Non-Uniformity of Shot Peening Coverage

INTRODUCTION

It would be very desirable if shot-peened components could have a uniform coverage of indentations. Unfortunately this is impossible to achieve. As a shot stream passes over a component's surface it induces non-uniform coverage. This is due to the variation of the indent ratio, Ar, that the stream imposes. Coverage is the effect that is caused by a particular indent ratio.

Indent ratio, **Ar**, is the ratio of total area of indents to target area. If $100mm^2$ of indents are imposed on a component target area of $100mm^2$, the **Ar** ratio is **1·0** but only induces a coverage of **63%**. With $400mm^2$ of indents imposed on a target area of $100mm^2$ the ratio is **4·0** which induces a coverage of **98%**.

Indent ratio, **Ar**, is the product of three factors, **peening time**, **t**, **average area of the indentations**, **a**, **and indenting rate**, **n**. Hence:

$$Ar = t * a * n$$

All of the three coverage controlling factors (**t**, **a** and **n**) vary everywhere on a peened component's surface.

Coverage – defined as the percentage of surface area indented at least once – is a beguiling parameter. That is for two reasons. Firstly, for peened components, it normally varies by only a few percent and secondly it often appears not to vary at all! Indent ratio, **Ar**, on the other hand is an effective control parameter. For example, doubling the peening time will double the indent ratio.

This article aims to show how indent ratio must vary with position on a peened component's surface. The variation of indent ratio is then translated into corresponding variations of coverage. Indent ratio variation is primarily due to the geometrical interaction between a shot stream and a component's surface. Ways of homogenizing indent ratio (and therefore coverage) are suggested.

SHOT STREAM INTERACTION WITH FLAT SURFACE

The simplest peening geometry is that of a right circular cone shot stream moving across a flat plate component. Fig.1(a) is a pictorial

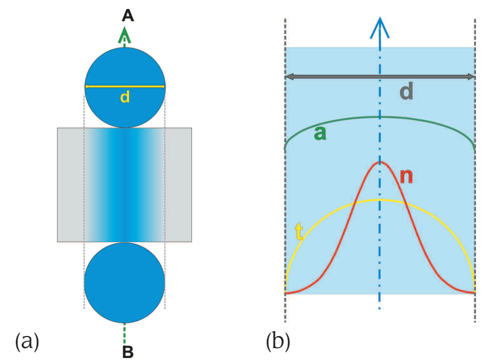

*Fig.1. Variation of (a) coverage across a shot-peened trace and (b) factors contributing to indent ratio, **Ar**.*

representation of the coverage produced by passing a shot stream of diameter, **d**, in a straight line, **B** to **A**, across a flat plate. Coverage is most intense on the center-line because that is where the indent ratio, **Ar**, is highest. Fig.1(b) is a schematic representation of the variation of the three factors contributing to **Ar**.

t is the amount of time that the shot stream is in contact with any particular spot on the component. For a circular-section shot stream that time varies precisely as a semi-circle.

n is the number of indents being produced per unit area per unit time. This is known to vary as an approximate 'normal distribution''.

The average area, **a**, of the indentations will be lower at the edges of the indented region than at its center. That is mainly because the shot particles at the surface of the shot stream cone travel more slowly than those at its center.

INTERACTION OF INDENT PARAMETER VARIATIONS

Indent ratio, **Ar**, is the product of the three contributory parameters t, a and n. Using fig.1(b) as a model indicates that the product varies as does a 'normal distribution' – albeit with 'lopped-off tails':

$$Ar = Ar_{max}*[\exp(-(x-50)^2/400)] \quad (1)$$

where Ar_{max} is the maximum value of **Ar**, **x** is the position of **Ar** across the trace in % and **50** is the center of the normal distribution.

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Fig.2 shows the 'normal' distribution predicted by equation (1) when $\mathbf{Ar_{max} = 4}$. The inclusion of the coverage levels illustrates the considerable difference between indent ratio variation and coverage variation.

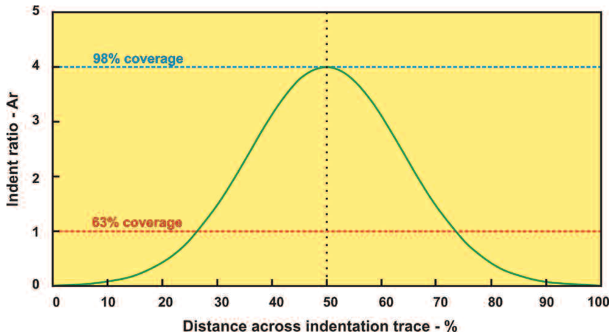

Fig.2 Model of indent ratio variation across an indent trace when Ar_{max} is 4·0

RELATIONSHIP BETWEEN INDENT RATIO AND COVERAGE

The known relationship between coverage, **C**, and indent ratio, **Ar**, is that:

$$\mathbf{C\% = 100[1 - exp(- Ar)]} \qquad (2)$$

Substituting the value of **Ar** from equation (1) into equation (2) gives that:

$$\mathbf{C\% = 100[1 - exp\{-Ar_{max}*(exp(-(x-50)^2/400))\}]} \qquad (3)$$

Equation (3) allows us to estimate the variation of coverage across shot peening traces and is plotted as fig.3 for different values of $\mathbf{Ar_{max}}$. Here a first pass, 1, has $\mathbf{Ar_{max}}$ = 1 with a maximum coverage on the centre-line of 63%. This first pass gives a coverage that varies widely across the peened trace. Subsequent equal passes, 2 to 7, impose increasingly uniform coverage about the centerline.

