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"FLOW AND FRACTURE BEHAVIOUR OF TUNGSTEN FIBER REINFORCED SUPERALLOY COMPOSITES – EFFECT OF SPECIMEN GEOMETRY"

By

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ABSTRACT

The influence of aspect ratio (i.e. width to height ratio) of test specimens on the flow and fracture behaviour of fiber reinforced composites is herein examined. The composite material was prepared by isostatic pressing of a Mar-M200 nickel-base superalloy matrix reinforced with 40% tungsten wires. Uniaxial compression forging was performed at a constant true strain rate of $3x10^{-4}$ S^{-1}, with temperature as parameter. The aspect ratio (wo/ho) of test blanks was made to vary between 0.3 and 3, loading being always normal to the direction of wire alignment.

It is herein established that peak flow stress values of composite material increase significantly with rising aspect ratio while severity of damage is shown to decrease. Furthermore, it is found that the fracture pattern is also influenced by specimen geometry. This may be attributed to some favourable effect of a hydrostatic compressive stress component which seeks to retard void formation and growth. Relevant practical implications are discussed.

1. INTRODUCTION

Fiber reinforced superalloy-matrix composite materials. offer a combination of oxidation resistance and high stiffness to density ratio coupled with ductility and toughness; these features make them good potential for use at elevated temperatures [1,2]. One principal drawback of these composites is that they are extremely difficult to form by conventional metal working processes due to the strongly anisotropic nature of their properties [3].

Isothermal forging might be used to complete the shaping and sizing operations of hot isostatically pressed composite components or to improve the coarse structure of composites produced by casting. In this process the fully bonded workpiece is compressed in a direction perpendicular to the fibers so that the material flows laterally into the die cavity to form the desired shape. The matrix deforms plastically while the fibers remain undeformed while they move laterally by the flowing matrix.

There is no metal flow along the direction of fiber reinforcement because of the rigidity of fibers and the bond between the matrix and fibers. This would result in a plane strain mode of deformation and metal flow occurs only in a lateral direction normal to the direction of fiber alignment.

Little work has yet been published on the response of fiber reinforced composites to deformation processing [4,5]. From this work it was concluded that rolling in the direction parallel to fibers is not feasible without extensive damage while high reductions were obtained in a direction perpendicular to the fibers. This suggests the feasibility of forging composite materials as long as there is no deformation along the direction of reinforcement.

Consequently, work was conducted with a view to examining the isothermal forging behaviour of refractory wire reinforced superalloy composites under well cotrolled laboratory conditions [6]. It was found that formability of composites is limited to low strains; this is due to early formation of voids at tensile poles of the fibers normal to the loading direction [7,8]. Forging at high temperature and/or low strain rate decreased flow resistance of the matrix and improved its formability. In this work the aspect ratio, width to height ratio (wo/ho) of test blanks was kept constant, i.e. its effect was not examined. With this view in mind this work was planned to examine the influence of the aspect ratio on the flow and fracture behaviour of these materials, also to discuss relevant practical implications. The system studied consisted of a nickel-base superalloy matrix reinforced with high strength thoriated tungsten wires.

2. PARTICULARS OF MATERIALS EXAMINED

The composite system studied consisted of a nickel-base superalloy matrix reinforced with 0.5mm diameter, high strength thoriated tungsten wire. Tungsten wire had a 3−4 μm thick coating of hafnium nitride to prevent nickel-induced recrystallization and consequential loss of fibers strength. The volume fraction of reinforcement was about 40%. This is a viable representative of composite material for high temperature applications. Composite billets were consolidated by hot isostatic pressing (HIPing) for two hours at 1150°C under a pressure of 103 MPa. Details of composite preparation is given in reference [9] and cross section of the as-HIPed material is shown in Figure (1).

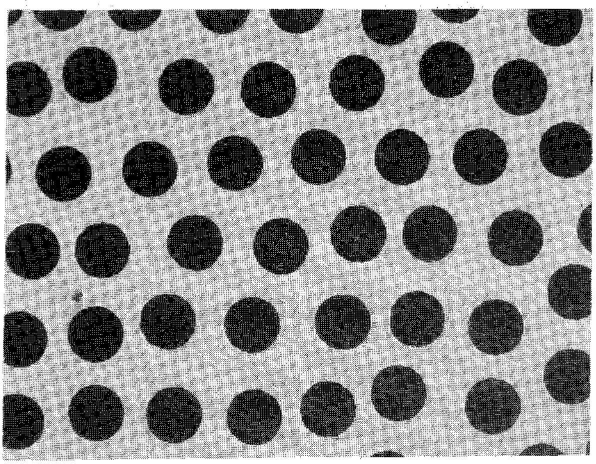


Fig. 1 : Cross section of as − HIPed composite material showing fiber distribution.

