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Claudia Barile, Caterina Casavola, Giovanni Pappalettera, Carmine Pappalettere

RESIDUAL STRESS MEASUREMENT BY ELECTRONIC SPECKLE PATTERN INTERFEROMETRY: A STUDY OF THE INFLUENCE OF ANALYSIS PARAMETERS

MERENJE ZAOSTALIH NAPONA ELEKTRONSKOM INTERFEROMETRIJOM ŠABLONA MRLJA: STUDIJA UTICAJA ANALITIČKIH PARAMETARA

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Adresa autora / Author's address:
Dipartimento di Ingegneria Meccanica e Gestionale, Politecnico di Bari, Italy, email: casavola@poliba.it

Keywords
- residual stress
- ESPI
- integral method

Abstract

Hole drilling (HDM) is the most widespread method for measuring the residual stress profile. HDM is based on the principle that a hole in the material causes stress relaxation; stress field around the hole changes so that the released strain can be measured in order to calculate initial residual stress. Recently, the use of optical methods, as measurement tool for the strain field generated around the drilled hole, has been investigated in place of the traditional strain gauge rosette technique. Optical methods have the advantage that guarantees very high sensitivity, provides much more significant statistics, eliminates error due to hole eccentricity, and reduces the cost in a single test. The accuracy of the final results depends, among other factors, on the proper choice of the area of analysis. Deformations detected by ESPI are in fact analysed within an annulus determined by two parameters, that is to say, the internal and the external radius. The choice of these parameters affects the final results in terms of measured residual stress. Results of this analysis are the object of this paper.

Ključne reči
- zaostali napon
- ESPI
- integralna metoda

Izvod

Metoda bušenja rupa (HDM) je najraširenija metoda za merenje profila zaostalih napona. HDM se zasniva na principu da rupa u materijalu izaziva otpuštanje napona (relaksaciju); naponsko polje oko rupe se menja tako da se otpuštena deformacija može izmeriti radi sračunavanja inicijalnog zaostalog napona. Nedavno je istražena primena optičkih metoda, kao alata za merenje deformacionog polja koje nastaje oko izbušene rupe, umesto primene tradicionalne tehnike mernom rozetom. Optičke metode imaju prednosti koje garantuju vrlo visoku osetljivost, pružaju mnogo više statističkih podataka, eliminišu grešku usled ekscentričnosti rupe i smanjuju troškove pojedinačnog ispitivanja. Tačnost konačnih rezultata zavisi, pored drugih faktora, od pravilnog izbora oblasti analize. Deformacije otkrivene metodom ESPI se zapravo analiziraju unutar opsega koji je određen sa dva parametra, tj. unutrašnjeg i spoljnog radijusa. Izborom ovih parametara se utiče na konačne rezultate izmerenih zaostalih napona. Cilj ovog rada su rezultati ove analize.

INTRODUCTION

Almost every material presents, as a result of production and manufacture, an intrinsic field of stresses known in literature as residual stresses. In some cases they are also intentionally introduced in order to increase fatigue resistance and fracture strength. Due to the relevance of the topic, a number of techniques have been developed in order to measure residual stresses. X-Ray diffraction can be used to measure interatomic strain caused by the presence of residual stresses /1, 2, 3/. This measurement allows calculating residual stresses once Young's modulus and Poisson coefficient are known. This kind of measurement is not destructive but in many cases it is limited to a few microns below the exposed surface. Penetration depth is increased up to tens of mm in systems using hard X-rays from synchrotron facilities, /4, 5/. Alternatively also diffraction of neutron beams can be exploited to determine residual stress /6, 7/.

Magnetic properties, such as Barkhausen noise, can also be exploited to evaluate residual stresses in ferromagnetic materials, /8/. For ultrasonic methods, the change in velocity of an ultrasonic wave propagating in the specimen can be related to the level of internal stress in the component, /9/. Photoelasticity can be applied for measuring residual stresses in glass, /10/. Also Raman and fluorescence spectroscopic techniques have been applied to evaluate the presence of residual stresses, /11/.

