X-RAY STUDY OF THE INHOMOGENEITY OF SURFACE RESIDUAL STRESSES AFTER SHOT-PEENING TREATMENT

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ABSTRACT

It is well known that shot-peening treatment increases the fatigue resistance of metals. It is considered that this effect is caused by compressive residual stresses arising in the treated surface. Usually the mean value of residual stress is taken into consideration to explain this phenomenon but the real residual stress state must be inhomogeneous due to the inhomogeneous character of deformation around the shot-peening indentation and due to the rough character of the shot-peened surface. In the present paper the following investigations were undertaken to analyse the inhomogeneity of the residual stress state after shot-peening:

1. Residual stress measurements at the bottom and top of a Brinell indentation, simulating a shot-peening indentation, were made with local X-ray diffraction.
2. The measurements of residual stresses in the peaks of roughness of a shot-peened surface were carried out. The experimental results permit the explanation of the specific character of the residual stress distribution in the surface layer after shot-peening.
3. Analysis of the specific behaviour of residual stress depending on a removed surface layer at the initial stage of the stress distribution curve.

INTRODUCTION

Shot-peening is the prevalent surface treatment for metals to increase the material’s resistance to fatigue failure or to corrosion attack. The general opinion is that increased resistance is caused by the compressive residual stresses arising after surface treatment. Nevertheless, this point of view needs refinements with regard to the character of surface deformation during shot-peening. The shot-peening action is a process of multiple indentation of a metal surface by small spheres. The inhomogeneity of plastic deformation in the indentation region follows from the nature of indentation and, as a result, this leads to an inhomogeneous distribution of residual stresses across the surface. Thus, to explain the increase in fatigue resistance caused by compressive residual stresses it is necessary to take into account the inhomogeneity of the stress distribution too.

Another problem is the influence of surface relief on residual stress measurements. The most frequently used stress measurement method to analyse the stress state of a shot-peened surface is the X-ray diffraction method. Because of the limited penetration X-rays into the metal this method is sensitive to surface relief [1,2].

Thus, the problems of measuring of residual stresses introduced by shot-peening treatment, include the analysis of the residual stress distribution of the type associated with a Brinell indentation region, and interpretation of experimental results in the case of stress measurements on a macroscopically rough surface. All these questions are analysed in present paper.
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METHODOLOGY AND EXPERIMENTAL RESULTS

Specimens of 100x100x30 mm³ were prepared for the Brine indentation investigation from ASTM A387 Gr5 steel plate. These specimens were subjected to indentation by a steel ball of 10 mm diameter. A force 70 kN produced an indentation 6 mm in diameter and 0.99 mm in depth. Figure 1a shows the deformation profile of a Brinell indentation.

Figure 1. Distribution of plastic deformation (a) and residual stress (b) across the Brinell indentation; \( \sigma_r \) and \( \sigma_t \) radial and transversal stress components.

X-ray stress measurements were made at the bottom of indentation and along its radius for points at a distance of 0.2 mm, 1 mm, 2.5 mm and 5 mm from the imprint edge. The incident beam size was 0.3x2 mm and two stress components in radial and tangential directions were measured by the \( \sin^2\psi \)-method [3]. (211) reflections using Cr-Kα radiation were examined to measure residual stresses. Experimental results of the residual stress distribution are presented in figure 1b. It is clear that residual stresses are different at the bottoms and on the peaks of surface relief features. Other plate samples, 3 mm in thickness, 200 mm long and 15 mm in width, were prepared for loading to determine stress-strain curves and to undertake the shot-peening treatment. The mechanical properties of the steel were determined from the stress-strain curve; yield stress is...
equal to 260 MPa and tensile strength to 450 MPa. The shot-peening treatment was performed using steel balls 0.7 mm in diameter; the velocity of balls was 0.14 m/sec. The treated surface is represented in figure 2. The mean diameter of the shot-peening indentations is 0.25 mm and the average height of indentation tops is above the initial thickness on 0.05-0.07 mm.

![Surface relief after shot-peening treatment](image)

**Figure 2.** Surface relief after shot-peening treatment. Enlarged 50x.

Residual stresses introduced by shot-peening were determined by the same X-ray technique mentioned above and the in-depth stress distribution was analysed by the method of polishing of surface layers. Correction of the stress distribution due to relaxation after layer polishing was made by a standard technique [4]. Figure 3 represents the residual stress distribution in the surface layer after shot-peening treatment. It also shows the distribution of residual stress at the bottom of a Brinell indentation after the polishing of surface layers up to 0.30 mm. Three measured points in this case show a slow decrease in residual stresses as a function of the thickness of removed layers.

![Graph of stress distribution](image)

**Figure 3.** Depth stress distribution after shot-peening treatment: 1-experimental stress distribution; 2-corrected stress distribution; 3-residual stress distribution at the bottom of Brinell indentation; 4-stress value at the peaks of surface.

