Application of the incremental hole drilling method for the measurement of residual stress distribution in shot-peened components.

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Introduction

Shot-peening is now a very well known manufacturing operation, the industrial applications of which are many and varied. The residual compression stresses generated in the surface layers of mechanical parts make this process a very useful tool for improving the resistance of manufactured parts to fatigue failure, corrosion fatigue or stress corrosion.

Various methods have been developed to measure residual stresses due to shot-peening. These include : the X-ray diffraction method (1-3), the incremental hole drilling method (4-6) and the bending deflection method (7). This document describes recent developments in the incremental hole drilling method and its applications in the field of shot-peening, together with the various measurement technique problems involved in this specific treatment.

Principle of the incremental hole drilling method (8)

The incremental hole drilling method is based upon the principle of the relief of residual stresses, following the removal of material by step-by-step drilling.
For each drilling depth, Z, the surface strains $\epsilon_i(Z)$ are measured using three gauges in a rosette, centred upon the hole concerned. When drilling is completed, the principal residual stresses $\sigma_1(Z)$ and $\sigma_2(Z)$ can be calculated, using equations containing the measured strains ($\epsilon_i(Z)$) and the calibration coefficients (A_{in} and B_{in}).
To determine the principal residual stresses (σ_{1hi} and σ_{2hi} , with $\sigma_{1hi} > \sigma_{2hi}$) and their directions with respect to any reference axis, for each depth hi , three independent strain measurements are required. The equation for the radial strain corresponding to principal residual stresses is :

$$\varepsilon_{in} (\theta_i) = A_{in} (\sigma_{1hi} + \sigma_{2hi}) + B_{in} (\sigma_{1hi} - \sigma_{2hi}) \cos 2\theta_i \qquad \text{Equ. 1}$$

Coefficients A_{in} and B_{in} depend upon the hole diameter, the positions of the strain gauges, the position of the layer i, the depth of the hole and the elastic constant of the material. θ_i is the angle between the first strain gauge and the maximum principal residual stress.

In the new approach, for a given drilling increment, surface strain changes due to the removal of the previous layer must also be considered.

Strains due to the actual removed layer are :

$$\epsilon_n^k = \epsilon_{mn}^k - \sum_{i=1}^{n-1} \epsilon_{in}^k \qquad k = 1,2,3 \qquad \text{Equ. 2}$$

ϵ_{mn}^k is the total strain measured on the surface when the n^{th} increment is removed. ϵ_{in}^k corresponds to that part of the total strain related to the i^{th} layer when the n^{th} increment is removed, and is calculated as follows :

$$\epsilon_{in}^1 = A_{in} (\sigma_{1hi} + \sigma_{2hi}) + B_{in} (\sigma_{1hi} - \sigma_{2hi}) \cos 2\theta_i$$

$$\epsilon_{in}^2 = A_{in} (\sigma_{1hi} + \sigma_{2hi}) + B_{in} (\sigma_{1hi} - \sigma_{2hi}) \cos 2 (\theta_i + \phi) \qquad \text{Equ. 3}$$

$$\epsilon_{in}^3 = A_{in} (\sigma_{1hi} + \sigma_{2hi}) + B_{in} (\sigma_{1hi} - \sigma_{2hi}) \cos 2 (\theta_i + \psi)$$

φ and ψ are the angles between the other two strain gauges, respectively, and the first strain gauge.

For a 45° rosette, the three unknowns θ_n, σ_{1hn} and σ_{2hn} can thus be calculated using the relationship :

$$\sigma_{1hn} = \frac{\epsilon_n^1 (A_{nn} + B_{nn} \sin 2\theta_n) - \epsilon_n^2 (A_{nn} - B_{nn} \cos 2\theta_n)}{2 A_{nn} B_{nn} (\sin 2\theta_n + \cos 2\theta_n)}$$

$$\sigma_{2hn} = \frac{\epsilon_n^2 (A_{nn} + B_{nn} \cos 2\theta_n) - \epsilon_n^1 (A_{nn} - B_{nn} \sin 2\theta_n)}{2 A_{nn} B_{nn} (\sin 2\theta_n + \cos 2\theta_n)} \qquad \text{Equ. 4}$$

$$\theta_n = \frac{1}{2} \tan^{-1} \left[\frac{\epsilon_n^1 - 2\epsilon_n^2 + \epsilon_n^3}{\epsilon_n^1 - \epsilon_n^3} \right]$$

In this case : $\varphi = 225°$, $\psi = 90°$

The calibration coefficients A_{in} and B_{in} are calculated using the finite element method which is modelled digitally, as described in ref. (6).