In this paper the attention is focused on the phase shifting electronic speckle pattern interferometry used in combination with hole drilling technique for measuring the residual stress profile. This method, being an interferometric method, can guarantee sensitivity of the order of a fraction of the illumination wavelength, it does not require any particular preparation of the surface, being applicable also to rough and curved surfaces, /12/, and it does not require application of a grating as in moiré interferometry. The main drawback of this technique is the necessity to properly isolate the system from vibrations in order to obtain fringe pattern with good contrast.

Several works are present in literature where ESPI has been used to measure strain and calculate residual stress. Focht and Schiffner, used an ESPI set-up to measure strain in thin metal sheets, /13/; a double beam ESPI interferometer was used by Baldi, /14/, to evaluate stresses in orthotropic materials; Diaz et al. have measured by ESPI the stress relieved by hole drilling in an aluminium plate subjected to an uniform uniaxial tensile stress, /15, 16/; Viotti et al. evaluated the accuracy and the sensitivity of this hole drilling and DSPI combined technique on aluminium thin plates subjected to a uniform uniaxial tensile stress and described a portable device to measure residual stresses /17, 18/ ; a mathematical method was proposed by Schajer and Steinzig for calculating residual stresses from hole drilling electronic speckle pattern interferometry (ESPI) data, independent of rigid-body motions, /19/; a method to cancel rigid body displacements that can be introduced when a hole drilling and digital speckle pattern interferometry (DSPI) combined system is used to measure residual stresses was proposed by Dolinko and Kaufmann, based on a least-square, /20/ .

In this paper some experimental considerations about error sources in the ESPI-hole drilling method are discussed. In particular, the influence of the area of analysis on the final results in terms of measured residual stresses. The inner and the outer radius of the area of analysis are changed and the corresponding variations in the measured residual stress profile are calculated.

MATERIAL AND METHODS

Experimental set-up for HDM+ESPI measurements

The ESPI hole-drilling measurement system (PRISM by Stresstech) used in this work is schematically shown in Fig. 1.

A beam from a DPSS laser source is split into two beams and focused into two monomode optical fibers. One beam is collimated and illuminates the sample, while the second beam passes through a phase shifting piezoelectric system and then goes to the CCD camera where it interferes with the light diffused by the optically rough surface of the specimen. The initial and final phases are evaluated by the 4-step phase shifting technique, which allows to detect deformations released at each step of the hole-drilling process.

The hole is drilled by means of a high speed turbine rotating at 35 000 rpm which is mounted on a precision travel stage. The cutter is made by tungsten coated with TiN and has a nominal diameter $d = 1.59$ mm.

Experimental measurements were performed on a titanium grade 5 specimen (200 mm × 20 mm × 3 mm). Preliminary X-ray residual stress measurement was performed in order to evaluate that initial stress field on the specimen and it was found a to be very low value of about 10 MPa.

Subsequently, the HDM + ESPI method is utilized to confirm this “unloaded” stress field (the hole was drilled to 0.8 mm depth in the centre of the specimen; each step was 0.16 mm).

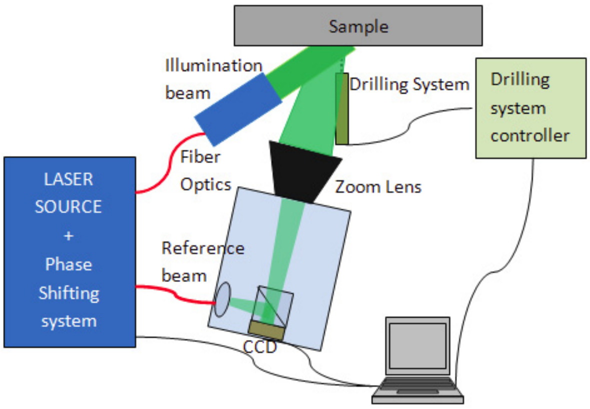

Figure 1. Experimental set-up for ESPI measurements of strains relaxed by HDM, /21/.
Slika 1. Shema eksperimentalnog ESPI merenja deformacija relaksiranih putem HDM, /21/

Discussion on analysis area

Strain measurements around the drilled hole are performed within an area delimited by two circles concentric with the drilled hole, Fig. 2.

