CHARACTERISATION OF QUENCHED IN RESIDUAL STRESSES GENERATED IN AL-LI MATRIX COMPOSITES

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Abstract

This work focuses on the quantitative assessment of residual stresses generated during quenching in aluminium MMCs.
There are various techniques available for residual stress measurement, 'Blind-hole drilling', X-ray, neutron diffraction, and each has its own inadequacies. The technique evaluated herein is 'Blind-hole drilling'. The main inadequacy of this technique being that the measurement depth is limited by the hole/strain gauge diameter; giving a maximum measurement depth of 1.30mm. To produce a thickness profile it is necessary to measure in increments of 0.05mm from the specimen surface. Extension of the technique was made possible by using both rosette and back-face strain gauges to measure the strains as material is removed. The strains are converted into principal stresses and a stress profile is produced. The stress profile follows fatigue crack front profiles produced using single edge notch specimens. The areas of the compressive and tensile region are in reasonable agreement. This work has extended the usefulness of a well used technique for residual stress measurement.

Introduction

Metal matrix composites, by dint of physical property differences between matrix and reinforcement, generate residual stresses during material processing and much information has been published[1-3]. It is well understood that differences in coefficient of thermal expansion between matrix and reinforcement can produce residual stresses during material manufacture and processing, especially in the case of heat treatable aluminium alloys such as aluminium-lithium. Residual stresses in aluminium alloys have been widely reported to have significant influence on the service life of finished components[4]. It is with this in mind that any significant test programme relating to metal matrix composites must be well aware of the level of residual stresses present in the material during testing and the influence of residual stresses on the test results. This has led to much investigation work for determination of realistic values for the residual stress distribution both on the microscopic and macroscopic level. The techniques which are described within this report when in combination provide a means for identifying residual stresses on the macroscopic scale in thick products, by using the "Blind-hole drilling" technique previously limited to a measurement depth of 0.5 times the hole diameter/strain gauge diameter, hence through thickness data could not be determined.

The residual stress measurement technique under study here is the "blind-hole" drilling technique, see Technical Note TN-503-3[5], which indicates the level of macroscopic residual stresses in the surface region. As a hole is drilled in the material surface the material around the hole relaxes and the hole will attempt to close up (since surface stresses are compressive). Strain gauges positioned around the hole will measure the surface deformation and this is converted into principal stresses. This measurement procedure is repeated at increments from the surface centre to a depth of 0.5 times the initial hole diameter which provides a measure of residual stresses up to a fixed depth into the sample. However, the technique is limited by the dependence of sensitivity to hole depth and the initial hole diameter which is generally the maximum possible for the gauge being used. The gauge type used in this investigation TEA-XX-062RK-120 (as supplied by Measurement Group Inc.) see figure 1, limited the measurement depth for reasonable sensitivity to $\approx$0.92mm, providing a minimal amount of information. The thrust of this work has been to develop the "blind-hole" drilling technique into a method for quantifying through thickness residual stresses, giving a better indication of the macroscopic residual stress profile remaining in materials after processing. The study here focuses on the residual stresses in an aluminium-lithium based MMC, however it is anticipated that the techniques developed will be applicable to all materials on which the "blind-hole" drilling technique is applied.

Here the "blind-hole drilling" technique is applied in unison with the "Treuting-Read" or "Layer Removal" technique[6], a method for determining the biaxial residual stress state in materials in an elastically homogeneous manner. This method assumes that the stresses only vary through the thickness of the material. This assumption is valid for the case of the quenched MMC under investigation in this study since the particulate distribution is homogeneous and the source of the residual stresses is a temperature gradient which only varies through the thickness of the material. In applying this method, thin layers of material are removed from the surface of the block. Removal of part of the stressed material disturbs the equilibrium of forces and bending moments, and thereby forces the remaining material to change its shape in order to maintain equilibrium. This change in shape produces a surface strain in the face of the sample. This can be measured using a single back face strain gauge and can be interpreted as a function of surface depth removed.

Experimental

The material under investigation is an aluminium-lithium alloy (AA8090) reinforced with 3μm particulate SiC. The material was manufactured by B.P. Metal Composites Ltd. using a powder metallurgy route including HIPping, forging, and rolling to a plate thickness of $\approx$ 15mm.

