X-Ray Diffraction and Hole-Drilling residual stress measurements of shot peening treatments validated on a calibration bench

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Abstract

The inverse problem of determining residual stresses from diffraction or relaxation methods is notoriously affected by a high sensitivity to errors in input data. A particular care must be devoted to ensuring that their input errors are minimized, and results shall come with a quantification of the corresponding uncertainties.
Residual stress measurements are often validated by comparing the results of different techniques. Although this approach can strengthen the measurement confidence, it does not highlight potential biases of the methods.
The authors presented a calibration bench [1, 2] which can impose a known bending distribution on a specimen while simultaneously performing an X-Ray Diffraction (XRD) or Hole-Drilling Method (HDM) residual stress measurement. Since the external load can freely be applied and removed, Bueckner's superposition principle [3] can be exploited to simultaneously identify both the reference bending distribution and the actual residual stress distribution with the same experimental setup. As the first is accurately known, the bench provides a direct estimation of the achieved accuracy. Moreover, it can reveal systematic errors in the chosen procedures.
Two shot peening treatments were analyzed on the calibration bench with both XRD and HDM. First, residual stresses on the surface were evaluated with XRD measurements, then electrochemical material removal was performed to investigate stresses at higher depths. After that, HDM measurements were carried out and compared with the results of XRD. Both methods were also used to identify the known bending stresses: that provided an additional validation of the residual stress results.

Keywords Residual stress, X-Ray Diffraction, Hole Drilling, Shot-peening, Calibration bench

Introduction

The hole drilling method (HDM) [4] is a well-established technique for measuring residual stresses, due to its low cost and its in-field applicability. It is standardized by ASTM E837 procedure [5], which can be carried out with commercially available devices, such as the MTS3000-Restan by SINT Technology. It is known to be affected by a high sensitivity to errors in input data, particularly near the surface, where stresses depend only on few measurement points and are affected by errors in the zero-depth datum, and at high depths, where the method loses sensitivity. Due to this, it is often complemented with X-Ray Diffraction (XRD), which exploits Bragg's law to identify residual stresses near the specimen surface [6], with a typical penetration depth of about 10 μm. Stresses at higher depths can be investigated by removing layers of material, generally through electropolishing.

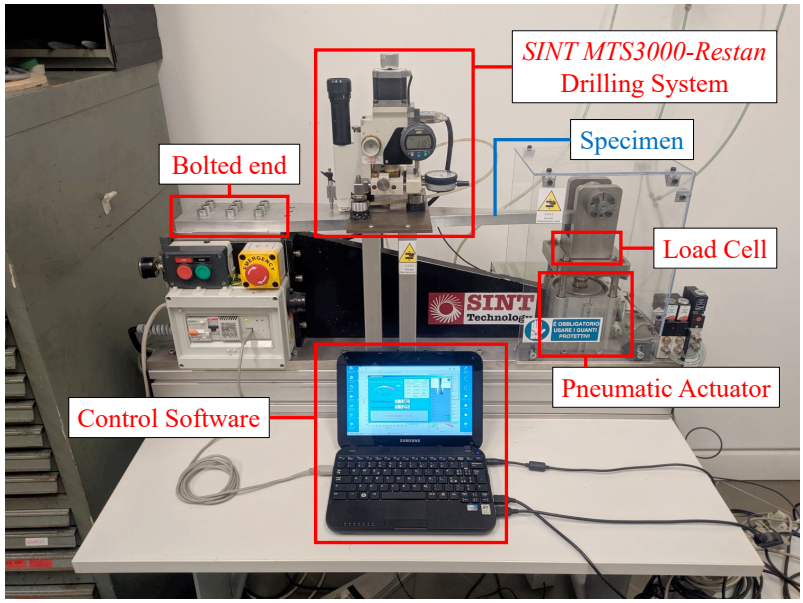

Fig. 1. Description of the calibration bench.

XRD is also sensitive to the crystallographic properties of the material under investigation and to the strategies used to identify the diffraction peak. Therefore, every application requires a careful evaluation of the instrumentation setup, in order to gain confidence on the obtained measurements.

