Fine increment hole-drilling method for residual stress measurement, proposal of a calibrating apparatus

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ABSTRACT

The paper proposes a new test rig designed to improve the reliability and the precision of the fine increment hole-drilling method. The method is intended to separate the contribution of the relaxed strains caused by a controlled external load and that produced by residual stresses in the specimen. An external load producing bending is applied thus inducing in the measured region linearly variable mono-axial stress known with good accuracy. The external stress can be used as reference for the residual stress measurement. Corrections related to hole drilling eccentricity and start drilling point can be accurately considered for the reference bending then applied to residual stresses measurement.

The technique is applied to an aluminum alloy 7075-T651 plate, surface treated with shot peening process, deduced residual stress distribution is reported in good agreement with independent X-ray diffraction measure.

Introduction

Hole drilling is one of the most widely used technique for residual stress measurements, due to its precision and low cost. Standard ASTM E 837-01 [1] is limited to the uniform distribution of residual stresses, whereas it is well known that residual stresses usually feature high gradient through the depth, particularly if residual stresses are induced by surface treatments such as shot peening, especially with small bead size. The incremental hole drilling method can be used to evaluate the non-uniform residual stress distribution as shown by Schajer [2,3]. The strain measurement is performed for each hole depth increment to achieve information on the residual stress gradient, from relaxed surface strain. Influence functions for the incremental hole drilling were proposed by Beghini and Bertini [4] by which relaxed strains can be analytically related to the residual stress distributions for any kind of rosette, hole diameter and elastic material.

Valentini [5] developed an apparatus able to perform fine increment hole drilling, by means of a high speed automatically controlled air turbine drill. Valentini et al. [6] used the apparatus to experimentally determine the effects of eccentricity and sequence of increments steps on residual stresses measurement.

The idea of use a reference known stress was already proposed by Rendler et al. [7], however in the present apparatus it is applied to the incremental hole drilling, by means of a reference bending load. Advantages are shown in the paper, along with some preliminary experimental results.

Test rig apparatus

The specimen to be used in the proposed apparatus is basically a cantilever beam. One side is fixed to the basement, the other one can be transversally loaded by a pneumatic actuator. The actuator carries a load cell in order to monitor the applied bending force (for reference strain measurement) with good precision (below 0.25%). The proposed test rig is reported in Figure 1.

In order to produce prevailing bending stress (with negligible shear stress) the cantilever beam is long in comparison with its thickness, as can be clearly deduced from Figure 2(a). When using a reduced size specimen, it can be bolted to suitable fixture that extend the force arm, as depicted in Figure 2(b). The specimen region where the hole is performed was tapered in order to produce a region where the bending stress is constant, avoiding longitudinal stress gradient, as suggested in ASTM standard ASTM E 251-92 [8]. Moreover, distances between measuring spot and bolted flanges were designed to be long enough to obtain the actual deformation, induced by bending load, very similar to that predicted by the beam theory. Differences between the maximum stress in the actual configuration were found by FE three dimensional analysis to differ from the elementary beam theory below 1%. Particular care was devoted to the assembly procedure in order to avoid misalignments.
between the specimen axis and the position of load application. Indeed, if the alignment is not assured, torsion deformation is induced in the specimen, reducing the reliability of the reference bending strain measurement.

The drilling and measure automatic equipment is the RESTAN produced by SINT Technology [5]. The drilling equipment features a step motor to accurately position the drilling tool as well as control the hole depth increment. The drilling tool is driven by a small high speed air turbine (400'000 rpm). The eccentricity between the strain gage rosette and the hole center is a well known possible source of bias in the hole drilling method. To reduce eccentricity the drilling equipment is positioned through a micrometric screw guide, and a monocular optical microscope helps the operator in the hole drilling positioning.
The drilling tool is made by carbon tungsten plus surface treatment by TiAlN, more details are reported in Ref. [9]. The initial contact condition is checked by an electric contact between the drilling tool and the specimen to be tested, however surface roughness (as due to machining or surface treatment) can lead to a premature initial drilling point.

Rosette used has 3 independent strain gages. The strain-gauge signal is conditioned by HBM amplifier Spider 8. Each strain-gauge generates a strain signal, according to the scheme illustrated in figure 3, then the three quantities $\varepsilon_1, \varepsilon_2, \varepsilon_3$ are available after each hole step depth increment. The rosette $X$ direction is accurately aligned to the specimen axial direction then bending stress is $\sigma_b = E \varepsilon_1$, before drilling.

Equipment details are summarized in Table 1.

