Residual Stress Distribution in Shot Peened Plates

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ABSTRACT

By shot peening plates of different thickness, an effective depth and an average magnitude of the induced residual stresses can be determined. This effective depth of the residual stress layer corresponds well with that obtained by removing the shot peened layer by electrolytic polishing.

KEY WORDS

Shot peening, residual stress measurement, stress source concept, beam bending theory.

INTRODUCTION

A well-known measure of the shot peening process is given by the Almen-intensity, which results when a plate of a normed size, called Almen-strip, is shot peened. As this value gives no information about the depth and magnitude of the residual stresses, a method is developed from which an approximate determination of these values can be obtained. Specifically, we demonstrate that an effective depth and an average magnitude of the induced residual stresses can be evaluated if plates of different thickness are shot peened under identical conditions.

THE STRESS SOURCE CONCEPT

After shot peening the surface of an Almen-plate, it will bend upwards, and its curvature can be easily measured. It is assumed (Al-Hassani, Niku-Lari, 1982) that the effects of shot peening can be described in terms of a so-called "stress source" which balances the bending and axial stresses produced by the plate as it tends back to its undeformed state. The residual stress (source stress + bending and axial stresses) is thus considered to be the result of a stretching action, uniformly distributed over the entire surface, followed by an elastic unloading. Simple beam bending theory then leads to the following relation between the arc height f and the source stress distribution $\sigma_p(z)$, where z denotes the distance from the surface (Roth, Strässler, Bernasconi, 1983).

$$f = - \frac{3}{2} \frac{\ell^2}{E \cdot H^3} \int_o^H dz \; \sigma_p(z) \; (\frac{H}{2} - z) \qquad (1)$$

with ℓ = relevant length for arc height measurement, H = plate thickness, E = Young's modulus

INFORMATION FROM MEASUREMENTS OF THE ARC HEIGHT f(H)

A set of Almen-plates with different thicknesses H is shot peened under identical conditions. If $H \geq H_{min}$ for all plates, and if H_{min} is not too small, we may assume that the following two conditions are satisfied:

(A) There exists some $d < H_{min}$ such that $\sigma_p(z) = 0$ for $z \geq d$.

(B) $\sigma_p(z)$ is independent of H for $H \geq H_{min}$.

Equation (1) can then be written in the form

$$H^3 f(H) = s(H-H_o) \quad , \tag{2}$$

where H_o and s are independent of H as long as $H \geq H_{min}$:

$$H_o = 2 \int_o^d dz\, z\, \sigma_p(z) \Big/ \int_o^d dz\, \sigma_p(z) \tag{3}$$

$$s = -\frac{3}{4}\frac{\ell^2}{E} \int_o^d dz\, \sigma_p(z) = -\frac{3}{4}\frac{\ell^2}{E} H_o \bar{\sigma}_p \tag{4}$$

The function $H^3 f(H)$ is thus linear in H, so that H_o and s are easily determined from two or more measurements of f(H) at different H-values. H_o represents a measure for the depth of the source stress profile $\sigma_p(z)$, and $\bar{\sigma}_p$ defines an average magnitude of the source stress.

EXPERIMENTS

A set of plates with different thicknesses was produced by grinding the standard Almen-strips (C-type: 2.4 mm, A-type: 1.3 mm, N-type: 0.8 mm thickness). Four series of these plates were shot peened with different pressures (2, 3, 4 and 5 bar) using steel shot with an average size of 0.6 mm (shot type S 230). The arc height f(H) of these strips was measured by using a standard Almen gage No. 2 with a gage length of 32 mm.

By plotting the data according to equation 2, different H_o-values are obtained for different peening intensities (see Fig. 1). With increasing peening pressure an increase of the effective depth from 104 μm at two bars to 186 μm at five bars is observed (Table 1).

