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Bending test rig for validating the hole drilling method residual stress measurement

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Abstract. This paper shows a large validation activity of the strain gage Hole Drilling Method. The residual stress measurements can not be validated easily, unless with Round Robin activity and/or comparison with other residual stress measurements such as X-ray diffraction. An accurate validation procedure is reported in the present paper, using a bending test rig. The bending stress experimentally simulates a residual stress (known with uncertainty lower than 1%) that was considered as the reference stress distribution. The results showed very accurate measurement in terms of relaxed strain distributions, that were compared with the prediction obtained with the Influence Function technique. The differences were in the order of 0.5 με as standard deviation on a large number of tests. The bending stress prediction was consequently very accurate and the stress differences were smaller than 3 MPa showing the accuracy potentiality of the method.

Introduction

The Hole Drilling Method (HDM) is a simple and accurate technique for residual stress measurement starting from a flat free surface. A small hole diameter is drilled concentric with a three grids strain gage rosette. The recorded measure is the relaxed strains obtained as the result of the stressed material removal after each hole increment. The relaxed strains at different hole depths are then elaborated according to numerical procedures [1, 2, 3] and the residual stress distribution, acting on that specific point of the body, before drilling, is found. Significant improvements were obtained in the recent years both in terms of hole drilling performance precision [4] and about the numerical technique to deduce the residual stress from the relaxed strains [2, 3, 5, 6], also showing accurate comparison results with X-Ray Diffraction [7, 8, 9]. The HDM measurement verification is a key issue, especially under controlled and repeatable conditions. The validation can be performed by a calibrating test apparatus [8] instead of comparing with different technique measurements. The proposed equipment, Fig. 1, experimentally simulates a residual stress distribution as bending stress, that is known with good accuracy from the beam theory. This reference stress can then be compared with the HDM output result. The accuracy validation was primarily performed in terms of relaxed strain. The measured relaxed strain (experimental), produced by the only bending stress component, decoupled from any residual stress in the specimen, can be compared to the calculated (expected) relaxed strain obtained from Influence Function calculation [2, 3], after having precisely measured the load, the material elastic properties, and the hole geometry parameters (diameter and eccentricity components). The bending stress was then obtained as the result of the HDM numerical procedure calculation, compared to the reference bending stress. Finally, a statistical analysis of the results was proposed.

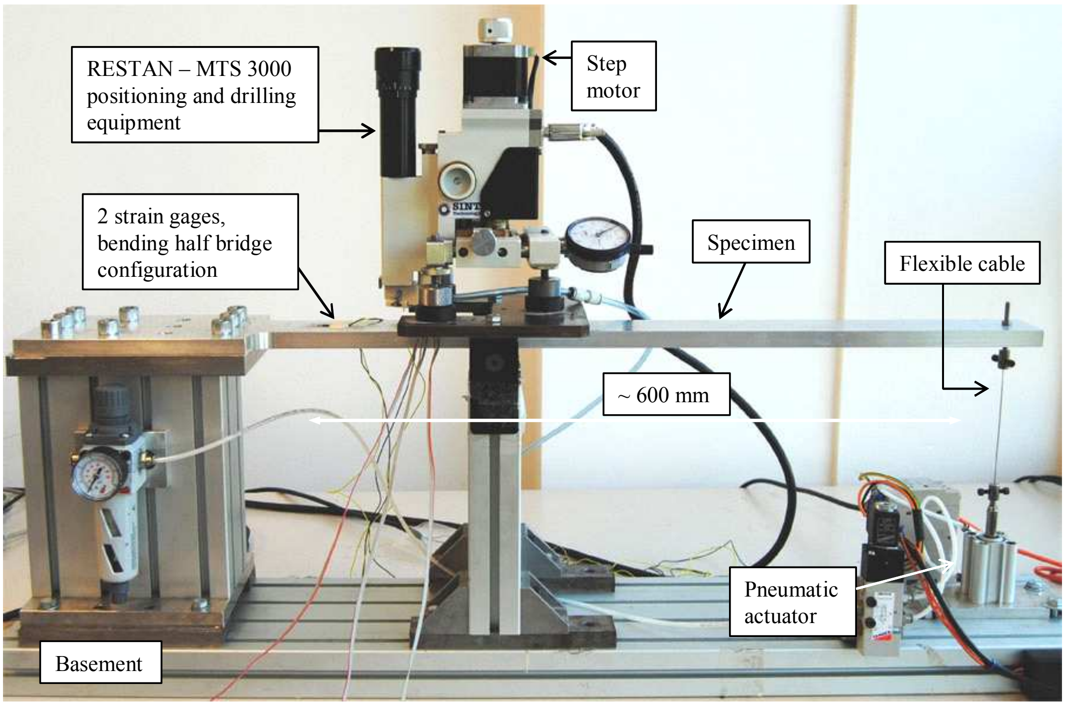


Figure 1: Bending test bench to experimentally simulate a known reference residual stress.