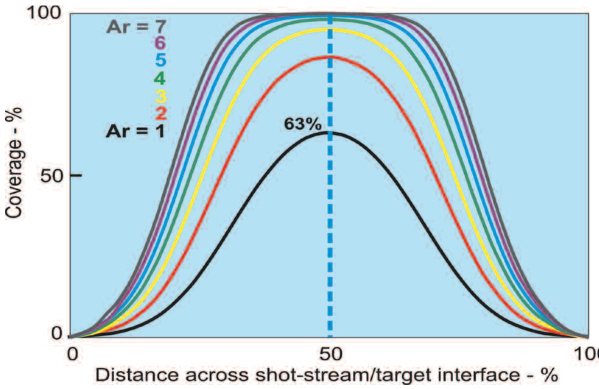

*Fig.3 Effect of maximum indent ratio, **Ar**, on coverage variation across the interface between a uniform conical shot stream and a flat target.*

An indent ratio, **Ar**, of 4 imposes a <u>maximum</u> coverage of 98%. It follows that a larger indent ratio would be needed to achieve "full coverage" (98%) over a reasonable fraction of the stream/target interface. Fig.4 contrasts the variations of indent ratio and coverage when $\mathbf{Ar_{max} = 6}$.

The variations of coverage shown in figs.1(a) and 4 are substantial. They reflect what happens in practice. Passing a conical shot stream over a flat plate component is analogous to trying to paint a wall using a round paint brush – coverage variation is then all too obvious. As with

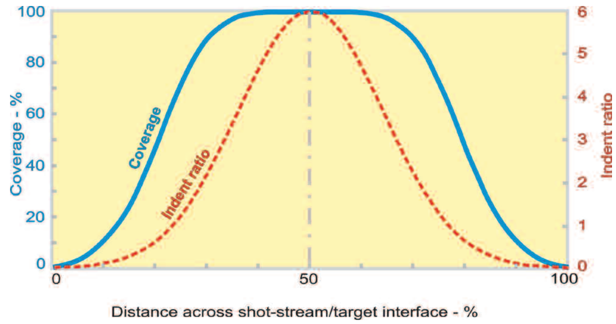

*Fig.4 Variation of Coverage, **C**, and Indent ratio, **Ar**, across a peened trace when $\mathbf{Ar_{max} = 6}$.*

the analogy, a more uniform coverage is achieved by using a series of overlapping parallel strokes/passes.

OVERLAPPING SHOT STREAM PASSES

Components are normally peened by using several passes which involve overlapping. There must be some degree of overlapping in order to avoid having completely unpeened areas. It is the degree of overlapping that is important. Fig.5 represents three degrees of overlap – 50, 60 and 70%. When dealing with this problem it must be noted that only **Ar** values are mathematically additive. <u>We cannot simply add coverage values</u>.

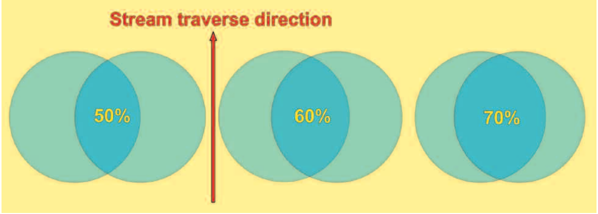

Fig.5 Model of parallel shot streams overlapping by 50, 60 and 70% of their diameters.

Fig.6 is a pictorial representation of the variation in coverage, caused by overlapping of parallel passes. The 'stripe effect' can only be observed on peened components when low coverage values have been applied. That is because we cannot normally distinguish between a 'high degree of coverage' and a 'very high degree of coverage.' If, however, the **Ar** ratio varies between say 1 and 2, then coverage varies from about 63% to 86% - which is normally detectable.

Fig.6 Representation of variation of coverage for overlapping parallel passes.

Quantification of coverage variation due to overlapping requires the application of equation (3). The following is an example that illustrates how such an application can be carried out.

Example: Effect of Parallel Pass Separation on Coverage Variation When a Nominal "100% Coverage" is Specified. Parallel passes will have normal distributions that have different centers. Equation (3) can be modified to accommodate these different centers:

$$\mathbf{Ar = Ar_{max}*[exp(-(x-d)2/400)]} \qquad (4)$$

where **d** is the position of the pass center - as a % of shot stream width.

