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Thermoelastic analysis of crack propagation in AA6082 Friction Stir Welded Joints

R. Di Sante[1, a], P. Cavaliere[1,b], G.L. Rossi[2,c] and A. Squillace[3,d]

[1]Dept of Innovation Engineering, University of Salento, Lecce, Italy

[2]Dept of Industrial Engineering, University of Perugia, Perugia, Italy

[3]Dept. of Materials and Production Engineering, University of Naples “Federico II”, Naples, Italy

[a]raffaella.disante@unile.it, [b]pasquale.cavaliere@unile.it, [c]gianluca@unipg.it, [d]squillac@unina.it

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Abstract. Thermolastic Stress Analysis (TSA) has been recently developed as a direct investigating method for the study of the stress field around the crack tip of a cyclically loaded structure. The advantage of using measurement techniques based on the thermoelastic effect lays in the fact that stress intensity factors may be determined based on the effective stress distribution around the crack tip rather than calculated from the crack length and amplitude of cyclic loads. This paper reports results related to fatigue tests on Friction Stir Welded alluminium alloys sheets. Fatigue crack propagation experiments were performed by employing single-edge notched specimens, in tension-tension condition with R=0.1, up to failure. The application of TSA allowed the monitoring of crack formation and growth in real time, providing the actual stress distribution around the crack tip for the different technological parameters used in the welding process. Stress intensity factors were determined based on the TSA data and compared to those calculated using an ABAQUS FE model.

Introduction

In the last 20 years, fatigue crack propagation has been mainly monitored using the SPATE system, based on the evaluation of the thermoelastic effect. This phenomenon is due to the fact that when a structural component is cyclically loaded, it experiences small and reversible temperature variations. Special infrared cameras, called differential, allow the analysis of the variable temperature component of the loaded materials and therefore of the thermoelastic effect. In this way, studies on the crack initiation and propagation are made possible with high temporal and spatial resolution. The SPATE system [1] is affected by very long acquisition time, as the measurement is in this case based on a scan carried out on the test sample surface limiting the usable frequency range of analysis. The DeltaTherm system, developed more recently and used in this study, allows instead the real-time analysis of the crack propagation, due to a much faster data acquisition [2].

Application of the TSA to welded materials [3, 4] is quite new. Study of the fatigue behavior of welded structures has a relevant role in the engineering practice as welded parts are often the main causes of damage. Weld characteristics, which vary depending on the process technique and used parameters, are able to influence the fatigue behavior of welded joints together with residual stresses. In recent years, a new type of welding, named Friction Stir Welding (FSW), has demonstrated to produce very good sound joints especially in the applications to light alloys welds [5] and present, in particular, superior fatigue properties with respect to joints obtained by traditional techniques (see for example [6]).

In this paper, the measurement and analysis technique based on thermoelasticity is applied to the fatigue behavior study of specimens obtained from Friction Stir welded alluminium sheets. Samples are single-edge notched in the welded area to infer stress intensity factors from the experimental data on the stress distribution. Results are finally compared to numerical values from ABAQUS obtained by modeling the specimens fatigue behavior.

Thermoelastic stress analysis (TSA)

TSA is based on thermoelastic effect, reported in the literature for the first time by Lord Kelvin in 1853 [1], but already observed by Ghough during simple experiments on rubber strands. This phenomenon is due to the fact that when a structural component is cyclically loaded, it experiences small and reversible temperature variations (tenths of mK). The conversion from mechanical to thermal energy is reversible only if the material is behaving elastically and the thermal variations are proportional to sum of principal stresses. The relation between them in the case of linear elastic and homogeneous materials can be written as:

$$\Delta T = \frac{-\alpha T}{\rho C_P}\Delta(\sigma_1 + \sigma_2)\,. \tag{1}$$

α is the thermal expansion coefficient, T is the absolute temperature of the material, ρ is the density and C_P is the specific heat at constant pressure and σ_1 and σ_2 are the principal stresses. Perfect adiabatic conditions would be achieved only if the thermal conductivity of the material was null and no stress gradients were present on the test specimen. However, if the loading frequency is relatively high, the presence of non-adiabatic effects is minimized.

Materials and experimental procedure

The material under investigation was a 6082 commercial aluminium alloy produced by Pechiney under the form of rolled plates of 4 mm thickness. 200mm length x 80mm, large plates were welded perpendicularly to the rolling direction, after standard T6 heat treatment. Such thermal treatment results in a considerable improvement of the material corrosion resistance. Six different welding conditions were studied. The employed rotating speeds and advancing speeds of the threaded tool were 1600 RPM, 230, 325, 460 mm/min and 1000 RPM, 165, 230 and 325 mm/min respectively. The nib of the tool had a diameter of 6.0 mm and was 3.9 mm long. A 14 mm diameter shoulder was used and the tilt angle was set equal to 3°. All the specimens surfaces were machined in order to eliminate all the surface asperities. The residual stresses were measured in transversal direction with respect to the loading one by employing X-ray diffraction.

