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Residual Stress Measurement by ESPI Hole-Drilling

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Abstract

ESPI (Electronic Speckle Pattern Interferometry) is an optical method, used here to analyze the stress relief brought about by drilling a hole incrementally. Measurement times are substantially reduced compared to the standard hole-drilling method since no strain-gages have to be applied. Since repeat measurements can be made easily and quickly, measurement quality and stress distribution across the sample surface can be assessed well. This presentation focuses on practical measurement examples from different materials after shot-peening and under bending load. Factors affecting the measurement results are discussed.

Keywords: Residual Stress Measurement; Incremental Hole-Drilling; ESPI; Drilling Parameters

1. Introduction

Hole-drilling combined with strain gage measurement is one of the most commonly used techniques for measuring residual stresses. The measurement process itself is quite fast. Yet a new strain gage has to be attached to the sample for each measurement and the surface has to be properly prepared so that the strain gage can measure the sample behavior correctly.

Optical surface measurement techniques have benefitted from the development of digital cameras and computers and now offer a realistic alternative. ESPI uses laser light to capture images of the measurement surface before and after each drilling increment so that surface displacements due to the stress relief can be quantified. The Prism[*] instrument uses a laser beam that’s split into two; one of them is phase-shifted. Each surface condition is described by four images with a fixed phase relationship due to the phase-shifting. This allows determining surface displacements as a small fraction of the wavelength used (532 nm).

While strain gages generate average data from very few areas around the hole, the ESPI images deliver 10,000s of pixels with displacement information. Although the pixel data are quite noisy, the analysis is full field [1]. A principal difference is that the data analysis is not based on strains but correlates displacements directly with stresses via a set of coefficients.

In practice, the elimination of the strain gages makes it more practicable to perform multiple measurements on a sample. Repeat measurements are essential for verifying precision and learning proper technique, especially when the measurement quantity is hard to verify by other means.

The measurements were made on aerospace aluminum, tool steel O1 and a polycarbonate, representing materials with very different drilling behavior. The idea was to test the capabilities of this measurement system in this regard. The quality of the results is assessed using repeat measurements and by comparisons with calculated bending stresses.

2. Instrument

The drill is an electric high-speed precision spindle system with a speed range of 5,000 to 50,000 rpm. The drilling area may be illuminated by a single laser beam, with the reference beam combining with the object beam inside the camera, or by both beams in symmetrical configuration for purely in-plane displacements (Fig. 1). The only sample preparation is the application of a thin spray paint layer that eliminates the

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[*] Prism® is a registered trademark of American Stress Technologies, Inc., Pittsburgh, PA, USA

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reflectivity of a metallic surface and increases the amount of diffuse light reflection that carries the desired information.

Two-fluted, TiN coated, square-end end mills were used for all measurements. Rotation speeds and other drilling parameters were adjusted depending on the sample material.

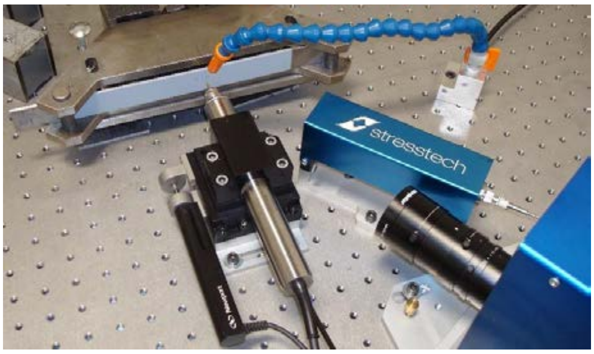

Fig. 1. Measurement setup for a- sample under bending load: sample, drill, camera, illumination stand and chip air block.

Most of the results shown here made use of a separately controlled device for orbital drilling. Added orbital motion of the drill has been used for the hole-drilling technique for a long time [3]. It benefits the hole quality. Drilling without orbital motion is here referred to as plunge drilling.

Data analysis considers the pixels in a user-defined, ring-shaped area around the hole. The stress calculation follows the Integral Method with optional regularization (a smoothing method). Both are equivalent to the process recommended in the ASTM standard for strain gage hole-drilling [2]. The hole size was determined using an image with the hole and a scale.