<table>
<thead>
<tr>
<th>Tool</th>
<th>Model</th>
<th>Company</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extensimeter rosette</td>
<td>K-RY61-1S/120R-3-0.5m</td>
<td>H.B.M.</td>
</tr>
<tr>
<td>Extensimeter amplifier</td>
<td>Spider 8</td>
<td>H.B.M.</td>
</tr>
<tr>
<td>Residual stress automatic measurement equipment</td>
<td>RESTAN - Ø1.6 mm</td>
<td>SINT Technology</td>
</tr>
<tr>
<td>Drilling tool</td>
<td>CTT – Ø1.6 mm</td>
<td>SINT Technology</td>
</tr>
<tr>
<td>Micrometric gage</td>
<td>2119SB-10</td>
<td>Mitutoyo</td>
</tr>
<tr>
<td>Load cell</td>
<td>RSCA C1</td>
<td>H.B.M.</td>
</tr>
<tr>
<td>Displacement sensor</td>
<td>CLS1322-100mm</td>
<td>Active Sensors</td>
</tr>
</tbody>
</table>

Table 1. Equipment details

Operating parameters are reported in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth increment speed</td>
<td>mm/min</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Maximum hole depth</td>
<td>mm</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Hole step increment</td>
<td>mm</td>
<td>0.02</td>
<td>For depth ranging from 0.0 mm to 0.5 mm</td>
</tr>
<tr>
<td>Hole step increment</td>
<td>mm</td>
<td>0.05</td>
<td>For depth ranging from 0.5 mm to 2.0 mm</td>
</tr>
<tr>
<td>Delay time</td>
<td>s</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Operating parameters used during testing procedure.

**Testing procedure**

The frame for the strain gage rosette is shown in figure 3. The eccentricity parameters $e, \beta$ are related to lengths $x_1, x_2, y_1, y_2$ (measured from the strain gage rosette center) by simple geometry relations:

$$ x_e = \frac{x_1 + x_2}{2} ; \quad y_e = \frac{y_1 + y_2}{2} ; \quad e = \sqrt{x_e^2 + y_e^2} ; \quad \beta = \tan^{-1} \left( \frac{y_e}{x_e} \right) $$

(1)

Figure 3. (a) Strain gage rosette configuration, and hole eccentricity definition. (b) Hole depth stepping definition.
Even though eccentricity is reduced as little as possible, before performing the test, residual eccentricity \( e, \beta \) can be evaluated with the aid of the optical microscope after the test. By measuring the four distances \( x_1, x_2, y_1, y_2 \) (as shown in figure 3(a)). Also the effective hole diameter \( D_{\text{eff}} \) can be measured and its value is usually found slightly larger than the nominal drilling tool diameter.

\[
D_{\text{eff}} = \frac{|x_1 - x_2| + |y_1 - y_2|}{2}
\]  \hspace{1cm} (2)

The testing procedure is performed as follows:
1. external bending load \( F_0 \) is applied to the cantilever beam and the actual load applied is measured;
2. three strain signals are measured while \( F_0 \) is applied: \( \varepsilon_i^{(F_0)} \), where \( i = 1, 2, 3 \);
3. drilling tool is positioned at the strain gage rosette center, \( \text{(with eccentricity as reduced as possible)} \);
4. drilling tool is put in contact to the specimen surface \( \text{(with the aid of the electric contact sensor)} \);
5. hole drilling is performed up to \( z_1 \) depth, without applying bending load;
6. strain signals are measured: \( \varepsilon_i^{(0)}(z_1) \), without applying bending load;
7. external bending load \( F_0 \) is applied then three strain signals measure is repeated: \( \varepsilon_i^{(F_0)}(z_1) \);
8. steps 6–7 are repeated after each \( j \) hole depth increment, and signals \( \varepsilon_i^{(0)}(z_j) \) and \( \varepsilon_i^{(F_0)}(z_j) \) are measured, up to a maximum depth \( z_{\text{max}} \).

According to the present notation, strain measurement before drilling can be indicated as zero depth drilling: \( \varepsilon_i^{(F_0)}(0) = \varepsilon_i^{(F_0)} \).

Before drilling (after step 2 of the testing procedure), the measured strains \( \varepsilon_i^{(F_0)}(0) \) can be very easily related to the external bending load applied to the cantilever beam, otherwise stiffness properties \( \text{\text{(Young’s modulus} E \text{ and Poisson ratio} \nu \text{)}} \) of the material could be known with little accuracy a-priori, since a previous accurate tensile test could not be available for the tested material. From the beam theory, as the bending load is applied, it follows that:

\[
\nu = -\frac{\varepsilon_i^{(F_0)}(0)}{\varepsilon_i^{(F_0)}(0)}
\]  \hspace{1cm} (3)

\[
E = \frac{F_0 h}{w h^2 / 6 \varepsilon_i^{(F_0)}(0)}
\]  \hspace{1cm} (4)

Where \( h \) is the lever of the bending force, figure 2(a), \( w \) is the width of the specimen at the hole section and \( h \) is the thickness of the specimen figure 2(b). It is worth noting that the ratio \( h / w \) should be constant along the whole length of the specimen, however the measure of the two quantities is recommended instead of considering the designed value of the ratio. The measure of the thickness \( h \) need to be taken with particular care, since it is usually a small quantity (4-10 mm) and then surface roughness can lead to a high relative error, moreover it is elevated at the square power, in Eq. 4, then the relative error introduced in the measure of \( E \) is doubled.