Bending test procedure

The specimen used in the present bending test bench is a flat (rectangular cross section) cantilever beam, fixed at one end, and loaded at the other end by means of a pneumatic actuator. The material used for the specimen is a high strength aluminum alloy. Light alloys have lower Young's modulus than steels, then a small force is required to have a significant bending strain. The material yield stress was never exceeded, after imposing bending, being a high strength material. The specimen bending bar was milled at both sides to have an accurate flatness, at the measurement surface, and a well defined thickness. A specific surface preparation was required for installing the strain gages. The surface roughness was manually slightly increased, by using the sand paper 320 and then the sand paper 400 grit. The machining residual stress (or any previous residual stress) was decoupled from the bending stress, as shown in the following, thus not interfering with the validation. The test procedure is a sequence of specific steps. The calibration of the bending load is performed before drilling. The load applied by the actuator is preliminary unknown. A (half bridge) strain gage couple was applied near the fixed end of the bar. Initially, a known weight was hung at the loaded end of the bar, without the pneumatic actuator, through a flexible wire, to have the position of the axis of the load perfectly known. The half bridge strain gage signal was measured and the proportionality constant between strain gage reading and applied bending load was easily found. After re–introducing the pneumatic actuator, the performed load was accurately deduced by means of the proportionality constant. The maximum error was estimated being lower than 1%. The (uniaxial) stress due to bending was easily obtained from the beam theory, Fig. 2(a), Eq. 1:

$$\sigma_{\mathrm{Be}} = 6\frac{F\,b}{w\,h^2} \tag{1}$$

where: b is the distance between the load axis and the rosette strain gage center; w,h are width and height of the beam cross section, respectively, and F is the load imposed by the pneumatic actuator.

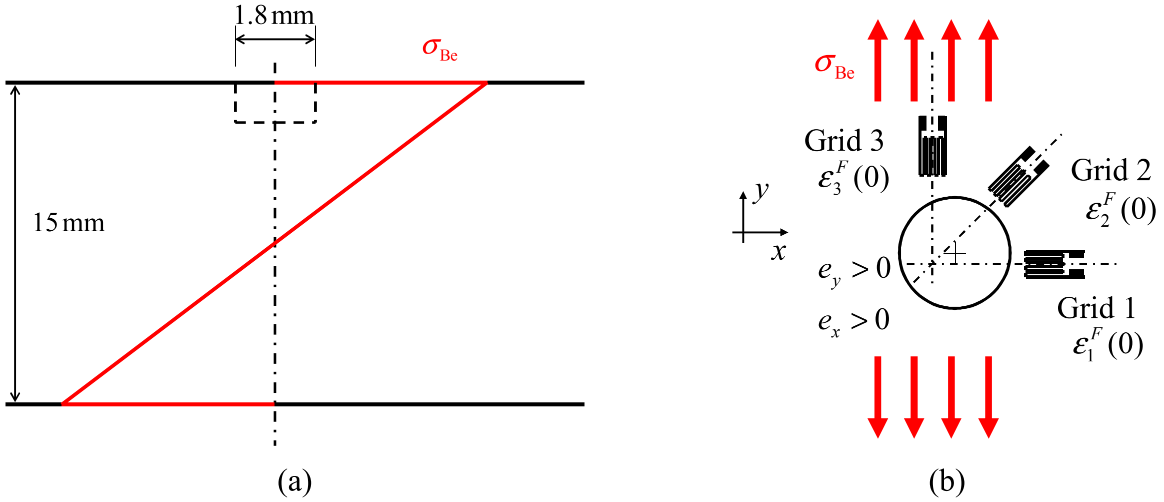


Figure 2: (a) Linear distribution of the bending stress. (b) Orientation of the strain gage rosette grids and hole eccentricity definition.

