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Young Stress Analyst Competition Finalists

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Automatic crack growth rate measurements in mini-samples by means of Digital Image Correlation and inverse method

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Introduction

The paper presents the results of crack propagation rate investigations performed on mini-samples made of Al 5483 alloy. Digital Image Correlation (DIC) measurements and inverse method was applied for automatic stress intensity factors and crack tip position measurements. Tests were performed using the horizontal hydraulic testing stand coupled with optical lens or light microscope.

DIC [1-3] is non contact optical method for displacement measurement on the sample surface. Digital images of speckle patterned surface are recorded and small subsets of the area of interest are compared by means of computer algorithms to find the best fit between deformed and reference images. As the result the displacement maps are obtained. The accuracy of displacement measurement depends on the resolution of camera and magnification and may achieve 0.01 pixel.

Results and discussion

Two optical systems with different magnification and different methods of achieving the pattern necessary for DIC measurements were used. The first set-up (with small magnification) consisted of optical lens which allowed whole 4x4mm sample gauge section observation and white and black spray paint was applied for patterning the surface. In the second set-up (with large magnification) metallographic microscope was utilized and allowed to observe sample microstructure (by means of build-in white light source and polarization filters) as well as speckle pattern for DIC produced by means of laser light which interfere on the sample surface roughness.

For both cases of experimental setup cyclic loading of samples \(F_{max}=300\text{N}, R=0.1, f=10\text{Hz}\) was hold on for the time of capturing high quality images of sample surface. Registered digital images were analyzed using commercially available Vic2d software [4]. After analyzes displacement measurement data was exported to ASCII files and processed by iterative algorithm written in Matlab.

The inverse method similar to presented in [5] with moving subarea of fitting process [6] was applied for calculations. As the input data initial values of \(K_I, K_{II}, \) crack tip position \(x_0, y_0, \) Young’s modulus \(E\) and Poisson ratio \(\nu\) were given. The algorithm read the displacement data for horizontal and vertical directions and the iterative procedure found the best fit between the analytical model of displacements near the crack tip and measurement data. using Newton-Raphson method for
changing initial values of $K_\text{I}$, $K_\text{II}$, $x_0$ and $y_0$. Also the rigid body motion ($T_x$ and $T_y$) and rotation ($R$) searching was added to the computer code to reduce the sample movement influence on the results. Therefore the optimal set of 7 parameters was searched for each image.

The picture of painted sample surface for small magnification set-up is presented in Figure 1 a and obtained pattern is appropriate for DIC measurements. Figure 1 b and c present comparison of white light and laser light conditions for the same moment of the test recorded using large magnification set-up. Usage of white light and polarizing filters allowed for the observation of crack tip interaction with the microstructure while laser light interfering on the sample surface gave good pattern for DIC measurements.

![Figure 1: Sample surface pattern: a-small magnification set-up, b-large magnification set-up with laser light, c-large magnification setup with white light and polarizing filters](image)

The example of DIC measurements and displacement maps given by the model after parameters fitting is presented in Figure 2. Presented displacement map are located on the white background showing the total area of DIC measurements. The position of crack tip in the fitting area was chosen to be placed in 50% of its height and 50% of width.

![Vertical displacement map - DIC](image)  ![Vertical displacement map – model after fitting](image)
Horizontal displacement map - DIC

Horizontal displacement map – model after fitting

Figure 2: Example of displacement DIC measurements and fitting results for selected moment of mechanical tests ($K_I = 8.8\text{MPa}\cdot\text{m}^{0.5}$, $K_{II} = 3.05\text{MPa}\cdot\text{m}^{0.5}$) for large magnification set-up

Figures 3 and 4 present crack length vs. number of cycles and $da/dN-\Delta K_{I\text{Max}}$ plots made using data obtained by means of previously described fitting method.

Figure 3: Results for small magnification set-up

Figure 4: Results for large magnification set-up
Usage of small magnification set-up allowed for achieving results for low and medium amplitude range of Parris plot. Usage of large magnification set-up gave better resolution (more local measurement) of calculated $\Delta K$ values and showed the influence of grain boundaries in the low amplitude range. Propagating crack velocity depends on the distance from grain boundary and is higher when the crack is in the middle area of the grain.