Specimens were sectioned in the perpendicular direction along the weld line by employing an electrical discharge machine (EDM). The fatigue crack propagation experiments were performed by a resonant electro-mechanical testing machine under constant loading control up to 250 Hz sine wave loading (TESTRONIC^{TM} 50±25 kN, produced by RUMUL, SUI) and by employing single edge (1 mm) notched specimens obtained at 6 mm from the weld center on the advancing side. For all the tested materials it was used a value of R of 0.1.

The most recent version of the DeltaTherm system, DeltaTherm 1550 by Stress Photonics Inc. was used in this work. The sensitive element is a 320x256 pixel InSb focal plane array which operates in the 3-5 μm wavelength range. The system is equipped with a Lock-in system necessary to synchronize the acquisition with the external load signal (normally from the signal generator of the servocontrolled test machine). The Lock-in system allows a higher signal-to-noise ratio, reducing the effect of the thermal radiation due to the surrounding environment.

In order to establish a good correspondence between the thermal images and the stress maps, it is necessary to maintain adiabatic conditions during the tests. In fact, thermal transmission phenomena decrease the IR radiation associated to cycling load. The system resolution is 1 mK with an acquisition time of 30 s. Through suitable optics, it is possible to focus the stress analysis on 256 x 320 measurement points on a 3 x 4 mm area, with a spatial resolution up to 22 μm. In order to increase the surface emissivity, a black matt paint was used.

Results and discussion

The fatigue crack rate as a function of ΔK for all the joints at a load ratio of R=0.1 is shown in Fig.°1. For all the test specimens, the cracks propagated in direction perpendicular to the loading axis. It can be observed that the joints welded with a rotating speed of 1000 RPM are more sensitive to crack initiation with respect to the 1600 RPM case. In addition the joints welded at 1600 RPM show a crack growth rate lower than those welded with a rotating speed of 1000 RPM. As a general behaviour, all the welds show a decrease in ΔK threshold and an increase in crack propagation rate with respect to the parent material.

The residual stress states play a very important role in fatigue threshold and cracks growth. The difference in ΔK threshold can be attributed to the longitudinal residual stress profile, in the welds in which a compressive state was measured, the resistance to the crack initiation is higher due to a compressive state which opposes the tensile loading during the cyclic test.

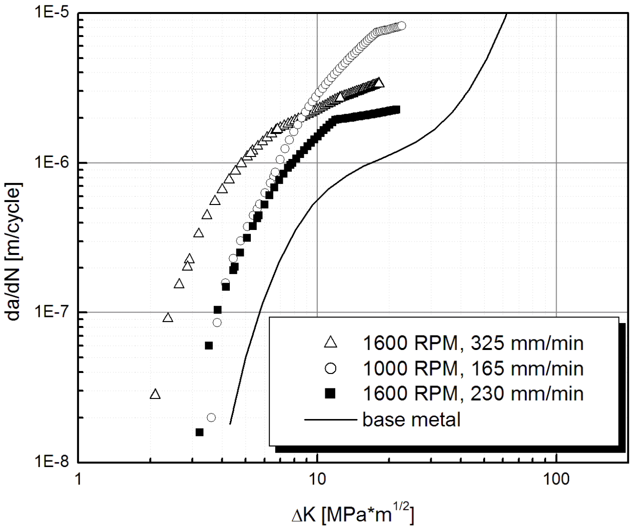

Figure 1. The fatigue crack rate as a function of ΔK for all the joints at a load ratio of R=0.1

In Fig.°2 a typical thermoelastic image is shown. Fatigue tests were in this case carried out at a frequency of 5 Hz and for R=0.1.