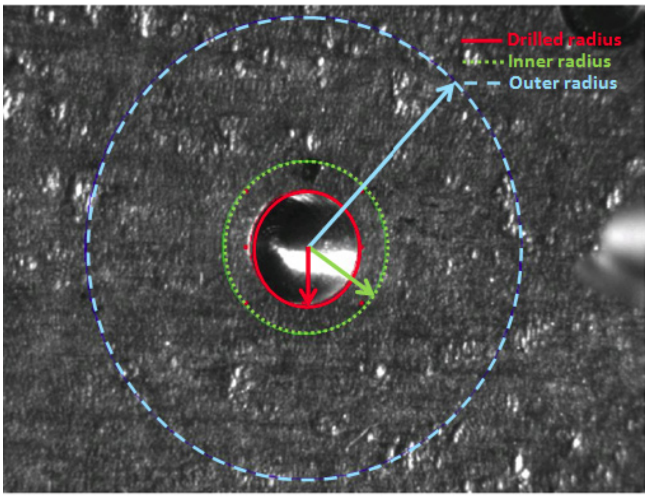

Figure 2. Screenshot of the area of analysis included between the outer circle (blue line) and the inner circle (green line). The red line identifies the drilled hole.
Slika 2. Prikaz oblasti analize između spoljašnje (plava linija) i unutrašnje kružnice (zelena linija). Crvena linija opisuje izbušenu rupu.

The size of the analysis area can affect results in terms of residual stresses. In fact, if the radius of the inner circle is too small, a region where plasticity effects occur is included in the calculation. On the other side, if the outer radius is too large, a region of very small deformations is considered and this can lead to an error in residual stress results.

In order to evaluate the influence of the analysis area, a bending stress state is induced on the specimen. The stress field is initially measured, setting the default values suggested by the software for both inner (R_{int}) and the outer radius (R_{ext}), which delimitates the analysis area around the hole. These values are defined in terms of ratio with the radius of the drilled hole (R_{hole}), so the suggested values are $r_{int} = R_{int}/R_{hole} = 2$ and $r_{ext} = R_{ext}/R_{hole} = 4$. In order to high-light the influence of r_{int} on obtained stress values, a new calculation is performed by changing the inner radius ratio in the range $r_{int} \in [2, 2.7]$ and keeping R_{ext} unchanged. Likewise, the outer radius ratio is changed in the range $r_{ext} \in [3, 4.358]$ while keeping R_{int} constant. The upper value 4.358 of r_{ext} range is limited by the image dimension.

Finally, a third evaluation is carried out by contemporarily changing r_{int} and r_{ext} in such a way to keep constant the analysis area, that is to say, the same number of pixels involved in the calculation.

RESULTS

Analysis of the influence of the area of analysis

Figure 3 shows the stress profiles calculated by keeping constant the radius ratio of the internal circle of analysis $r_{int} = 2$ and by changing the value of r_{ext}. Table 1 reports the stress values for default radius of $r_{ext} = 4$ and the percentage change of stresses using different r_{ext}.