Selection of strain rosette used for measurement

In the case of prestress shot-peening, the layer affected by plastic deformation is relatively thin, of the order of 0.1 mm to 1 mm. Optimum gauge configuration is therefore important, to obtain maximum measurement sensitivity.

Following a series of calculations using the finite element method (8) (fig. 1), it will be seen that sensitivity is good for hole depths up to 50 % of hole diameter. Sensitivity decreases significantly when depth exceeds 50 %. The curves also show that, in the case of uniform shear stress, loading ($\sigma_1 = -\sigma_2$) decreases more slowly than in the case of loading which is axi-symmetrical ($\sigma_1 = \sigma_2$). The latter case must therefore be used as a reference, to define the "significant" measurement area. It will be seen that the maximum measurable depth is 0.7 d, while optimum hole depth is considered to be around 0.5 d.

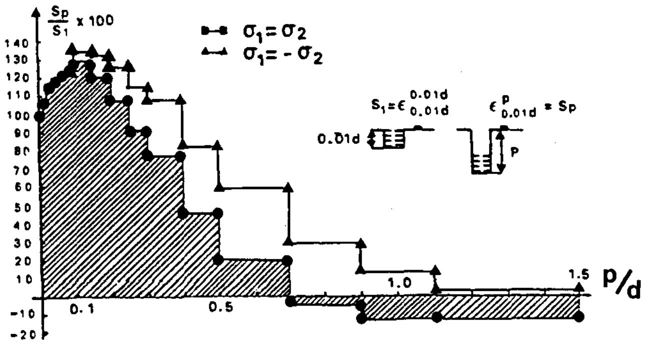

Fig. 1 : Sensitivity of strain measurement in depth for an axisymmetrical and uniform shear stress loading.

For shot-peening, the measurement area is generally less than 1 mm. Hole diameter should thus be around 2 mm. Small strain gauge rosettes are therefore recommended (e.g. VISHAY EA-XX-031 RE-120, EA-XX-062 RE-120, HBM RY61). The best compromise would seem to be offered by the VISHAY EA-XX-062 RE. Method sensitivity is around 20 MPa/μd for steels and 7 MPa/μd for aluminium alloys, for 20 μm of material removed. Smaller rosettes (VISHAY EA-XX-031-RE) pose a problem of drilling depth and centring accuracy, but the measured signal accuracy is almost doubled for a given thickness of material removed.

Drilling technique

As shot-peening residual stresses only cover a very shallow layer, and the stress gradient is extremely high, the drilling technique must guarantee extreme accuracy in the depth of hole drilled (around 1 μm), and must create neither strain nor over-heating. Also, the bottom of the hole must be flat, to respect the geometry used in the modelling of the calibration coefficients. Two drilling systems are recommended, to satisfy the above requirements (see (6)) :

1 - Drilling using a high-speed, compressed air turbine ((6), (9), (10)).

2 - Drilling using a fixed-bed milling machine, with a solid carbide cutter ((6)).

In the case of shot-peening, i.e. for drilling diameters of 0.8 mm to 1.6 mm, the optimum system drilling speed is between 4500 rpm and 10000 rpm, depending upon the material and the type of gauge rosette selected.

Applications

Table 1 shows the shot-peening conditions applied to the materials tested.