3. EXPERIMENTAL PROCEDURE

Test specimens were cut from the composite billet by means of a diamond-dressed wheel, then ground to final size. The dimension in the direction of reinforcement was 10mm in all cases. Width-to-height ratio (wo/ho) values herein obtained are 0.3, 0.67, 1.0, 1.5 and 3.0. Samples were deformed by isothermal compression between flat dies at a constant true strain rate of $3\text{x}10^{-4}\text{S}^{-1}$ and temperatures of 1100°C and 1200°C. Positive pressure of argon atmosphere was maintained during the tests in order to prevent oxidation of specimen and tooling. Figure (2) displays the layout of the system. It consists of a load frame, environmental chamber, MTS control system, exponentional function generator, induction generator, temperature controller and pertinent recorders. Details of test system are given elsewhere [10].

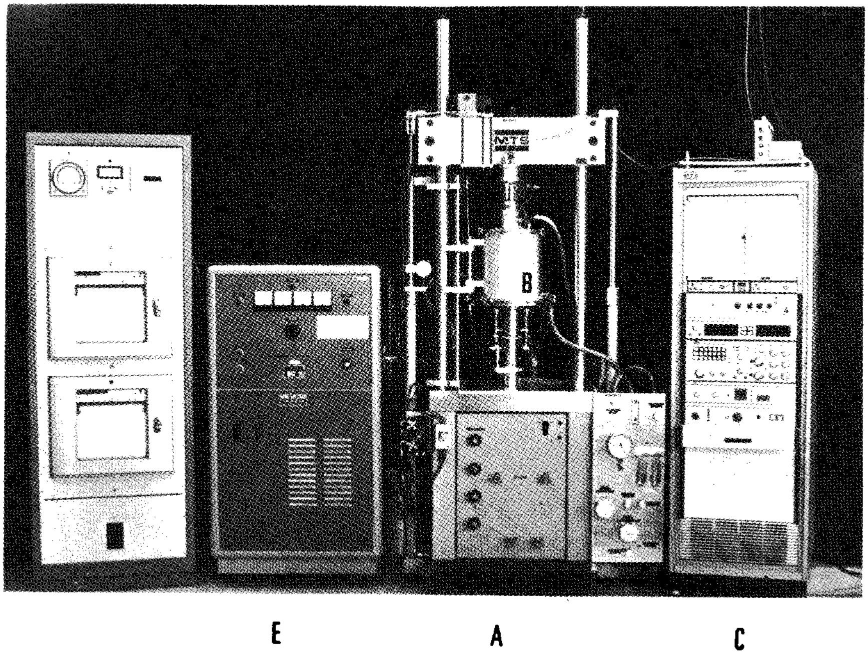


Fig. 2 : Layout of induction heating compression system showing.
(A) MTS load frame. (B) Environmental chamber,
(C) MTS control system. (D) Exponentional function generator,
(E) Induction generator. (F) Temperature controller & recorders.

In all tests loading was transverse to the direction of wire allignment as shown in Figure (3). No lubricant was used at the die billet interface in order to examine the frictional effects. Loads and specimen heights were monitored continously during the test using a load cell and a high temperature displacement transducer respectively. True stress-true strain flow curves were determined from these data using a computer. Selected specimens in the as-HIPed and as-forged conditions were sectioned normal to the direction of reinforcement and prepared for metallographic examinations.

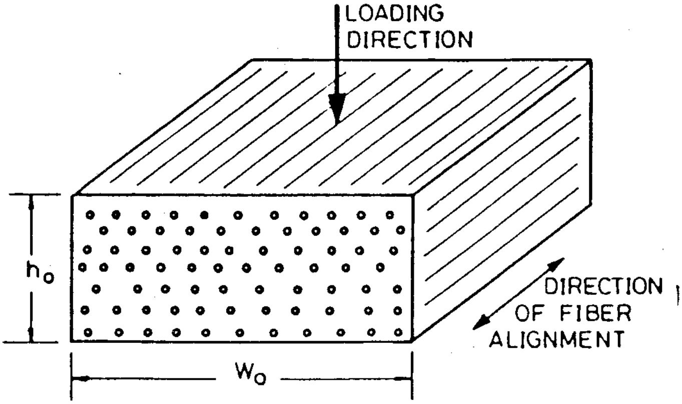


Fig. 3 : Specimen geometry for composite material indicating loading direction with respect to direction of fiber alignment.

4. EXPERIMENTAL RESULTS

4.1 Flow Behaviour

The effect of width to height ratio (wo/ho) at 1100°C and 1200°C are shown in Figures (4) and (5) respectively. The curves show an initial straight portion followed by work hardening to a peak flow stress. Beyond the peak, the composites exhibit flow softening primarily because the matrix softens due to deformation induced recrystallization and grain refinement [11, 12]. Part of the softening may also be attributed to void formation and matrix cracking.

