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" CONTROL OF VOID FORMATION DURING FORGING OF ADVANCED FIBER REINFORCED COMPOSITE MATERIALS "

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ABSTRACT

Increased interest has emerged in recent years in the development of fiber reinforced superalloy composite materials and the fabrication processes to produce composite turbine vanes and blades for advanced gas turbine engines. The composite system examined consisted of a Mar-M200 matrix containing 40% volume fraction of tugsten wires and was prepared by hot isostatic pressing. Results on the flow behaviour of these materials, under conditions simulating isothermal forging. indicated that extensive damage occurs at an early stage of deformation due to void formation at the fiber/matrix interface.

The objective of this paper is to discuss some of the parameters affecting void formation and damage in fiber reinforced composites and outline forging conditions where void formation can be reduced or even eliminated.

1. INTRODUCTION

For increased efficiency in heat engines, both automative and aerospace industries are demanding materials capable of withstanding higher temperatures along with increased load carrying capacity and fracture toughness. A comprehensive review of literature on artificial composites for high temperature applications revealed that metal matrix composites, reinforced with refractory metal fibers, are in the most advanced state of development among other high temperature composite materials (Islam, 1987). Tungsten or tungsten alloy wire (thoriated tungsten wire) is a major reinforcing agent.

Understanding of the fracture characteristics of artificial metal matrix composites during forming is necessary for their further and wider application at elevated temperature. Isothermal forging of a nickel-base superalloy reinforced with high strength tungsten wires was studied under controlled laboratory condition (Kandeil et al., 1982) and formability limits were pointed out (Kandeil and Wallace, 1984).

In the present paper, void initiation and growth in fiber reinforced composite materials is carefully examined and means of controlling this type of defect are outlined.

2. PARTICULARS OF COMPOSITE MATERIAL

The composite material used in this study was prepared from argon atomized nickel base superalloy (Mar-M200) powder and high strength thoriated tungsten wires of 0.5 mm diameter. The tungsten wires had a 3−4 um thick coating of hafnium nitride to prevent nickel-induced recrystallization. The volume fraction of wires in the composite was about 40% (Kandeil et al., 1982). Samples were consolidated by hot isostatic pressing (HIPing) following procedures described elsewhere (Mazzei et al., 1976). Typical microstructures of the as-HIPed composite material and the non-reinforced matrix material are shown in Figures (1) and (2), respectively.

3. FABRICATION OF COMPOSITE MATERIAL

The fabrication techniques used for different comination of fiber and matrix materials relate directly to the type of materials involved, the shape to be produced and the number required (Weeton, 1971). Some of the important fabrication methods utilized are listed in Table 1. It has been shown elsewhere (Kandeil et al., 1984) that a variety of defects may form in the composite blanks during processing. The flowchart for the manufacturing of the composite samples is shown in Figure (3). Description of these processes have been detailed by Mazzei et al. (1979), however, few points as related to void formation and fiber breakage are discussed below.

Table 1 – Potential Composite Fabrication Methods

General Method	First Step	Consolidation
1. Powder Metallurgy	Pack fibers in matrix or Slip cast matrix about fibers or Use fugitive binder to hold fibers together	Sinter, hot press or hot isostatic press
2. Foil Metallurgy	Use fugitive binder or "glue" to bond fibers to foil or Press foils (flat or grooved) about bond or continuous bond (roll foils about fibers)	Diffusion bond in hot press or hot isostatic press
3. Casting	Cast entire part Cast matrix about fibers-individual unit or continuous tapes	None-when casting entire part. Continuous tapes-hot press or hot isostatic press
4. Electro-deposit	Electroplate or form shapes or tapes, Electrophoresis	Hot press or hot isostatic press
5. Vapor deposit	CVD Ion plate Vaor-ion beam	Hot press or hot isostatic press
6. Metal spray	Plasma spray Motlen metal spray	Hot press or hot isostatic press

