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Residual stress analysis of shot-peened aluminum alloy by fine increment hole-drilling and X-ray diffraction methods

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Abstract

This paper proposes an analysis of the fine-increment hole-drilling and of the x-ray diffraction methods for residual stress measurement. This analysis was carried out on some shot-peened aluminum alloy samples, with particular attention to the surface. The shot-peening treatment introduces high compressive stress close to the surface of the sample, and for this reason it is widely used to extend the fatigue life of many mechanical components.
The hole-drilling method is based on the measurement of the surface strain relaxed during the incremental drilling of a small hole in the material. According to the ASTM E837-08 standard, the residual stress distribution can be measured over a typical depth of 1 mm.
X-ray residual stress analysis is based on the evaluation of interplanar distances in deformed samples along different orientations. This technique is suitable for the surface region, typically 10 – 40 µm. In-depth stress evaluation can be obtained by progressively thinning the sample and collecting diffraction patterns after each step.
The results obtained with the two methods are discussed, considering the different sources of uncertainty, to check the effectiveness of the two methods for the study of this class of materials.

Keywords: Shot-peening; X-ray diffraction; Hole drilling method.

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Nomenclature

XRD	X-ray diffraction.
HDM	Hole-drilling method.
ψ	X-ray incident angle.
$\varepsilon_1, \varepsilon_2, \varepsilon_3$	Rosette strain gage relaxed strains.
σ	Equibiaxial residual stress.

1. Introduction

The X-Ray Diffraction (XRD) and the Hole-Drilling Method (HDM) are the two main techniques for residual stress measurements on metal components [1]. XRD is especially suited to measuring the residual stress at the surface of a metal component, whereas HDM is conceived for measuring the residual stresses below the surface, and the surface residual stress value is just the first point of the residual stress distribution. Indeed, the most recent ASTM standard dedicated to the HDM, ASTM E837-08 [2], introduces a numerical procedure to calculate the residual stress distribution from the measured relaxed strain at drilled hole depth increments. However, XRD using the $\sin^2\psi$ technique [3, 4], also samples the material in a small depth from the surface. This depth depends on the material investigated and on the XRD angle, and it is in the order of a few µm for steels, and up to 20-30 µm for aluminum alloys [5]. The surface residual stress is mostly important for fatigue, whereas internal residual stresses can cause shape distortion even after machining, during component service life, because of slow residual stress relaxation. Fatigue is a well known surface phenomenon, thus in principle only the surface residual stress value should be taken into account. It has recently been experimentally demonstrated that residual stress can be incorporated in fatigue strength prediction according to the Critical Distance Theory, that introduces a specific material depth from the surface, and this can be applied also to the residual stresses [6]. In conclusion, residual stress at the surface and the residual stress distribution up to a small depth are both interesting to assess improvement or reduction of the fatigue strength of a structural metal component. Obviously, XRD can also be used to measure residual stress below the surface simply by removing a certain amount of material and repeating the diffraction measure on the new surface. This technique was applied and reported in the present research for the first steps, and was also applied before comparing the XRD and HDM results, obtaining successful comparative results [5, 7].

The HDM has recently been improved in terms of numerical evaluation of residual stress departing from measured relaxed strains, more specifically by introducing an eccentricity correction as input, instead of keeping the eccentricity error as low as possible. This calculation improvement was easily possible in the framework of the Influence Function method [8, 9]. Moreover, the HDM limitation of the plasticity effect was (partially) overcome by introducing a numerically based plasticity effect correction procedure [10] later experimentally validated [11].

The present paper proposes a comparison between surface and subsurface XRD and HDM residual stress measures on shot peened aluminum alloy flat bars. The values measured by the Hole Drilling Method agree with the values measured with the XRD method near the surface.

2. Investigated shot-peened aluminum alloy.

The material investigated is a high strength aluminum alloy 7075-T6, the composition of which is reported in Tab.1 [5], which is solution heat treated for 30 min. at 475 °C, further treated with water quenching, and finally aging at 120 °C for 6 hours.

Table 1. Aluminum alloy 7075 composition.

Mg %	Zn %	Cu %	Mn %	Cr %
2.1-2.9	5.1-6.1	1.2-2.0	0.3	0.18-0.28
Ti %	Si %	Fe %	Others %	Al
0.2	0.4	0.5	<0.2	Balance

Extruded thick bars (15 mm thick) were prepared with this aluminum alloy. Both surfaces of the bars were initially flattened by milling, and finally shot peened. The shot peening parameters are:

- bead material: PALCS230-8/10A-200%, steel bead S230, hardness 58 HRC;
- bead size: 0.600 µm
- shot impingement angle: 90°
- shot peening coverage: 200%
- Almen intensity: 8-10 A

Fig.1 shows a close view of the peened surface near the application of the rosette strain gage to perform the Hole-Drilling method. It is evident that the surface at the application of the strain gage was smoothed (few µm of material removed) to properly attach the strain gage on the specimen surface.

