Coverage:

Development, Measurement, Control and Significance

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Introduction

The prime objective with shot peening is to induce a 'skin' of compressively-stressed material that will improve the service performance of components. A necessary corollary of peening is that the surface is work-hardened by the impacting shot particles. This work-hardening normally improves service performance. On the other hand, excessive work-hardening exhausts the ductility of the surface material, leading to micro-crack formation and a reduction in service performance. As the particles impact the surface, they produce indentations that comprise a proportion of the surface area of the component. The term "coverage" is used to define the proportion of the shot peened surface that has been indented by the impacting shot particles. Hence expressions such as "99% coverage" are meant to indicate that 99% of the surface area has been indented at least once, whilst 1% of the area has not received any impacts at all. Central questions include: "How does coverage develop?" "How can coverage be measured and controlled?" "How does coverage vary?" "What is the optimum coverage" and "How does coverage relate to the required compressive surface residual stress?"

Coverage Development

Coverage development is generally explained using a simple model based on the random production of indentations. This model assumes that identical shot particles impact the surface at a constant rate (measured in impacts per unit area per unit time) producing identical circular indentations and that the indentations are distributed randomly. Fig. 1 shows a schematic representation of coverage developing progressively. In the first second of peening eight circular indentation areas have been produced, sixteen in two seconds, thirty-two in four seconds and sixty-four in eight seconds - equivalent to a constant rate of eight indentations per second. Each indentation has its centre within the outer square and the coordinates of the centres have been assigned using computer-generated random numbers. The inner square gives the true indication of the coverage that has been effected. It should be noted that multiple impacting occurs increasingly frequently as coverage develops.

The total area that has been 'impacted' can be measured using image analysis and, for this specific example, yields values of 15.67, 34.85, 46.87 and 77.10% for 1, 2, 4 and 8s respectively. These values are plotted in Fig.2 together with the coverage curve that relates to an infinitely-large area impacted at the same rate. That coverage curve is based on the Avrami equation (see ref. 1):

$$\text{Coverage}=100[1-\exp(-A.R.t)] \qquad (1)$$

where A=area of each impact, R is the rate of creation of impacts and t is the peening time.

It can be seen that the four experimental points do not lie precisely on the coverage curve. That is because the points refer to a <u>finite</u> sample and the curve refers to an <u>infinite</u> sample. This difference is both subtle and important. By way of analogy, consider the throwing of a perfectly-balanced six-sided dice. With six throws we may or may not get just one 'six'. The observed frequency of sixes' could vary from zero to six out of six throws! If, on the other hand, we threw the dice an infinite number of times then, for a perfect dice, the frequency would average out precisely at one in every six. With a very large number of throws, the frequency would be very close to one in every six.

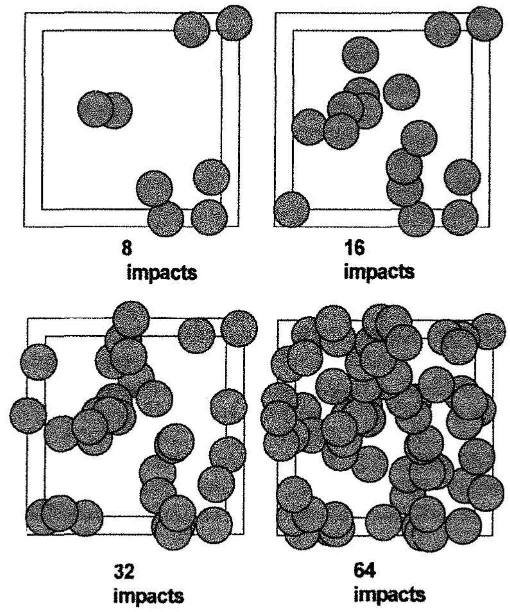


Fig.1 Model of Progressive increase in coverage.

