# RELATIONSHIP BETWEEN COVERAGE AND SURFACE RESIDUAL STRESS



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## ABSTRACT

Controlled, uniform, peening has been used to impose precise coverage percentages onto mild steel plate specimens. This was achieved by using an X-Y table to move the specimens under a single, precision-loaded, 2mm diameter indenter. X-ray studies have revealed a surprising relationship between percentage coverage and surface residual stress. Stress increases almost linearly with low coverages but reaches a maximum at about 80% coverage. At 100% coverage the induced compressive surface residual stress is about 20% lower than at the maximum. The as-received steel plate contained a low level of tensile surface residual stress. The maximum surface stress of about –350MPa is well above the tensile test yield strength for mild steel. Traverses were carried out at 90° to one edge of rectangular peened regions and to rows of overlapping indentations. It was found that compressive surface residual stress extends well into the unpeened regions. A model is presented to explain the character of the observed surface stress profiles.

Coverage, residual stress, stress modelling.

## INTRODUCTION

A pivotal problem in shot peening is to decide upon the optimum coverage that should be applied. Recent developments indicate that much less than the nominal "100%" is to be preferred for certain applications. A primary objective here is to investigate how the level of surface compressive residual stress changes with applied coverage. The effect of coverage on residual stress profiles has been established (Prévey and Cammett (2002). Tange and Okada (2002) have also studied the effects of coverage. Many applications involve masking of regions that are not to be peened. A secondary objective is, therefore, to establish how far compressive residual stress extends from the peened into the unpeened regions. X-ray residual stress measurement was selected as offering the most reliable and precise method of measuring surface stress variation. Mathematical models will be used to analyse observed stress variations.

## EXPERIMENTAL METHODS

A standard commercial grade of 40mm by 3mm rectangular-section hot-rolled mild steel was used throughout the experimental studies. This offered the advantage of being virtually stress-free in the as-received state and was known to have consistent properties for large lengths of material.

X-ray residual stress measurements were carried out using chromium $K_\alpha$ radiation that provides a stress-sensitive 211 diffraction profile for ferritic steels at about 156° 2θ. This procedure is very well established (Prévey, 1986). Two crossed pairs of divergence slits were used to control the shape of the irradiated area. Step-scanning diffractometer data was computer analysed to output values for residual stress and accuracy precision. A micrometer table was used to move each specimen along the diffractometer stage in steps of the required length.

An unusual procedure was used to produce controlled coverage percentages. An X-Y table moved the mild steel specimens under a single, 2mm diameter, indenter precision-loaded to 70kgf. This allowed rectangular arrays of 0.67mm diameter indentations to be produced. A major edge of each array was to be aligned with the line side of the irradiated area. Fig.1 shows typical arrays, which correspond to coverages of 35·3 and 99·7%.

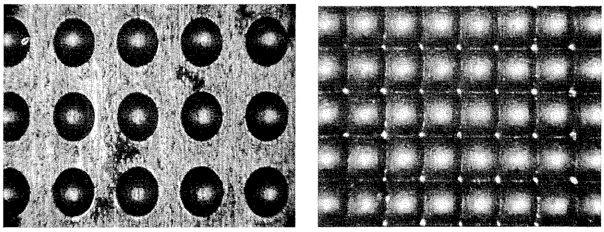

Fig.1 Ordered arrays of 0.67mm diameter indentations in mild steel, 2mm diameter indenter, 70kgf load, 1·0 and 0·5mm separations, 35·3 and 99·7% coverages respectively.

**EXPERIMENTS AND RESULTS**

Five arrays of 0·67mm diameter indentations on mild steel were produced. These square-pattern arrays had indentation spacings of 2·00, 1·50, 1·00, 0·71 and 0·50mm corresponding to coverages of 8·8, 15·7, 35·3, 70·5 and 99.7% respectively. X-ray surface residual stress measurements were made using 4mm by 4mm irradiated areas at the centre of each array. Stress values as a function of coverage are presented in fig.2 and as a cubic function. The variation is initially fairly linear, reaches a maximum compressive stress level at about 80% coverage and thereafter falls.

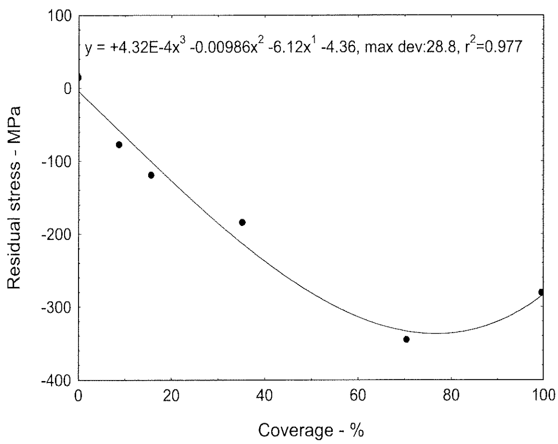


Fig.2 Variation of surface residual stress with coverage for mild steel.

