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Effect of homogenization treatment on fatigue behaviour of 2124Al/20 vol % SiC_p composite

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The fatigue behaviour of 2124Al/20 vol % SiC_p composite was studied in the as vacuum hot-pressed condition, as well as after a homogenization treatment subsequent to vacuum hot pressing. It was found that there was a significant improvement in the tensile strengths, fatigue threshold stress intensity range, ΔK_{th}, and cyclic fracture toughness, K_{fc}, as a result of the homogenization treatment. The improvement in the properties of the composite after homogenization is attributed to the dissolution of the coarse intermetallic precipitates present in the composite in the as-vacuum hot-pressed condition.

1. Introduction

The quest for lighter materials with high specific strength and stiffness has triggered the development of metal matrix composites (MMCs) as an alternative to traditional engineering alloys. The current focus is on aluminium-based MMCs reinforced with a discontinuous reinforcement in the form of whiskers or particulates as opposed to continuous fibres. This is because discontinuously reinforced MMCs are less expensive, possess isotropic properties and can be fabricated by conventional, mechanical and metallurgical processes. While interest in the whisker-reinforced composites is on the decline because of the health hazards imposed by handling the whiskers, intensive development work is being carried out on particulate-reinforced composites on account of their potential to attain substantial increases in strength and stiffness [1–5]. However, these materials exhibit low ductility, fracture toughness and fatigue crack initiation and growth resistance [6–11]. These properties must be significantly improved before these composites can find increasing use in structural applications.

The present work was concerned with a 2124 Al alloy matrix reinforced with 20 vol% SiC particulates. The study focused on the influence of a homogenization treatment on the fatigue crack growth behaviour of this composite.

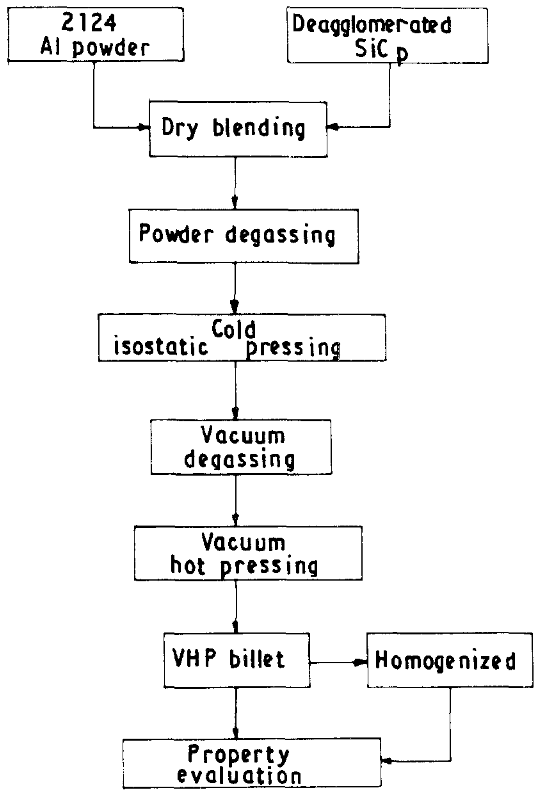

Figure 1 Schematic illustration of the process used for the manufacture of 2124 Al/20 vol % SiC_p composite.

2. Experimental procedure

The nominal composition of the matrix (2124 Al) in wt % was 4.4 Cu, 1.5 Mg, 0.6 Mn, balance aluminium. It was reinforced with 20 vol % silicon carbide particulates of 15 μm average size. The composite was produced using a powder metallurgy route. The process involves dry blending of the 2124 Al alloy powder with the reinforcement powder, followed by degassing, cold isostatic pressing and finally vacuum hot pressing. A schematic illustration of the process is shown in Fig. 1.

A composite billet was subjected to an optimum homogenization treatment which involved soaking the billet at 490° C for 96 h followed by air cooling. This homogenization treatment was selected on the basis of the hardness versus homogenization time plot (illustrated in Fig. 2) established for this composite [12]. Optical microscopy was used to study the microstructure of the composite in the as-vacuum hot-pressed condition and after the homogenization treatment. Tensile and fatigue behaviour of the composite were evaluated in the as-vacuum hot-pressed condition as well as after the homogenization treat-