As coverage develops so the number of repeat impacts increases. This is shown in Fig.3. The curves are again derived using an 'Avrami model', where identical, circular, indents are being created randomly, but at a constant average rate, over an infinitely large area (see ref.2). With 90% coverage the 'mode' (commonest) number of times a given spot has been impacted is twice, followed by 1, 3, 4, 5 etc. At 99%, the mode value is 4 and at 99.9% the mode value is 7. At 99.9% coverage, a significant number of regions will have been impacted more than twenty times! The model predicts that 100%

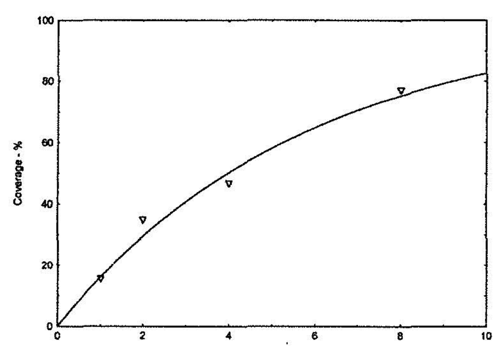


Fig.2 Comparison of coverages measured from Fig.1 with coverage curve prediction.

coverage is never reached - regardless of how long peening has been carried out. That is because we are assuming that an infinitely-large surface area is being peened. With a finite area and a finite number of components, the coverage can be100% but can never be guaranteed. Even with very intensively-peened components, we can only say that there is a high probability of 100% coverage over the whole of the peened area for an individual component.

It is argued here that we should aim at inducing a coverage that is uniform (in a macro sense) but which has an average value significantly less than 100%. There will be an optimum coverage value, below which represents under-peening and above which represents over-peening. This optimum value will depend largely on the material being peened. It should be remembered that the prime objective of peening is to produce a compressive 'skin' that optimises service properties, not the vain pursuit of trying to guarantee 100% coverage. That pursuit would involve excessive peening of the component, with the concomitant likelihood of exceeding the ductility of the material and reduction of the benefits of peening.

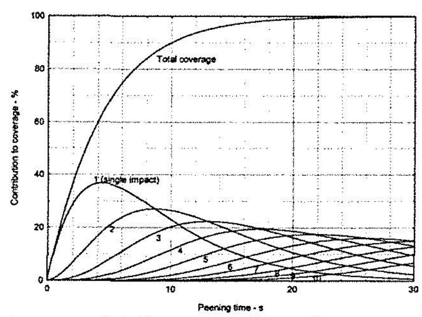


Fig.3 Contributions of different numbers of impacts to total coverage.

Coverage Control and Measurement

The first problem in controlling coverage is to be able to measure it accurately. Fig.4 shows a lightly-peened specimen at approximately 10x magnification. Because there are substantial areas of unpeened surface, it is possible to make reasonably-accurate measurements on the specimen. Quantitative measurements on such specimens can readily be made using image analysis procedures. Measurement becomes difficult and eventually impossible, however, as coverage approaches 100%. The measurement problems are exacerbated by the unpolished nature of the original surface. Manufacturers will not polish their components just to help coverage measurement! The unevenness of peened surfaces is the most important problem, especially as it prevents uniform focussing. Overlapping dimples have blurred edges that may, or may not, hide tiny unpeened areas.

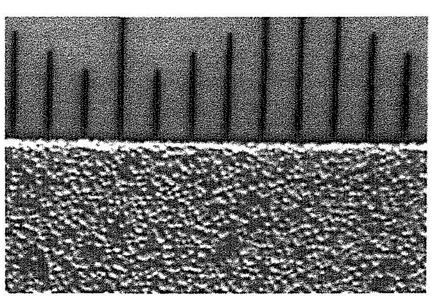


Fig.4 Aluminum specimen peened to 34.8% coverage using S170 shot, viewed at 10x magnification together with a metric ruler having millimetre graduations.

