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Residual stress determination by optical interferometric measurements of hole diameter increments

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ABSTRACT

The main questions, related to the residual stresses determination in thin welded plates by the general approach, are considered. The values of hole diameter increments in principal stress directions, obtained by both reflection hologram interferometry and electronic speckle-pattern interferometry, serve as the initial experimental information. The analytical basis shows that the formulae, which connect experimental data with residual stress components, represent unequivocally solution of the properly posed inverse problem. Simultaneous measurements of the local deformation response on the opposite faces of thin-walled object under study, when a single probe hole is drilled, is the essential condition of the general approach implementing. To do this, an optical system of combined interferometer is developed. The main feature of this optical set-up resides in a capability of simultaneous recording fringe patterns inherent in electronic speckle-pattern interferometry (ESPI) and reflection hologram interferometry on opposite specimen faces for the same through hole. The accuracy of the proposed method with respect to the residual stress components determination has been assessed by three different ways. It is shown that ESPI based interference fringe patterns of high density provides a fast and reliable way of determining residual stress values of the order 160–180 MPa at the weld seam proximity. Residual stress evolution due to cyclic loading is described through the use of ESPI data.

1. Introduction

Residual stress evaluation could, perhaps, be considered the most sophisticated problem encountered during mechanical formulation as well as model predictions. Residual stresses are inherent in most manufacturing processes that involve material deformation, different types of welding, heat treatment, machining, and processing operations that transform the shape or change properties of a material. It is simply impossible, in many situations, to determine the source and define the evolution of residual stresses with a high-enough accuracy to facilitate performing reliable numerical simulations. Such simulations are usually based on prescription of a wide set of unknown parameters, all of which cannot be characterized without doubts. Existence of residual stresses, in particular, is a serious problem that tends to hinders widespread use of advanced welded structures in different industrial sectors. As such, the problem concerning incorporation of predictive residual stress analysis into design, which would assume great importance in the aerospace, nuclear, and other niche industries, strongly demands availability of experimental data obtained with a high degree of reliability [1,2].

The hole-drilling method represents one of the most powerful and widely-used techniques for experimental characterization of residual stresses. The source of all traditional versions of the hole-drilling method is the pioneering study performed by Mathar [3]. The advent and rapid development of optical interferometric techniques, which are capable of contactless measurement of local displacement fields on metallic surfaces of actual objects, have led to realization of new capabilities with regards to hole-drilling residual stress measurements. In view of this realization, a number of studies performed over the past three decades have been directed towards combining the hole-drilling method with whole-field measurement techniques based on laser interferometry. The first of such approaches, independently developed by different authors, includes several versions of the classical holographic interferometry method as the preferred measurement tool [4–12]. A comprehensive overview of the current state of the art in the field of combining the hole-drilling method with optical interferometric measurements of the local deformation response for residual-stress determination has been presented in extant studies works [13–15]. Some essential features inherent in the successful implementation of the hole-drilling method for residual-stress characterisation for metallic as well as composite materials have been reported in [16–19].

An account of the most renowned literatures, which contribute significantly to the introduction of holographic and speckle-pattern interferometric measurements as a solution to the residual-stress problem, has been provided herein. One set of studies focused on the use of

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semi-automated and fully automated techniques for measurement of required deformation parameters. Some of these approaches involved use of automated holographic and speckle interferometric techniques characterized by an inclined sensitivity vector. In this method, only a single interferometric image is recorded and subsequently interpreted for each drilled hole [20–31]. This implies that optical system are sensitive to both, out-of-plane and in-plane, displacement components, and that each individual fringe pattern must be interpreted in terms of relative fringe orders for deriving initial experimental information, which is essential for obtaining values of the three residual stress components. The second approach adopted by certain studies was based on fully automated phase measurements and subsequent determination of in-plane displacement components via electronic (digital) speckle-pattern interferometry in conjunction with symmetrical dual-beam illumination followed by observation of required interference fringe patterns along a direction normal to the plane object surface [32–42]. The third set of researches was based on reflection hologram interferometry [43–46]. Implementation of holographic interferometric techniques for measurement of required deformation parameters corresponds to maximum sensitivity of the hole-drilling method with respect to residual stress determination. This could be attributed to high sensitivity of the measurement procedure with regard to all three components of strain-induced displacements. Besides, availability of high-quality holographic interferograms facilitates direct attainment of reliable quantitative results at the edge of a small hole. Attainment of such reliable results is possible starting from a hole measuring 1.5 mm in diameter. The hole-drilling method in combination with holographic interferometric measurements, therefore, represents the least destructive of all residual stress determination techniques concerning metallic materials.