External bending load strain and residual stress strain decoupling

The blind hole drilling methodology requires the relaxed strain (induced by the hole) to be converted into sub-surface stresses \( \text{(no matter if residual stresses or external load applied stresses are considered)} \). Therefore, if the analytical formulation from relaxed strain to sub-surface stresses is known [4], this can be applied to the external load as well.

It is clear that the \( \varepsilon_i^{(0)}(z_j) \) is the relaxed strain due to residual stresses:

\[
\rho_i^{(\text{RS})}(z_j) = \varepsilon_i^{(0)}(z_j)
\]  \hspace{1cm} (5)
where \( \rho \) is used instead of the \( \varepsilon \) to highlight that it is the relaxed strain, generated by the hole drilled up the depth \( z_j \) and (RS) indicates Residual Stresses. 

On the contrary the strain signal \( \varepsilon_{ij}^{(F_k)}(z_j) \) is coupled with the relaxed strain signal due to residual stresses. To decouple the two:

\[
\rho_i^{(B)}(z_j) = \left( \varepsilon_{ij}^{(F_k)}(z_j) - \varepsilon_{ij}^{(o)}(z_j) \right) - \varepsilon_{ij}^{(F_k)}(0) 
\]

\[
(6)
\]

where (B) indicates bending.

The need of subtracting the quantity \( \varepsilon_{ij}^{(F_k)}(0) \) might appear misleading, the reason is that the input for the analytical procedure (to find sub surface stress distribution) is the relaxation induced by the presence of the hole. To assure formal continuity between Eq. 5 and Eq. 6, they should be rewritten as follows:

\[
\rho_i^{(RS)}(z_j) = \varepsilon_{ij}^{(o)}(z_j) - \varepsilon_{ij}^{(o)}(0) 
\]

\[
(7)
\]

\[
\rho_i^{(B)}(z_j) = \left( \varepsilon_{ij}^{(F_k)}(z_j) - \varepsilon_{ij}^{(o)}(z_j) \right) - \left( \varepsilon_{ij}^{(F_k)}(0) - \varepsilon_{ij}^{(o)}(0) \right) 
\]

\[
(8)
\]

However it is obvious that \( \varepsilon_{ij}^{(o)}(0) = 0 \) (strain signal without bending and before drilling), then Eqs. 5,6 are obtained again. Eqs. 7-8 are of interest only if the initial strain signal is not initialized as zero. The improvement in terms of precision of the hole drilling method, due to the external applied bending, is the possibility of analytically processing strain information given by \( \rho_i^{(B)}(z_j) \) to find the well known bending stress distribution. The procedure to convert \( \rho_i^{(B)}(z_j) \) (also valid for \( \rho_i^{(RS)}(z_j) \)) into stress distribution is reported in Ref. [4] where the Influence Function technique is applied. After this operation, a perfect match between bending stress distribution and analytically obtained from \( \rho_i^{(B)}(z_j) \) is expected. Indeed, any mismatch can be attributed to measure procedure errors, such as:

- inadvertently failure of one (or more) strain gage signal;
- hole eccentricity, though the present apparatus is provided with a dedicated equipment to have little eccentricity;
- actual initial drilling point; though the present apparatus is provided with an electric contact detector, the surface roughness can lead to a premature contact between the specimen and the drilling tool.

Therefore it is here suggested to apply the analytical procedure to convert \( \rho_i^{(B)}(z_j) \) into the bending stress distribution and compare to the reference bending stress. If the accuracy found is good enough, this is the “double check” of the reliability of the residual stress measure, then \( \rho_i^{(RS)}(z_j) \) can be converted into residual stresses distribution with confidence of accuracy.

On the contrary if the match between the bending stress distribution found from \( \rho_i^{(B)}(z_j) \) and the reference is not satisfactory corrections can be introduced until the reference bending stress is retrieved. Same corrections can be applied to the conversion from \( \rho_i^{(RS)}(z_j) \) to residual stresses after.

**Applications**

Ref. [10] proposes an application of the present apparatus where eccentricity correction is tested. The material tested was a annealed stainless steel AISI 304. Although annealing some residual stresses are expected, since \( \varepsilon_{ij}^{(o)}(z_j) \) were not exactly zero, however it was considered a good way to separate the bending signal reference to the residual stress.