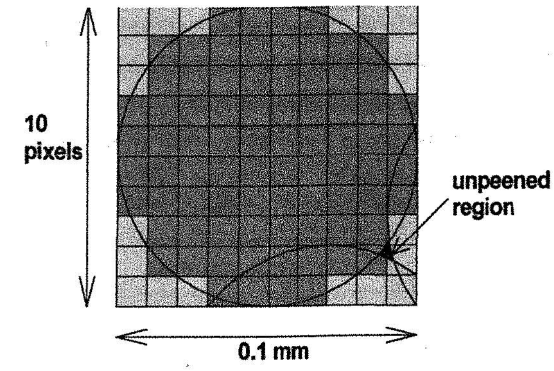


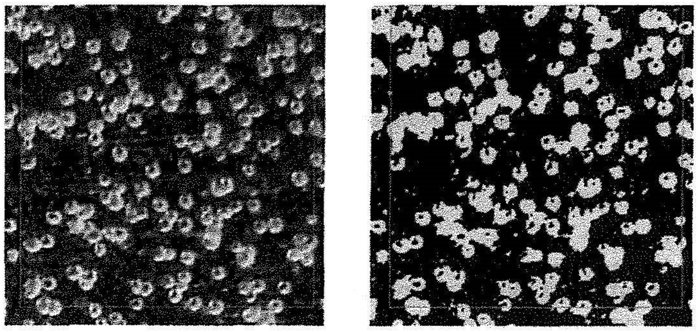
Fig.5 Pixellation of a 0.1mm diameter indent, together with overlapping indents and unpeened region.

It is obviously impossible to measure infinitesimally-small unpeened areas. Measurements involving very small unpeened areas will also be impossible using current technology. Consider, for example, a 10mm by 10mm area that is to be photographed for examination at 10x magnification. The 'on-screen' size of the image at 10x magnification will be 100mm by 100mm. Assume that the camera has a capability of recording a 1 megapixal image. That is equivalent to a 1000 by 1000 pixel square image. Hence, each square millimetre of specimen surface corresponds to 100 by 100 pixels. If we now consider indentations made by, say S110 or S170 shot, the indent diameter will be in the region of 0.1mm. That, then, corresponds to a 0.1mm diameter circle inscribed within a square that is imaged by just 10 pixels by 10 pixels. Fig.5 shows a representation of that situation.

If (and it is a very big 'if') the camera were capable of perfect separation of peened and unpeened regions then the indent would appear as the darker pixels (in monochrome) - giving a 'jagged circle'. The 'unpeened region' developed between three overlapping indents, shown in Fig.5, is less than one pixel in any direction and therefore could not be detected. The area of the single 'unpeened region' shown is about 0.1% of the total 0.1 by 0.1mm area. Hence, we see that we could not determine whether the coverage was above 99.9%. Indeed, with ten such small unpeened areas in the overall square we cannot even determine if 99% coverage has been reached.

The precision of quantitative image analysis coverage measurements depends upon the quality of the original image. A low quality image, seen as Fig.6 (a), has been deliberately used in order to illustrate the problems that may arise. The corresponding binary image, shown as Fig.6 (b), is unable to distinguish between the reflectivity of the unpeened areas and the bottom of the indents. Hence, 'dots' appear in the centre of most of the indent images. Accurate analysis of the image would have to be based on only measuring the enclosed area' of each identified indent (hence including the 'dots3 and also ignoring the specks between the indents. Far better, and easier, is to have a good quality image to work on!

Reliable measurements can, however, be made on surfaces that contain a substantial proportion of unpeened area. It is therefore proposed that coverage control can, and should, be based on measurements made on surfaces that have received much less than 99%. The following case study is intended to show how such control could be exercised.



(a) (b)

Fig. 6. Optical image (a) and binary image (b) of aluminum peened with S170 shot, 10x magnification.

Case Study of Coverage Control

A component is to be peened using four identical passes with the aim of imparting precisely 99.9% coverage. The only variable that can be used for control purposes is the rate of flow of shot. Polished strips of material, that are identical in composition and properties to that of the component, are available.

The first step could be to fit a polished test strip into the peening facility - in a similar way to that of fixing Almen strips. The strip is given a single pass at a known, intermediate, rate of shot feed. After peening, several areas of the strip are photographed and image analysed for coverage. The average coverage was found to be, say, 74.6%. We can substitute that value into the Avrami coverage equation (1) to give:

$$74.6 = 100[1-\exp(-A.R.1)] \qquad (2)$$

where the second '1' represents the first pass of the four that are to be applied; A, the area of each indentation, is assumed to be constant and R is directly proportional to the rate of flow of shot.

