigmaScan), was used to determine the percentage of coverage. An image taken after the 1st pass was used to determine the indentation radius of different shots. Figure 2 show an example of coverage determination by image analysis.



1 pass, 37.7% coverage 4 pass, 76.64911 % 8 pass, 95.05208%

Figure 2: Development of coverage in 7150 alloy with shot S230

4 Results

For the application of the Avrami equation the average radius of the indentations was measured from photographs taken after the first pass, as in Fig. 2, while the area of the shot spread was measured from wide metal strips peened along the centre. Regarding the Holdgate equation, the values of the ratio a/S after the first pass were obtained from a regression analysis of the experimental determinations. The regression equation is:

$$\frac{a}{S} = b_0 + b_1 x_1 + b_2 x_2 + b_3 x_1^2 + b_4 x_2^2 + b_5 x_1 x_2 \qquad (5)$$

x_1 = shot diameter (mm)
x_2 = impingement angle (^{o})
b_0 to b_5 = regression coefficients

Solutions for the regression coefficients were solved using a Microsoft Excel program. The predicted expressions for both materials are as follows:

4.1 Al 2024

$$\frac{a}{S} = 1.43 - 1.72 x_1 + 1.48 \cdot 10^{-3} x_2 + 0.56 x_1^2 - 4.40 \cdot 10^{-6} x_2^2 + 9.71 \cdot 10^{-4} x_1 x_2 \qquad (6)$$

4.2 Al 7150

$$\frac{a}{S} = 1.43 - 1.72 x_1 + 1.48 \cdot 10^{-3} x_2 + 0.56 x_1^2 - 4.40 \cdot 10^{-6} x_2^2 + 9.71 \cdot 10^{-4} x_1 x_2 \qquad (7)$$

Figure 3 shows the comparison of coverage development as predicted by the two theoretical methods together with experimental results, while **Figure 4** shows the effect of shot size, angle of impingement and target material on the rate of coverage.

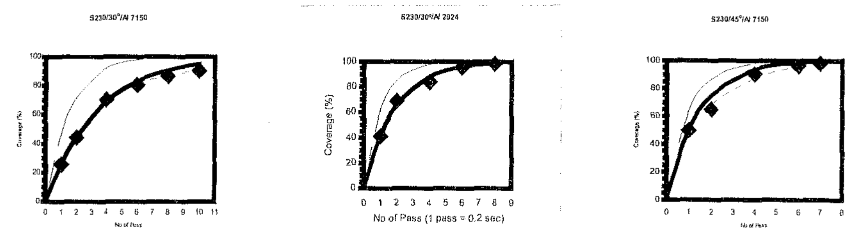


Figure 3: Comparison of coverage results obtained with the Avrami equation (fine line), Holdgate method (coarse line) and experimental (dash line and symbols)

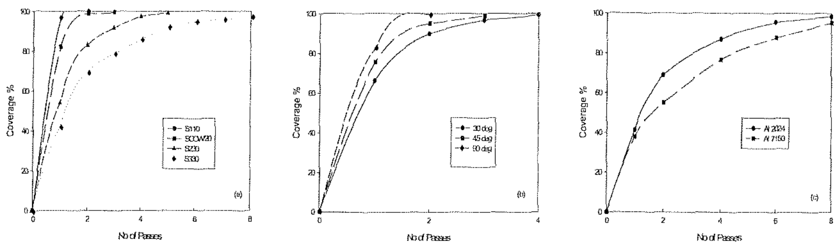


Figure 4: Coverage development (a) in Al 2024, 90^{0} angle of impingement, using different shot sizes, (b) Al 2024, shot SCCW20, using different impingement angles and (c) in two different materials, shot S230 and 30^{0} angle

5 Discussion and Conclusions

The experimental method used to determine coverage is reliable provided high quality images are obtained from previously polished samples. The SigmaScan program can be used for a faster and easier coverage determination.

Application of the Avrami equation requires the determination of two parameters which are the indentation radius, r and the shot spread area, A. These two parameters are determined from simple experimental tests.

Application of the Holdgate model requires the determination of the coverage ratio after an initial interval time of shot peening. This ratio is obtained directly from experimental measurements, or can be obtained by regression analysis of peening data. Coverage predictions by the Holdgate model are more accurate than those obtained using the Avrami equation.

Coverage development is faster using fine size shots. At a fixed mass flow rate the number of shots impacting the sample is higher using a fine shot than a coarse shot. Coverage development is faster at an impingement angle of 90^{0} followed by 45^{0} and 30^{0}. The area of shot spread at impingement angle of 90^{0} is smaller than at 45^{0} or 30^{0}. Thus, the number of shots per unit area is higher at a 90^{0} impingement angle. Coverage development is faster in Al2024 compared to Al7150, which is a reflection of the softer Al2024 material. The indentations created by shots impacting Al2024 are bigger than in Al7150, which explains the faster coverage rate in Al2024.

The time taken to achieve 98% coverage in Al2024 and Al7150 is faster than the time taken to achieve saturation in an Almen strip. This was expected because the hardness of the aluminium specimens is lower than the hardness of Almen strips (steel). The ratio of the time taken for 98 % coverage to the time taken for saturation, t_{cov}/t_{sat} was observed to be between 0.10~0.36 for Al2024 and 0.12~0.48 for Al7150. A clear relationship between this ratio and the shot type or angle of impingement could not be obtained.

6 References

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