To this aim, the authors presented a calibration bench [1, 2] which can impose a known bending distribution on a specimen while *simultaneously* performing an X-Ray Diffraction (XRD) or Hole-Drilling Method (HDM) residual stress measurement. Any issue regarding setup, instrument calibration or material crystallographic properties gives rise to notable differences between the reference bending distribution and its identified counterpart. Since the identification of the applied bending distribution is carried out with the same setup used for the residual stresses, the achieved accuracy in the identification of bending stresses is a direct validation of the residual stress measurements.

The bench is shown in Fig. 1. Details of the system are available in [1]. The identification of the bending stress distribution is based on two measurements, respectively in the unloaded and in the loaded configuration. Assuming linear elasticity, the difference between the two corresponds to the effect of the bending distribution alone, while measurements in the unloaded configuration involve residual stresses in the specimen.

In this work, the bench was used to validate XRD and HDM measurements on a shot peened 7075-aluminum specimen, reported in Fig. 2.

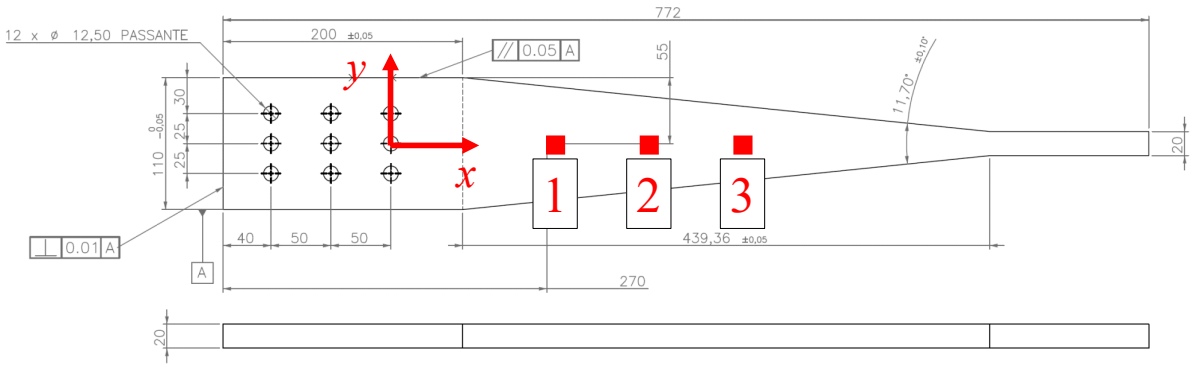

Fig. 2. Technical drawing of the aluminum specimen. The three measurement points on each specimen side are reported with red squares. The reference system is also shown.

Experimental Methods

The two sides of the specimen were shot peened with two different treatments, commercially known as AZB425 and CEB120, carried out at Peen Service srl. Details on their corresponding shot peening parameters are available in [1].
Three measurement points were marked on each side of the specimen (as in Fig. 2), then the following test campaign was conducted for each treatment:

- Surface XRD residual stress measurements were carried out at Peen Service srl on all three points, with a Stresstech Xstress3000 diffractometer. These measurements are labeled as Lab. 2 in Tables 1-2.
- Surface XRD residual stress measurements were repeated in a double-blind setting at University of Pisa on all three points, with a GNR SpiderX Edge diffractometer, shown in Fig. 3(a). These measurements are labeled as Lab. 1 in Tables 1-2. The experimental setup was validated on the calibration bench by identifying near-surface stress values of the bending distribution at two increasing load levels.
- HDM measurements were performed with a MTS3000-Restan equipment on points 1 and 2. For each drilling step, strains were sampled in both the unloaded and the loaded state, to simultaneously identify both the bending and the residual stress distribution.
- XRD depth profiling through electropolishing was carried out on point 3, up to a depth of about 0.1 mm. Diffraction measurements were performed with the GNR SpiderX Edge diffractometer.