Surface residual stress profiles were produced for several of the peened specimens used in the preceding experiment. The irradiated area was reduced to a line 12mm long by 1mm thick. This area was moved incrementally along a measurement line as shown in fig.3.

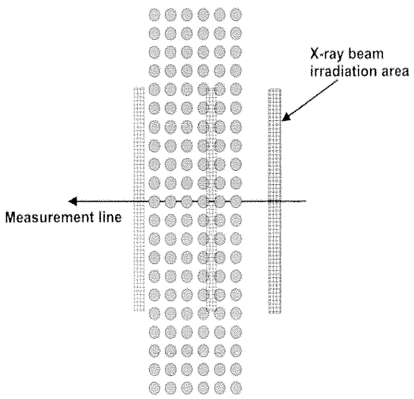


Fig.3 Schematic scale drawing of X-ray beam area and relative movement.

The primary objective was to determine the variation of induced residual stress with distance. Measurement values are shown in fig.4 for the 0·50mm spaced indentation specimen, together with a superimposed representation of the peened area – to scale.

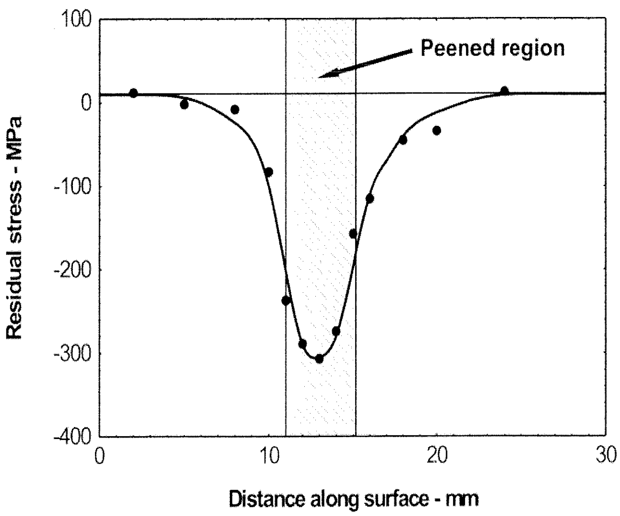


Fig.4 Residual stress profile, 0·67mm indents, 0·50mm separation, 99·7% coverage.

It can be seen from fig.4 that the compressive surface residual stress extends well outside the peened area. The extension is approximately 5mm on either side. That corresponds to some fifteen times the radius of each indentation. Similar stress extensions were found for the other specimens in the series.

Single rows of overlapping 0·67mm diameter indentations into mild steel were produced, as illustrated in fig.5.

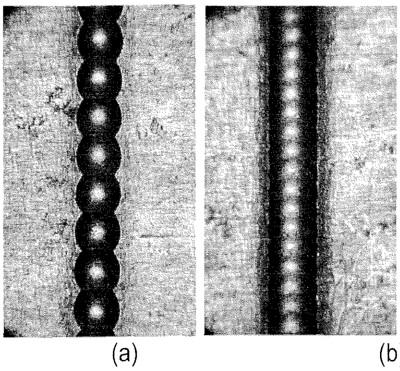


Fig.5 Single rows with 0·67mm diameter indentations separated at 0·50 and 0·25mm intervals for (a) and (b) respectively.

X-ray surface residual stress profiles were obtained by using incremental movements along measurement lines at 90° to the rows. The objective was to separate the effect of having adjacent rows of arrayed indentations. For these measurements the specimen-irradiated area was reduced to 4mm by 1mm (normal to the indentation line). Two traverses were made on the specimen having 0·25mm separation (shown as (b) in fig.5). The corresponding measurements are presented in fig.6. Very similar stress profiles were obtained for the 0·5mm separation row.

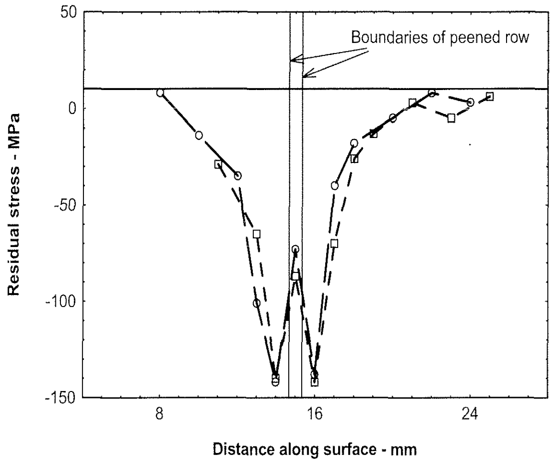


Fig.6 Surface residual stress profiles for single row of indentations in mild steel.

