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Residual stress determination in friction stir butt welded joints using a digital image correlation-aided slitting technique

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Abstract This paper presents an incremental cutting method for evaluating the longitudinal residual stresses in a butt welded thin plate via combining the traditional residual stress measurement methods and the advanced optical technique. The proposed approach, which can be called digital image correlation (DIC)-aided slitting technique, introduces a successive extension slot to a specimen and employs the DIC technique to measure the released displacement profiles of the cutting sections after each cutting increment. Then the displacement profiles are used to directly calculate the residual stress distributions up to the slot tip and hence, a stress distribution can be obtained after a cutting increment. Finally, all of the stress distributions are averaged to ultimately determine the original residual stress field. This method does not include any complex experimental operations or tedious derivation, and the resolution of stress variation is greatly improved by the continuous measurement of the released displacements. The presented method has been preliminarily verified by a specimen with residual stress introduced by a four-point bending test. The results show that residual stresses determined by the DIC-aided slitting technique agree well with those from finite element (FE) prediction. The residual stress in a friction stir welded aluminum specimen obtained by the presented technique is also consistent with the evaluations given by X-ray diffraction. Furthermore, the residual stresses obtained by the DIC-aided slitting technique demonstrate higher accuracy and stability than the evaluations derived by the DIC-aided contour method.

1. Introduction

The application of advanced joining technologies, such as friction stir welding (FSW),[1] in the fabrication of aircraft structural components is recognized as one of the most promising methods to reduce structure weights and save manufacture costs.[2,3] However, residual stresses are induced in structures during a welding process and consequently influence the

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structural integrity assessment.[4,5] Paulo et al. [6,7] investigated the effects of FSW residual stresses on the bulking behaviors of aluminum stiffened panels and aluminum plates, respectively. They reported that the collapse loads of the stiffened panels were not influenced by the stress field, but the residual stresses led to a decrease in the compressive strength of the aluminum plates. The effect of FSW residual stresses on fatigue properties was studied by Citarella et al. [8] using numerical and experimental methods, and the results indicated that the stress fields led to considerable differences in the fatigue crack growth rates. Hence, precise evaluation of residual stresses is important and necessary. The most popular techniques for the measurement of welding residual stresses include diffraction methods and mechanical methods.

Diffraction-based techniques are the most important nondestructive means of determining residual stress distributions, e.g., the X-ray diffraction method and the neutron diffraction method. Most of the diffraction methods are characterized by high precision and automation compared to mechanical methods. Sutton et al. [9] examined the residual stresses in 2024-T3 aluminum friction stir butt welds using the neutron diffraction technique, and an asymmetric distribution with respect to the weld centerline was obtained by the three-dimensional residual stress mapping. However, diffraction methods are only available in professional facilities, resulting in huge measurement costs, and they are sensitive to surface conditions or microstructural changes.[10]

Mechanical methods are mostly destructive and always rely on redistributing the residual stress due to an introduced slot or a small hole that can generate new surfaces and release the original stress field in the object.[11] The hole-drilling method, the crack compliance method, and the contour method are the most popular destructive methods. There are many advantages for the hole-drilling method, such as accessible necessary equipment and easy operation. Residual stresses in thick aluminum friction stir welded butt joints were measured by Xu et al. [12] using the hole-drilling method, and the influences of welding parameters on the stress magnitude were analyzed. Nevertheless, the hole-drilling method has a limited spatial resolution, and errors will arise due to localized yielding if residual stresses exceed approximately 50% of the yield.[13,14] The crack compliance method improves the resolution of the residual stress variation with depth and has the ability to measure both small and very large parts. However, in the first decade of the 21st century, an unknown stress distribution was usually expressed as a series expansion in the inverse solutions,[15–17] which significantly influenced the accuracy of results and always suffered from non-convergence or fitting problems,[18,19] making the crack compliance method quite cumbersome to use. Nowadays, Schajer's [20] pulse method is routinely used in the inverse solutions for its straightforward conception and concise algebraic operation. In some specific cases especially for laminated composites, the pulse method is necessary because it requires no initial assumption about the continuity of the residual stress distribution.[21–24] However, the surface gauge in the crack compliance method would eventually respond quite weakly to the release of sub-surface stresses and might result in instability problems.[18] As a relatively new method for measuring residual stresses, the contour method[25] is analytically straightforward and simple to apply. From one stress component measurement using the standard contour method to multiple stress components mapping using the multiple-cut contour method[26] or the multi-axial contour method[27], the contour method has got rapid development by Prime and his co-workers in recent years and became increasingly popular. Liu and Yi [28] and Richter-Trummer et al. [29] have proven that the contour method could be applied successfully to aluminum friction stir welded plates and reveal the internal residual stresses within the joints. Prime [30] has also presented advanced applications of the contour method, which is called a two-step process, to determine hoop stresses in cylinders and discontinuities. Moreover, the contour method was combined with the X-ray diffraction method or the hole-drilling method by Pagliaro et al. [31] to measure residual stresses in inaccessible regions using the superposition rule. Nevertheless, the assumption of a flat cut in the contour method is overly restrictive and misleading, which makes error minimization and correction important and necessary. Efforts were made by Prime and Kastengren [32] for providing an iterative finite element (FE) procedure to reduce errors, but it seemed to be tedious and time-consuming.

Recently, a significant amount of studies have tried to combine the traditional mechanical methods and the advanced optical techniques together to seek a better evaluation for residual stress. Strain gauge elements are usually replaced because the measured volumes in an optical system are continuous displacements but not discrete deformations. Ponslet and Steinzig [33] exploited an electronic speckle pattern interferometer system to improve the results of strain gage hole-drilling. Schajer et al. [34] presented a full-field, multi-axial computation technique for determining residual stresses using the hole-drilling method with the digital image correlation (DIC) technique. Moreover, residual stresses across interfaces at macro- and micro-scales were measured by Blair et al. [35] using slitting and DIC, while Winiarski et al. [36] also mapped residual stress distributions at micro-scale in amorphous materials via the DIC technique.

In this work, the ideas of the crack compliance method and the contour method are considered. A technique characterized by sequential cutting and multiple inverse solutions as well as displacement measurements in each cutting step using the DIC technique, is presented to provide more accurate and reliable assessment for residual stresses in a welded thin plate. Considering that the transverse (perpendicular to weld) residual stresses are usually much smaller than those in the longitudinal direction (parallel to weld) in welded joints, only the longitudinal residual stresses are taken into account in this paper. Furthermore, the proposed DIC-aided slitting technique is analytically simple and easy to implement.

2. Methods and procedure

2.1. Concept

Based on the linear elastic superposition principle, the released displacements of the newly generated surface caused by an introduced slot can be used to determine the corresponding released stresses, i.e., $\boldsymbol{\sigma} = f(\boldsymbol{u})$, where $\boldsymbol{u}$ means the measured displacements and $\boldsymbol{\sigma}$ represents the original residual stresses. The idea is that if a specimen is sequentially cut into two parts, the released displacement profile after each cutting increment can be measured to calculate the original stress distribution up to the slot tip, as shown in Figs. 1 and 2. Therefore, until

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