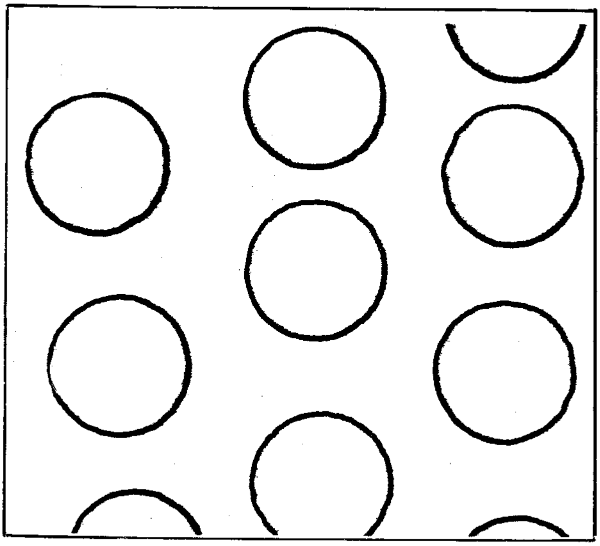

Fig. 1 : Cross-section of composite material pressed at 1150 °C /103 MPa/ 2 hours.

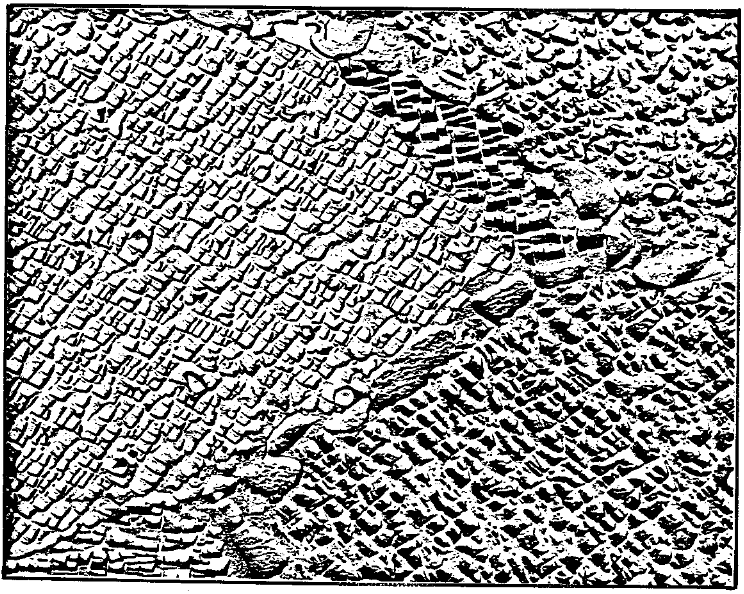

Fig. 2 : Microstructure of the matrix material.

Prior to coating, the tungsten fibers were subjected to straightening, surface polishing and cleaning (Hakim, 1975). During these processes fiber damage may take place. As shown in Figure (3), composite tapes (piles) were fabricated from the coated reinforcing fibers and matrix alloys tapes. These tapes were stacked and inserted into a mild steel container for hot isostatic pressing (HIPing). HIPing involves the simultaneous application of isostatic pressure and temperature to metal powders contained in an evacuated, pressure tight, deformable envelope. The pressure forces the powder particles together and cause diffusion bonding between the matrix and the fibers. HIP consolidated powders normally exhibit greater than 99% of the theoretical alloy density, however, voids and fiber cracking may occur depending on the HIPing condition. Originally, HIPing conditions of 1050 °C/103 MPa/2 hr were used (Kandeil et al., 1984). Consolidation was not complete and sound bonds between the tungsten fibers and the matrix were not achieved, Figure (4). Consequently, the pressing temperature was raised to 1150 °C resulting in full consolidation, as shown in Figure (1). After HIPing the container was removed by machining and the billet ground down to parallel faces. Different cutting techniques were examined to minimize mechanical damage to the fibers and matrix during cutting. Originally spark machining was used, but it was abandoned because of the poor surface finish produced and the slow cutting rates involved. Cutting with a low speed saw produced good surface finish but was very slow. Diamond dressed cutting wheel was used without causing any apparent damage to the composite specimens.

Subscale forging blanks were deformed by isothermal forging between flat dies at constant true strain rates following procedure described previously (Kandeil et al., 1982). Details of the hot compression testing apparatus were described by Immarigeon et al. (1980).