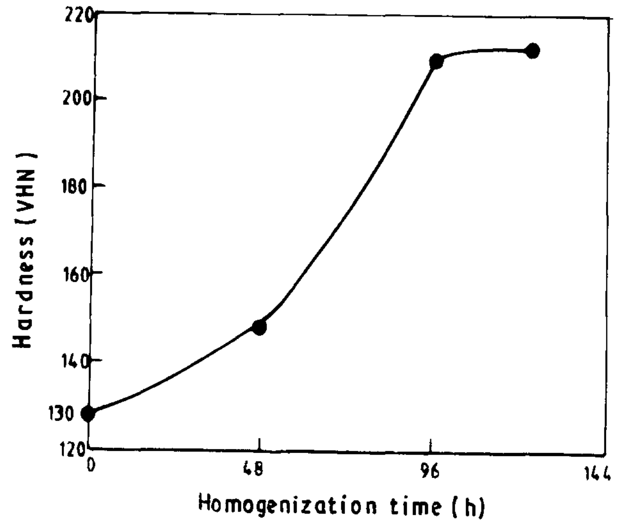

Figure 2 Vickers hardness versus homogenization time for 2124 Al/20 vol % SiC_p composite at a soaking temperature of 490°C.

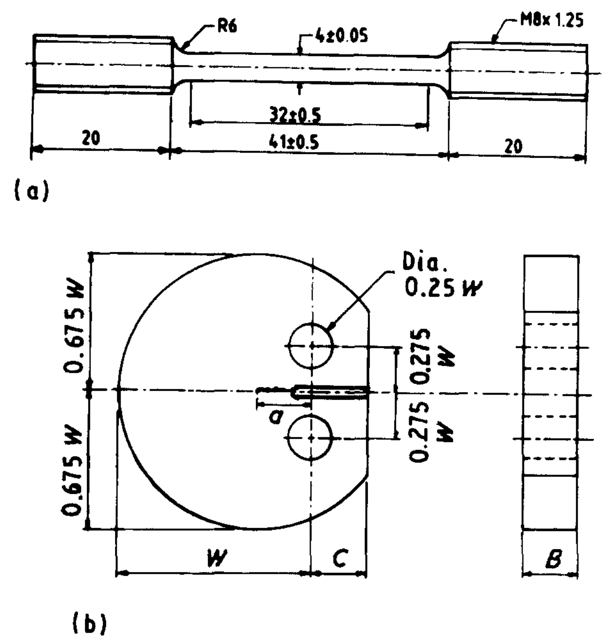

Figure 3 Specimen designs for (a) tensile and (b) fatigue crack growth tests.

ment, on a computer-controlled Instron-8500 servo-hydraulic testing machine. Tensile tests were performed on the specimen, as shown in Fig. 3a, at a strain rate of $6.67 \times 10^{-4} s^{-1}$ using a 25 mm extensometer. Disc-shaped compact tension specimens (illustrated in Fig. 3b) with $W = 51$ mm, $B = 8$ mm and $C = 12.75$ mm were employed for fatigue crack growth testing as per ASTM standard E-647 [13, 14]. The test involves tension-to-tension cyclic loading at a frequency of 15 Hz using a R ratio of 0.1. The fatigue crack growth was measured using crack opening displacement (COD) gauge of 5 mm size having extension up to 40%. In order to cross-check the crack lengths determined by the compliance technique using the COD gauge, crack growth was additionally measured through an optical microscope. It was found that crack length measurements by both techniques were consistent and hence the compliance technique was used for crack growth rate and stress intensity factor calculations. The fracture surfaces of the fatigue crack growth specimens were studied in a ISI-100 scanning electron microscope to understand the fracture mechanism.

3. Results and discussion

A representative optical micrograph in the as-vacuum hot-pressed condition is illustrated in Fig. 4a. The microstructure shows a reasonably good distribution of the SiC particulates in the matrix with very little evidence of clustering of the particulates. The microstructure also appears to be void free and is a confirmation of the complete densification achieved during vacuum hot-pressing. However, a significant amount of copper-rich coarse intermetallic inclusions (2–15 μm long) with a high aspect ratio can be seen in the microstructure (Fig. 4b) of the composite in the as-vacuum hot-pressed condition. These inclusions are most likely formed during the hot-pressing operation carried out above the solidus temperature. A representative microstructure after the homogenization treatment described earlier is illustrated in Fig. 5. It can be observed that the homogenization treatment