During room temperature fatigue testing of specimens taken from this plate the crack-front developed in a bowed manner, i.e. it tunnelled at the centre but showed little extension in near surface regions. The results presented in a previous report[7] indicate that the near surface region in the composite is in compression and hence promotes the bowed nature of the fatigue cracks. It was also observed that these residual stresses were inherent to the processing treatments used for heat treatable aluminium alloys, i.e. they were generated during cold water quenching from the solution treatment temperature.

In order to be fully able to interpret the influence of quenched in residual stresses on the levels of stress intensity at the crack-tip it is necessary to be able to identify the residual stresses through specimen thickness (from the surface to the centre). Thus an expansion of the "blind-hole" drilling technique to encompass the measuring distance of 6mm (typical 1/2 thickness for fatigue samples under examination) was necessary. This was made possible by use of the blind-hole drilling technique in conjunction with back-face strain gauge measurements by using the following procedure.

"Blind-hole drilling"

When drilling the hole it is important that the hole is concentric with the hole drilling target on the strain gauge and the hole produced should be cylindrical, flat bottomed and with sharp surface corners. The holes were drilled using diamond tipped drill-bits (designated Komer 805 016) with a tip diameter of approximately 1.7mm. The strain data ϵ_1, ϵ_2 and ϵ_3 from gauges 1, 2 and 3, represented in figure 1, were processed using a software package to produce the principal residual stresses present at each increment of depth. The biaxial residual stresses σ_x and σ_y were determined in increments of 0.0508mm from the specimen surface to a depth of approximately 1.25mm. The hole diameter D_0 created during the analysis was measured optically and found to be approximately 1.85mm. It is important to note that at depths corresponding to $Z/D_0 > 0.5$, incremental relief has very little effect on observed strains and it is assumed that quantitative interpretation of incremental strain data for depths beyond Z/D_0 cannot be made under the present analysis conditions.

"Layer removal"

Extension of the blind-hole drilling technique beyond its maximum depth of accuracy ($Z/D_0 \leq 0.5$) as discussed above was required to obtain an overall picture of the residual stress distribution across the whole thickness of the test specimen. Therefore the surface layer of the specimen was slowly removed to a depth of $Z/D_0 = 0.5$ using a diamond coated grinding wheel with surface cooling to prevent additional stresses being imparted to the fresh specimen surface. Following this surface layer removal step a new strain gauge was attached to the fresh surface with the same orientation as used previously. This process of surface removal followed by hole drilling analysis was continued to the centre of the specimen and the whole process is summarised in figure 2. During the course of this surface removal process it was found that the specimen tended to bend to redistribute the residual stress distribution as the amount of compressive stresses in the upper layer are altered. To take account of this a measurement of the change in stress on the upper surface of a second identical specimen was made by using a back face strain gauge. The type of surface gauge used was a single gauge R.S. 2mm strain gauge (Stock No. 632-146). The surface layers were removed in increments of 0.0508mm and for each increment removed special care was taken to allow the back face strain gauge value to stabilise before measurements were made (30 minutes for each increment). A schematic of the two processes is presented in figure 3 and indicates the position of the 'blind-hole' on the upper surface and the position of the strain gauge on the back face. The orientation of the two gauges provided strain measurements in the 'x direction' only as is indicated in figure 3.

Results

As has been reported previously[7] the mean residual stresses in the near surface region of 3μm SiC particulate reinforced aluminium-lithium alloy reach a mean stress level of - 37 MPa and hence the surface is in compression consistent with the reduced level of crack front tunnelling seen in the near surface region during fatigue testing, see figure 4.

Extension of the 'blind-hole' drilling technique has provided information from the surface to the specimen centre, with the 'x-component' stress designated in figure 3 presented in figure 5 as a function of distance to the specimen centre. It can be seen from this data that the macroscopic residual stress level peaks at a compressive level of -80MPa $\approx$ 1.5mm from the original specimen surface and then steadily reduce to zero as the centre of the specimen is approached. These results indicate that macroscopic residual stresses at the specimen mid-thickness reduce to zero which appears to be incorrect since compressive residual stresses in the near surface regions must be balanced by tensile residual stresses in the specimen interior. This analysis, however, is incomplete because it does not take into account the stress relief (bending) which accompanies surface layer removal and which is considered in the analysis below.