Presented results show applicability of the optical measurements of displacements near the crack tip for automatic evaluation of the parameters determining crack growth rate for tests performed on mini-samples. The method may be especially useful for nanostructured materials available in small volumes for testing. There is a possibility for measuring crack propagation rate in material phases of different mechanical properties.

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**References**


Using source fields to characterize a material thermomechanical behavior in a single measurement.

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1. Introduction

Fatigue characterization of materials is a time consuming and expensive statistical process commonly undertaken in industry. During these last decades, some authors proposed rapid experimental methods to estimate the fatigue limit based on the material temperature increase under cyclic loading [1, 2].

Experimental methodologies for rapid charactarisation of the thermomechanical behaviour of materials are thus of first interest. This work proposes an original method to characterize the dissipative sources of a material at multiple alternate stress in a single measurement.

2. Experimental procedure and results

When a material is alternatively loaded, two main phenomena are observed (Figure 1): the material temperature changes simultaneously with the applied stress (thermomechanical coupling) and the mean of the temperature increases (dissipative energy).

The dissipative and thermomechanical sources (respectively $d_1$ and $S_{th}$) can be estimated on flat specimens by solving the two dimensional heat balance equation [3]:

$$
\rho C \left( \frac{\partial \theta}{\partial t} - \frac{\partial \theta}{\partial t} \right)_{(t=0^{-})} - k \Delta_2 \theta + \rho C \frac{\theta}{\tau_{th}^{2D}} = d_1 + S_{th}
$$

with $\theta$ the temperature field variation at the surface of a flat specimen, $\rho$ the mass density, $C$ the specific heat and $k$ the thermal conductivity. $\Delta_2$ is the two dimensional laplacian operator, $\tau_{th}^{2D}$ is a time constant representing

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the radiative and convective heat exchange and $t = 0$ is the time when the solicitation is started.

All the results presented in this work have been obtained on a pre-strained 316L specimen machined in a 3 mm thick steel plate (Figure 2). The temperature of the specimen surface $\Omega_{zou}$ (20 × 30 mm) has been measured thanks to an infrared camera at a sampling frequency of 350 Hz.

In this work, the applied stresses are lower than the yield limit of the pre-strained specimen and the loading frequency is of $f = 14$ Hz.

![Specimen geometry](image)

**Figure 2:** Specimen geometry.

**First step:**

First, the specimen has been uniaxially loaded by an harmonic solicitation. A loading ratio $R_\sigma = \frac{\sigma_{\min}}{\sigma_{\max}} = 0.1$ has been chosen ($\sigma_{\min}$ and $\sigma_{\max}$ are respectively the minimum and maximal stress) and the alternate stress $\sigma_a$ has been increased step by step.

The spatial average of the dissipative energy has been measured at each step using the method described in [4] (diamonds in Figure 3).

**Second step:**

The same specimen has then been misaligned of about 5 degrees in the machine grips (Figure 4, center) and harmonically loaded at two stress levels ($R_\sigma = 0.1$).

**Fields of dissipative and thermoelastic sources** have been computed from the heat balance equation (Equation 1) [5] (Figure 4, left and right).
Figure 3: Dissipative energy per cycle $E_{d_1}$ (left scale) or heat rate $d_1/\rho C$ (right scale) versus the trace of the alternate stress tensor $Tr(\sigma_a)$.

Figure 4: Misaligned specimen (center) and associated dissipative (left) and thermoelastic (right) source fields.
The obtained source fields are heterogeneous due to the specimen misalignment and a correlation between the fields is observed. For each point $M$ of the specimen, one has thus the values of the local dissipative and thermoelastic sources.

Moreover, in adiabatic conditions (high enough loading frequency), the thermoelastic sources $S_{th}$ are directly related to the trace of the alternate stress tensor $Tr(\sigma_a)$ [6]. The data on these source fields have been plotted in Figure 3. The results overlap the dissipative sources measured in uniaxial loading. An example of the source fields scattering obtained in uniaxial conditions have also been presented in Figure 3.