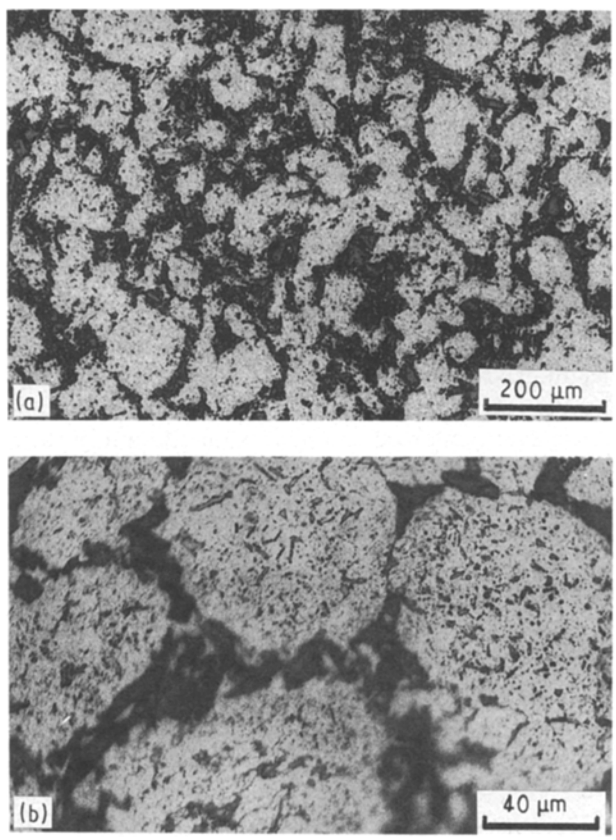

Figure 4 Optical microstructure of 2124 Al/20 vol % SiC_p composite in the as-vacuum hot-pressed condition illustrating (a) uniform distribution of SiC particulates and (b) coarse intermetallic inclusions.

has significantly decreased the amount and size of the intermetallic inclusions. This could be attributed to the dissolution of the intermetallic inclusions in the matrix.

Tensile test results along with hardness values for the composite are listed in Table I in the as-vacuum hot-pressed condition as well as after the homo-

TABLE I Effect of homogenization treatment on mechanical properties of 2124 Al/20 vol % SiC_p (VHP) composite

Condition	Tensile 0.2% YS (MPa)	UTS (MPa)	Elongation (%)	E (GPa)	Hardness (VHN)
VHP	238	245	0.60	92	130
VHP + hom.	300	348	0.85	95	210

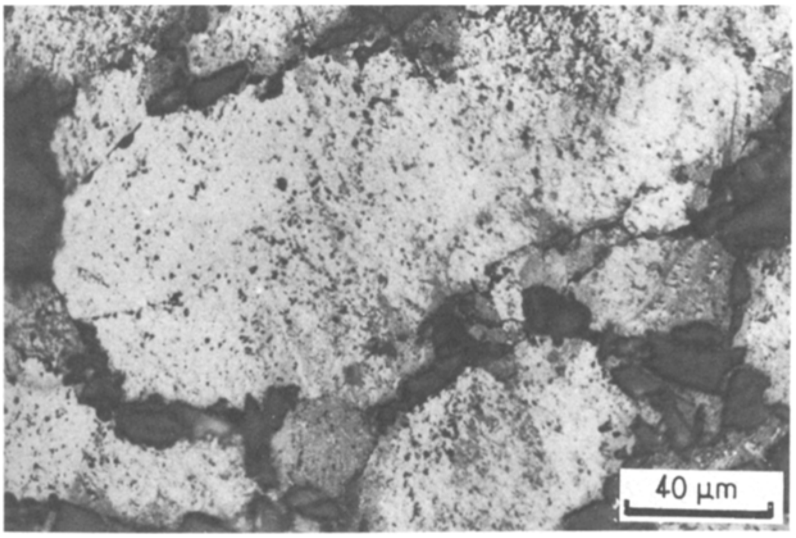

Figure 5 Optical microstructure of 2124 Al/20 vol % SiC_p composite after the homogenization treatment illustrating the absence of coarse intermetallic inclusions.

genization treatment. It can be seen that the homogenization treatment has resulted in a significant improvement in the strength and hardness of the composite, while the increase in elastic modulus was marginal. The improvement in the strength properties could be attributed to the dissolution of the coarse intermetallic inclusions. These coarse inclusions, because of their high aspect ratio, act as stress concentration sites in addition to the silicon carbide particulates in the vacuum hot-pressed condition. A back-scattered scanning electron micrograph, shown in Fig. 6, of a perpendicular section to the fracture surface of a tensile specimen clearly illustrates the process of void formation at the intermetallic inclusions in the composite in the as-vacuum hot-pressed condition.

The absence of such inclusions in the homogenized condition delays the fracture initiation process resulting in a higher strength for the composite after the homogenization treatment. Another factor which could have contributed to the improvement in strength of the composite as a result of the homogenization treatment is that the dissolution of the intermetallic inclusions in the matrix results in an increase in the solid solution alloying elements in the matrix, thereby increasing the strength of the matrix and, as a consequence, that of the composite.