XRD measurements were carried out with the $\sin^2\psi$ method, using a chrome anode and looking for the lattice spacing of {311} planes. In order to obtain the full stress tensor without any simplifying assumption, each XRD measurement was actually performed in three directions at angles of 0°, 45° and 90° with respect to the *x* axis. The etching depth obtained with electropolishing was measured with a micrometer dial gauge, shown in Fig. 3(b).
HBM RY61K strain rosettes (shown in *Fig. 4*) were used in HDM measurements. Holes were drilled with an inverted cone tool having a diameter of 1.8 mm, powered by an air turbine rotating at more than 300.000 rpm. A maximum depth of 1.2 mm was reached in 0.01 mm steps. Then, the hole diameter and eccentricity were measured through an optical microscope with crosshairs, included in the MTS3000-Restan system. Eventually, the stress distributions from 0 to 1 mm depth were obtained with the Influence Functions method [7], Tikhonov regularization and the Morozov discrepancy principle [8].

(a) (b)

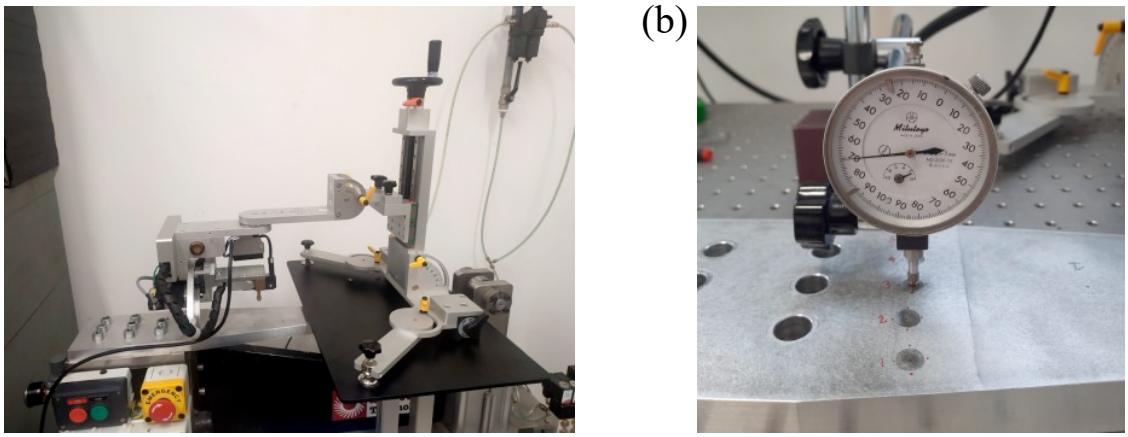

Fig. 3. (a) GNR SpiderX Edge Diffractometer, mounted on the calibration bench.
(b) Measurement of etching depth with a dial gauge.

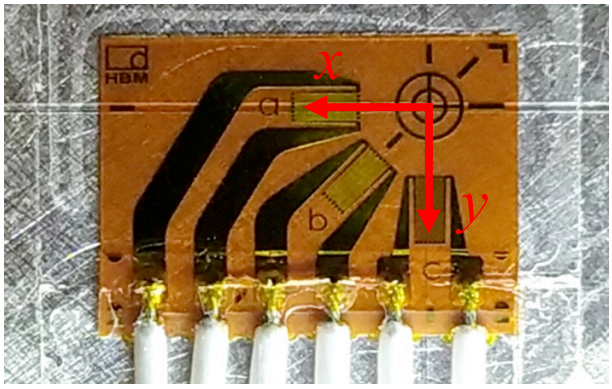

Fig. 4. Strain rosette (HBM RY61K) applied on the upper face of the specimen, aligned with the specimen reference system.

Experimental Results

Results of the XRD surface measurements are reported in Tables 1-2. For comparison, the near-surface stress values obtained through HDM measurements are also reported therein. For each treatment, point 3 was used to carry out the XRD depth profiling, so the corresponding HDM value is not available.
In *Fig. 5*, the validation data for XRD surface measurements are reported. Each graph refers to a component of the applied (plane) stress tensor, extracted from the three measurements at different orientation.
In *Fig. 6*, the bending stress distributions identified during HDM measurements are shown. The applied stress distributions were accurately characterized with the procedure described in [2].
In *Fig. 7*, the residual stress distributions obtained with HDM measurements on points 1-2 are compared with the XRD depth profiling performed on point 3.