The flow stress increases significantly with the increase in (wo/ho) while degree of softening appears to be rather independent of this ratio. Increasing the forging temperature from 1000°C to1200°C is shown to reduce the overall flow stress of the composites. The degree of softening, however, appears to decrease slightly at the higher temperature. It is also noticeable that the increase in flow strength after first fall beyond the peak is more pronounced at the higher width to height ratio values for both temperatures, Figures (4) and (5).

4.2 Metallographic Observations

The purpose of the metallographic examinations was to determine the nature, extent and distribution of damage in the forged composites as a function of the initial width to height ratio (wo/ho). Attention is directed to sections cut perpendicular to the direction of wire alignment. However, few samples were cut parallel to the direction of reinforcement, Figure (6). The major form of damage is associated with matrix-fiber delamination resulting in the formation of cavities (cat eyes) oriented normal to the loading direction, Figure (7).

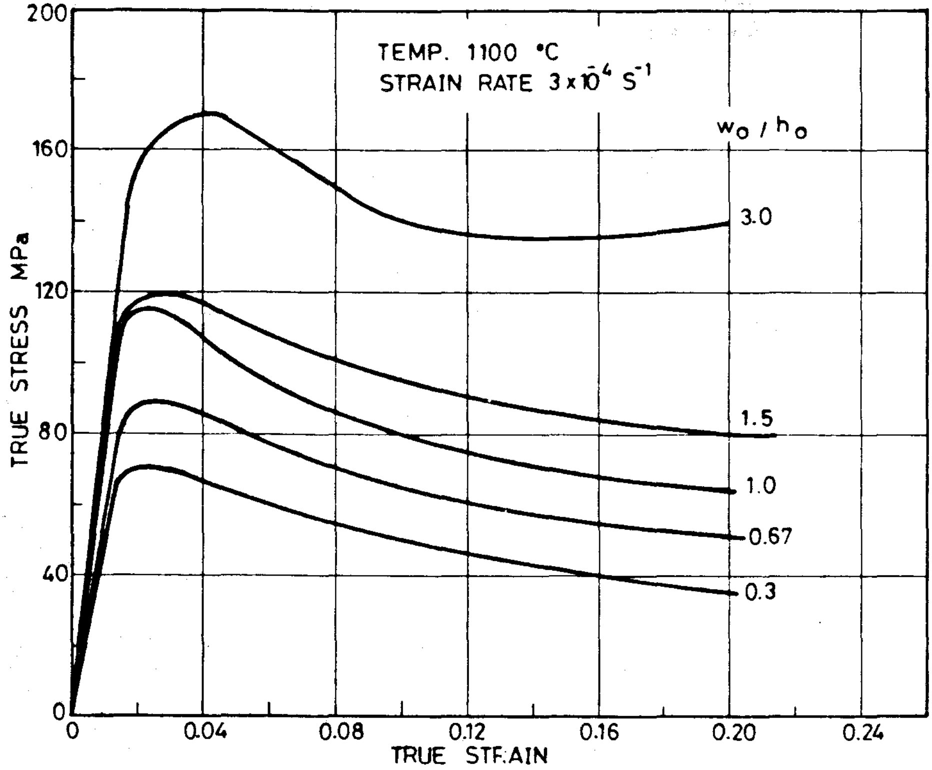


Fig. 4 : Flow curves of composites deformed at 1100° and 3×10^{-4} S^{-1} showing the influence of varying w_0/h_0 ratio.