Material		N°	Shot	Almen Intensity	Coverage
Aluminium alloy	7075	1a	Glass beads d = 0.4 mm	6 - 8A	200 %
	7075	1b	S170	10 - 12A	100 %
Cast Iron	MN350-10	2	S170	12 - 14A	100 %
	MN700-2	3	S170	12 - 14A	100 %
	GS700-2	4	S170	12 - 14A	100 %

Table 1

Figure 2 shows the results obtained on the shot-peened 7075 aluminium alloy of test pieces 1a and 1b.

For this material, it will be seen that the maximum residual stress value does not vary significantly with the shot-peening conditions. However, the plastically deformed depth changes, depending upon the treatment. In this case, the diameter and nature of the shot are extremely important. An increase in shot diameter deepens the residual stress and increases the plastically deformed depth. This result is interesting as, in this type of material, it has been found that increasing the plastically deformed layer extends the fatigue life of the part (11).

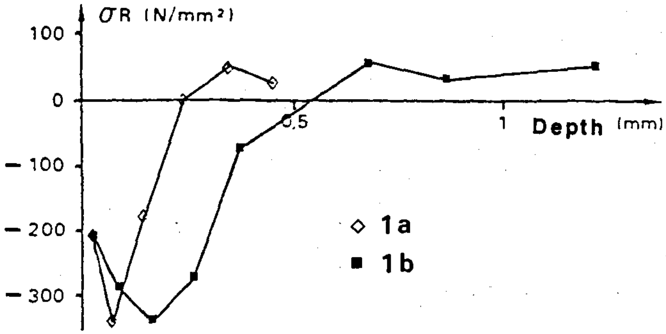

Fig. 2 : Comparison of residual stresses obtained on shot-peened aluminium 7075, with two different treatments.

Residual stresses were measured for shot-peened cast iron components (test pieces 2, 3 and 4), and the results are shown in figure 3.

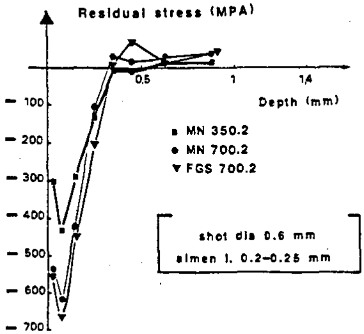

Fig. 3: Residual stresses obtained on test pieces 2, 3 and 4.

Analysis of the above results leads to the following conclusions:

- As in the case of steels, residual stresses generated by shot-peening increase with the mechanical characteristics of the material concerned.

- Maximum compression stress values obtained for the various test pieces (2, 3 and 4) are similar to the basic material tensile strength value for MN 350-10 cast iron, and around 80 % to 85 % of the basic material tensile strength for MN 700-2 and GS 700-2 cast irons. These stress values are thus very high in relation to the mechanical characteristics of the cast irons tested. In the case of MN 350-10 cast iron, the high deformation capacity of this grade (A = 16 % to 18 %) probably provokes the very high residual stresses in relation to its tensile strength. It should also be pointed out that the mechanical properties of cast iron, in compression, are frequently far superior to its properties in traction.

- In terms of appearance and in terms of the residual stress generated by shot-peening, the behaviour of nodular cast irons is not very different from that of steels. The value and distribution of these stresses depend mainly upon the mechanical characteristics (hardness, elastic limit, deformation capacity) and the shot-peening conditions.

The preceding text describes the analysis of parts which were simply shot-peened. In industry, another, more efficient treatment is frequently used. This involves subjecting a part to traction or bending, before the shot-peening operation (strain peening). Reference (12) describes an example of this technique, tested using the incremental hole method. In the case of a leaf spring, the transversal and longitudinal stress results obtained on parts, shot-peened with and without prestressing, were compared under various conditions. It was found that the transversal stresses did not vary significantly with the various treatments. Conversely, the residual longitudinal compression stresses (in the direction of the prestress) and the depth of the area under compression both increased considerably. The value of the increase varied directly with the prestressing level.

It was also found that the maximum stresses were always close to the surface. This is probably due to a bending prestress, which results in maximum stress on the surface. Using this treatment, the fatigue life of parts could be significantly increased.