Material elasticity parameters: Young's modulus E and Poisson's ratio ν can be accurately measured, with a preliminary bending load, before drilling, using strain measurements of the strain gage rosette $\varepsilon_1^F(0), \varepsilon_2^F(0), \varepsilon_3^F(0)$, Eq. 2:

$$E = \frac{\sigma_{\mathrm{Be}}}{\varepsilon_3^F(0)}, \quad \nu = -\frac{\varepsilon_1^F(0)}{\varepsilon_3^F(0)} \tag{2}$$

According to Fig. 2(b), the grid 3 should be aligned with the beam axis. The manual strain gage installation, unavoidably, introduces a misalignment. However, the angle between the grid 3 and the beam axis can be found from the Eq. 3 (that is a very accurate approximation for small values of α):

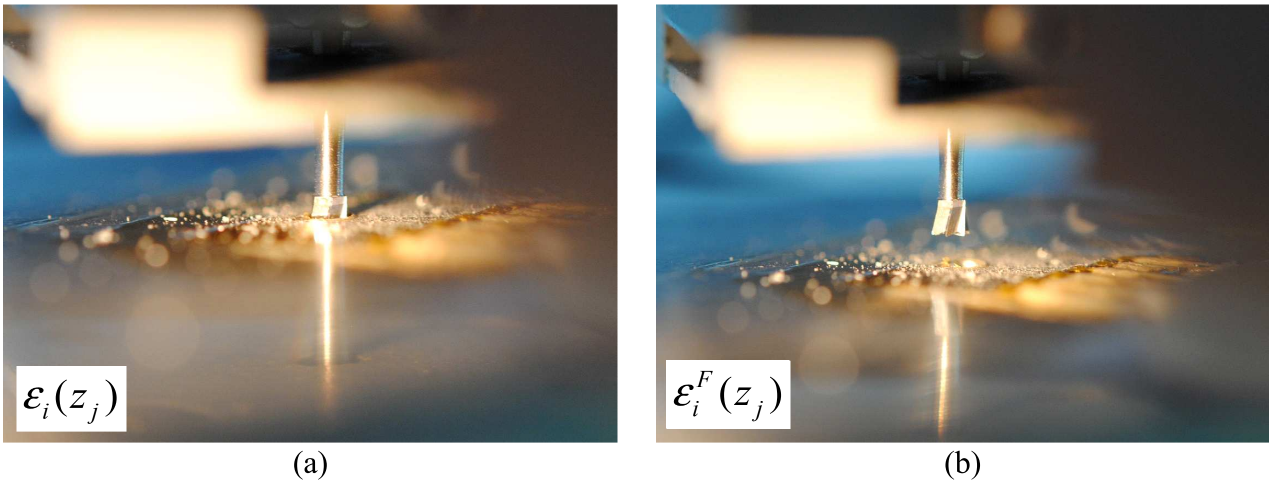
$$\alpha = \frac{1}{2}\frac{\varepsilon_1^F(0) - 2\varepsilon_2^F(0) + \varepsilon_3^F(0)}{\varepsilon_1^F(0) - \varepsilon_3^F(0)} \quad \text{[rad]} \tag{3}$$

The drilling operation is performed with a high speed air turbine, running at 400 000 rpm and generating a 1.8 mm hole diameter with incremental depths, Fig. 2 (a). The diameter is accurately measured after drilling, for each test, through a monocular and two dial gages also to find the residual eccentricity. The testing procedure requires two strain measurements for each drilling depth increment: *with* the bending load applied $\varepsilon_i^F(z_j)$ and *without* the bending load $\varepsilon_i(z_j)$, where i is the grid index $(i = 1,2,3)$ and z_j is the depth of each j–th increment, Fig. 3. A dedicated software was implemented to automatically perform the entire procedure. The usual maximum depth was set at 1.3 mm, with 130 drilling depth steps (0.01 mm each depth increment step).

The measured strains need to be decoupled in order to deduce just the relaxed strain related to the bending stress. The Residual Stress relaxed strains $\varepsilon_i^{\mathrm{RS}}(z_j)$ and the Bending relaxed strains $\varepsilon_i^{\mathrm{Be}}(z_j)$ are obtained as:

$$\begin{aligned} \varepsilon_i^{\mathrm{RS}}(z_j) &= \varepsilon_i(z_j) \\ \varepsilon_i^{\mathrm{Be}}(z_j) &= \varepsilon_i^F(z_j) - \varepsilon_i(z_j) - \varepsilon_i^F(0) \end{aligned} \tag{4}$$

Strain $\varepsilon_i^F(0)$ needs to be subtracted, in the second of the Eqs. 4, since the relaxed strains are defined as the effect of the introduction of the drilled hole, so they need to be zero at zero depth.