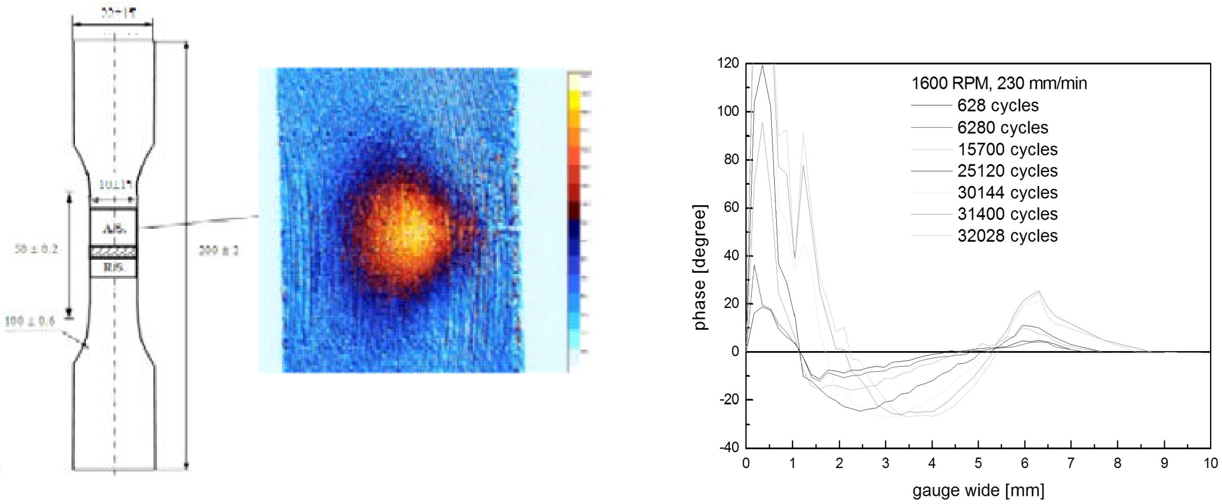

Figure 2. Specimen geometry and typical thermoelastic image (left) and phase diagrams (right).

Stress intensity distribution were mapped using the calibration factor *A* calculated assuming that the material is isotropic and homogeneous, while the stress intensity factors were obtained after the determination of the crack tip position through phase map observation. Typical phase diagrams for different values of the cycles number are shown in Fig.°2 (left). It was already observed that crack tip position may be located where the phase sign becomes negative approaching the crack tip from its aperture. Where the phase is negative, plasticity effects take place preventing adiabatic conditions.

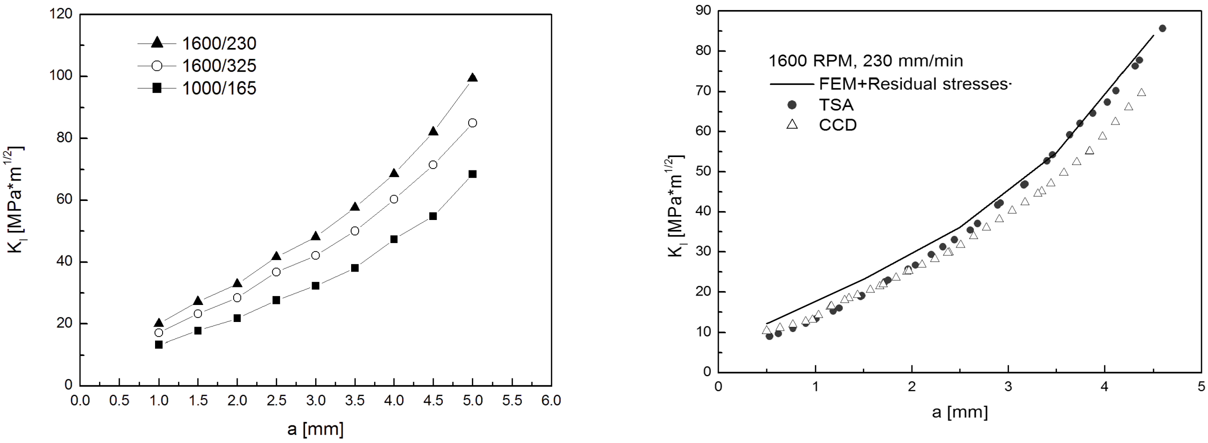

Figure 3. Theoretical stress intensity factors, SIF (left) and comparison of theoretical, corrected and experimental SIF(right).

In Fig.°3 theoretical and experimental stress intensity factors are reported. Theoretical values were obtained modeling the fatigue behavior using the ABAQUS software and were finally corrected using an estimation of the contribution due to residual stresses. Results obtaining using also a CCD camera are reported for caomparison. It may be seen that thermoelastic data approach very well the corrected theoretical data.

Conclusions

In this paper the thermoelastic stress analysis has been presented as a technique with relevant capabilities with respect to the study of fatigue fractures. Results regarding fatigue tests on FS welded specimens have highlighted the possibility of studying relevant effects related to the welding process, due for example to residual stresses. Comparison between theoretical results corrected for the presence of residual stresses and stress intensity factors inferred from TSA agreed fairly well, showing that this experimental technique is able to quantitatively account for them.

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