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Residual stress measurements by ESPI-HDM in titanium grade 5: comparative measurements with different hole diameters

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Abstract

Hole Drilling Method (HDM) is the most common approach to measure residual stresses in components; along the years it has greatly grown up in equipment sophistication. Nowadays, in fact, full field optical techniques are becoming increasingly adopted in replacing strain gage transducers. The introduction of these techniques can guarantee several advantages; for example higher sensitivity can be achieved and the long and expensive step of transducers application can be avoided. When performing the measurement many experimental and setting parameters are involved and they can greatly affect the quality of the final measurement. The hole diameter, for example, strongly affects the entity of the relieved strain. Drilling a hole with a bigger diameter allows to obtain higher strain that are easier to measure. On the contrary, a small diameter should be preferred in view of the subsequent repairing process. Furthermore, using higher diameter of the drill bit could compromise the analysis itself in case of complex geometry. In this work a well-known state of stress was introduced in a Ti6Al4V specimen. Measurements were performed by using two different diameters of the drilling bits: 1/16'', 1/32''. Results were critically compared with the analogous ones reported in literature for aluminum and steel.

Keywords: Drilling bit; ESPI; Hole diameters; Residual stress; Titanium grade5.

1. Introduction

The HDM is the most general approach used to measure residual stress profiles in materials [1]. It consists in executing a very small hole, tolerable or repairable, and then in measuring the relieved strain by using a strain gage rosette placed in an area close to the hole itself. Nowadays HDM together with X-ray diffraction [2] are the only practices subjected to standardization, even if, in the last years, traditional HDM has been modified by replacing strain gage transducers with optical techniques, as those based on Electronic Speckle Pattern Interferometry (ESPI). This technique ensures full-field data, higher sensitivity, it significantly reduces the test preparation time connected with the transducers application [3,4] and it could be easily applied on a great variety of materials [5,6].

Three major aspects of HDM, as summarized by Schajer [7], have greatly developed in the last years, providing significant advances of the technique: the execution of the drilled hole, the measurement of the resulting deformations around the hole and the computation of the corresponding residual stresses. A number of factors contribute to determine the final quality of the measurement such as the drilling rotation speed [8-10], the hole shape [11-15], the number of increment steps [16,17] and the cutter milling diameter [10]. When the ESPI technique is adopted to measure the displacement field some other factors must be

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accurately determined and set such as the illumination and the detection angles [18] or, in the post-processing stage, the choice of the analysis area [19] that is to say the portion of the captured image, limited by an internal and an external radius, in which data are elaborated to calculate the residual stresses. In some cases it is also relevant to analyse the combination of some of these factors as it was done in [20,21] where it was studied how the variation of the drilling rotation speed affects the choice of the optimal analysis area.
In this paper the choice of the cutter milling diameter is discussed. It is known, in fact, that the strain field magnitude measured at a certain distance from the hole depends on the squared value of cutter diameter [22]. In many industrial applications it could be fundamental to decrease the hole diameter, in order to measure the residual stress field close to welding zones or in correspondence of small surfaces. However the small size of the hole could lead to increasing percentage errors in the measuring process. In scientific literature there are few studies concerning with this topic. In [23] differences in terms of strain relaxation, measured on the three strain gages of a rosette are compared for two cutter diameters 1/16'' and 1/32''. Those are the most commonly used hole diameters as it was also stated in [24]. Recently, Upshaw et al. [10] studied the effects of using different drill-bit diameters on aluminum and stainless steel specimens. They observed that the smaller drill-bit diameter provides scattered data in stainless steel and not in aluminum samples. Authors justified this attitude considering that the elastic modulus in stainless steel is much higher than in aluminum and for this reason surface displacement are smaller and harder to be measured in steel. Based on these considerations it is not easy to infer in advance what could be the response of the Ti6Al4V titanium alloy.
In this paper Ti6Al4V specimen was loaded in a four-point bending frame in order to introduce a well-known state of stress along the longitudinal axis. ESPI - hole drilling measurements were then performed by using two different drilling bits whose diameter was 1/16'' and 1/32'' respectively. Ti6Al4V is an interesting material to be studied in view of its very good strength-to-density ratio, and good corrosion resistance, properties that lead to an increasing demand of this material in aircraft industry; furthermore those characteristics joined with the high biological compatibility, guaranteed by this material, are expanding its application also in the biomedical field [25].

2. Materials and methods

Tests were performed on a Titanium grade 5 (Ti-6Al-4V) specimen (248.5 mm x 42.5 mm x 3.0 mm). It was loaded in a four-point-bending frame in order to introduce a known stress state on the sample (Figure 1).