Fatigue crack growth rate (da/dN) is plotted against stress intensity factor range (ΔK) in Fig. 7, for both cases, to evaluate the fatigue crack growth behaviour of the composite. It can be observed that the composite subjected to the homogenization treatment exhibits a superior fatigue crack growth behaviour as

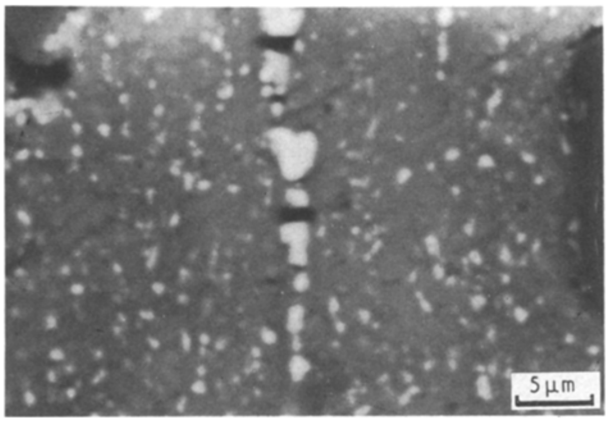

Figure 6 Back-scattered scanning electron micrograph illustrating void formation at coarse intermetallic inclusions.

compared to the composite in the as-vacuum hot-pressed condition. The threshold stress intensity range, ΔK_{th}, for the composite improves from 6 MPa $m^{1/2}$ to 12 MPa $m^{1/2}$ as a result of the homogenization treatment. Similarly, the cyclic fracture toughness, K_{fc}, determined for both specimens as the last value of K prior to fast fracture, also increases from 8 MPa $m^{1/2}$ to 15 MPa $m^{1/2}$ after the homogenization treatment.

Scanning electron micrographs of the fracture surfaces formed between ΔK_{th} and K_{fc} for the composite in the as-vacuum hot-pressed and after the homogenization treatment are illustrated in Fig. 8. It can be

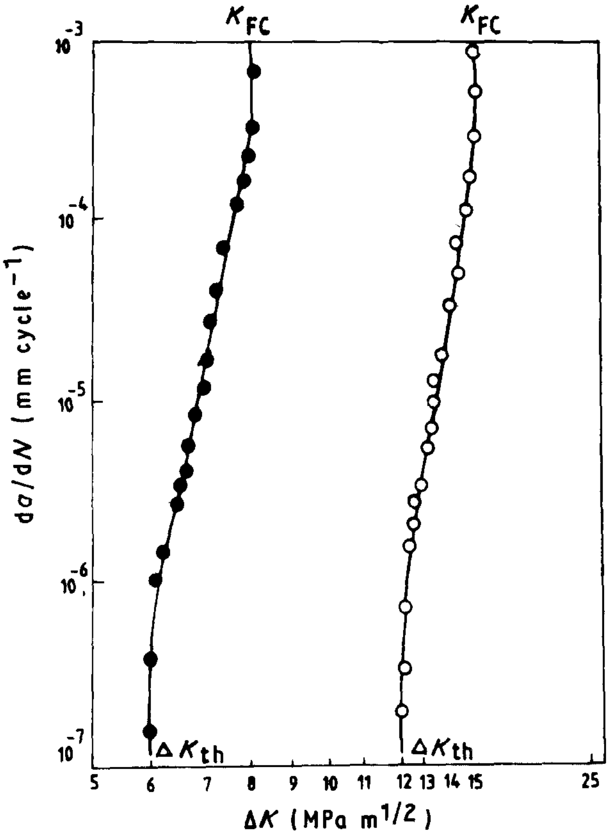

Figure 7 Fatigue crack growth rate (da/dN) versus stress intensity range, ΔK, for 2124 Al/20 vol % SiC_p composite in the (•) as-vacuum hot-pressed condition and (o) after the homogenization treatment.