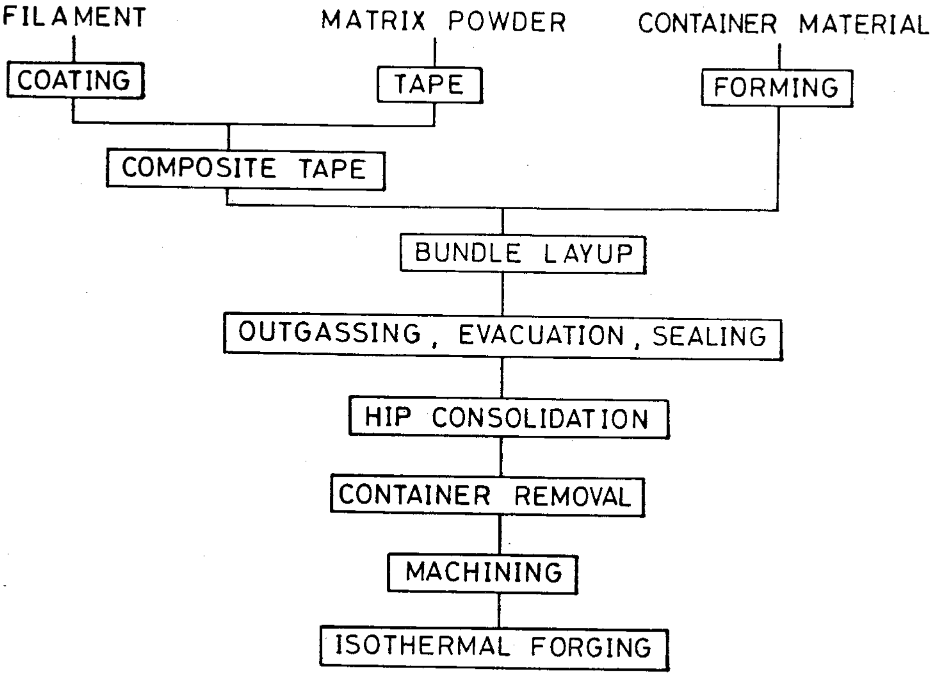

Fig. 3 : Flowchart for the manufacturing of composite specimens.

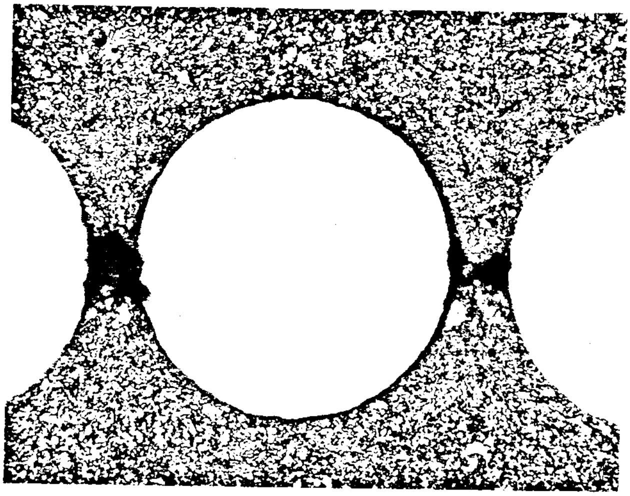

Fig. 4 : Cross-section of composite material pressed at 1050 °C /103 MPa/ 2 hours.

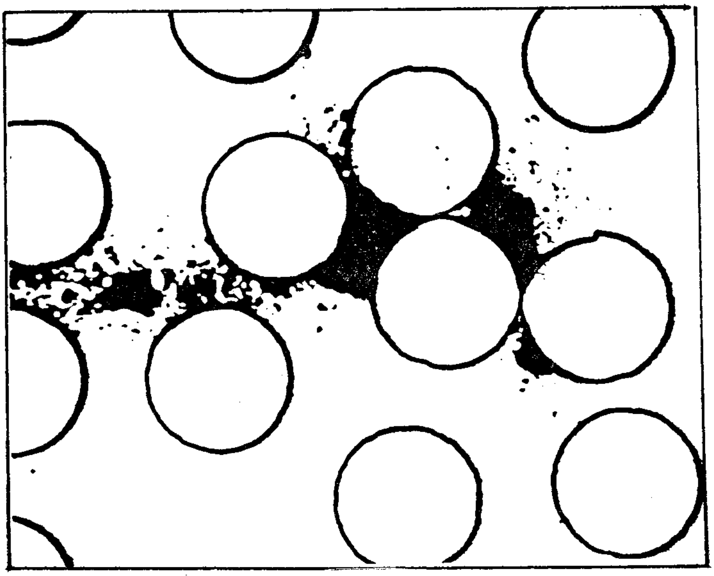

Fig. 5 : Cross-section of composite material showing voids in areas of nonuniform distribution of fibers.