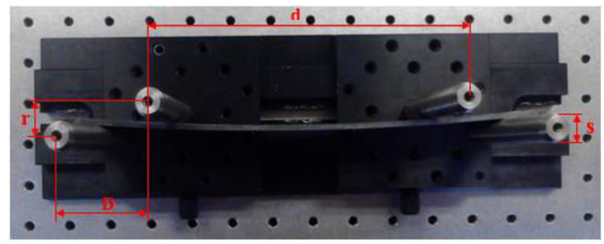
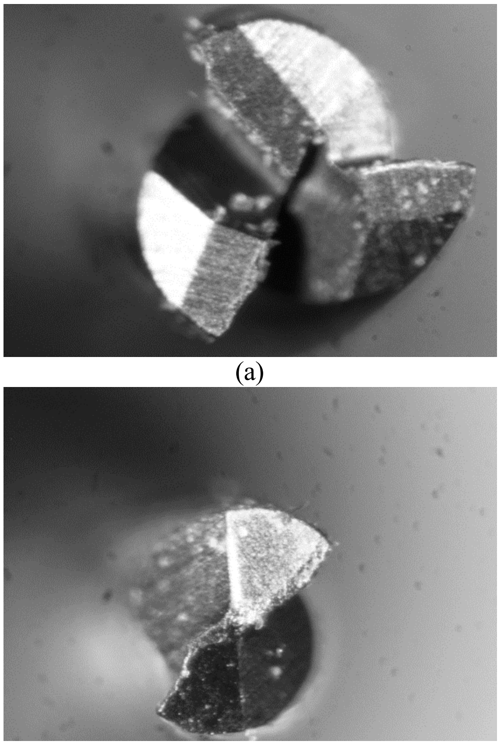


Fig. 1. Set-up for four-point bending test and indication of geometrical parameters.

The sample was loaded so that an unidirectional longitudinal stress field is obtained with means values, along the profile $\sigma^{mean}_{xx}= \sigma_1^{mean}$=114 MPa and $\sigma^{mean}_{yy}= \sigma_2^{mean}$ =10 MPa, θ=1.2°. It was important to guarantee that the measured stress only refers to the applied external reference load by avoiding to include any initial residual stress field. To this purpose preliminary X-ray (XRD) residual stress measurements were performed in order to asses if the *as received* material can be considered free from stress or it has to undergo to relieving process.
After this initial check the hole is drilled by means of a high speed turbine which is mounted on a precision travel stage. Turbine rotation is electronically controlled and it was set to 35000 rpm. Two cutters were used: 1/16'' drill-bit diameter having three cutting edges, 1/32'' drill-bit diameter having two cutting edges (Figure 2).
A diode pumped solid state laser source (λ=532 nm) was used in order to illuminate the sample and generate the speckle pattern which is then recorded by a CCD camera (Figure 3). Light diffused by the sample is made to interfere on the CCD matrix with a reference beam. Four-step temporal phase shifting algorithm is adopted in order to obtain the phase.
The HDM+ESPI method was used to evaluate the external four-point bending applied stress. The overall experimental set-up is shown in Figure 3.
According to [10] and considering the two drill-bit diameters, holes were drilled up to 0.40 mm, each incremental step was 40 μm. The holes were drilled in an area close to the maximum deflection, in order to avoid any effects due to the curvature of the bent sample.



(a)

(b)

Fig. 2. Optical microscope images of (a) 1/16'' and (b) 1/32'' cutters, after 8 drilled holes.

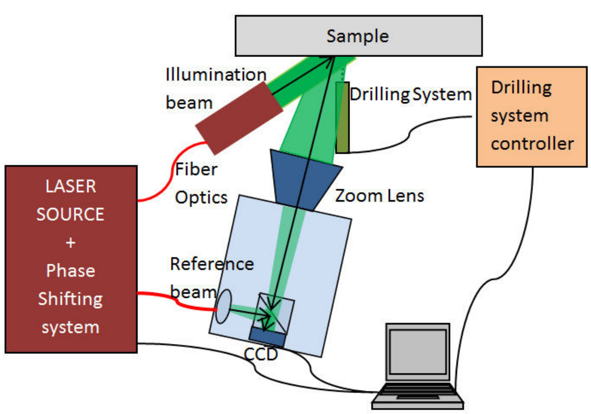


Fig. 3. HDM+ESPI set-up.

The distance between the centers of the holes was set equal to 6 times the drill-bit diameter to minimize the interaction between the holes, according to [10].

For each drill increment the corresponding speckle pattern was recorded at four different positions of the piezoelectric translator. These intensity maps were subtracted from the reference intensity pattern recorded on the sample before starting the drilling procedure. This operation allows to obtain fringe pattern encoding the information about the displacement experienced by the sample along the sensitivity vector. Once displacement maps were obtained stresses were calculated based upon the procedure ilustrated in [26].

3. Results and discussion

Recorded correlation fringe pattern obtained in correspondence of three different drilling steps are shown in Figure 4.

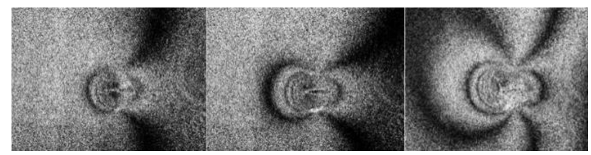


Fig. 4. Fringe patterns recorded at three different drill-increments: from left to right respectively at 0.1 mm, 0.2 mm and 0.4 mm.