(a) (b)

Figure 3: j-th depth increment step, strain measurement with and without the bending load.

Test results

A total number of nine tests was reported along with elaborations and statistical analysis. As previously introduced, the validation was performed both in terms of relaxed strain predictions and reference bending stress compared to the HDM result.

Relaxed strain validation. Fig. 4 shows an example of comparison between the experimental bending relaxed strains (dots) and the expected relaxed strain (dashed lines). It is evident that the two distributions are almost perfectly matching.

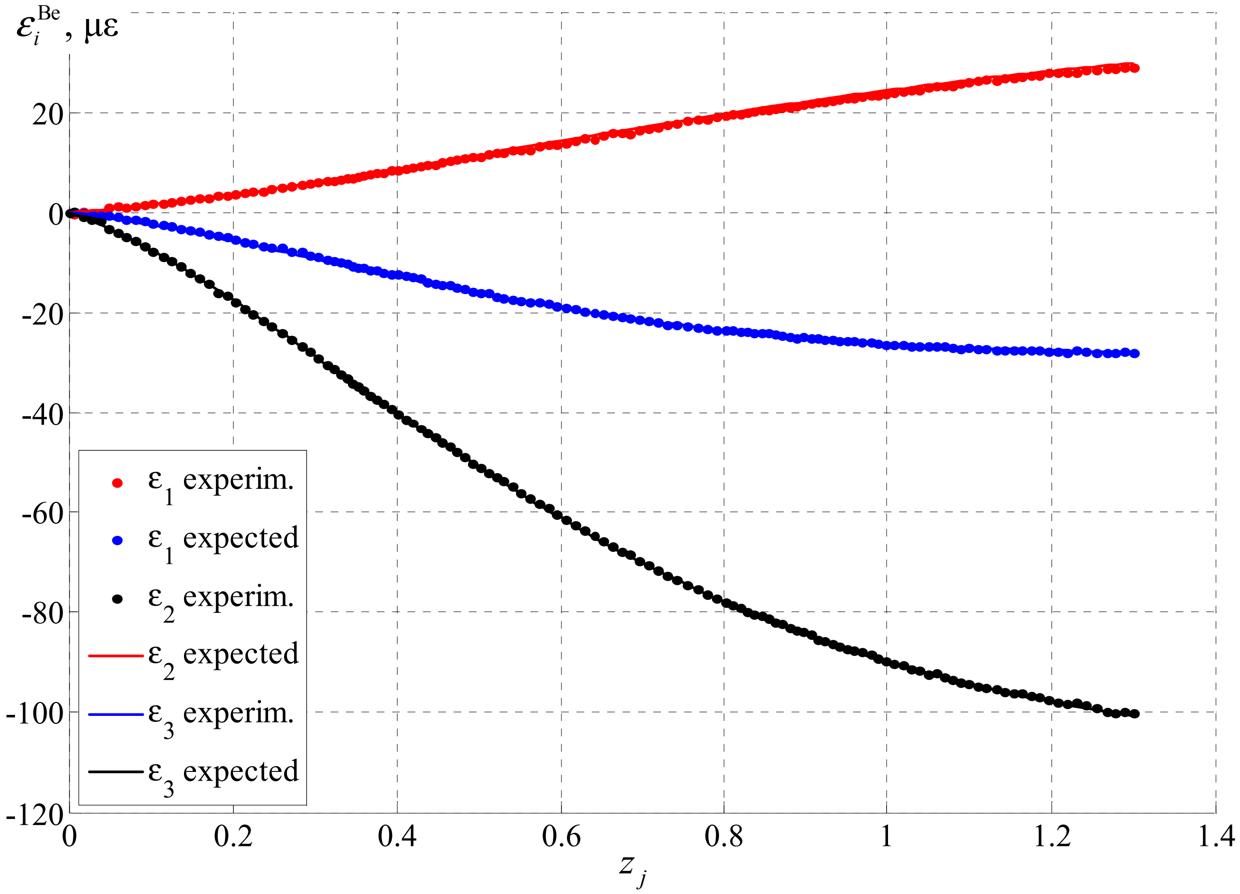


Figure 4: Measured relaxed strain components vs. expected comparison.