There are two outstanding features of the residual stress profiles. The first is that compressive stress has been induced for a distance of some fifteen times the indent radius on either side of the peened row. Secondly, it appears that the compressive stress level is lower in the centre of the peened row than it is on either side. The similar profiles found for the specimen with 0·50mm indentation separations showed that the effect is reproducible.

## MODELLING OF RESIDUAL STRESS PROFILES

The variation of surface residual stress adjacent to a peened area can be modelled using a 'normal distribution' type of equation. Equation (1) shows such an equation that is appropriate for the profiles presented in fig.6:

$$\sigma = -140\,(\exp\,(-(d\hat{}2)/10) + S \qquad (1)$$

where $\sigma$ is residual stress, $d$ is distance from edge of peened area and $S$ is the stress level of the unpeened material.

A plot of equation (1) is given in fig.7.

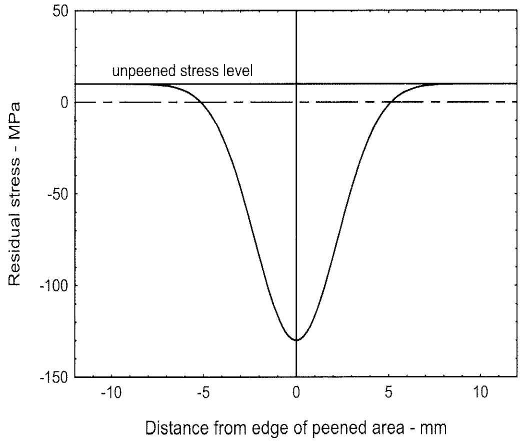


Fig.7 Stress profile adjacent to peened area as represented by a normal distribution.

The surface residual stress distribution across a peened area can be modelled by adding contributions from separate normal distributions. Fig.8 shows such a representation based on a narrow peened region with isolated indentations. Stress profiles from individual indentations add together to form the composite stress profile.

## DISCUSSION AND CONCLUSIONS

It is well-established that peening produces a surface layer that contains a high level of compressive residual stress. That stress is caused by the inhomogeneous tensile plastic deformation surrounding and under indentations. This research indicates that the relationship between induced compressive surface residual stress and the percentage coverage is not linear.

A maximum average surface compressive residual stress occurs at well below 100% coverage. That is very significant and merits further study. At this stage the reason for the effect is not clear. It is reasonable, however, to associate repeated tensile plastic deformation with a degree of stress relief.

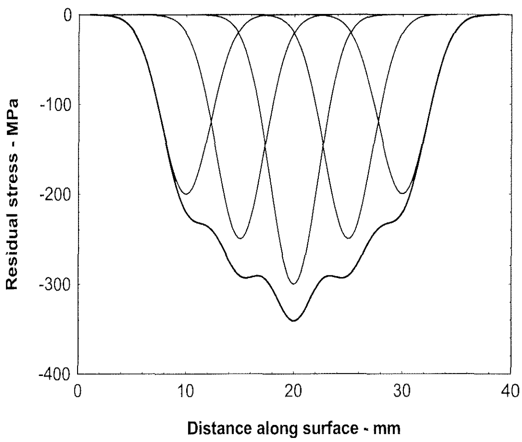


Fig.8 Model of surface residual stress distribution for a narrow peened region with separated indentations.

Observed residual stress levels exceed the nominal yield strength of the mild steel used because of the severe work-hardening imposed by peening. The use of 'uniform' rather than 'random' indentation has allowed extremely precise coverages to be applied. The size of indentation used in this research is larger than that used for most commercial peening operations. It is to be expected, however, that the spread will be directly proportional to the diameter of the indentations. A significant difference between uniform and random peening lies in the number of multiple indentations that occurs. With uniform peening, 99·7% coverage was achieved with no area receiving more than double indentation. The total area of indentations applied was only 1·4 times the area of coverage. With random peening at 99·7% coverage the mode value of indentations is seven.

The observed spread of induced surface compressive residual stress away from the edges of peened areas is significant. Residual stresses, as with all elastic stresses, cannot change abruptly. That means that the unpeened regions in components with more than 90% coverage will still have high levels of compressive residual stress. The change in stress level adjacent to a peened area has been simulated by a normal distribution. That normal distribution has a spread characterised by a standard deviation of approximately 2·2mm for 0·67mm diameter indentations.

Future research will include studying the separate effect of mutiple indentation. Repeating the number of complete coverage arrays can precisely simulate multiple indentations.

## REFERENCES

[1] Prévey, P S and Cammett, J T, The Effect of Shot Peening Coverage on Residual Stress, Cold Work and Fatigue in a Ni-Cr-Mo Low Alloy Steel, Proc. ICSP8, 2002, p295.
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[3] Prévey, P S, Metals Handbook, **10**, p380.