Validation of a Synthetic Bitmap for the Development of Residual Stress Assessment Using Thermoelastic Stress Analysis

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Abstract

Thermoelastic stress analysis (TSA) is combined with finite element modelling to provide a novel means for residual stress assessment. Previous work has shown that TSA has the ability to measure the change in thermoelastic response when a material has undergone different levels of plastic strain. That work utilised a reference specimen that contained no plastic strain, in industry it will often be the case that a reference specimen does not exist. The present paper develops a synthetic bitmap that acts as an artificial reference specimen. This bitmap is compared to the TSA results for the physical reference specimen, and been used in place of the physical reference. In both instances, there is strong correlation between the results using the model reference and results using the physical reference.

Introduction

Several methods exist to measure residual stress; however these are point-data methods, time consuming, destructive, expensive, or require the use of off-site laboratories to be completed. Therefore a need for a full-field, quick, non-destructive, and relative cheap process that can measure a component in-situ is identified. Thermoelastic stress analysis [1] (TSA) is a full-field, non-destructive technique where the small temperature changes that arise during elastic loading are related to the stress changes. The temperature change is measured using an infra-red (IR) detector. It is proposed that TSA has the potential to provide a basis for a new means of residual stress assessment. Previous work [2] has shown that a change in thermoelastic response that occurs when different levels of plastic strain are applied to a material can be observed using TSA. The change in temperature (ΔT) obtained from TSA is related to the sum of the changes in principal stresses [1] ($\Delta(\sigma_1 + \sigma_2)$):

$$\Delta T = -KT\Delta(\sigma_1 + \sigma_2) \qquad (1)$$

where T is the surface temperature and K is the thermoelastic constant. $K = \frac{\alpha}{\rho C_p}$ where α is the coefficient of linear thermal expansion, ρ is density, and C_p is specific heat at constant pressure.

Comparing the thermoelastic response of a specimen that has undergone plastic straining to the response from a reference, or zero plastic strain, specimen, the regions that have undergone plastic strain can be identified [2]. A further calibration step is required to ascertain the value of plastic strain within the region, and then a non-linear model may be created that provides the residual stresses.

Previous work [2] used three 100 x 300 x 10 mm aluminium-2024 specimens that contained a central circular hole of 16 mm diameter (two of the holes had undergone cold expansion) to demonstrate that TSA could reveal regions that had experienced plastic straining. The experiments used a reference specimen with 0% plastic strain applied to the holes and deformed specimens with 2% and 4% plastic strain applied to the holes. Having shown the possibility of using a physical reference specimen to reveal regions that have experience plastic strain, it should be considered that for a general component a physical reference specimen may not be available or possible to manufacture. Therefore another means of obtaining a 'residual stress free reference' must be devised. Hence creating, a synthetic thermoelastic bitmap using finite element analysis (FEA) to be used as an artificial reference specimen is the next step in the process and the object of the present paper.

Development of a Synthetic Bitmap

As the experimental data for the 'hole-in-plate' specimens was available, the first stage in the synthetic bitmap development was to create a model (created in Abaqus 6.13-3) of the plates used in [2] and define an appropriate mesh. This consists of a 'global' model, with a coarse mesh of 5 x 5 mm elements used to find displacements which are applied as boundary conditions in a submodel with a much finer mesh of 0.1 x 0.1 mm elements around the hole. The submodel has a denser mesh that allows for a more accurate result without increasing computation time; this is necessary for future applications as modelling a complex, 3D structure with a high density mesh is not practicable. A mesh density study, which used the maximum stress in the direction of loading in the vicinity of the hole as the target value, was carried out. The geometry of the plate used in [2] was such that infinite plate conditions could be assumed. Therefore a stress concentration factor of 3 was used to determine the maximum stress in the loading direction; the mesh used quadratic elements and an ordered mesh, with coarse elements in the global model and fine elements in the submodel.

The second stage was to verify the synthetic bitmap results against the TSA results from the reference specimen used in the experimental work. A K value of 9.85 x10^{-12} Pa^{-1} was used, as it was derived in [2] from experiments. Application of K to the model stress data allowed a field of $\frac{\Delta T}{T}$ to be constructed. Fig. 1 shows both the FEA results and the TSA results, and Fig. 2 shows the stress results in both the horizontal and vertical directions through the centre of the plate. In the experimental data the effects of motion at the hole edge are clear and there may be some local plasticity which affects the response. However the very good comparison between the two data sets validates the model and the synthetic bitmap approach.