Fig. 5 shows the differences between measured and expected, all tests superimposed. Grids 1, 2, 3, are reported separately (see grids orientation in Fig. 2(b)). An evident and remarkable result is that the mean value of the test differences is never larger than 0.5 με, moreover the standard deviation of these differences is marginally larger for high values of the hole depth, slightly exceeding 0.5 με for the 3rd grid (aligned with the load), and lower elsewhere.

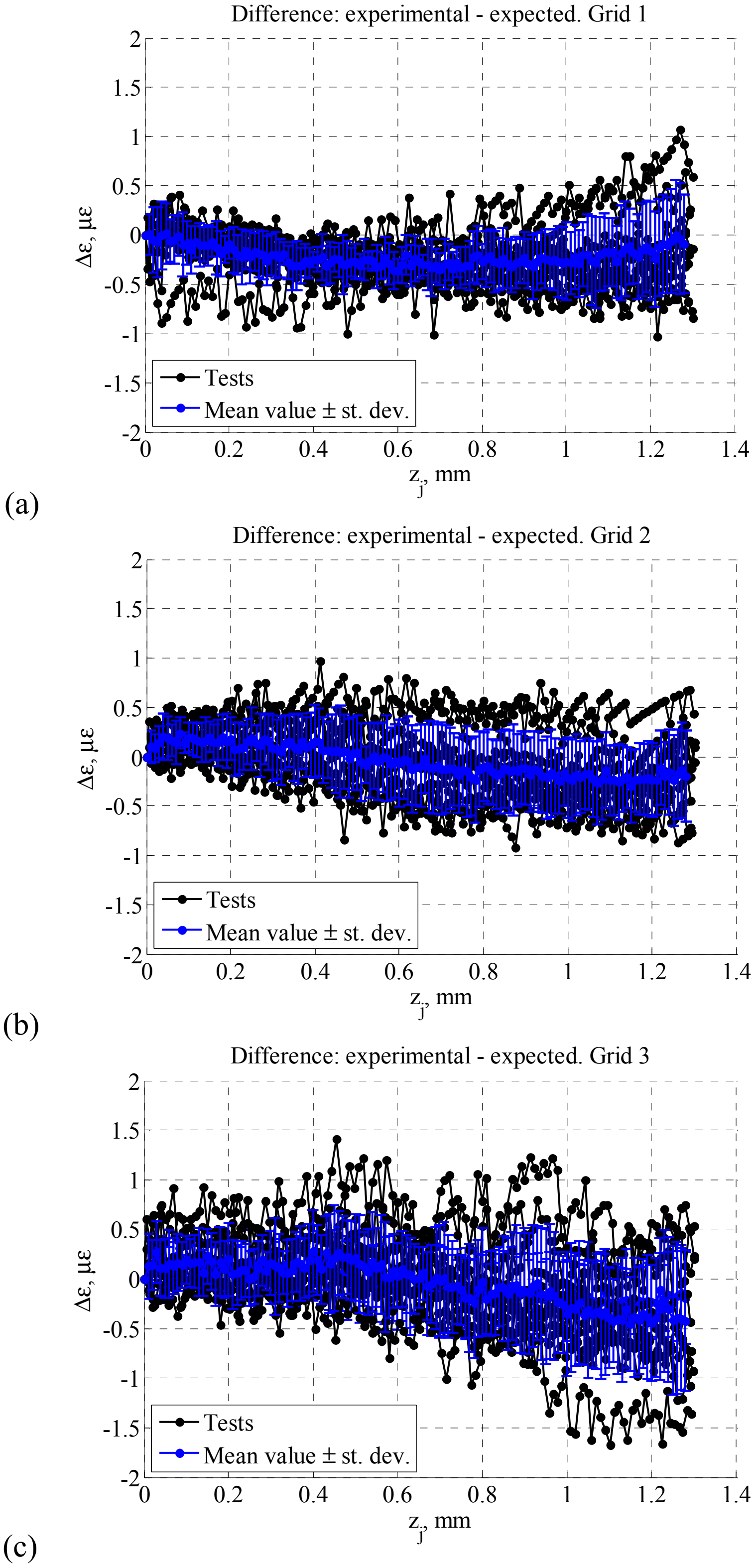


Figure 5: Statistical analysis of relaxed strain experimental-expected differences for the three grids.

