POUŽITELNOST ESPI PRO MĚŘENÍ ZBYTKOVÝCH NAPĚTÍ

ESPI APPLICABILITY TO RESIDUAL STRESSES MEASUREMENTS

Otomar ŠEDIVÝ, Stanislav HOLÝ[1]

Abstrakt

Zbytková napětí jsou napětími, která jsou přítomna v součástech i bez působení vnějších sil. Jejich vznik je spojen s technologií výroby nebo s používáním součásti. Při zatížení dochází k superpozici s napětími vyvolanými vnějším zatížením. Jejich existence často značně negativně ovlivňuje bezpečnost a životnost součástí. Proto je v technické praxi důležité určování těchto napětí.

Jako vhodná metoda pro měření zbytkových napětí se jeví Electronic Speckle Pattern Interferometry (ESPI) v kombinaci s odvrtávací metodou. Cílem této práce bylo posoudit vhodnost použití této metody na základě literární rešerše a provedených experimentů. Oproti tradiční odvrtávací metodě poskytuje navržená metoda celoplošná 3D-měření uvolněných deformací, redukuje čas měření a potlačuje některé chyby (excentricita, vliv teploty). Na základě provedeného výpočtu se výše uvedená metoda se jeví jako vhodná. Zbytková napětí lze určovat s relativní chybou 7,5%, což je výsledek srovnatelný s 10% tradiční odvrtávací metody.

Klíčová slova: Electronic Speckle Pattern Interferometry, měření zbytkových napětí.

Abstract

Residual stresses are present in parts also when no external forces are acting. They arise during technology process or by part use. When parts are loaded, the superposition with stresses caused by external forces takes place. The residual stresses often negatively affect the part safety and lifetime. Their determination is thus very important.

The Electronic Speckle Pattern Interferometry (ESPI) and the Hole-Drilling combined technique seems to be an appropriate method for measurement of residual stresses. The aim of this work was to consider the applicability of this method in terms of literature sources and performed experiments. In comparison with the traditional Hole-Drilling method the suggested technique offers three-dimensional whole-field measurements of relieved strains, reduces measuring time and suppresses some errors (eccentricity, temperature effect). The proposed technique seems to be suitable. It is possible to determine residual stresses with a relative error of 7.5%, what represents comparable result of 10% by the Hole-Drilling strain gauge method.

Keywords: Electronic Speckle Pattern Interferometry, residual stresses measurement.

INTRODUCTION

The Hole-Drilling method is based on drilling a small hole, which causes partial residual stresses release. Corresponding strains are measured on the object surface by strain gauges and the

[1] Ing. Otomar ŠEDIVÝ, prof. Ing. Stanislav HOLÝ, CSc., ÚMBaM, FSj ČVÚT v Praze, otomar.sedivy@fs.cvut.cz, stanislav.holy@fs.cvut.cz

Lektoroval: Dr.h.c. prof. Ing. František TREBUŇA, CSc., KAMaM, SjF TU v Košiciach, frantisek.trebuna@tuke.sk

directions and magnitude of principal residual stresses are determined by calibration constants [1]. This method is standardized [2].

The Electronic Speckle Pattern Interferometry (ESPI) is an optical method that uses Speckle-Effect. By comparison of three pairs of object images all three point-displacement-components in the investigated area can be determined contactlessly [3].

It is possible to use ESPI instead of strain gauges by the Hole-Drilling method. The non-contactness of the measurement apparatus, absence of strain gauge (no influence of eccentricity, temperature and integration over its length) and time saving represent the advantages of the technique. The strains are determined in all points of the field as first derivatives of displacement and when split into more steps, their magnitude can be arbitrarily big.

Lately, preliminary measurements concentrated on determination of residual stresses by the mentioned combined technique have been provided. Thin specimens with known stress distribution simulating a real relieved stress state were examined [4]. The relieved displacement fields are measured by ESPI, the strains are determined and magnitude of the stresses is computed by known equations [1].

EXPERIMENTAL PART AND COMPUTATIONS

Experiments

The experimental part was focused on measurements testing the applicability of designed ESPI apparatus. The strain-stress curves of steel sheets during the simple tension test were measured. The obtained strain–stress diagram with two unloading cycles from the plastic state shows figure 1. The curve labelled “Strain gauge” represents the comparing measurement with strain gauge on the other side of the sample. The maximal difference between both measurements makes 1.5 % [5]. Further measurements of sample-unloading from the plastic deformation of 10% were performed. By these experiments the use of strain gauges would be practically impossible if suppression of material relaxation and creep is required.