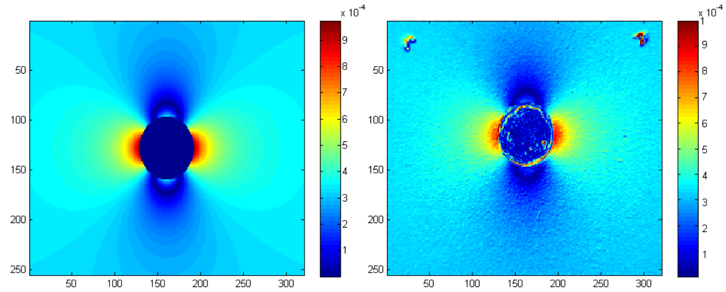

Fig. 1a (left): FEA absolute $\frac{\Delta T}{T}$ bitmap. Fig. 1b (right): TSA absolute $\frac{\Delta T}{T}$ bitmap.

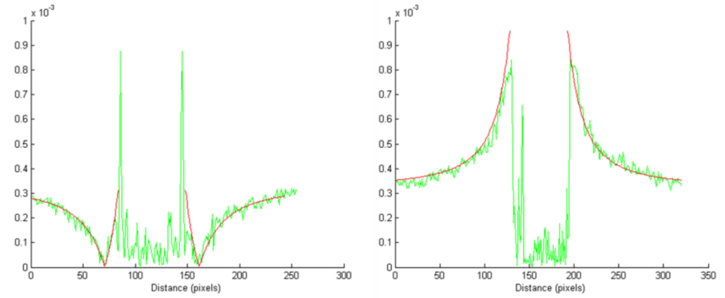

Fig. 2a (left): Vertical line plots from Fig. 1 with the FEA in red and the TSA in green. Fig. 2b (right): Horizontal line plots from Fig. 1 with FEA in red and the TSA in green.

To reveal regions affected by plastic strain, the reference dataset is subtracted from the dataset under investigation. The synthetic bitmap was used as the reference specimen to analyse the 4% plastic strain TSA dataset. Fig. 3 shows a comparison between subtracting the physical reference dataset from the 4% dataset (Fig. 3a), and subtracting the artificial reference dataset from the 4% (Fig. 3b). The regions that experience plastic strain are visible on either side of the hole. In [2] X-ray diffraction confirmed the residual stress levels around the hole. The data is presented here is in the form of $\frac{\Delta T}{T}$ because K is a non-temperature dependent variable, as the surface temperature values were not known in the original experimental work. This approach has introduced additional noise in the data hence future work will use the experimental T bitmap to create a ΔT dataset from the FEA data.

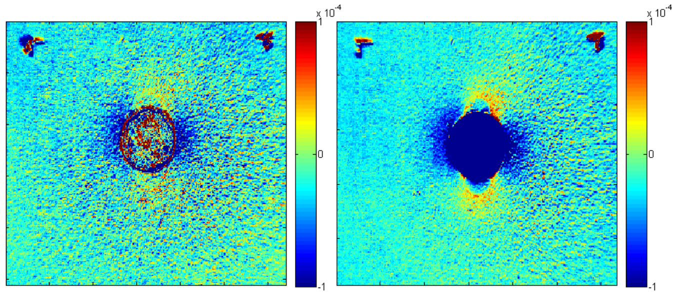

Fig. 3a (left): $\frac{\Delta T}{T}_{4\%} - \frac{\Delta T}{T}_{0\%}$ thermal map of just TSA acquired data [2]. Fig. 3b (right): $\frac{\Delta T}{T}_{4\%} - \frac{\Delta T}{T}_{FEA}$ thermal map, using the FEA synthetic bitmap in place of the reference dataset.

Conclusions

An FEA submodel has been developed of a hole-in-plate specimen. This model was used to produce a synthetic, thermoelastic bitmap to provide the reference data for thermoelastic stress analysis. The validity of the bitmap has been successfully proven against a reference dataset shown 0% plastic strain, before being used as the sole reference dataset with the TSA data from a plate having undergone 4% plastic strain; the results of which compared favourably with those from previously published work using a physical reference.

References

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[2] Robinson, A.F., Dulieu-Barton, J.M., Quinn, S., and Burguete, R.L., “The Potential for Assessing Residual Stress Using Thermoelastic Stress Analysis: A Study of Cold Expanded Holes,” Experimental Mechanics 53, 299-317 (2013).