This very accurate result validates both the measurement system and also the Influence Function procedure [2]. The eccentricity and the alignment angle correction both contributed to this result. Without eccentricity and rosette angle corrections, the maximum differences would be in the order of few με. Even though the random error is low (as shown in Fig. 5), it can be further smoothened by introducing an approximating polynomial function for each grid strain sampling distribution. Fig.6 shows the standard deviation of the measured to polynomial fit difference, as dependent on the polynomial order n, Eq.5. It is evident a *plateau* for a small value of the polynomial order, moreover the standard deviation plateau value is similar to the random errors reported above.

$$s_i = \sqrt{\frac{\sum_{j=1}^{m} (\varepsilon_i(z_j) - \varepsilon_i^p(z_j))^2}{m-n}}, \quad i = 1,2,3 \tag{5}$$

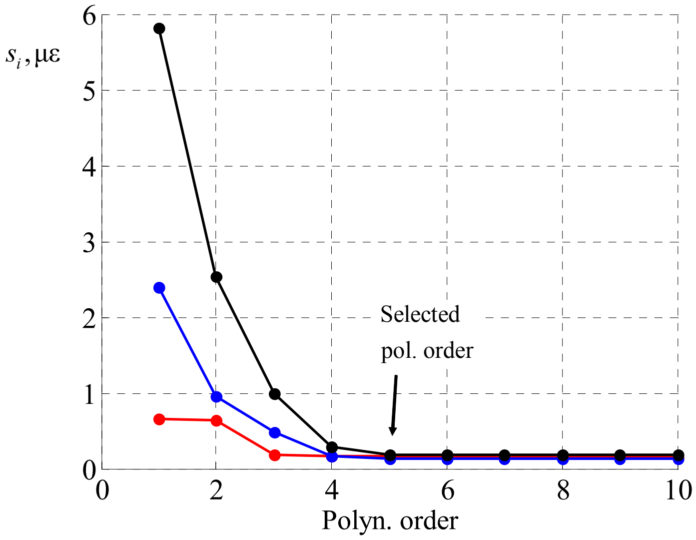


Figure 7: Polynomial order selection.

Reference stress validation. The bending stress distributions were calculated by introducing the polynomial fit relaxed strains, and the other test parameters accurately measured during the experimental procedure, as reported above. Fig. 8 shows four examples of the result. The reference bending stress (red line) is very accurately approximated by the Hole-Drilling output. Also the other two components can be considered for validation. The transversal bending stress component is zero (*uniaxial* stress), while the shear stress is small, depending on the rosette alignment angle.

Finally, Fig. 9 shows an overall comparison of all the nine tests, reported as same reference stress level. The relative difference standard deviation is approximately 0.5 MPa and slightly larger at the surface position. The maximum difference was never larger than 3 MPa.

Conclusions

- The bending test bench offers a very accurate validation tool for the Hole Drilling Method.
- The expected relaxed strains were calculated with the influence function technique and then compared to the measured experimental relaxed strains. The standard deviation of the differences was as low as 0.5 με.
- The stress validation reported very accurate comparisons of the bending stress components. The stress accuracy was found in the order of few MPa. The entire procedure, both experimental and analytical, was then validated.
- This study showed a valid residual stress prediction even at the surface, with an imposed very fine resolution and this is consistent with high gradient shot-peening with small bead size residual stresses [10], where the compressive stress distribution is very near the surface.