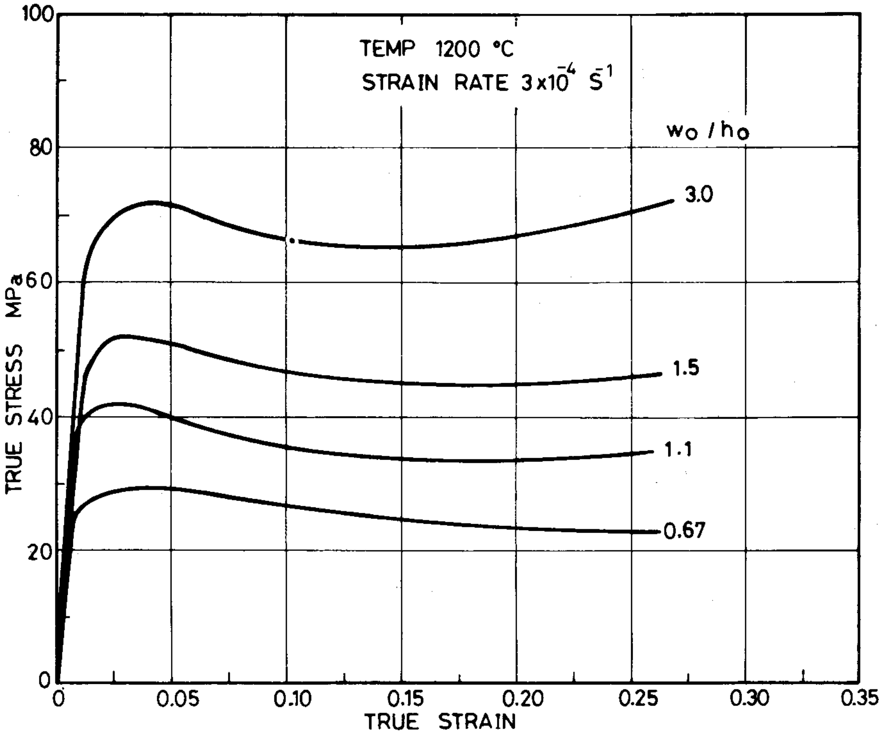
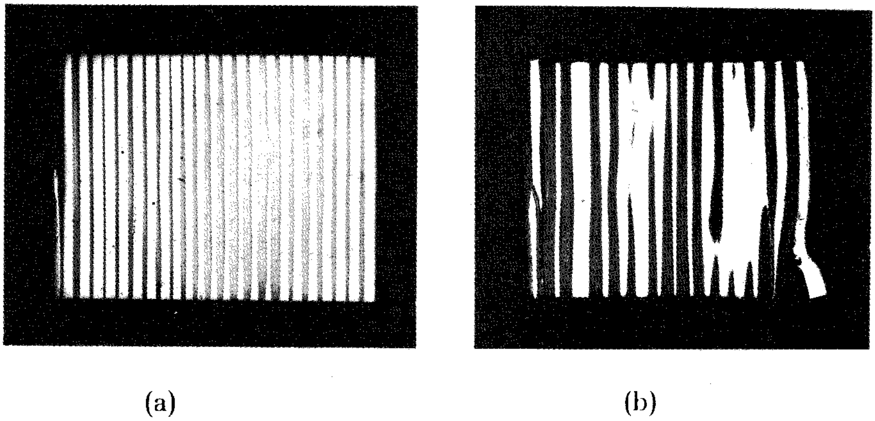


Fig. 5 : Flow curves of composites deformed at 1200 °C and 3 x 10^{-4} S^{-1} showing the influence of varying w_o/h_o ratio.


(a)

(b)

Fig. 6 : Longitudinal sections of composite specimens
(a) as-hiped. (b) forged to some 30% strain.