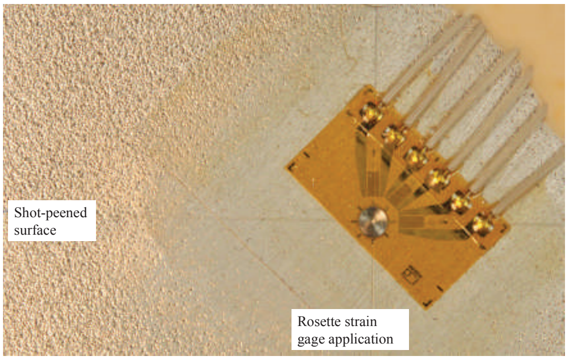


Figure 1. Close view of the shot-peened surface near a rosette strain gage application.

Figure 2 – Automatic system for the residual stress measurement by the hole drilling method (mechanical device)

3. Measurement System.

The Restan-MTS3000 system, produced by SINT Technology, was used for the hole drilling method. The system is composed of a mechanical device (Fig.2), an electronic device, control software (RMS) and back calculation software (EVAL). The main features of the system are the following:

- High speed air turbine (350000 RPM)
- Automatic control of the feed motion of the drilling tool by stepper motor

- Automatic electrical detection of the initial drilling depth
- Complete control of testing, processing of data and corrections by personal computer
- Automatic acquisition of a great number of strain measurements in depth

The strain gages used are: HBM K-RY61-1.5/120R.

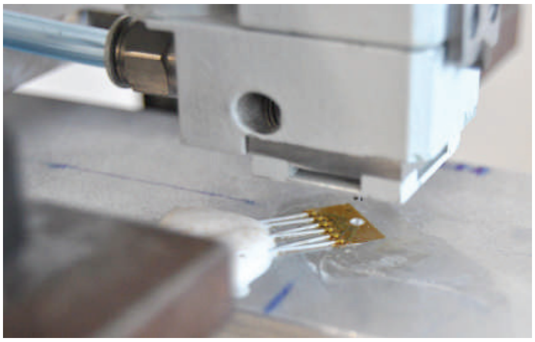
The residual stresses were calculated by the HDM method using the constant spline function with 100 calculation points (the original acquired strain points) with eccentricity correction between the drilled hole and the center of the strain gage rosette [8-9]. The calculation in compliance with ASTM E837:08 [2] was also performed.

The x-ray stress analyzer Xstress 3000 (StressTech) was used to measure the stresses imposed on crystallite material by X-ray, based on the phenomenon known as Braggs Law. The main features of the system are the following:

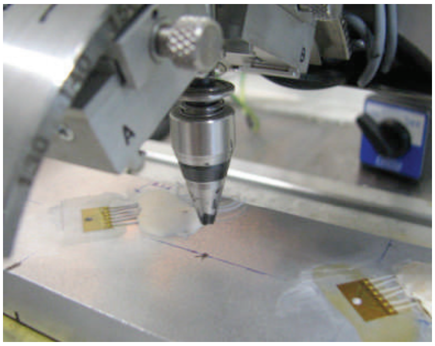
- Angular resolution: 0.029°/pixel, 512 pixels/12.8 mm, Vertical positioning accuracy: ± 0.003 mm
- Psi angle inclination -40° +40°, oscillation ± 1°, 2 theta 125°-162°
- Automatic calibration and data elaboration software by Cross Correlation method

4. Results.

The surfaces of the bar were measured both with Hole-Drilling and X-ray diffraction and it was found that the residual stress distribution along the surface position was quite uniform. Therefore, relevant comparisons were obtained by testing surface positions, with both XRD and HDM, near each other, Fig.3.



(a)



(b)

Figure 3. (a) Detail of the Hole Drilling Method equipment. (b) Detail of X-ray diffraction equipment.

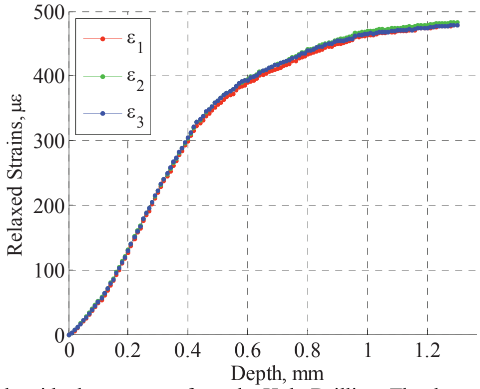


Figure 4. Evidence of equibiaxial residual stress state from the Hole-Drilling. The three relaxed strain readings are very similar.