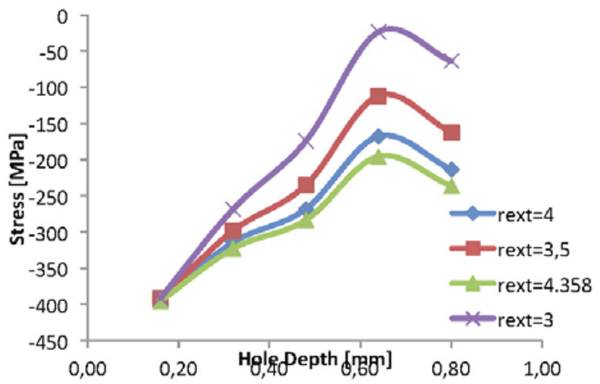

Figure 3. Plot of the stress profiles calculated in correspondence of different values of r_{ext} and by keeping constant the value of the internal radius ratio $r_{int} = 2$.
Slika 3. Dijagram profila napona izračunatih u zavisnosti od vrednosti r_{ext} i zadržavajući konstantnom vrednošću unutrašnji odnos radijusa $r_{int} = 2$

Table 1. Summary of the calculated stress for default radius of $r_{ext} = 4$ and the percentage change of stresses $\Delta\sigma_{xx}$ using different r_{ext}.
Tabela 1. Pregled sračunatih napona za zadati radijus $r_{ext} = 4$ i procentualna promena napona $\Delta\sigma_{xx}$ primenom različitih r_{ext}

Depth (mm)	σ_{xx} (MPa) ($r_{ext} = 4$)	σ_{xx} (MPa) ($r_{ext} = 3$)	$\Delta\sigma_{xx}$ % ($\Delta r_{ext} = -1$)	σ_{xx} (MPa) ($r_{ext} = 3.5$)	$\Delta\sigma_{xx}$ % ($\Delta r_{ext} = -0.5$)	σ_{xx} (MPa) ($r_{ext} = 4.358$)	$\Delta\sigma_{xx}$ % ($\Delta r_{ext} = +0.358$)
0.16	–393.5	–391.3	0.6	–392.0	0.4	–395.3	0.5
0.32	–314.5	–268.5	14.6	–298.3	5.1	–323.0	2.7
0.48	–268.3	–174.5	35.0	–235.3	12.3	–283.5	5.7
0.64	–168.0	–23.6	86.0	–112.0	33.3	–195.5	16.4
0.80	–213.5	–64.1	70.0	–162.8	23.7	–236.8	10.9

It can be observed that increasing the external radius of analysis to the maximum value $R_{ext} = 6.97$ mm ($r_{ext} = 4.358$), which means an 8.95% of variation with respect to the default value, the calculated stress at 0.64 mm depth changes about 16%.

Analogously, decreasing the external radius of analysis to the value $R_{ext} = 4.8$ mm ($r_{ext} = 3$), which means a 25% of variation with respect to the default value, the calculated stress at 0.64 mm depth changes about 86%.

As the analysis area expands by increasing the r_{ext}, the relaxation effect produced by the hole is less intensive at the outer and the calculated stress value is affected by this circumstance.

A further investigation on analysis area is performed as follows: the radius ratio of the external circle of analysis $r_{ext} = 4$ is kept constant and the value of r_{int} is changed (Fig. 4). Table 2 summarizes the corresponding numerical stress values with the indication of the percentage variation with respect to the stresses calculated by using the default value $r_{int} = 2$.

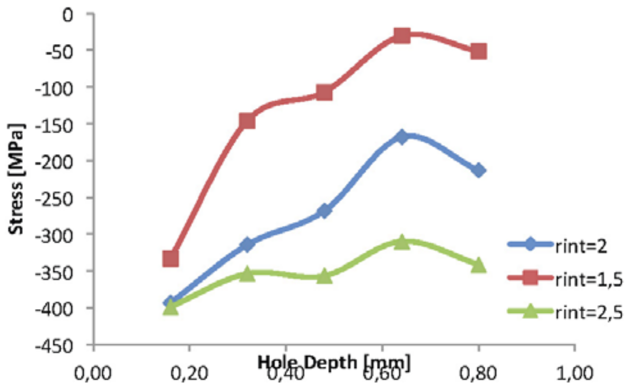

Figure 4. Plot of the stress profiles calculated in correspondence of different values of r_{int} and by keeping constant the value of the external radius ratio $r_{ext} = 4$.
Slika 4. Dijagram profila napona izračunatih u zavisnosti od vrednosti r_{int} i zadržavajući konstantnom vrednošću spoljni odnos radijusa $r_{ext} = 4$