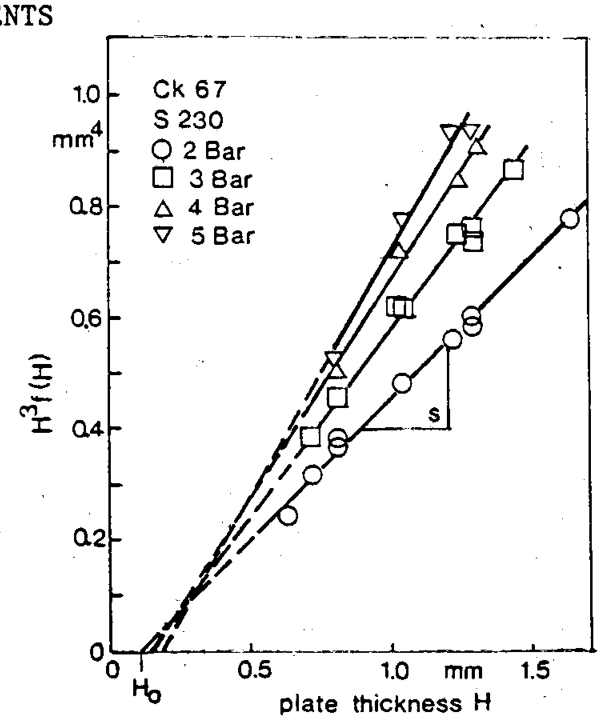

Fig. 1: Determination of H_o for different peening intensities (shot type S 230).

Table 1

shot size	Almen-intensity A mm/100	peening pressure in bar	effective depth H_o in µm	average magnitude of the residual stress σ_p in MPa	electropolished removed layer in µm
S 230	28	2	104	1275	119
	36	3	138	927	142
	41	4	145	1412	188
	44	5	186	1240	179
S 110	14	1.5	88	585	76

By inserting these H_o-values and the corresponding slopes s of the straight lines into equation (4), and taking ℓ = 32 mm and E = $2 \cdot 10^5$ MPa, an average magnitude of the source stress can be calculated. These values (Table 1) cannot directly be correlated to the peening pressures, but they are at least in a stress range expected for this steel (which has a yield point of 1275 MPa). In this connection one should also note that the scatter in the data of Fig. 1 leads to a rather large uncertainty for the value of σ_p (see formula (4)).

The plots of Fig. 1 reveal further limitations of the method: For plates of small thickness, condition (A) above does not apply. In this case peen-forming of the plate takes place, which is easily recognized by an inhomogeneous bending of the plate. For plates with thicknesses between 1.5 and 2.0 mm the data often no longer exhibit a linear behavior. This may be explained by the fact, that for thicker plates the depth of the shot-peened layer is too small in comparison to the bulk material. Thus deviations due to inhomogenities in material properties play an increasing role.

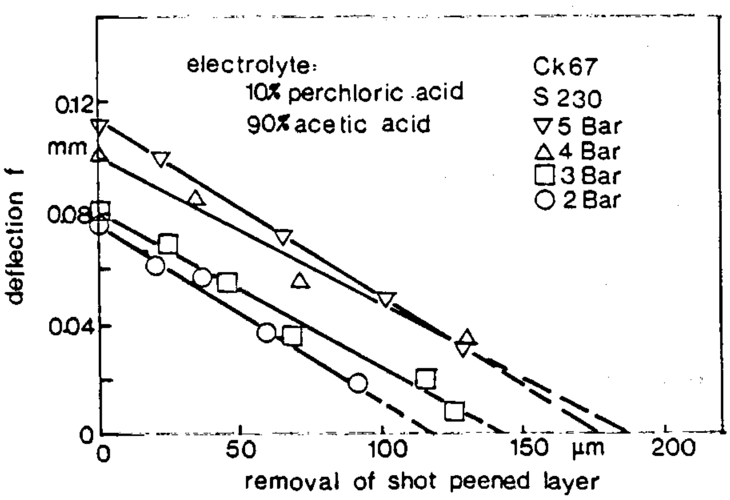

Fig. 2: Determination of the shot peened layer for different peening intensities.