We can easily solve equation (2) giving us a value for A.R of 1.3548. That value can then be fed back into equation (2) - together with 2, 3 and 4 to represent the subsequent passes. That then gives us the total coverages that will have been imparted at each pass - 93.344, 98.283 and 99.55% for 2, 3 and 4 passes (at the A. R rate of 1.3548). The coverage after four passes is therefore less than the required 99.9%. We then substitute the required 99.9% into the equation to find the value of A.R that will give us 99.9% coverage. This yields a required A.R value of 1.7269. Comparing that value with 1.3548 tells us that we need to increase the flow rate by some 27.5% in order to achieve precisely 99.9% coverage from four passes. The actual calculations made by the author are shown in Fig.7 where "x" has been used for the initial A.R combination and "y" for the required, adjusted, A.R rate.

If the required coverage had been 99.99% rather than 99.9% then the shot flow rate would have had to be increased by 70.0% (derived using the same procedure as before). For 99.999% coverage the procedure predicts a required increase in shot flow rate of 112.4%. It should be noted that such very high coverage values would very probably exceed the value required for optimum service performance enhancement. Note that 'A' has been assumed to be constant throughout each pass. A more sophisticated equation than (1) can be used which would accommodate the probable progressive reduction in dimple size, A.

Mathcad Worksheet for Peening Coverage

$$100(1-\exp(-1\cdot x)) = 74.2$$

1.3548

$$100(1-\exp(-2\cdot 1.3548)) = 93.344$$

$$100(1-\exp(-3\cdot 1.3548)) = 98.283$$

$$100(1-\exp(-4\cdot 1.3548)) = 99.557$$

$$100(1-\exp(-4\cdot y)) = 99.9$$

1.7269

$$\frac{1.7269-1.3548}{1.3548} = 0.275$$

Fig.7 'Mathcad' worksheet used to predict required change in shot flow rate.

Coverage and Surface Residual Stress

Shot peening of components induces a two-dimensional, highly-beneficial, compressively-stressed surface layer over the whole surface. One major reason why shot peening is so consistently effective is that it is such a 'forgiving' process. By that it is meant that a complete protective skin of compressive residual stress is inevitable provided that the coverage does not fall to a very low value in any critically-stressed region. Hence, we can always expect improvements in service performance by the shot peening of components. The presence of small areas that have not been impacted does not mean that there are 'weak points' in the surface. That is because it is not the dimples that generate the compressively stressed areas but rather the deformation zone under and around the dimples. Fig.8 shows a single impact area, its adjacent deformation zone and a representation of the concentric 'envelope' of compressively-stressed material. The level of compressive stress falls the further it is from the centre of the impact area.

The intention with Fig.8 is simply to illustrate that both the impact area and the deformation zone have <u>finite</u> dimensions whereas the envelope is <u>infinite</u> (no specific border). The finite dimensions of the impact area are determined by the shot size, energy, material strength, etc. The finite dimensions of the surrounding deformation zone are determined by how far from the impact centre the yield strength has been exceeded - there is therefore a sharp 'cut-off' for plastic deformation. Compressive residual stress values, on the other hand, fall progressively with distance from the <u>centre of the impact area</u> i.e. the maximum compressive stress values will be under the impact area. The fall in stress magnitude away from the

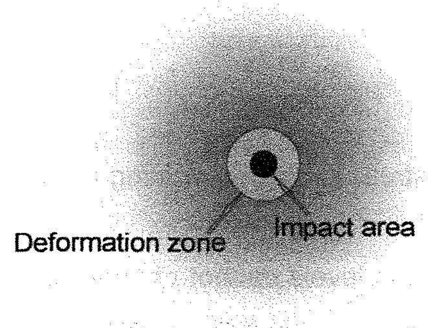


Fig.8 Schematic representation of impact area, deformation zone and surrounding compressively-stressed envelope.

impact area is represented in Fig.9, by means of concentric isostress circles and includes several impact areas - in order to illustrate overlapping stress contours. Due to the "principle of superposition of stresses", the overlapping stress contours will merge to form a continuity of residual compressive stress over the surface. If the pre-peened surface contained tensile residual stress then that is replaced by the compressive residual stress induced by peening.