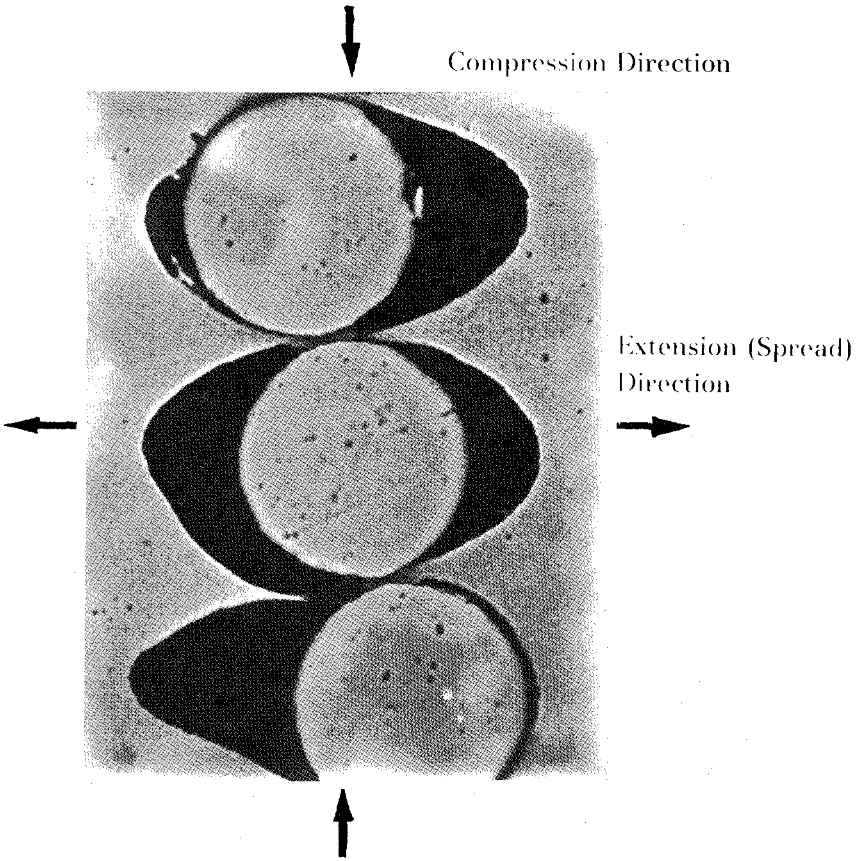
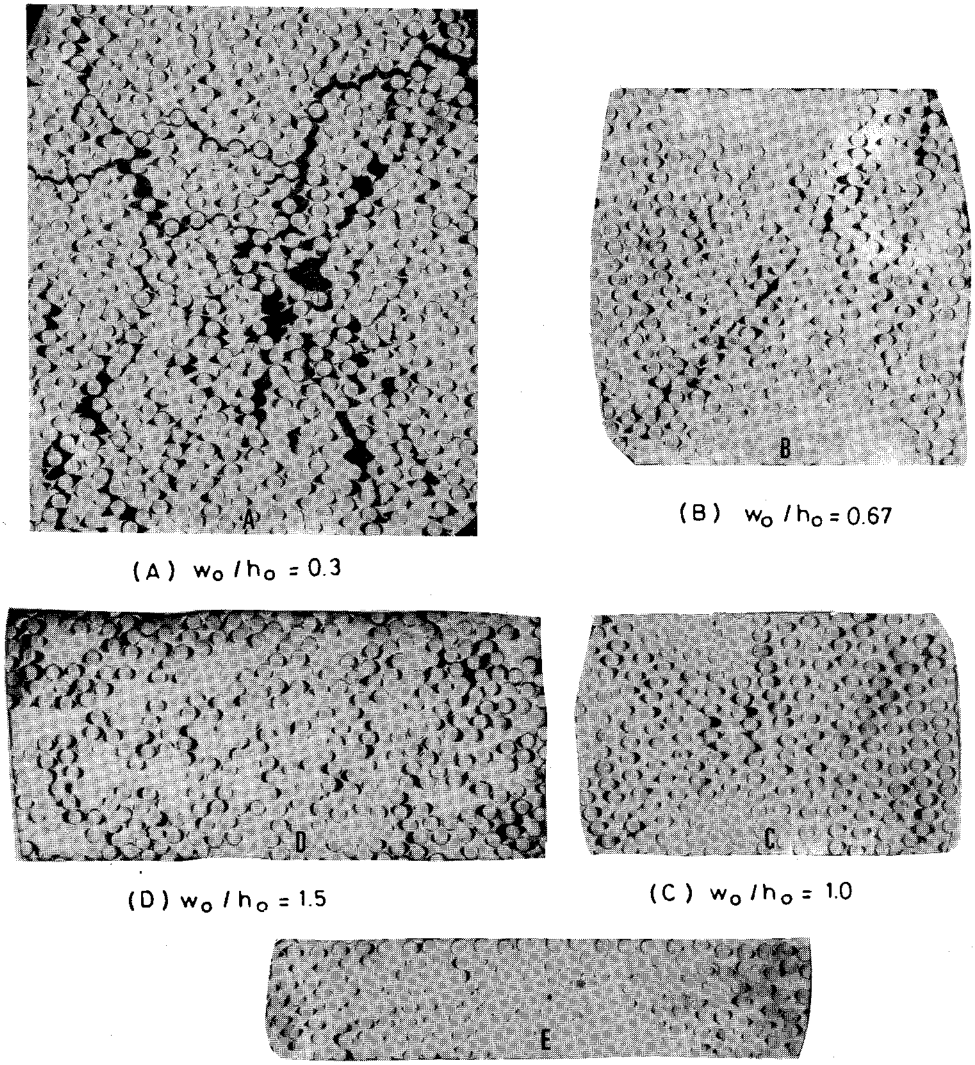


Fig. 7 : **Typical voids around fibers in forged composites.**

Transverse sections of composite specimens deformed to strains of 0.2 are shown in Figure (8). The fracture pattern and void distribution to be greatly influenced by the width to height ratio of the specimens. Most damage occurred in intense shear bands inclined at about 45° to the loading direction for wo/ho ratios of 0.67 and 1.5, Figure 8 (B) & (C).