Table 2. Summary of the calculated stress in correspondence of a variation of the internal radius of analysis. The corresponding percentage errors on the calculated stress are shown in the last three columns.
Tabela 2. Pregled sračunatih napona u zavisnosti od promene unutrašnjeg radijusa. Odgovarajuće procentualne greške sračunatog napona su prikazane u poslednje tri kolone

Depth (mm)	σ_{xx} (MPa) ($r_{int} = 2$)	σ_{xx} (MPa) ($r_{int} = 1.5$)	$\Delta\sigma_{xx}$ % ($\Delta r_{int} = -0.5$)	σ_{xx} (MPa) ($r_{int} = 2.5$)	$\Delta\sigma_{xx}$ % ($\Delta r_{int} = +0.5$)
0.16	–393.5	–333.3	15.3	–399.0	1.4
0.32	–314.5	–145.8	53.6	–353.5	12.4
0.48	–268.3	–106.7	60.2	–356.5	32.9
0.64	–168.0	–30.3	82.0	–310.0	84.5
0.80	–213.5	–51.4	75.9	–341.5	59.9

It can be observed that by changing the internal radius of analysis of about 25 %, corresponds to an average variation on the residual stress of about 80% (82% in case of decreasing the radius, 84.5% in case of increasing the radius). In this case, percentage variations in the calculated stress are rather high if compared to the case of changes in r_{ext}. Moreover, it can be observed that stress could be much more sensitive to changes in R_{est} if calculated at deeper depth with respect to surface. It should also be considered that local effects such as plasticization around the hole could affect the stress calculated in correspondence of the lower R_{int}.

Finally, Figure 5 and Tables 3 and 4 report experimental results obtained by contemporarily changing r_{int} and r_{ext} in such a way that the size of the analysis area is kept constant.

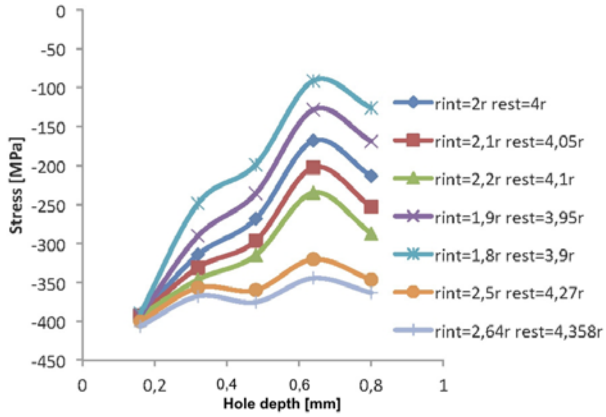

Figure 5. Stress profiles calculated in correspondence of r_{int} and r_{ext} while keeping constant the value of the area of analysis.
Slika 5. Dijagram profila napona sračunatih u zavisnosti od r_{int} i r_{ext} pri konstantnoj vrednosti oblasti analize

Table 3. Summary of the calculated stress in correspondence of a variation of both internal and external radius of analysis. The variation is done so to keep constant the area of analysis.
Tabela 3. Pregled sračunatih napona u zavisnosti od promene unutrašnjeg i spoljnog radijusa u analizi. Variranje je urađeno tako da je zadržana konstantna oblast analize

Depth (mm)	σ_{xx} (MPa) r_{int} = 1.8 r_{ext} = 3.9	σ_{xx} (MPa) r_{int} = 1.9 r_{ext} = 3.95	σ_{xx} (MPa) r_{int} = 2 r_{ext} = 4	σ_{xx} (MPa) r_{int} = 2.1 r_{ext} = 4.05	σ_{xx} (MPa) r_{int} = 2.2 r_{ext} = 4.10	σ_{xx} (MPa) r_{int} = 2.5 r_{ext} = 4.27	σ_{xx} (MPa) r_{int} = 2.64 r_{ext} = 4.358
0.16	–398.5	–393	–393.5	–392.8	–392.5	–400.0	–406.5
0.32	–248.5	–290.3	–314.5	–330.8	–346.3	–356.8	–367.8
0.48	–198.8	–235.8	–268.3	–296.5	–315.0	–359.8	–375.3
0.64	–90.9	–128.2	–168	–202.3	–234.8	–320.3	–344.5
0.8	–126	–168.8	–213.5	–252.8	–287.0	–346.3	–363.3