3. Conclusion

- The stress heterogeneities due to misalignments can be observed on thermoelastic source fields. If these heterogeneities are large enough, dissipative and thermoelastic source fields are correlated.
- When loaded under to the material yield stress, the thermomechanical behaviour of the 316L can be characterized in a single experiment thanks to a slightly misaligned specimen. In this case, the uniaxial or multiaxial thermomechanical behaviour of the material are identical.

References


Fragment Impact Modelling of Spiral-strand Cables

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Abstract This submission presents the results of a preliminary numerical study of an un-tensioned spiral-strand cable subjected to explosively formed fragment impact. An effective approach to generate finite element models of multi-layer spiral-strands with complex contact conditions has been devised. The modified Johnson-Cook model coupled with the Cockcroft-Latham fracture criterion was used to model the steel material of both the cable and the fragment.

Keywords: Spiral-strand cable, Fragment impact, Non-linear FEM, Perforation and Penetration

1. Introduction

Lightweight cable-supported structural systems are widely used in the design and construction of sports stadia and bridges as depicted in Fig. 1, but their robustness and resilience against explosively formed fragment impact remains largely unknown.

![Fig.1 Use of cables in stadia and bridges](image)

Recent research has highlighted that there are a number of potential mechanisms capable of inducing abrupt cable loss, including the impact of explosively formed fragments travelling at high velocity.

2. Study objectives

1. Evaluate the penetration and perforation resistance of a typical 50 mm spiral strand cable.

2. Estimate a reduced cable breaking load based on damage level and compare with the design resistance of the cable.

3. The numerical model

Spiral-strand cables are composed of many individual high-strength steel wires which have a strength range of 1550MPa to 1770MPa. The cables are commonly manufactured using circumferential layers spirally wound around a central wire and spun in opposite directions as shown in Fig. 2.
The cable under consideration here is a 50 mm un-tensioned spiral-strand cable which consists of 87 individual wires. The cable model was constructed using a sequential process which is highlighted in Fig. 3. A JavaScript in LS-DYNA was developed to morph the geometry of each layer around the central wire.

The fragments have been modeled as standard 20 mm fragment simulating projectiles as shown in Fig 4a and b. The fragment has been simplified in the numerical model to a 20 mm diameter \times 20 mm long solid cylinder as shown in Fig 4c.
The final model consisting of both the cable and fragment is shown in Fig. 5.

Four fragment velocities, 250 m/s, 500 m/s, 750 m/s, and 1000 m/s, were considered in this study to evaluate the penetration and perforation resistance of the cable. The material models used were the Modified Johnson-Cook constitutive relation coupled with the Cockcroft-Latham fracture criterion.

4. Results and discussion

Fig. 6 shows the damage profiles obtained from each simulation output as intense regions of plastic strain.

(a) 250 m/s FSP impact
(b) 500 m/s FSP impact
(c) 750 m/s FSP impact
(d) 1000 m/s FSP impact

Fig. 6 Cable penetration and perforation plots
The damage sustained in each simulation was localized to the impact zone. In all cases total cable perforation was not achieved and only in simulation Cases 2, 3 and 4 was penetration achieved, although the damage level and penetration depth increased with an increase in fragment velocity. An estimation of the penetration depth in each simulation can be made considering the number of layers damaged which is highlighted in Table 4.

The results of each simulation have been used to determine the residual load capacity of the cable after impact. This was achieved by converting the extent of cable damage into a reduced cable breaking load by deducting the tensile capacity of significantly damaged individual wires from the minimum breaking load (MBL) of the cable, which in this case is 2400kN. The design resistance of the cable $Z_{r,d}$ is derived by dividing the MBL by a partial safety factor of 1.65 in accordance with Eurocode 3. Therefore the design resistance of this specific cable is 1455 kN.