Table 1. Summary of surface residual stress measurements – Normal stress σ_{xx} [MPa]

	HDM	**XRD (Lab. 1)**	**XRD (Lab. 2)**
AZB425 - 1	-259	-275	-270
AZB425 - 2	-255	-280	-274
AZB425 - 3	//	-246	-258
CEB120 - 1	-238	-246	-255
CEB120 - 2	-275	-242	-268
CEB120 - 3	//	-235	-249

Table 2. Summary of surface residual stress measurements – Normal stress σ_{yy} [MPa]

	HDM	**XRD (Lab. 1)**	**XRD (Lab. 2)**
AZB425 - 1	-293	-261	-262
AZB425 - 2	-276	-241	-265
AZB425 - 3	//	-251	-259
CEB120 - 1	-260	-249	-256
CEB120 - 2	-232	-244	-260
CEB120 - 3	//	-230	-256

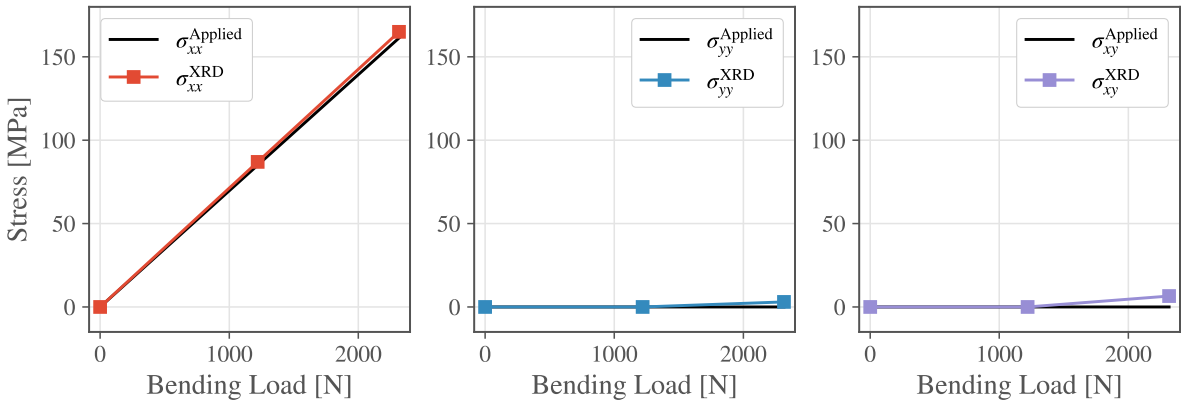

Fig. 5. Validation of XRD surface stress measurements, through identification of an accurately known bending stress distribution. The bending load is applied in two steps.

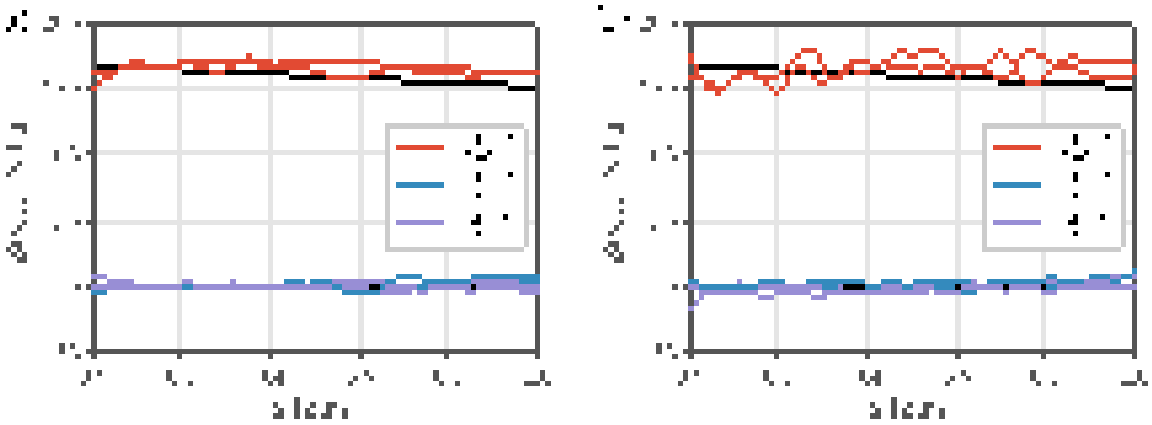

Fig. 6. Bending stress distributions identified during the four HDM measurements. The reference distributions are reported as black lines. (a) AZB425. (b) CEB120.