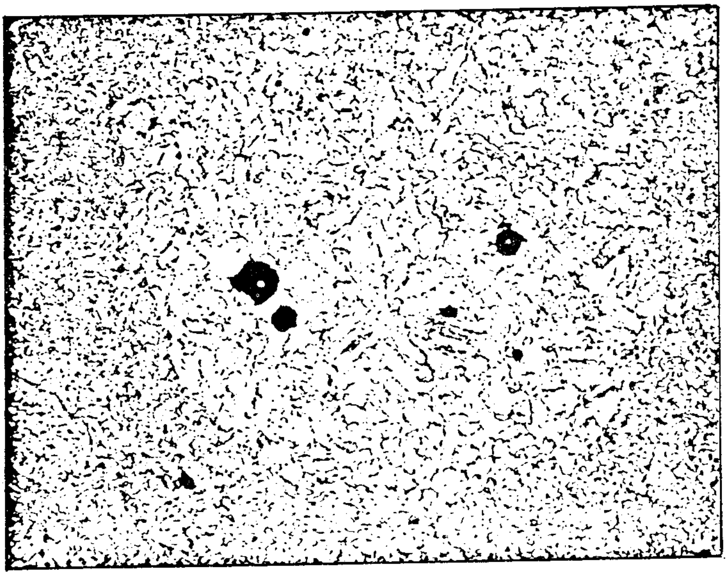

Fig. 6 : Voids in the interior of large powder particles.

4. FRACTURE BEHAVIOUR

Preforging Damage. It has been shown that a variety of defects may be present in the as-HIPed material (Kandeil et al., 1984). These include voids in the matrix and fiber cracking. Voids were observed mainly in areas of nonuniform distribution of fibers and at the interface of adjacent matrix tapes, Figure (5). In few occasions, voids were also observed in the interior of large powder particles where coarse grains existed, Figure (6). Fiber cracking of the type shown in Figure (7) was also observed. A detailed study was conducted on these cracks (Kandeil and Holt, 1978) and it was concluded that the cracks were present in the wires prior to deposition of the diffusion coating i.e. prior to forging and possibly during drawing or straightening of the wires. All these defects are important since they may grow or act as initiation sites for new defects during forging.

Forging Induced Damage. As stated above, a variety of defects were present within the as-HIPed material prior to forging. However, more damage was introduced during the forging process. The nature of the damage occured in the forged composites and the influence of temperature, strain and strain rate were determined by metallographic examination and have been reported elsewhere (Kandeil et al., 1984). This damage includes fiber cracking, extensive cavities at the fiber/matrix interfaces, matrix cracking and occasional random microvoids in the matrix. Typical examples of these defects are shown in Figure (8). Severe damage was observed in composites forged at faster strain rates while less damage was observed in composites forged at slower strain rates. Similarly, less damage was observed in composites forged at the higher temperatures.

5. VOID CONTROL

Powder processing can be employed to provide enhanced formability in otherwise difficult to work materials. Moreover, control of the powder processing operations can lead to further gains in workability with superplastic properties being achieved under certain conditions. It has been established that the forming characteristics of the composites are strongly influenced by the flow properties of the matrix alloy itself and these in turn are influenced by particle mesh size and forging condition (Kandeil et al., 1980), consolidation parameters (Wallace et al., 1976) and thermomechanical processing (Kandeil et al., 1983). Some of these parameters as related to void formation and control are discussed below.

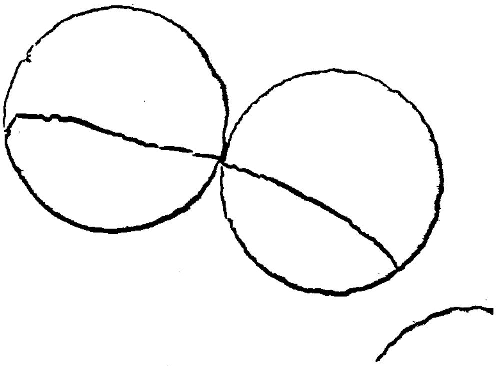

Fig. 7 : Fiber cracking in as-HIPed composite material.