Table 4. Summary of the percentage variation of the calculated residual stresses with respect to the stresses calculated by using the default values r_{int} = 2 and r_{ext} = 4.
Tabela 4. Pregled procentualne promene sračunatih zaostalih napona s obzirom na napone sračunate primenom zadatih vrednosti za r_{int} = 2 i r_{ext} = 4

Depth (mm)	$\Delta\sigma_{xx}$ % r_{int} = 1.8 r_{ext} = 3.9	$\Delta\sigma_{xx}$ % r_{int} = 1.9 r_{ext} = 3.95	$\Delta\sigma_{xx}$ % r_{int} = 2.1 r_{ext} = 4.05	$\Delta\sigma_{xx}$ % r_{int} = 2.2 r_{ext} = 4.1	$\Delta\sigma_{xx}$ % r_{int} = 2.5 r_{ext} = 4.27	$\Delta\sigma_{xx}$ % r_{int} = 2.64 r_{ext} = 4.358
0.16	0.9	0.1	0.2	0.2	1.6	3.3
0.32	21.0	7.7	5.2	10.1	13.4	16.9
0.48	25.9	12.1	10.5	17.4	34.1	39.9
0.64	45.9	23.7	20.4	39.8	90.6	105.1
0.8	41.0	20.9	18.4	34.4	62.2	70.2

It can be observed that for a 25% increase of the internal radius and by keeping constant the area of analysis corresponds to a variation on the residual stress of about 90.6% at 0.64 mm. By an increase of 8.95% of the external radius the variation on the residual stresses at 0.64 mm is about 105%.

CONCLUSIONS

In this work the influence of the variation of the analysis parameters is carried out. The study of the influence of the area of analysis has shown that a 25% variation of the internal radius of analysis can introduce errors of about 80% on the measured stress, and a 25% variation of the external radius of analysis can introduce errors of about 86% on the measured stress. Such a big influence suggests, as a future work to find a method to look for optimal values for these parameters.

If the size of the analysis area is kept constant while increasing about 8% the external radius, the variation on the residual stresses goes up to 105%. Analogously, if the internal radius is increased 25% by keeping constant the size of the area of analysis, the variation on the residual stresses goes up to about 91%.

Such a big influence suggests, as a future work, to find a method to look for optimal values for these parameters.

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Instability
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Boundary Element Methods and Their Applications in Gradient Materials
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Multiscale Modeling of Biological Systems
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Atomistic Modeling & Simulation of Mechanical Properties and Fracture of Materials
Fracture of Metallic Nanomaterials and Metallic Glasses
Simulation and Testing of Crack Propagation on All Length Scales

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Notification of Acceptance of Papers: January 25, 2013

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Honour Lectures

Opening Honour Lecture: Subra Suresh (USA)
President's Honour Lecture: Alberto Carpinteri (Italy)
Closing Honour Lecture: Yiu-Wing Mai (Australia)

Publication of papers

All accepted papers will be published in the proceedings of ICF13 in the form of CD-ROM. The proceedings, together with a book of abstracts, will be provided to the participants at registration. Selected papers will be published, after peer review, in some special issues of international journals.

Secretariat Office

Ms. Yanan Tang & Mr. Liang Guo
The Chinese Society of Theoretical and Applied Mechanics
No. 15 Beisihuanxi Road, Beijing 100190, China
Tel: +86-10-62559209
Fax: +86-10-62559588
Email: ICF13@cstam.org.cn
http://ww.icf13.org