(A) $w_o / h_o = 0.3$

(B) $w_o / h_o = 0.67$

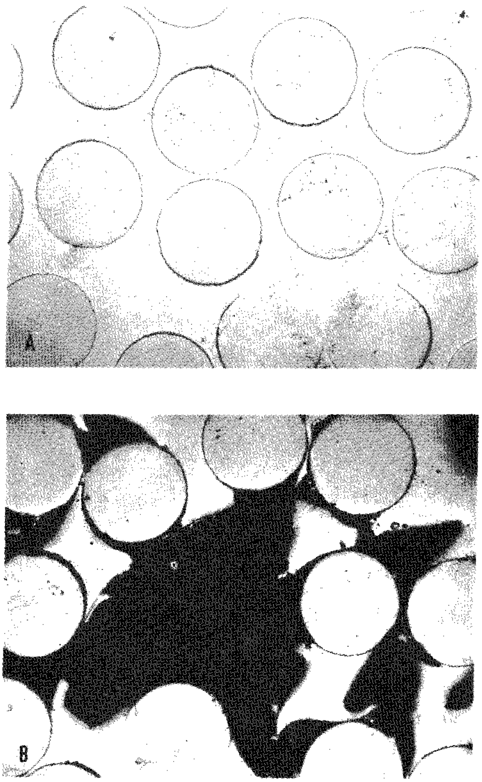
(D) $w_o / h_o = 1.5$

(C) $w_o / h_o = 1.0$

(E) $w_o / h_o = 3.0$

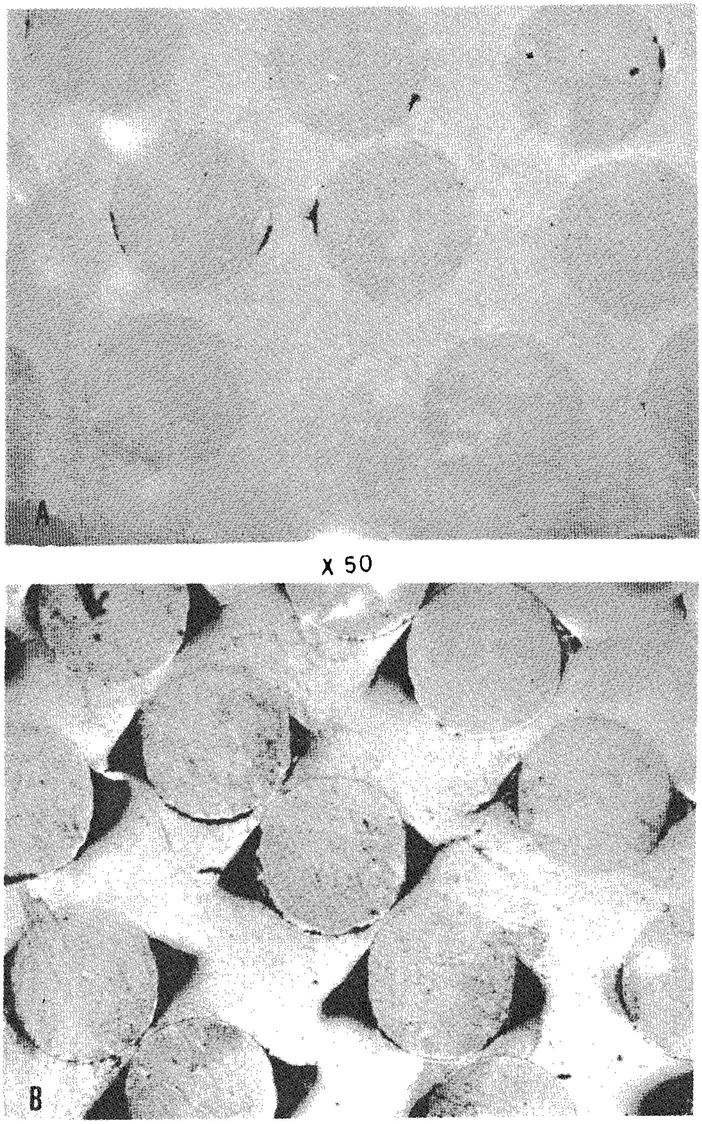
Fig. 8 : Transverse sections of composite specimens deformed to a strain of 0.2 at 1100 °C and 3×10^{-4} S^{-1} showing the influence of varying the width / height ratio on the fracture patterns.

For lower values of the aspect ratio, extensive damage occurred in the central region of the specimen while no damage was observed at the middle region near the die/billet interface, Figure 9 (A) & (B). At high ratio values however, the damage appears to be more centred in the outer region of the specimen as compared to the central region. This is shown in Figure 8 (E) and enlarged sections are displayed in Figure (10). Similar results are obtained at 1200°C, Figure (11).



X 50

Fig. 9 : Transverse sections of composite specimens ($w_0/h_0=0.3$) deformed to a strain of 0.2 at 1100 °C and 3×10^{-4} S^{-1} showing,
(A) Sound composite in the central region at the die/billet interface.
(B) Severe damage in the central region of specimen midway from top and bottom interfaces.