3. Measurements

A shot-peened aerospace aluminum sample (alloy 7075) was used for a study comparing plunge and orbital drilling with different amounts of eccentricity. Shown here is a small subsection of results described in more detail in [4]. Figure 2 shows the three results for each of three conditions: plunge drilling and hole drilling with tool sizes one half (orbital drilling) and one quarter (ring drilling) of the fixed feature diameter of ~1.6 mm. The plunge drilling results, though with decent repeatability, show the most variability (Fig. 2a). Both others are much more consistent.

The average curves from these measurement sets are shown in Figure 3. The differences are relatively small, but should be characteristic due to the high measurement repeatability. At the lowest depths, the plunge drilling curve is shifted to less compressive stresses. This effect is understandable because the hole shape deviates from the cylinder shape that is assumed for the coefficients. Square-end end mills leave an inverted cone on the hole bottom after plunge drilling. The actually removed material is thus significantly smaller than the coefficients expected for the very lowest depths and the stresses are thus underestimated. This effect is magnified by regularization even though a relatively small factor was used, as indicated by the limited smoothness of the individual measurements (Fig. 2).

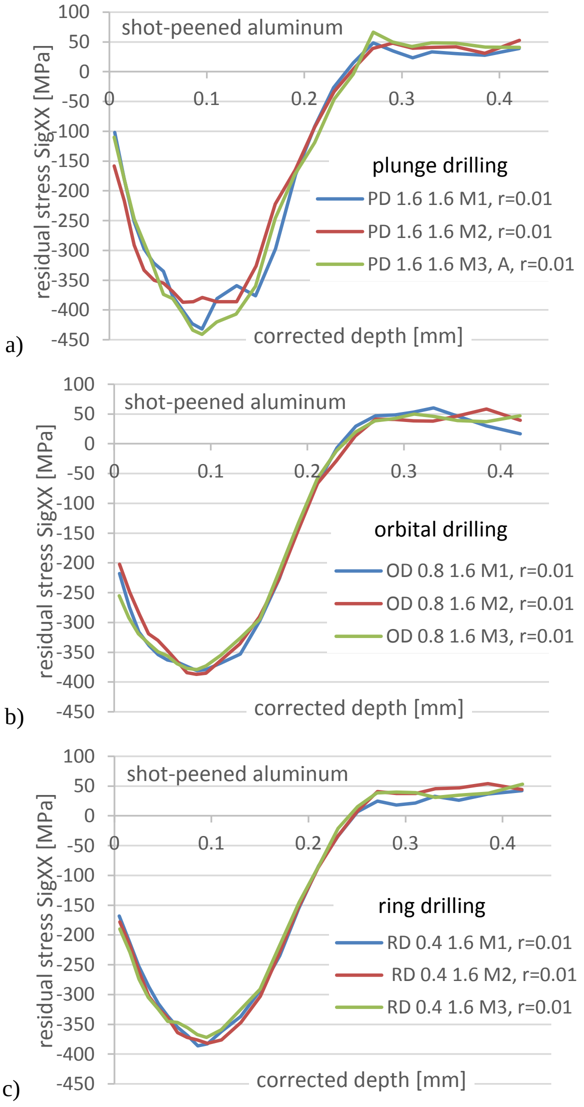

Fig. 2. Repeatability is poorer for plunge drilling than orbital or ring drilling. The feature size is 1.6 mm, the tool sizes 1.6 (a) to 0.8 (b) and 0.4 mm (c).

A similar, but smaller shift to lower stresses at small depths is found for ring drilling where the ring width is relatively large. The complete depth profiles for rings with a diameter three or four times the tool size are quite close to orbital drilling of a hole with twice the tool size. This is understandable by considering that the displacement measurements are solely made outside the ring and that any stresses from the remaining column can only affect them via the "ring bottom".

Further indications that the shot-peening results are reasonable are the fact that stresses in different directions are very similar (Fig. 3) and that shear stresses are negligible.