The results of the damage assessment for each simulation are shown in Table 4 with reduced cable breaking loads and penetration depths estimated.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Fragment velocity (m/s)</th>
<th>No. of wires damaged post impact</th>
<th>Estimation of fragment penetration depth (mm)</th>
<th>Estimation of reduced cable breaking load post impact (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>250 (Fig. 6a)</td>
<td>0</td>
<td>0</td>
<td>2400</td>
</tr>
<tr>
<td>2</td>
<td>500 (Fig. 6b)</td>
<td>3 (in layer 5)</td>
<td>5 mm approx.</td>
<td>2300 approx.</td>
</tr>
<tr>
<td>3</td>
<td>750 (Fig. 6c)</td>
<td>4 (in layer 5)</td>
<td>19 mm approx.</td>
<td>2023 approx.</td>
</tr>
<tr>
<td>4</td>
<td>1000 (Fig. 6d)</td>
<td>5 (in layer 5)</td>
<td>23 mm approx.</td>
<td>1870 approx.</td>
</tr>
</tbody>
</table>

As can be seen from Table 4, the estimated reduced cable breaking load is not less than $Z_{r,d}$ in all cases, which in terms of design for static loading would suggest that the cable would not rupture when subjected to such fragment impact velocities.

5. Conclusions

In this submission, a method currently under development to assess the penetration and perforation resistance of spiral-strand cables has been demonstrated. An effective approach to generate finite element models of multi-layer spiral-strands with complex contact conditions has been devised and applied in fragment impact studies and a brief discussion of the results has been provided. The modified Johnson-Cook model coupled with the Cockcroft-Latham fracture criterion was used to model the steel material of both the cable and the fragment in LS-DYNA. It has been shown that a 50 mm un-tensioned spiral strand cable is able to resist perforation and axial rupture when subjected to...
fragment impact velocities of up to 1000 m/s. Laboratory tests are being carried out to validate the numerical modeling.

Acknowledgments

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Paint Coating Characterisation for Thermoelastic Stress Analysis

Introduction

Thermoelastic stress analysis (TSA) [1] is a well established experimental technique based on the ‘thermoelastic effect’. When a material is subjected to a cyclic load, the strain induced produces a cyclic variation in temperature, $\Delta T$, that can be related to the change in the sum of the principal surface stresses, $\Delta (\sigma_1 + \sigma_2)$,

$$\Delta T = -KT_0\Delta (\sigma_1 + \sigma_2) \quad (1)$$

where $T_0$ is the absolute temperature and $K$ is the thermoelastic constant.

The motivation for this work is an opportunity for TSA to be used as the basis for a new non-destructive, non-contact, full-field residual stress assessment technique. The presence of residual stress results in very small, but measurable changes in the thermoelastic response; these changes (of a few mK) are significantly less than those expected to be resolved during standard TSA (a few hundred mK). When using highly sensitive infra-red detectors for TSA on metallic materials, the specimen is typically coated with a thin layer of black paint to enhance and standardise the surface emissivity and is known to greatly influence the results if not applied correctly. It is therefore very important that any deleterious effects of the surface coating are minimised, to enable measurement of the very small changes in thermoelastic response associated with residual stress.

Previous TSA studies have typically used ‘two passes of RS matt black’ paint. It is questionable if ‘two passes’ provides the accuracy required for this type of sensitive work due to the operator dependent nature of applying a coating. The objective of this work is to assess the effects of paint type, thickness and loading frequency on the thermoelastic response and quantify optimum coating characteristics for TSA based assessment of residual stress. Comparison of experimental data and theoretical predictions is provided.

Coating Characteristics

There are three main reasons for using a high emissivity coating [2]:

- To enhance and maximise the radiant energy emitted
- To standardise the surface emissivity
- To avoid reflected heat radiation
There are also two important types of signal attenuation that arise from surface coatings: thermal lag, and thermal drag-down. Thermal lag is caused by the insulating effect of the paint coating; an increase in coating thickness results in a smaller $\Delta T$ at the paint surface than at the substrate surface. Thermal drag-down is a phenomenon relating to both the paint thickness and the loading frequency; heat is transferred to the coating from the substrate, and as the loading frequency increases the heat will not flow sufficiently quickly and thus a lower value of $\Delta T$ is recorded. Modelling the response as a thermal wave problem, Welch and Zickel [3] showed the relationship between frequency and paint thickness could be split into four distinct regions as shown in Figure 1, where the high emissivity coating region is the ideal coating regime to be operating within.