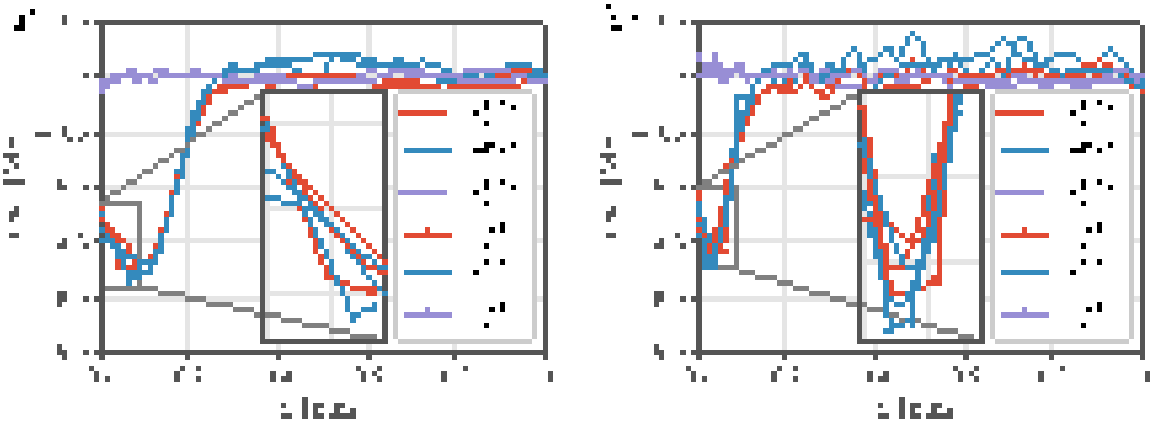

Fig. 7. Obtained residual stress distributions. The HDM measurements on points 1-2 are reported as dashed lines, while the XRD measurements on point 3 are reported as squares connected by solid lines. (a) AZB425. (b) CEB120.

Discussion and Conclusions

The validation phase confirmed that the instrumentation setup had been properly carried out. In particular, XRD surface measurements captured the stress fields produced by the bending load with notable accuracy (see Fig. 5). A slightly bigger error (in the order of 10 MPa) was obtained for σ_{xy} at the biggest load. That is still consistent with the fact that σ_{xy} is obtained as a linear combination of XRD measurements at the three orientations, so its precision is expected to be lower.
On the other hand, HDM measurements were able to capture the bending stress distribution along the entire hole depth (see Fig. 6). The achieved absolute error is about ±25 MPa, which is aligned with the state of the art [9]. Note that in this case the error is not particularly pronounced at the surface, where HDM is instead known to be prone to higher uncertainties.
Surface measurements reported in Tables 1-2 show comparable results across different measurement techniques and between the two diffractometers. Measurements show a variability which is compatible with the typical uncertainties of the methods [6].
The two residual stress profiles obtained with HDM for each shot peening treatment (shown in Fig. 7) are consistent with the ±25 MPa error achieved in the identification of the bending distribution. The XRD stress profiles obtained with electropolishing correctly mimic the trend of HDM curves. For a given depth value, the discrepancy can be up to 50 MPa. Uncertainties in the etching surface planarity and in the measurement of etching depth likely affect the achieved accuracy, which is still reasonable for engineering applications.
The presented calibration bench allows one to validate the chosen setup before and during residual stress measurements, both with XRD and HDM. For example, an unacceptably textured specimen material, insufficient grain statistics, or issues in the strain gauge bonding would immediately result in huge errors in the identification of the bending distribution.
Since the specimen can be designed with different materials and geometry, the calibration bench is particularly useful to investigate residual stresses produced by new surface treatments, with an increased measurement confidence provided by the validation phase.

References

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