The first pass will have a **d**-value of **50**. A **d**-value of **150** for the second pass would be too large - the passes would touch rather than overlap. As a first guess we can assume an overlap of 50%. Hence we have a **d**-value of 100 for the second pass, 150 for the third parallel pass and so on. The combined **Ar** values with $\mathbf{Ar_{max} = 5}$ are then:

$$\mathbf{Ar = 5\ [exp(-(x-50)^2/400) + exp(-(x-100)^2/400) + exp(-(x-150)^2/400) + ...]} \qquad (5)$$

Substituting the value of **Ar** from equation (5) into equation (3) and then plotting gives the coverage variation shown in fig.7. The coverage varies in a cyclical manner from a maximum of 99% to a minimum of 87%. Repeating the exercise with a greater overlap, 60%, gives the result (also shown in fig.7) that coverage now varies from 99% to 97%. This might, or might not, be regarded as satisfying an overall "100% coverage requirement." Increasing the overlap to 70% certainly satisfies the requirement - the coverage <u>minimum</u> exceeds 99%. It is significant that the 'Coverage period' of the cyclical fluctuation of coverage is equal to the separation of the parallel stream centers.

It may be concluded that an overlap of between 60 and 70% is required to satisfy the specification.

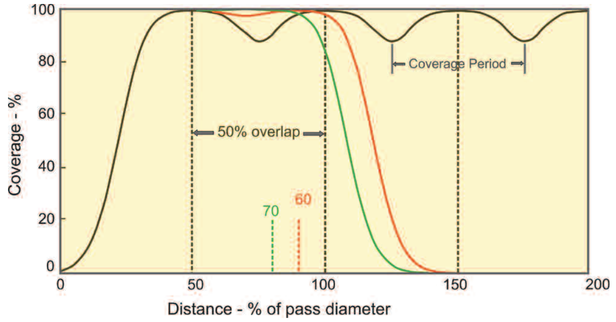

Fig.7 Effect of degree of overlap on coverage induced by parallel passes.

MULTIPLE INDENTATION, INDENT RATIO AND COVERAGE VARIATION

The greater the indent ratio the greater are both the coverage and the degree of multiple indentation. Fig.8 indicates the effects on multiple indentation of applying two different indent ratios – 4 and 8 – inducing coverages of 98.2 and 99.97% respectively (both being above "Full coverage" of 98%). The <u>average</u> number of indentations has doubled with doubling of the indent ratio. More significant, however, is that a significant percentage of the surface suffers at least 14 indentations when **Ar** equals 8.

Indent ratio and coverage both vary when overlapping shot stream passes are applied. Harmful indent ratios may occur due to either repetition or overlapping of shot stream passes having high **Ar** values.

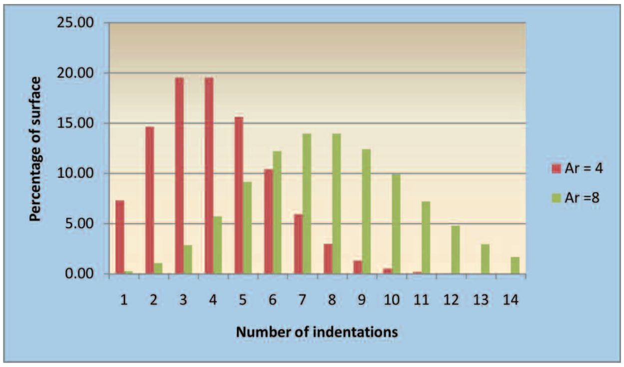

Fig.8. Percentage of surface receiving different numbers of indentations.

DISCUSSION and CONCLUSIONS

Practical shot peening is multifarious in that a wide variety of component geometries and materials are involved. Skill and ingenuity are required in order to achieve acceptable levels of coverage and intensity at all specified locations. The concepts described in this article show why it is impossible to achieve absolute uniformity of coverage.

Coverage variation due to shot stream/flat surface interfacing has been analyzed. The unavoidable coverage variation that occurs for that situation would be greater if the shot stream was angled to the component's surface. A circular impacting area then becomes elliptical – enhancing the 'sharpness' of the normal distribution of indent ratio. Wheel-blast peening would be predicted to give even greater coverage variation - because of both angling and the enhanced shot stream 'hot spot' that is present – if applied to a large flat area.

A circular-section shot stream imparts a wide range of indent ratios and corresponding coverage levels. This is particularly significant when identical passes are to be made over the same region of a component. One familiar example is that involving the generation of Almen saturation curves. It is important that the axis of the shot stream is aligned with the major axis of the Almen strip – centralizing the 'stripe' of coverage. Misalignment will induce eccentric coverage relative to the major axis – hence affecting arc height.

The prime objective with shot peening is to induce a compressively stressed surface layer that enhances service performance of components. Coverage and intensity level attainment are secondary objectives. A completely continuous compressively-stressed surface layer is generated at coverage levels well below 50%. The magnitude of the residual compressive stress increases with coverage to a maximum value and then falls as 100% is being approached. That is consistent with the growing evidence that optimum service performance normally occurs at coverage levels below 98%. It follows that coverage variation about an optimum level is better than exceeding the optimum level at all points of the shot-peened surface.