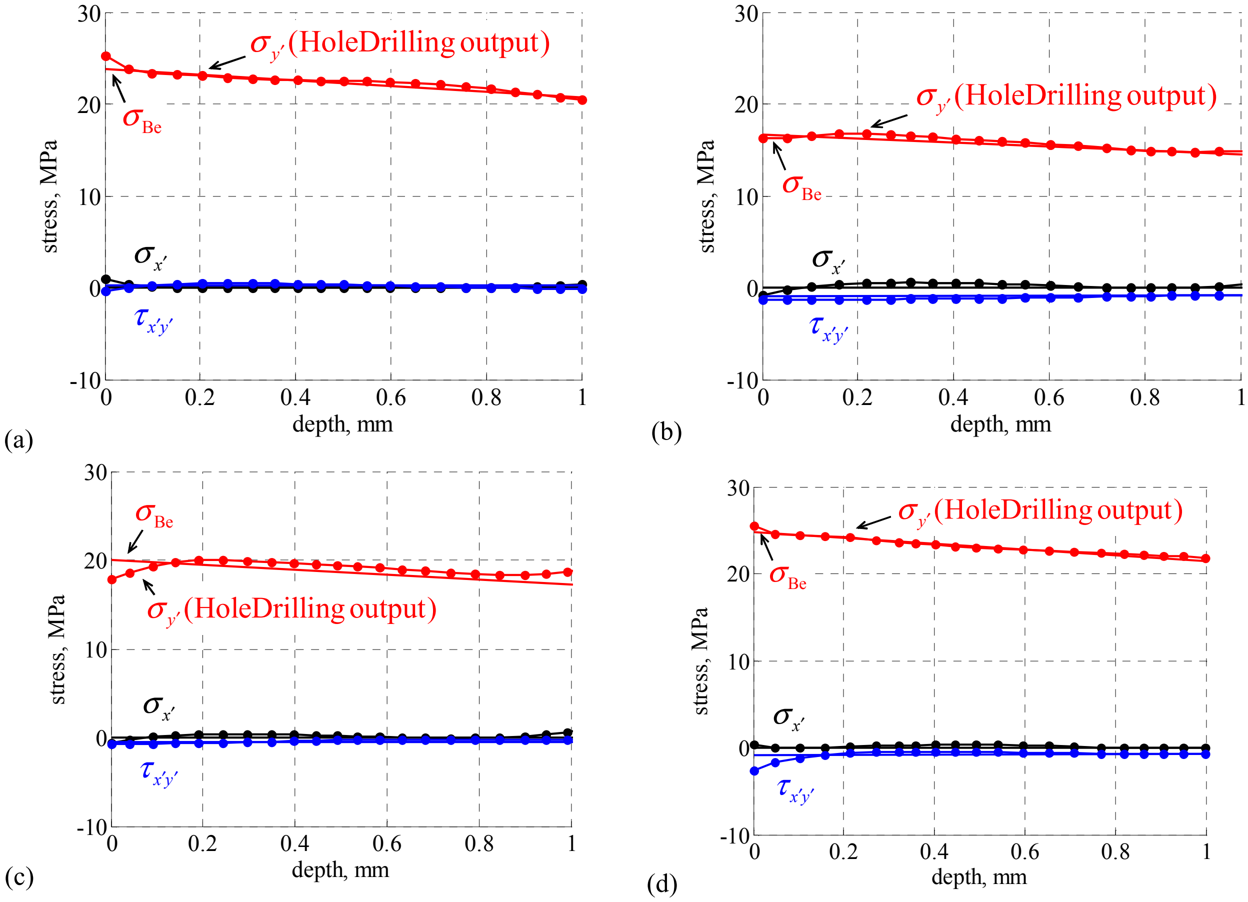


Figure 8: Reference bending stress components comparison examples.