Determination of residual stresses from experimentally obtained data represents an inverse problem — the main difficulty associated with any measurement procedure [47,48]. This implies that the measured displacement components must be accurately converted into required residual stress values. Such a transition always demands introduction of certain analytical and/or computational relations, which, in the general case, cannot be experimentally established. A set of required relations, in this study, have been referred to as the transition model, the form of which directly depends on the type of residual stress field under study, which is generally unknown prior to performing experiments. In thin-walled structures, the type of residual stress field is defined by the relation between the membrane and bending residual stress components. In most practical cases, a choice of the transition model could only be based on measurement data obtained over a single face of the structure (one-sided measurements).

Consequently, all afore-mentioned techniques of any interferometric nature were developed based on the prescription of a definite type of residual-stress state under study; i.e., whether a single through hole or blind hole is drilled in the material [20–46]. Off-axes holographic and speckle-interferometric approaches are based on measuring displacement components at points located away from the hole edge [20–41]. Moreover, most interference fringe patterns are obtained for cases wherein projections of the sensitivity vector onto the plane surface of the specimen under study do not coincide with principal stress directions. These directions are generally unknown prior to the experiment. All these facts lead to the necessity of calculating a wide set of so-called calibration coefficients (constants) and involving multiple-point overdeterministic approaches of different types for residual stress determination [20–38,41,48–51]. For through-hole drilling, the required formulation follows from the theoretical solution proposed by Kirsch [52]. Calibration coefficients in the case of blind-hole drilling could reliably be obtained via various finite element calculations. Prescription of a definite residual-stress field of interest with local displacement component values being measured at different points located away from the hole edge, therefore, constitutes an essential part of all above-mentioned techniques.

Such an approach strongly demands introduction of the *aposteriori* analysis of the accuracy of results obtained, especially if thin-walled structures have to be inspected. Three main approaches can be considered suitable for this purpose. The first approach was initially proposed and employed in earlier studies [20,21,45] and subsequently implemented elsewhere [25,33–40,42,50]. Its essence resides in maintaining an actual stress field with known parameters uniform over a large area of the object surface. The second approach involves performing investigation of the residual stress field, the parameters of which could be more or less reliably predicted from the known solution [20–23,26–30]. Drilling holes inside stress fields of any of the two above-mentioned types allows direct comparison of obtained and predicted actual or residual stress values. The generally accepted method of accuracy analysis is based on the use of an overdetermined system of linear equations, solutions to which could be determined via different least-squares algorithms [26–31,51]. This approach might be considered as being fairly reliable, albeit only for blind-hole drilling inside thick-walled structural elements. This is because in such cases, plane stress conditions, without any bending, are rigorously valid over the load-free surface of an object.

Residual stress fields inherent within thin plates are often characterized by both, membrane and bending components. This fact considerably strengthens all problems concerning the correct choice of the transition model, and makes the third method concerning the choice and verification of a transition model — based on the construction of the so-called reference fringe patterns of the second kind — the most preferable in the case of through-hole drilling [42,44,53–55]. A similar approach could also effectively be used in the case of blind-hole drilling [21,28,41,48–50,56]. Here, a fine coincidence between actual interferograms and reference fringe patterns takes place when the transition model involved corresponds to an actual residual stress field of interest. If no such correlation is achieved, the question on the accuracy of residual stress determination remains open. Unfortunately, the latter situation is often typical of welded joints in thin-walled structures, which find wide application in aerospace engineering. From a mechanical perspective, this implies that the residual stress field of interest comprises membrane as well as bending components. In such cases, there exists no unique correspondence between forms of specific fringe patterns and the actual residual stress state. Likewise, a solution to the corresponding inverse problem might lead to considerable errors in residual stress determination. It is, therefore, suggested that data obtained on two opposite faces of a thin-walled structure when a single hole is drilled through it (two-side measurements) must be considered as initial information. Moreover, all initial experimental information must be obtained along principal stress directions [57,58]. This sophisticated procedure can effectively be realized by means of reflection hologram interferometry.

Remarkable properties of reflection hologram interferometry with regard to residual stress determination in plane structures subjected to through- and blind-hole drilling have previously been established and comprehensively demonstrated [53–58]. Of these properties, the unique capability of recognizing principal strain directions corresponding to a given stage of fringe patterns reconstruction is particularly important. This fact represents a key point in the development and implementation of the general approach for residual stress determination in thin-walled structures. Main bases of the general approach have been developed in extant studies [57–59], and the prescribed procedure is capable of determining both, membrane and bending residual stress components with the highest possible accuracy without preliminary prescription of the type of stress field of interest proceeding from experimental data obtained via reflection hologram interferometry. The essence of the general approach based on two-side measurements of through hole distortions along principal strain directions resides in the capability of obtaining unequivocal solutions to correctly formulated inverse problems. This fact represents the main difference between the proposed method and all previously followed approaches, which are based on combining single-probe hole drilling with advanced whole-field measurements of required deformation parameters.