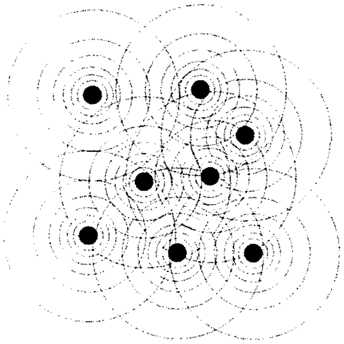


Fig.9 Overlapping compressive isostress circles emanating from several impact zones.

Another important factor is that stress levels cannot change abruptly. It is therefore physically impossible to have regions of tensile surface residual stress, or even regions of very low compressive residual stress, in a shot peened component that has been given a uniform, substantial, coverage.

Discussion and Conclusions

The preceding arguments lead to three main conclusions:

1. That there is no need to try to achieve very high coverages for peened components,
2. Effective coverage control can be exercised by measuring the coverage at an early stage, invoking the appropriate coverage formula and then controlling the shot flow rate for a given peening regime and
3. There is an important difference between finite and infinite estimates of coverage.

Accurate measurement of very high coverages is not possible. It would be difficult to imagine a defensible procedure that claimed to identify, let alone ensure, 100% coverage over the whole surface of a peened component. It is important that the optimum coverage should be established for different materials working in different types of service condition. That is because the prime objective is to induce a compressively-stressed surface 'skin' that optimises service properties. Over-peening will lead to a deterioration of the peened surface, due to the exhaustion of ductility. Under-peening, on the other hand, will correspond to the surface not reaching optimum hardness (by work hardening) and a consequent reduction in the thickness of the 'skin' of compressive stress. It is reasonable to suppose that, for many materials, the optimum coverage will be less than 90%.

Quantitative coverage control could become an effective tool in precision shot peening. A fundamental advantage is that the coverage/peening time curve has such a simple shape with the corresponding Avrami equation having only one variable - assuming fixed dimple diameters. That compares with the complex shape of an Almen saturation curve, which requires three or four parameters for accurate analysis. Hence, only one measurement is needed to predict the progress of the coverage/peening time curve - for constant peening conditions. The use of fixed dimple diameters is a simplification and real peened areas contain dimples with a range of diameters. That does not invalidate the argument that final coverage can be predicted from an intermediate stage of peening. The constant diameter concept can be equated with the average diameter of a range of dimple sizes.

It has been shown that control based on small, but accurate, changes in the shot flow rate could be very efficient. As with most acceptable control procedures it is necessary to have reference standards. Quantitative chemical analysis, for example, relies upon having a range of standard specimens of known composition. Measurements are then expressed relative to that of the nearest available standard.

Reference standards for the coverage control procedure outlined in the case study should include:

1. A set of standard' digital photographs of different materials peened to different, agreed, coverages. The image analysis procedure could then be regulated to match the standards.
2. A set of standard peened specimens, again of different materials peened to different, agreed, coverages. The imaging/analysis technique could then be regulated.

The accuracy of coverage measurements would be improved by employing test strips, of the component material, that had been polished, or at least fine ground. Image analysis procedures should allow for a large number of impact areas to be measured at one time. That is in order to smooth out the difference between a finite sample size and the value predicted for an infinitely-large sample.

Uniformity of coverage over the whole surface is important. This can also be monitored more effectively if measurements are made at intermediate stages of peening.

Finally, coverage and peening intensity (as measured by means of Almen saturation curves) are not the same thing. They reflect different aspects of peening control. An accurate knowledge of coverage for a peened component will relate to the integrity of the protective skin' of compressive residual stress. In addition, measurements of coverage refer to the component material itself. Peening intensity, on the other hand, refers to the 'severity' of peening applied to Almen strips - which are, necessarily, of a standard steel specification and condition.

References

1 Kirk D and Abyaneh M Y. Theoretical Basis of Shot Peening Coverage Control, Proceedings of the Fifth international Conference on Shot Peening, Oxford, 1993, pp 183-190.

2 Abyaneh M Y and Kirk D, Fundamental Aspects of Shot Peening Coverage Control Part Three: Coverage Control versus Fatigue, Proceedings of the Sixth international Conference on Shot Peening, San Francisco, 1996, pp 456-463.