To improve the fatigue life of welded parts, finishing treatments are being increasingly developed, especially since the introduction of high elastic limit steels, and shot-peening is one of the most widely used methods. Figure 4 shows the results obtained on fatigue test pieces which were welded and then shot-peened along the weld toe, under various conditions (13). In this case, a special VISHAY rosette (CEA-XX-062 UM-120) was used, to get as close as possible to the weld. Residual shot-peening stresses (compression) were observed on the surface, with welding stresses (traction) in the sub-layer.

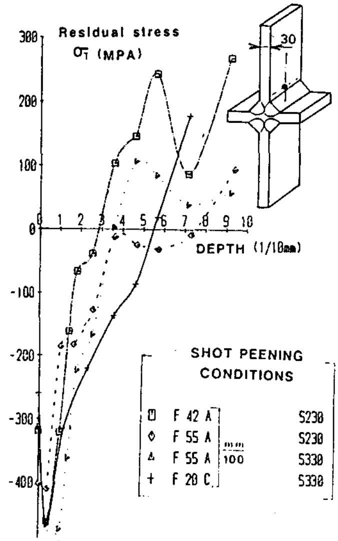

Fig. 4: Shot-peening residual stress profiles, measured by the incremental hole drilling method, for E 36.4 steel, in the direction perpendicular to the weld toe (σ_T).

The duplex austenite-delta-ferrite steels are becoming increasingly used in modern industry. Figure 5 shows the results obtained on shot-peened URANUS 45 steel, using the incremental hole method and the X-ray diffraction method (the X-ray diffraction tests were conducted at the ENSAM-PARIS). The stresses measured using the former method were macroscopic and those measured using the latter method were residual stresses measured in both phases (α and γ). It will be seen that the two methods give similar results in the case of shot-peening as, in this case, the residual stresses present in each material phase are not significantly different. Other comparisons between the hole drilling and X-ray methods also show comparable results for the two methods, which are based upon very different principles (6)(14).

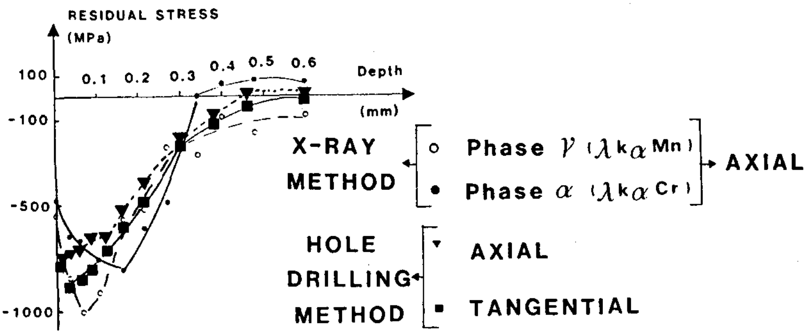

Fig. 5: Comparison between the hole drilling methode and X-ray diffraction method, on shot-peened URANUS 45 steel. Conditions : cast steel shot, dia. 1 mm., Almen Intensity 19 - 21 A.

Conclusion

The above results indicate that the incremental hole drilling method is suitable for measurement of the residual stress profile in depth, in the case of shot-peening. The accuracy provided by the latest developments in this technique not only allows the maximum residual stress to be measured, but also the compression stress layer to be defined, which has a considerable influence upon the effectiveness of prestress shot-peening. Using this method, a specific treatment can rapidly be optimised, as a stress profile only requires two hours of testing. The field of application of the method, for this type of treatment, was demonstrated by applying the method to various materials (steels, light alloys, cast irons, two-phase steels).

The specific measurement problems posed by shot-peened parts have been discussed, such as optimum gauge rosette selection, drilling conditions, etc...

The incremental hole drilling method is one measurement method which complements other existing methods. In addition, it offers advantages for coarse grain materials or those with significant sub-layer texture, which pose problems when using the X-ray diffraction method (stainless steel, nickel-based alloy, for example IN 100).

Recent developments in the incremental hole drilling method, both theoretical and experimental, will probably result in the early development of industrial applications of this method, due to its simplicity and rapidity.

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