Strain measurements \( \varepsilon_{ij}^{(F_k)}(z_j) \) are shown in Figure 5, while relaxed bending stress \( \rho_i^{(B)}(z_j) \) are reported in Figure 6.

By applying procedure suggested in Ref. [11], the eccentricity is taken into account and information \( \rho_i^{(B)}(z_j) \) is converted into bending stress distribution. Figure 6 proposes the comparison between relaxed bending stress measured and calculated from the known bending stress distribution. The good matching found in figure 6 allowed for confidence on the possibility to convert \( \rho_i^{(RS)}(z_j) \) into residual stress information with good accuracy.
Shot peening treatment was applied to aluminum alloy AA 7075-T651 plate, with $h = 4.08 \text{ mm}$, $w_h = 41.15 \text{ mm}$.

The specimen was loaded by applying a remote bending load $F_0 = 9.225 \text{ N}$, $b_h = 556 \text{ mm}$. Material stiffness properties were deduced, as previously described: $E = 72.23 \text{ GPa}$, $\nu = 0.31$.

Shot peening treatment parameters are: CE B120, beads size range is 0.063 - 0.125 mm, Almen intensity 4.5 N, treatment coverage 100%. ZIRBLAST® fused ceramic beads were used for the treatment. Beads material properties are reported in Table 3,[12].

<table>
<thead>
<tr>
<th>Specific gravity</th>
<th>Bulk density</th>
<th>Young modulus</th>
<th>Poisson coef.</th>
<th>Vickers hardness</th>
<th>Rockwell HRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.85 $\text{ g cm}^{-3}$</td>
<td>2.3 $\text{ g cm}^{-3}$</td>
<td>300 $\text{ GPa}$</td>
<td>0.27</td>
<td>700 HV</td>
<td>60</td>
</tr>
</tbody>
</table>

Table 3. ZIRBLAST® bead properties.

Relaxed strain obtained $\rho_j^{(RS)}(z_j)$ on the aluminum alloy plate are reported in Figure 6 (a),(b) for imposed step increment of 0.010 mm and 0.020 mm respectively. Residual stress distribution are modeled with the linear-spline approximation [4], from
relaxed strain of Figure 6, and reported in Figure 7. Residual stress measurement conducted with X-rays diffraction technique, performed on the same shot peening treated material, is also reported for comparison.

Due to the relatively small size of the beads, the layer with residual stress depth is very thin, therefore both measure produce results with a relatively poor resolution.

Figure 6. Residual stress distribution measured on AA 7075-T651 after B120 shot peening surface treatment: (a) imposed increment 0.010 mm, (b) imposed increment 0.020 mm.

Figure 7. Residual stress distribution measured on aluminum alloy 7075-T651 plate, after B120 ZIRBLAST® shot peening treatment. Hole Drilling measures compared with X-rays technique.

Considering Figures 6,7 it is also remarkable that the three measurements (two with the Hole Drilling method and one with the X-ray diffraction technique) were produced at three different spots surface treated with just nominally same shot peening process. Therefore the scatter found can be also attributed to the actual local residual stress field instead of the different method or resolution adopted.

Relaxed strain reported in Figure 6 were also interpreted according to the integral method [4], instead of linear-spline, however numerical instability was found, since small initial measure strain error is amplified along the depth path of the residual stress distribution. Linear-spline approximation was then preferred, at least for the present high stress gradient distribution.
Conclusions

The paper proposes a test rig for automatically performing residual stress measurement through the fine increment hole drilling technique. It is also proposed a procedure by which a reference bending stress is applied in order to have a “double check” of strain measurements and improve deduced residual stress distribution confidence.

Inaccurate knowledge of material elastic properties is readily overcome exploiting the bending configuration before drilling. Hole eccentricity is reduced as much as possible since the hole positioning operation is helped by a micrometric screw and an optical monocular microscope, however residual eccentricity is measured after drilling and small eccentricity correction can then be applied.

Initial drilling point is also a well known reason of bias along with the incremental hole drilling method. An electric contact is used to accurately detect initial drilling point, moreover the here introduced reference bending load is particular useful, indeed immediately below the surface the reference bending stress has large value, which is effectively detected by relaxed strain, suggesting initial drilling point correction.

Shot peening residual stress distribution, induced on an aluminum alloy 7075-T651 plate, is measured with the proposed technique and comparison provided with X-ray diffraction residual stress measure technique, showing a quite good match.

Acknowledgments

The authors are grateful to Eng. M. Bandini from PeenService S.r.l., Bologna, Italy, for providing shot peening treatment on the here tested specimens, and to Eng. S. Brogelli from Sint Technology S.r.l., Calenzano (FI), Italy, for performing tests with the apparatus proposed, property of Sint Technology.

References