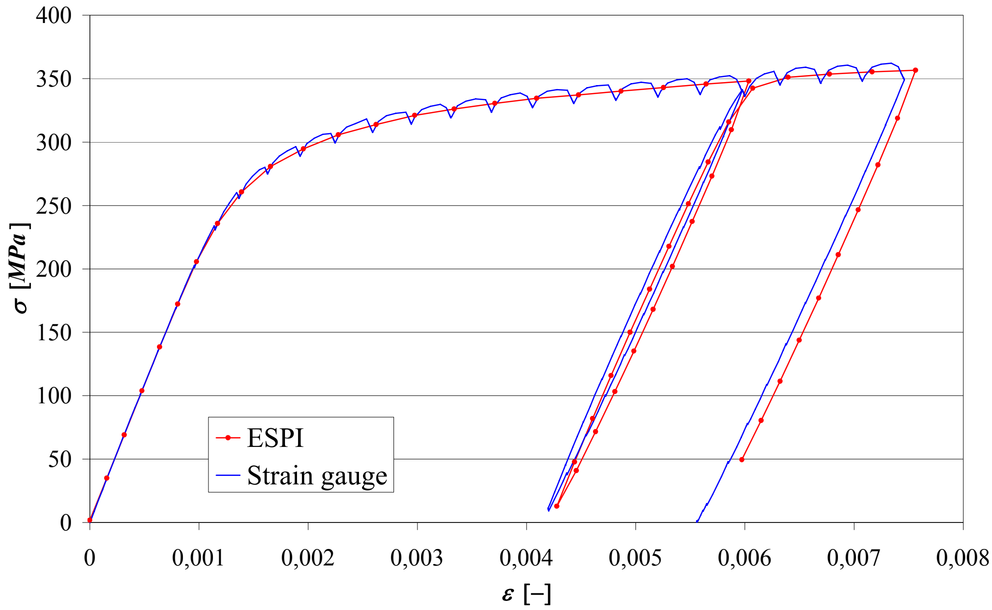

Fig. 1 Strain–stress diagram obtained by ESPI and strain gauges

Apparatus parameters

The properties and the influence of the ESPI apparatus were also examined. The apparatus displacement resolution is equal to $2{,}7.10^{-9}$ *m* by the designed arrangement. The minimal theoretical measurable deformation for investigated area 12x12 *mm* makes 0,2 $\mu m/m$, but for real measurements 20 $\mu m/m$ are reasonable. The in-plane resolution of the apparatus is 1 $\mu m/m$. This value is equal to the resolution required by [2]. In comparison to ESPI, stricter requirements are imposed on residual stress measurements provided by strain gauges because of the in chapter 1 mentioned effects.

Computation of relieved displacements

The displacements caused by relief of residual stresses by the drilled hole of diameter r_0 in the coordinate origin of a plate loaded by uniaxial homogeneous tension in *x*-direction can be computed with Kirsch´ equations in Cartesian coordinates *x*, *y* [4]:

$$u_x(x,y)=\frac{(\nu+1)\sigma r_0^2}{2E}\frac{\cos\delta}{\sqrt{x^2+y^2}}\left[\frac{\nu+5}{\nu+1}-4\sin^2\delta-\left(1-4\sin^2\delta\right)\frac{r_0^2}{x^2+y^2}\right], \quad (1)$$

$$u_y(x,y)=\frac{(\nu+1)\sigma r_0^2}{2E}\frac{\sin\delta}{\sqrt{x^2+y^2}}\left[\frac{\nu-3}{\nu+1}+4\cos^2\delta+\left(1-4\cos^2\delta\right)\frac{r_0^2}{x^2+y^2}\right], \quad (2)$$

where $\delta = \arctan(y/x)$, *E* is Young´s modulus, ν Poisson´s ratio and σ the magnitude of uniaxial stress in the *x*-direction.