On the stress axis of the graph presented in figure 3 the stress value point corresponds to the stress measured predominantly at the peaks of surface relief features obtained after the shot-
peening treatment. For this kind of measurement the bottoms of shot-peening imprints were filled with fine powdered material having a high X-ray absorption. Thus, it is possible to realize the predominant reflection from a surface area, which is free from contributions by the absorbing powder, that is to say one which corresponds to the peaks or tops of the shot-peening indentations. Stress value measured in this case were equivalent to those represented on the stress axis in figure 3.

DISCUSSION

The experimental results presented have shown inhomogeneous character of the residual stress distribution across the surface for both an isolated indentation and multiple indentations after shot-peening treatment. This inhomogeneity is a result of inhomogeneous plastic deformation around the indentation imprint and stress relaxation at the peaks of surface relief. These results, especially those resulting from the experiment with absorbing material allow an explanation of the curve of residual stress distribution versus depth of sample represented in figure 3. The typical view of this curve and many others [5] is that the stress value on the treated surface is always less than the subsuperficial stress measured after removing of surface layer with thickness of 0.05-0.1 mm. This effect can be explained by the fact that the regions with negligible residual stresses are the sharp ledges or peaks of relief surface which are removed more intensively than the bottoms of indentations which exhibit significant stresses. After polishing, a new surface becomes smooth and the portion of overstressed regions increases; as a result, the mean stress value increases too and the stress distribution across surface becomes more homogeneous. This is the main factor explaining an increase in residual stresses at the initial stage on the stress distribution curve represented in figure 3. Another factor which may also influence the initial value of superficial stress is connected with the averaging of measured stresses along the irradiated area. Figure 4 explains the basis of averaging along the indentation area which occurs during X-ray stress measurements.

Figure 4. Characteristics of the shot-peening imprint and schematic representation of the averaging of X-ray stress measurements across the indentation surface.
According to this schematic diagram the stress component at any point with spherical coordinates $\phi$ and $\psi$ (see figure 4) is:

$$\sigma_x(\phi, \psi) = \sigma_r \cos^2 \psi \cos^2 \phi + \sigma_t \sin^2 \phi,$$

where $\sigma_r$ and $\sigma_t$ are radial and tangential stress components on spherical surface of indentation. The average value of residual stress across the indentation surface in any direction (X-direction on scheme in figure 4) will be expressed as follow:

$$\bar{\sigma}_x = \frac{1}{S} \int_0^{2\pi} \int_0^\alpha \sigma_x(\psi, \phi) R^2 \sin \psi \sin \phi \sin \phi \, d\psi \, d\phi,$$  (2)

If to propose an equality of residual stress along indentation surface or $\sigma_r = \sigma_t = \sigma_{res}$, then

$$\bar{\sigma}_x = \frac{R^2}{S} \int_0^{2\pi} \int_0^\alpha \left( \sigma_{res} \cos^2 \psi \cos^2 \phi + \sigma_{res} \sin^2 \phi \right) \sin \psi \sin \phi \sin \phi \, d\psi \, d\phi,$$  (3)

where $S$ is integrated area equal to area of a spherical imprint with radius $R$; $\alpha$ is angle based on the arc of cross section of spherical indentation. From figure 4, $\alpha$ is determined as

$$\alpha = \arcsin \frac{L}{2R},$$  (4)

where $L$ is the diameter of the imprint.

Calculation of this integral gives the following expression for average stress value:

$$\bar{\sigma}_x = \frac{\sigma_{res}}{6} \left( 4 + \cos \alpha + \cos^2 \alpha \right),$$  (5)

If $\alpha = 0$ then $\bar{\sigma}_x = \sigma_{res}$. A photograph of the shot-peened surface is shown in figure 2 which gives an average diameter of indentations equal to 0.25 mm. For a steel ball diameter of 0.7 mm, $\alpha$ is equal $\approx 20.9^0$. Thus, in our case, the average stress value determined from expression 5 is equal to:

$$\bar{\sigma}_x = 0.97 \sigma_{res},$$  (6)

This result means that the influence of averaging is negligible and the main factor explaining the initial behavior of the stress distribution curve in figure 2 is the inhomogeneity of plastic deformation around the indentation and stress relaxation at the peaks of the shot-peened surface.

**CONCLUSION**

It has been shown that the residual stress state across a Brinell indentation is characterized by an inhomogeneous stress distribution; the tops of the indentation $\sigma_r$ and $\sigma_t$ differ in magnitude and sign.

Multiple indentations or a shot-peening surface treatment do not remove the inhomogeneity of residual stresses and stresses at the peaks of roughness surface are relieved, as confirmed by the experiments.

Stress inhomogeneity and stress relief at the peaks of surface relief explain the initial stage of the depth versus stress distribution curve where superficial residual stresses are less than stresses after layer removing.

The stress relieved state at the peaks of roughness is the main cause of stress decreasing on the shot-peened surface.

The influence of averaging on the spherical surface is negligible.
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REFERENCES