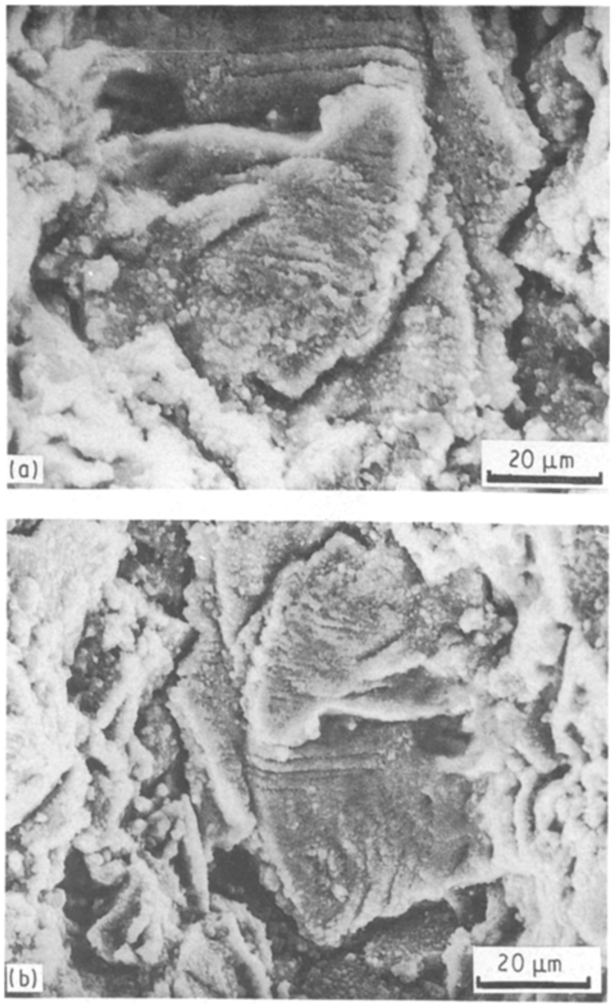

Figure 8 SEM fractographs of 2124 Al/20 vol % SiC_p composite in (a) as-vacuum hot-pressed condition and (b) vacuum hot-pressed + homogenization condition.

observed that few isolated patches of striations were found in both cases, but these regions were not typical of the fracture surface. No features attributable to the formation or scrapping of relatively thick surface oxides or of crack surface rubbing were found in either case. Relatively few broken SiC particles were found in both cases. It can be concluded that fractographic examination does not provide any assistance in distinguishing the fracture mechanisms in the two cases.

The threshold is an expression of the effects of fatigue crack closure and is directly linked, as has been demonstrated by Davidson [15]. Davidson has proposed a model which associates the slip characteristics of the material with the magnitude of ΔK_{th}. This model assumes that crack growth can occur only when dislocations are emitted from the crack tip. Davidson has hypothesized that crack growth ceases when the stress at the tip of the slip line of length r_s emanating from the crack tip equals the flow stress, because dislocations can no longer be driven away from the crack tip. This leads to the following expression for ΔK_{th}

$$\Delta K_{th} = \sigma_f(2\pi r_s)^{1/2} \quad (1)$$

where σ_f is the flow stress and r_s is the mean free path of dislocation motion which is equal to [16]

$$r_s = (2d/3)[(1 - V_f)/V_f] \quad (2)$$

where d is the particle size and V_f is the volume fraction. Thus it can be seen that fatigue threshold stress intensity range depends not only on the yield strength of the composite, but also on the particle size and volume fraction of the particles. As has been discussed earlier, fracture can initiate at the coarse intermetallic inclusions which are more or less of the same size as the SiC particulates. This implies that the effective volume fraction of the particles contributing to crack initiation is increased from 20% to about 25% for the composite in the as-vacuum hot-pressed condition because of the presence of about 5% coarse intermetallic inclusions. Substitution of the appropriate values of yield strength, particle size and volume fraction in Equations 1 and 2 results in the prediction of fatigue threshold stress intensity range for the composite of 3.3 and 5.2 MPa m$^{1/2}$ in the as-vacuum hot-pressed condition and after the homogenization treatment, respectively. The theoretical predictions are slightly lower than the experimentally observed fatigue threshold stress intensities of 6 and 12 MPa m$^{1/2}$ for the two cases. However, the trend of doubling of the fatigue threshold as a result of the homogenization treatment can be predicted theoretically. This further confirms that the dissolution of the coarse intermetallic inclusions as a result of the homogenization treatment is the primary cause of the increase in the fatigue threshold stress intensity range of 2124 Al/20 vol % SiC_p composite. Similarly, the increase in cyclic fracture toughness, K_{fc}, can also be attributed to the dissolution of the coarse intermetallic inclusions.

4. Conclusion

There is a significant improvement in the tensile properties, fatigue threshold stress intensity range, ΔK_{th}, and cyclic fracture toughness, K_{fc}, of a 2124Al/20 vol % SiC_p composite as a result of a homogenization treatment, which involves soaking the composite at 490° C for 96 h. The improvement in the properties is attributed to the dissolution of the coarse intermetallic inclusions present in the microstructure of the composite in the as-vacuum hot-pressed condition, as a result of the homogenization treatment.

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