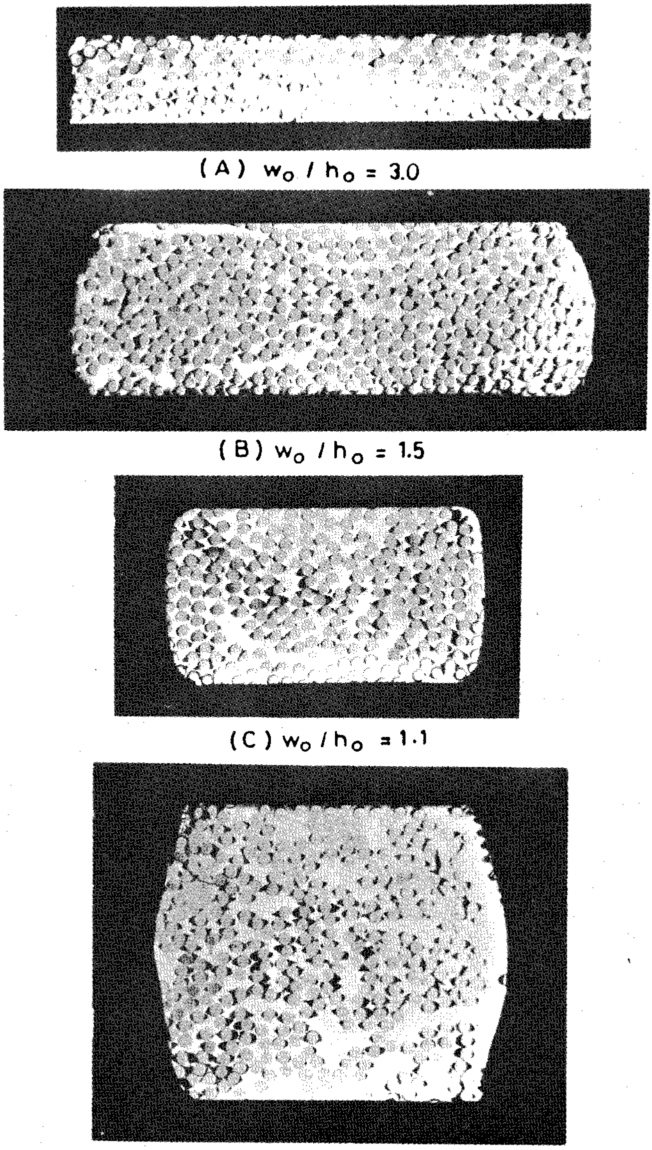
x 50

x 50

Fig. 10 : Enlarged sections of composite specimens ($w_0/h_0 = 3$) deformed to a strain of 0.2 at 1100 °C and 3×10^{-4} S^{-1} showing,

(A) Less damage at the middle.

(B) More damage at the edges.



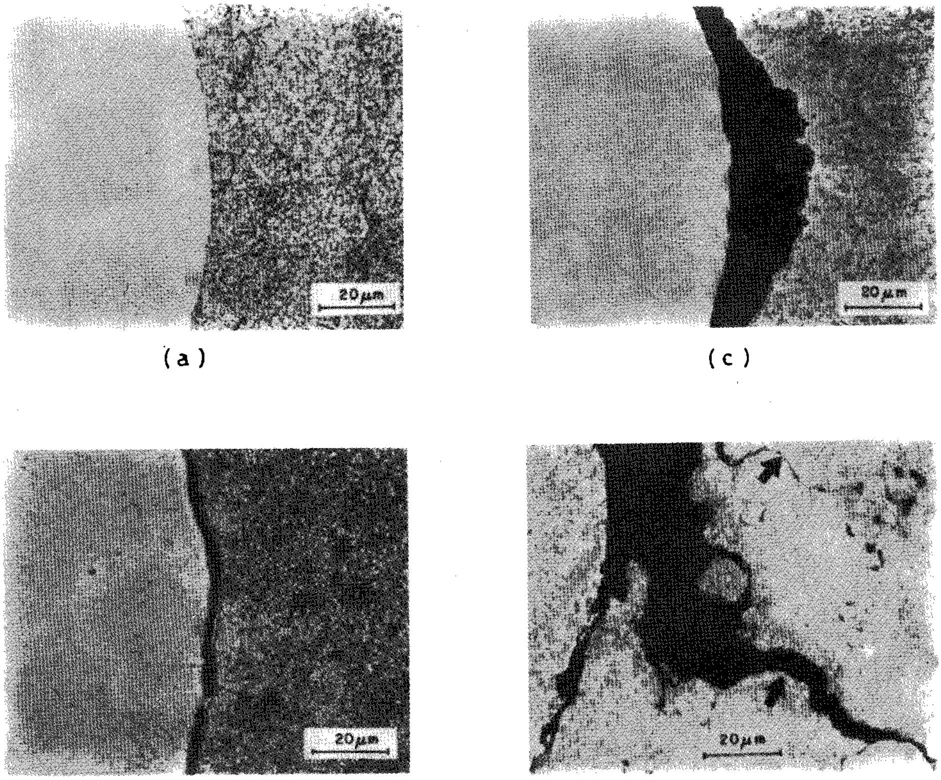
(A) $w_o / h_o = 3.0$

(B) $w_o / h_o = 1.5$

(C) $w_o / h_o = 1.1$

(D) $w_o / h_o = 0.67$

Fig. 11 Effects of width / height ratio on the fracture patterns of composites deformed to a strain of 0.2 at 1200 °C and 3×10^{-4} S^{-1}



(a) (c)

(b) (d)

Fig. 12 : Micrographs showing void initiation and growth at the fiber / matrix interface.

5. DISCUSSION OF TEST RESULTS

Test results displayed in Figures (4) and (5) clearly show the significant influence of the aspect ratio of composite blanks on the flow behaviour of these materials. Increasing the aspect ratio from about 0.7 to 3.0 is shown to result in about 90% increase in peak flow stress of composites deformed at 1100°C, while this rise reached some 150% at 1200°C for same strain rate.