These equations are valid for linearly elastic material, i.e. for $\sigma < 50\%$ of yield stress. For steel ($E = 2{,}1.10^5$ *MPa*, $\nu = 0{,}3$, $r_0 = 1$ *mm* and $\sigma = 10$ *MPa* corresponding to 5% of yield stress, the displacement on the hole border is $u_x = 9{,}52.10^{-5}$ *mm*, corresponding to deformation $\varepsilon_x = -80$ $\mu m/m$ determined on the path of 0,2 *mm* for u_x ($x = 1{,}2$ *mm*, $y = 0$ *mm*) $= 7{,}94.10^{-5}$ *mm*. These values are measurable by the apparatus with a relative error of 2%. The equation (1) and its first derivative are represented in fig. 2.

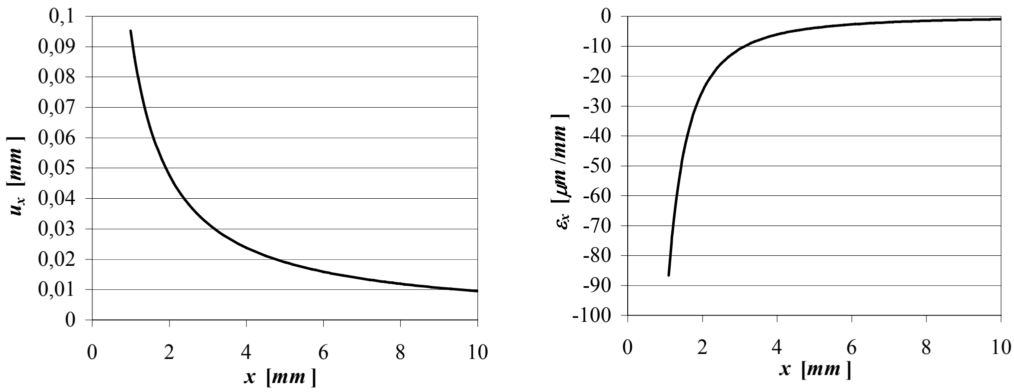

Fig. 2 u_x and ε_x computed for $E = 2{,}1.10^5$ *MPa*, $\nu = 0{,}3$, $r_0 = 1$ mm and $\sigma = 10$ *MPa* according to equation (1)

The existing apparatus can be used in above-mentioned manner to residual stresses measurements, and in comparison to other apparatus thanks to bigger CCD-Chip has even better properties. The accuracy of used systems is comparable with Hole-Drilling with strain gauges and reaches for 10% of yield stress 7,5% [4], what is comparable with 10% of the traditional Hole-Drilling method [2].

During the determination of smaller residual stresses measured by ESPI some complications could arise, especially by incremental drilling, when deformations relieved in one step are relatively small. The maximal displacement measured is actually not limited. When the load is divided into more steps, the total point displacement is the sum of displacements between the steps.

CONCLUSION

The existing apparatus can be used for residual stresses measurements from 5 to 50% of yield stress. It is possible to determine residual stresses with a relative error of 7.5%, what represents comparable result of 10% by the traditional Hole-Drilling method.

Further, it is planned to measure the strains of samples with hole, loaded by tension, to provide FEM simulation and compare these results, to design an algorithm for automatic evaluation of residual stresses even bigger than 50% of yield stress, to provide measurements on real object and compare them with strain gauge measurements.

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REFERENCES

[1] LU, J. (ed.).: *Handbook of Measurement of Residual Stresses*. Lilburn: The Fairmont Press, 1996. 238 s. ISBN: 0-132-55738-X.

[2] ASTM E 837-01. *Standard test method for determining residual stresses by the hole-drilling strain-gage method*. 2001.

[3] CLOUD, G. L.: *Optical Methods of Engineering Analysis*. New York: Cambridge University Press, 1995. 503 s. ISBN 0-521-63642-6.

[4] VIOTTI, M. R., KAUFMANN, G. H.: *Accuracy and sensitivity of a hole drilling and digital speckle pattern interferometry combined techniquie to measure residual stresses*. Optics and Lasers in Engineering, 2004, vol. 41, no. 2, p.297–305. ISSN 0143-8166.

[5] ŠEDIVÝ, O.: *Grundlagen und Anwendung der elektronischen Speckle-Interferometrie (ESPI) für die Analyse elastisch-plastischer Werkstoffeigenschaften: diploma thesis*. Chemnitz: Technische Universität Chemnitz, 2003. 48 s.