It is noted that the (compressive) residual stress state is almost equibiaxial at any depth, because of the inherently isotropic shot-peening treatment, in spite of a preexisting directional residual stress state due to extrusion. Clear evidence of equibiaxial residual stress is that the relaxed strain readings of the three grids of the rosette strain gage, Fig.1, are almost equal, Fig.4.

The comparison between the two measurement techniques is reported in Fig.5 for three different specimens treated with the same shot-peening process.

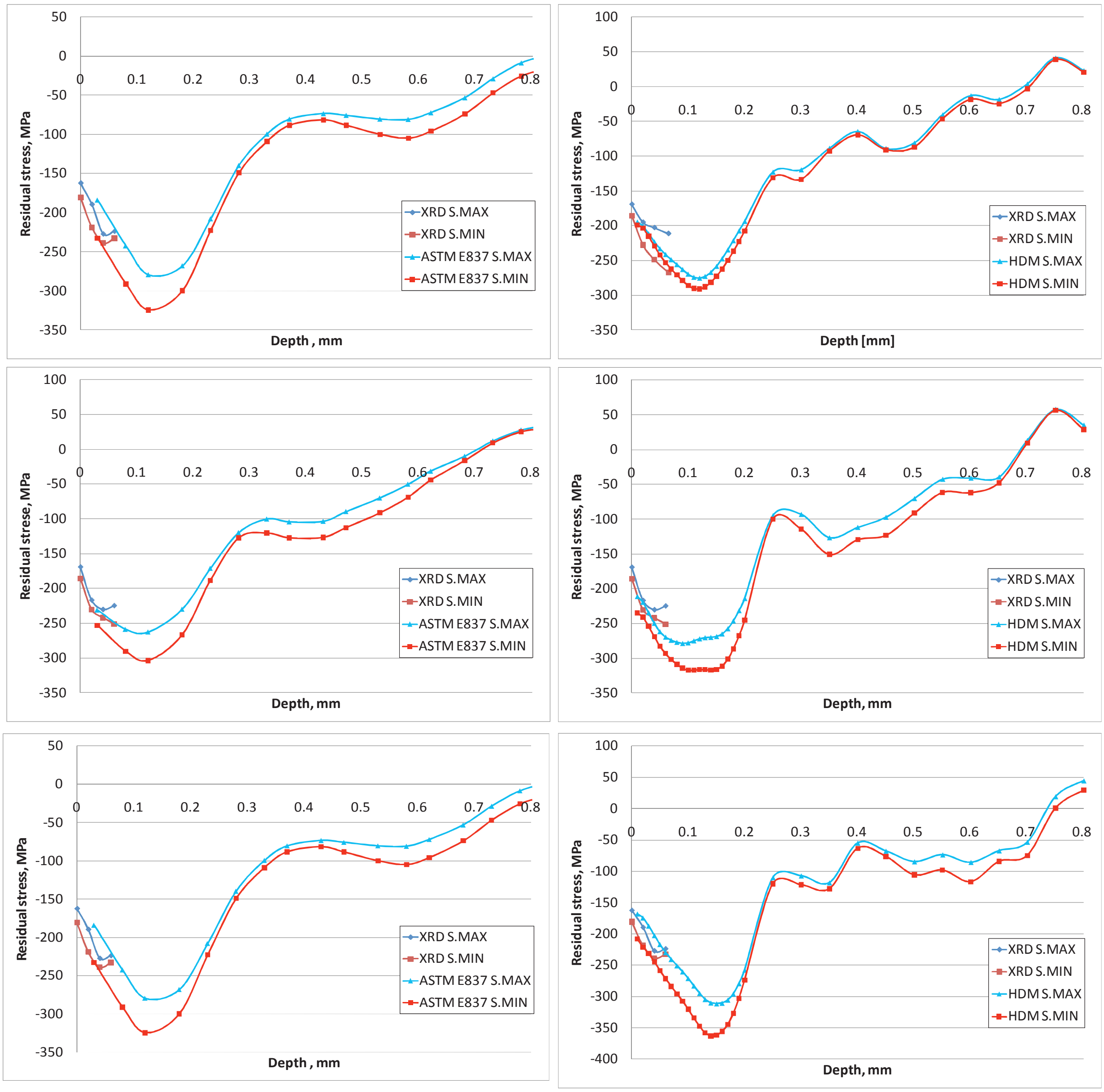


Figure 5. Comparison between Hole Drilling measurement and XRD measurements, for 3 different specimens. On the left HD calculation with the ASTM E837-8 Method (X), on the right calculation with the HDM Method (X)

5. Conclusions

The comparison of the residual stress measurement techniques was successful near the surface.

With the hole drilling method it is possible to make hole drilling measurements from 0.01-0.02 mm below the surface up to 1.2 mm, with the strain gage rosette HBM K-RY61-1.5/120R, by using the HDM Method.

An appropriate interpolation can predict the residual stress values on the surface; these values are very similar to the values measured by X-ray diffraction.

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