The change in surface residual stresses as a consequence of incremental surface layer removal has been analysed in one direction by using back face strain gauge measurements. The change in microstrain with each 0.0508mm increment of surface removed was recorded and hence converted into increments of stress using the simple stress-strain relationship:-

$$\sigma = E \times \epsilon$$

where;

σ = upper surface stress level (MPa),
ϵ = microstrain measurement from back face strain gauge,
E = Young's Modulus (taken as 100GPa for 3μm particulate composite).

The two strains measured from the 'blind-hole' drilling technique and the surface layer removal procedure are directly additive and can be used to calculate the macroscopic residual stress distribution, for the 'x direction' described in figure 3, from the surface to the centre of the specimen. A plot of these combined stress components is presented in figure 6 and indicates the actual macroscopic residual stress distribution to the specimen centre. Hence, the near surface region is under a compressive stress peaking at a level of 65 MPa and the centre region exhibits a level of tensile residual stress peaking at 75 MPa.

Discussion

From the above work to develop through thickness residual stress data it has been shown quantitatively that the residual stresses in the 3μm particulate reinforced composite extend to the centre of the specimen and become tensile in near centre regions. This highlights the driving force to produce bowed fatigue cracks with increased crack front extension in the tensile region at the specimen centre. It has also been found that a force balance of the tensile region is in close agreement with a force balance of the compressive region, thus verifying the validity of the results.

It is suggested that the residual stresses thus determined can be extended and included in analyses for calculating the stress intensity ahead of the crack-tip during crack growth through regions of known residual stress. However, more analysis is required to provide 2-D stress profiles.

Conclusions

1. A destructive test technique has been developed to provide an estimate of the specimen macroscopic residual stresses through thickness in particulate reinforced metal matrix composites.

2. A force balance of the compressive and tensile regions measured during the analysis is in close agreement thus validating the analysis.

3. The maximum calculated compressive value is 65MPa and the maximum tensile value is 75MPa.

References

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Acknowledgements

Support for the author (PDC) from a S.E.R.C. C.A.S.E. award from B.P. Metal Composites Ltd. is gratefully appreciated together with useful discussions held with R.B.Newbery.

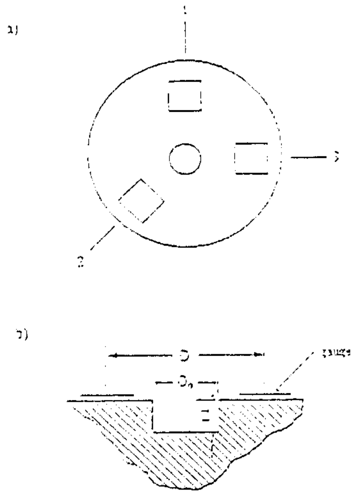

Figure 1. (a) Schematic diagram of the strain gauge used, (b) sectional view of hole.

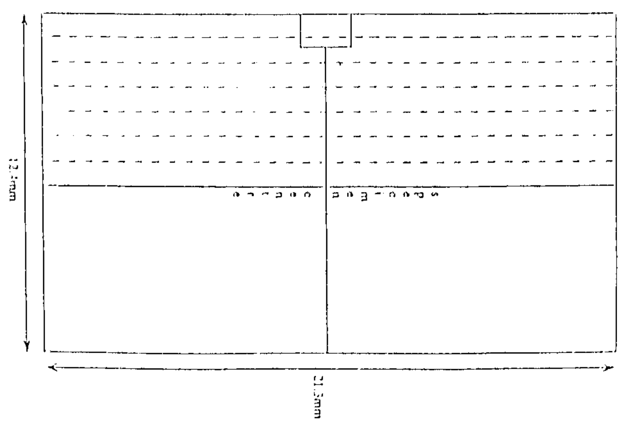

Figure 2. Surface removal followed by blind-hole drilling to the centre of the specimen