Table 1 shows results corresponding to three different holes drilled using the 1/16'' drill-bit diameter. Table 2 shows results corresponding to three different holes drilled using the 1/32'' drill-bit diameter. Data report principal stresses σ_1, σ_2 and their angle θ calculated along the 0.4 mm of the drilled hole. For each measured parameter the mean value was evaluated.

Table 1. 1/16''drill-bit diameter: σ_1, σ_2, θ evaluated on three holes.

	Hole	σ_1 $[MPa]$	σ_2 $[MPa]$	θ [°]
	1	107	9	-1.43
	2	103	6	-1.16
	3	115	11	-0.38
Mean value		108	8	
St. Dev.		6	2	

Table 2. 1/32''drill-bit diameter: σ_1, σ_2, θ evaluated on three holes.

	Hole	σ_1 $[MPa]$	σ_2 $[MPa]$	θ [°]
	1	114	29	-1.43
	2	124	33	-1.16
	3	138	30	-0.38
Mean value		125	31	
St. Dev.		12	2	

By comparing the results reported in the two tables it can be inferred that, in both cases results concerning with the measurement of the longitudinal stress are consistent with the expected theoretical values. Also the standard deviation found in all cases is comparable so that no significant influence in terms of data point scattering can be observed. However, it must be observed that higher error is found when measuring the minimum stress by using the 1/32” drill bit. This means that attention must be paid when measuring small values of the stress, and correspondingly small values of displacements, in titanium by using a small drill bit diameter. Concerning with the measurement of the angle θ it can be said that good results with low and comparable dispersion are obtained with both the drill bit diameters.

Analogous considerations can be done by observing data recorded at different depths for both drill-bit diameters as it is reported in Figures 5 and 6.

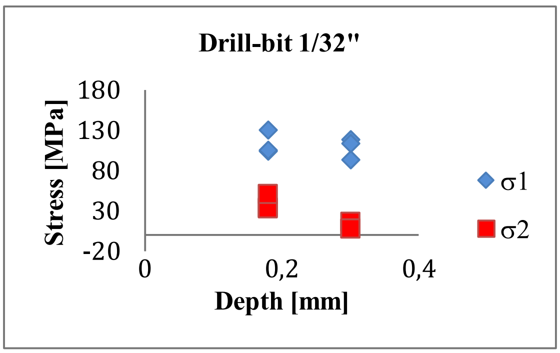


Fig. 5. Principal stresses evaluated at two different depths set with 1/32’’ drill-bit.

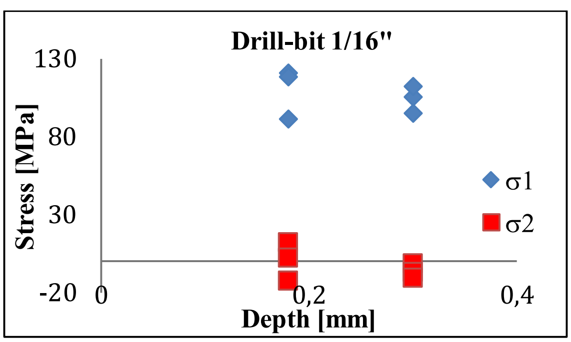


Fig. 6. Principal stresses evaluated at two different depths set with 1/16’’ drill-bit.

It results that, for the level of applied load considered, the cutter mill diameter didn’t affect substantially the measurement accuracy on titanium specimen and this represents an important result that should be compared with the analogous results reported in literature for steel. In that case, in fact, substantial influence of the drill-bit diameter was found. Explanation for this discrepancy can be found by comparing the Young moduli of the two materials. In the case of steel the higher value of the Young modulus coupled with the choice of a small diameter drill-bit leads to a low strain field around the hole more difficult to be detected and measured and, as a consequence, more subjected to measurements errors. The opposite behaviour can be observed analysing aluminum results.

Moreover it should be underlined that better results are obtained in measuring the minimum residual stress by the 1/16” drill-bit. This can be explained starting by two considerations: firstly given the low value of the minimum stress the resulting displacement field is low and more subjected to measurements errors. Secondly, for the given set-up geometry the sensitivity vectors is directed along the longitudinal direction of the specimen while the direction of the minimum stress is about directed along the transverse direction. This implies that the displacements introduced by this stress component are divided by the Poisson ratio so they are further reduced in magnitude and more difficult to be measured.

4. Conclusions

A Ti6Al4V specimen was tested in a four-point bending frame in order to introduce a well-known state of stress along the longitudinal axis. Measurements were then performed by using two different drilling bits in ESPI - HDM combined methods: 1/16’’ and 1/32’’. It was found that comparable results were found with respect to the measurement of the maximum stress and of the inclination angle. This also indicates a good machinability of the material with both the adopted diameters. However some discrepancies were found when the minimum stress was measured with the smaller cutter also due to the fact that the component of the minimum stress is orthogonal to the sensitivity vector for the geometric configuration adopted in this experiment

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