![Figure 1: Contour plot of the thermoelastic response of a coating [3]](image)

The theoretical results predicted in [3], see Figure 1, suggest that the optimum conditions for TSA are very low frequencies (0.1 Hz to 1.5 Hz) and low paint thickness (80 to 400 $\mu$m). For most metals, it is not practical to obtain TSA data at such low frequencies because any stress gradient in the specimen will result in heat transfer and a non-adiabatic response. Typical loading frequencies for TSA of metals are between 10 to 30 Hz, suggesting the coating response is from the coating diagnostic region. Typical paint coating thicknesses for TSA (10 to 50 $\mu$m) are lower than those suggested by the theoretical model and would fall within the opacity limited region. There is clearly a trade-off to be made between achieving adiabatic conditions and ensuring the attenuation of the thermoelastic response due to paint thickness and loading frequency is not significant.
Experimental Methodology and Results

A straightforward method of accessing the validity of TSA data is to obtain $K$ (see Equation (1)) experimentally, and compare it to a value derived from the literature. Tensile strip specimens were cyclically loaded in uniaxial tension to produce a known stress distribution in the central section and $T$ and $\Delta T$ measured to enable direct calculation using Equation (1).

Nine different paint types were tested on aluminium tensile strip specimens, with different surface finishes and colours. RS matt black was found to perform the most consistently over the largest range of loading frequencies, vindicating its previous use. To investigate paint thickness, mild steel (AISI 1016) specimens were used, and variation of thickness achieved using successive passes of paint. Data was recorded at loading frequencies between 5 Hz and 35 Hz in increments of 2.5 Hz, and the results are presented in Figure 2.

![Figure 2: Effect of paint thickness on the thermoelastic constant](image)

The thermoelastic constant for mild steel calculated from material properties is $3.02 \times 10^{-12}$ Pa$^{-1}$ and is shown in Figure 2 as a black line. Good agreement is found for loading frequencies of between 7.5 and 15 Hz for paint thickness of 2 to 3 passes. As frequency and paint thickness increase, the phenomenon of thermal drag-down can be seen as the thermoelastic constant rapidly decreases. Confocal microscopy was used to quantify the paint thickness, showing that 2 to 3 passes represented 12 to 29 µm.
Experimental vs. Theoretical Response

Figures 3 to 6 show a comparison of the theoretical and experimental coating response for an AISI 1016 steel specimen with paint thickness ranging from 5 to 40 μm and loading frequencies from 2.5 to 35 Hz. The vertical scales of $\Delta T$ and infra-red flux are proportional, and there is very good agreement between the experimental and theoretical data. The model consistently predicts a decrease in response with either increasing loading frequency or paint thickness. The experimental data follows a similar trend but shows that if either the frequency or the thickness is small the variation of the other will not cause a significant decrease in response; this is not predicted by the theoretical model. Secondly, the theoretical model implies the optimum coating characteristics are a very thin coating, loaded at a very low loading frequency. The experiments showed that if either the paint thickness or the loading frequency is too low, a significantly reduced thermoelastic response is recorded, indicating that in reality a much thicker paint coating is necessary to achieve a high emissivity coating.

Figure 3: Variation in experimental paint coating response

Figure 4: Variation in theoretical response of paint coating
These differences suggest that in certain instances the analytical model does not accurately predict the thermal response, and therefore having practical knowledge is very important for both experimental design and interpretation of results.

Conclusions

This work was motivated by a new residual stress methodology although the findings are directly relevant to any thermoelastic stress analysis that utilises a paint coating.

The following conclusions have been made with regard to the optimum coating characteristics for TSA on metallic materials where high accuracy and quantitative stress data is required:

1. RS black paint is a suitable paint coating for thermoelastic stress analysis of metallic materials.
2. A cyclic loading frequency between 7.5 and 15 Hz should be employed; higher frequencies are possible with careful consideration of the coating thickness.
3. Acceptable paint thickness for thermoelastic measurements range are 2 to 3 passes of paint (15 μm and 25 μm).

These recommended test conditions are directly applicable to steel, but are expected to be similar for other metallic materials. If high resolution and accuracy is an important requirement then the effects of paint thickness and loading frequency may need special consideration.
References