It should be pointed out that voids are normally concentrated in bands or regions of heavy slip and that they nucleate at inclusions or irregularities [13, 14]. In fiber reinforced composites, fibers do not deform and act as rigid inclusion causing void formation, Figures (7), (8) and (10). Ashby [15, 16] has developed a dislocation model of plastic flow around rigid inclusions contained within shear bands. In his work, Ashby demonstrated that particles within shear bands will have tensile stresses set up at particle poles. This can be explained by examining the interaction between a spherical hole and a slip band as follows. Under tensile loading the spherical hole will tend to elongate and flatten into an ellipse, with maximum extension occurring roughly parallel to the tensile axis while greatest contraction lies roughly perpendicular to it.

Should the hole contain a spherical rigid particle or a circular fiber, totally bonded to the walls of the hole, the metal will attempt to take up the elliptical shape, but being constrained by the particle, it will retain its spherical shape. This will result in a tensile stress in the direction of elongation and a compressive stress in the transverse direction. A crack would form at the interface as the tensile stress reaches a critical value, which is the stress required to produce separation of the matrix and the fiber. Decohesion will not occur if the bond strength at the fiber matrix interface exceeds the maximum tensile stress component of the plastic flow.

From metallographic results, it can be observed that fibers cause fracture by a process that may be thought of as having three stages, viz. initiation by separation of fibers from matrix, growth of resulting holes and coalescence of holes to form a macroscopic crack. This is best illustrated by the micrographs of Figures (8) and (12). It is evident from the results of Figure (12) that the bond strength between the coating and the matrix is stronger than that between the coating and the fibers. Obviously any increase in the bond strength at the interface and/or decrease in flow resistance of the matrix by appropriate powder selection and subsequent processing of the composites, should be beneficial to their formability.

It should be emphasized that lateral flow perpendicular to the fiber direction leads to frictional shear at the die/billet interface and this surface shear is directed towards the center of the billet, opposing metal flow, Figure (13). Assuming sliding friction, the magnitude of this frictional shear is μp, in which p is the normal pressure between die and billet and μ is the coefficient of friction. The distribution of lateral pressure q and vertical pressure p can be determined from equilibrium of an element from a rectangular specimen in a plane strain mode of deformation and can be found in the literature [17, 18].

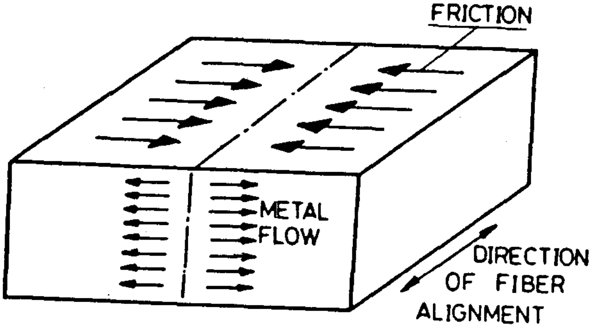


Fig. 13 : Directions of metal flow and opposing friction at the die / billet interface.

While the lateral pressure is zero at the edges of the test specimen, it attains its maximum value at the center. Therefore it is expected that the damage is minimum at the central region of composite specimens and increases towards the edges where the lateral pressure is at a minimum. This is applicable to all aspect ratio values as shown by the photographs of Figures (8) and (11). It should be mentioned, however, that damage tends to become more severe in the central region of the specimens half way from the top and bottom interfaces and that the severity of damage increases for the lower values of the aspect ratio, Figure 8 (A). Similar results have been reported by Erturk [3, 5], who found that high interface friction suppressed void formation in aluminium composites reinforced with stainless steel fibers. These results illustrate the influence of hydrostatic compressive stress in retarding void formation and in improving ductility in fiber reinforced composites.

It should be emphasized, however, that the present open die forging simulation presents a particularly severe test since appreciable secondary tensile stresses are generated normal to the direction of forging, thereby increasing the stresses which cause the major damage, namely voids at the tensile poles of the fibers. In contrast with closed die forging, the large components of hydrostatic compressive stress would tend to reduce the tensile components, thereby enhancing ductility and improving formability.

6. CONCLUSIONS

The following conclusions may be drawn from present investigation:

1. Flow stress of the composite material increases significantly with the aspect ratio wo/ho and tends to increase with higher temperature.
2. Forging of composites normal to wire alignment is shown to result in a plane strain mode of deformation with virtually no deformation in the direction of reinforcement.
3. Formability of composites is limited to low strains due to the formation of voids at the tensile poles of the fibers normal to the loading direction. The critical parameter in this case is the strength of the fiber/matrix interface relative to that of the matrix.
4. Void formation may be reduced or even eliminated by increasing the aspect ratio wo/ho of the composite billet or increasing friction at the die/billet interface.
5. To escape void formation at the edges of the blank, where compressive stress is low, extra matrix material may be added to exert back pressure on the composite in these critical regions. These extra materials can be machined off after forging.

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