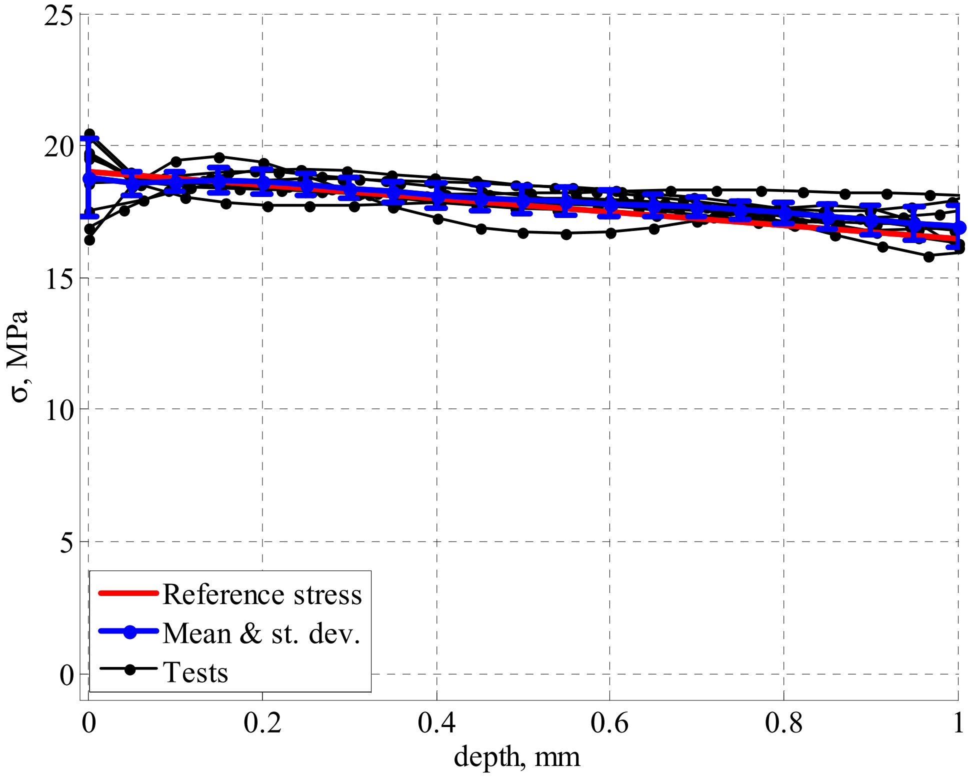


Figure 9: Reference bending stress comparisons and statistical analysis results.

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References

[1] ASTM, International, West Conshohocken, PA, Standard Test Method for Determining Residual Stresses by the Hole–Drilling Strain–Gage Method, 2008, ASTM E837-08.

[2] M. Beghini, L. Bertini, and L.F. Mori, Evaluating Non-Uniform Residual Stress by the Hole-Drilling Method with Concentric and Eccentric Holes, Part I: Definition and Validation of the Influence Functions, Strain 46(4) (2010) 324-336. DOI: 10.1111/j.1475-1305.2009.00683.x

[3] M. Beghini, L. Bertini, and L.F. Mori, Evaluating Non-Uniform Residual Stress by the Hole-Drilling Method with Concentric and Eccentric Holes, Part II: Application of the Influence Functions to the Inverse Problem, Strain 46(4) (2010) 337-346. DOI: 10.1111/j.1475-1305.2009.00684.x

[4] A. Ajovalasit, M. Scafidi, B. Zuccarello, M. Beghini, L. Bertini, C. Santus, E. Valentini, A. Benincasa, and L. Bertelli, The hole–drilling strain gauge method for the measurement of uniform or non–uniform residual stresses, AIAS Working Group on Residual Stresses, September 2010, AIAS – TR01.

[5] M. Beghini, L. Bertini, and C. Santus, A procedure for evaluating high residual stresses using the blind hole drilling method, including the effect of plasticity, Journal of Strain Analysis for Engineering Design 45(4) (2010) 301-318 , CEGB Prize paper winner 2010 (Journal of Strain Analysis 2010 best paper).

[6] M. Beghini, C. Santus, E. Valentini, A. Benincasa, Experimental verification of the hole drilling plasticity effect correction, Materials Science Forum 681 (2011) 151-158. DOI: 10.4028/www.scientific.net/MSF.681.151

[7] E. Valentini, C. Santus, M. Bandini, Residual stress analysis of shot-peened aluminium alloy by fine increment hole-drilling and X-ray diffraction methods, Procedia Engineering 10 (2011) 3582-3587. DOI: 10.1016/j.proeng.2011.04.589

[8] E. Valentini, M. Beghini, L. Bertini, C. Santus, and M. Benedetti, Procedure to Perform a Validated Incremental Hole Drilling Measurement: Application to Shot Peening Residual Stresses, Strain 47(s1) (2011) e605-e618. DOI: 10.1111/j.1475-1305.2009.00664.x

[9] V. Fontanari, F. Frendo, T. Bortolamedi, P. Scardi, Comparison of the hole-drilling and X-ray diffraction methods for measuring the residual stresses in shot-peened aluminium alloys, Journal of Strain Analysis for Engineering Design 40(2) (2005) 199-209. DOI: 10.1243/030932405X7791

[10] M. Benedetti, V. Fontanari, C. Santus, and M. Bandini, Notch fatigue behaviour of shot peened high–strength aluminium alloys: Experiments and predictions using a critical distance method, International Journal of Fatigue 32(10) (2010) 1600–1611.DOI: 10.1016/j.ijfatigue.2010.02.012