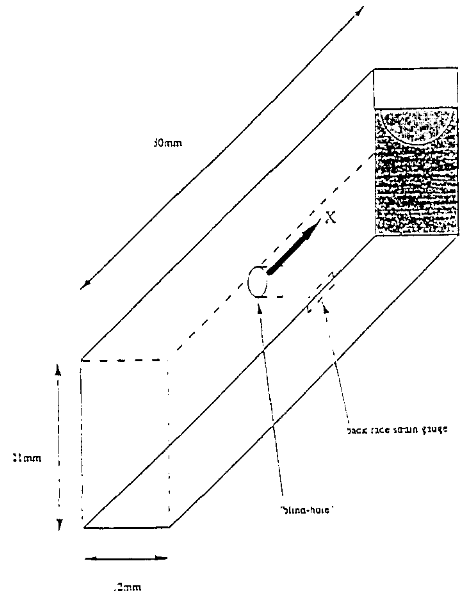

Figure 3. A schematic diagram of the combined surface removal techniques employed.

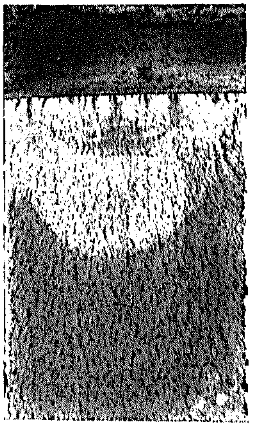

Figure 4. The crack front profiles formed during fatigue testing of the 3μmparticulate reinforced composite at room temperature.

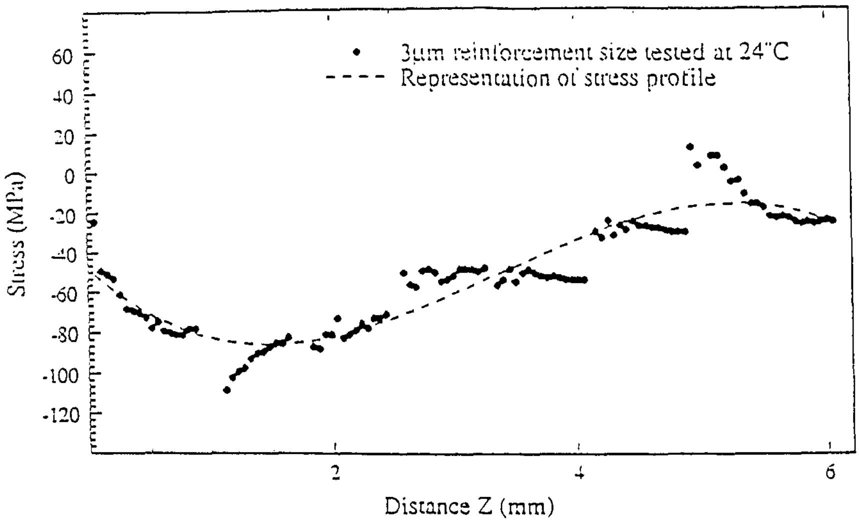

Figure 5. σx (residual stress in the x direction) vs. Z (hole depth), for the 3μm reinforced composite to the specimen centre.

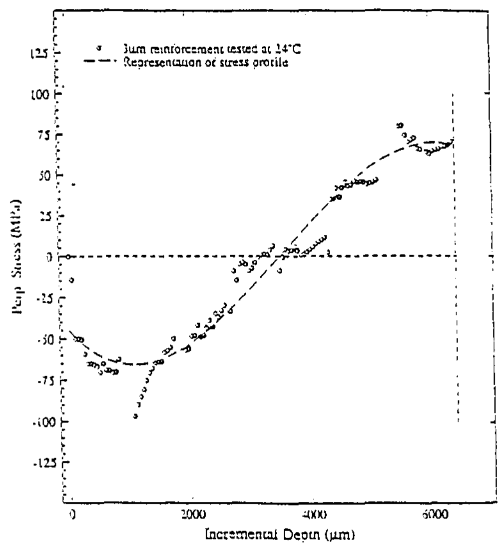

Figure 6. σx (residual stresses in the x direction) vs. Z (hole depth), for the 3μm reinforced composite to the specimen centre.
This figure gives the combination of both blind-hole drilling data and back face strain gauge information.