The evaluated H_o-values were experimentally checked by the following method (Niku-Lari, 1982): The shot peened layer of one plate of each series was stepwise removed by electrolytic polishing. When the deflection of the plate is entirely relieved, the amount of the removed layer is equal to the shot peened layer. Fig. 2 illustrates that these values can be evaluated by extrapolation, and Table 1 shows that - except at 4 bar - the correlation of the electropolished removed layer with the H_o-value is quite good.

Another set of plates was shot peened with a much lower Almen-intensity of 14 A (mm/100), using steel shot with an average size of 0.3 mm (S 110). In this case the plot according to equation (2) exhibits a smaller scattering (Fig. 3), and due to the lower intensity also plates with smaller thicknesses could be used without being peen-formed. Further improvement in the accuracy of the method is obtained by measuring the arc height of the plates between a much higher length of 66 mm instead of 32 mm. In this way the error due to two-dimensional deflection, which is rather pronounced in thinner plates, is reduced.

The experimental check by removing the shot peened layer (Fig. 4) shows that the thickness of this layer and the H_o-value again compare very favorably (Table 1). In comparison to the series which have been peened with a higher intensity using S 230, a smaller H_o-value of 88 µm and only half of the average magnitude of the residual stress (585 MPa) is obtained when using S 110.

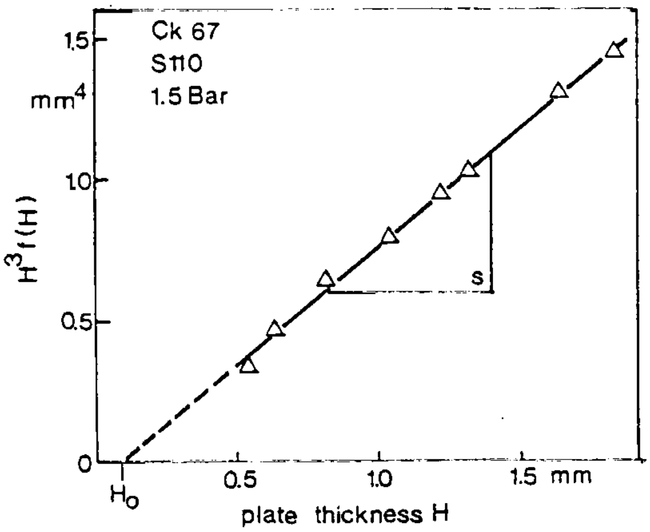

Fig. 3: Determination of the effective depth H_o (shot type S 110).

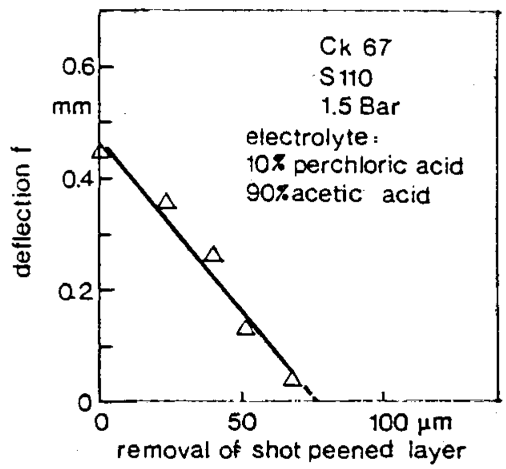

Fig. 4: Determination of the shot peened layer (shot type S 110).

CONCLUSIONS

We have demonstrated that information about the magnitude and the depth of the induced residual stresses can be obtained by shot peening plates of different thickness.

This simple procedure represents a better description of the shot peening process than the usual Almen-intensity measurement. The Almen-intensity is defined by a single parameter (the arc height) and does not contain direct information about physical changes in the material. The two parameters H_o and $\bar{\sigma}_p$, on the other hand, characterize the residual stress distribution induced by the shot peening process.

The method can also be applied to obtain a rough evaluation of the optimum shot-peening parameters in terms of the residual stress distribution. The effects of the shot-peening process on the fatigue properties, however, can only be estimated if the exact stress profile is known. This can, e.g., be determined from the arc height variation (see Fig. 2 and 4) by using Niku-Lari's "bending-deflection method" (Niku-Lari, 1982).

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