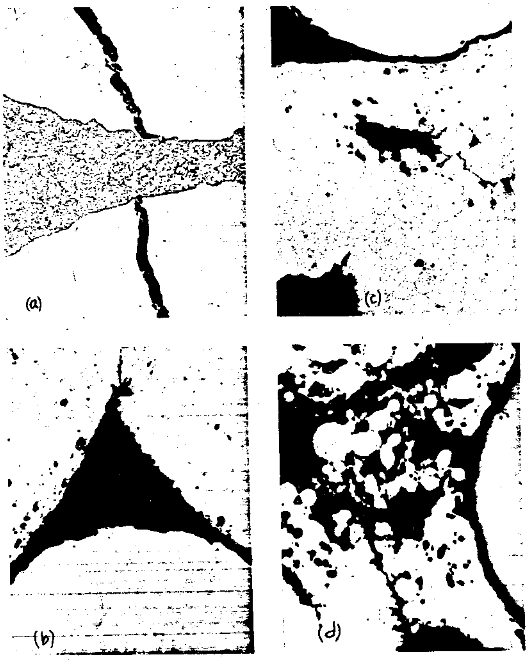

Fig. 8 : Forging induced defects:
(a) Fiber cracking
(b) Matrix cracking
(c) Voids at fiber/matrix interface
(d) Microvoids in the matrix.

Mesh Size Selection. Although there is no detailed evidence of a direct relationship between grain size and particle size in argon atomized powders, observations by Kandeil et al. (1980), indicated that the coarse particles remain underformed because of their higher resistance to flow. Similarly, during forging, most of the deformation takes place in the regions of fine grains and these grains recrystallize to an even finer grain size. In contrast the coarser particles show little evidence of deformation and recrystallization, and hence discontinuities and voids are created at their surface boundaries.

Results on the flow behaviour of different mesh sizes of the matrix material is depicted from previous work (Kandeil et al., 1980) and is shown in Figure (9). These results indicate somewhat lower flow strength for the finer mesh size at all temperatures and strain rates examined. Although the improvement in formability gained with these fine mesh compacts are small but not negligible particularly at the lower strain rates which would be contemplated for the forging of the composite. It is therefore possible that, by selecting an even finer mesh size, resistance to flow could be diminished further and improved ductility of the composites could be obtained. Similarly, powders having finer grain sizes, such as those obtained by Rapid Rate Solidification, or Thermomechanically Processed Powders which recrystallize dynamically during hot-pressing to an ultra-fine grain size might be considered for the composite manufacturing.

Consolidation (HIPing) Parameters. Consolidation parameters should be chosen as a compromise between two conflicting goals. A low HIP temperature will minimize matrix fiber interaction whereas a high HIP temperature will yield improved densification of the composite material. Consolidation temperature of 1150 °C was sufficient to obtain full densification in the present composite system (Mazzei et al., 1986). In any case consolidation temperature should not exceed the ν^1 solvus temperature in order to retain the very fine grained, weak, superplastic structure in the matrix material as indicated by Wallace (1976).

Forging Conditions. As indicated earlier, the ductility of the composite material is governed by that of the matrix and increases at higher temperatures and slower strain rates. Extensive damage and cracking occur at relatively lower temperatures and faster strain rates and increase with the amount of deformation. Various types of forging induced defects are shown in Figure (8). It should be pointed out that most of the void nucleation and growth occurs at the tensile poles of the fibers normal to the loading direction and becomes more intense in areas of maximum shear. This void formation is likely to be a function of the secondary tensile stress components developed at the horizontal poles of the fibers and of the relative strength of the matrix and interface. It was pointed out by Erturk et al. (1974) that this secondary tensile stress is proportional to the applied vertical compressive stress which is strongly dependent on the temperature and rate of deformation. Hence, cracking is more extensive at fast strain rates and/or low temperatures.

It was shown that a critical strain exists in the composites where the load again increases after first falling from its peak value (Kandeil et al., 1982). This critical strain is shown to be the strain at which the fibers come into contact with each other. Beyond the critical strain, the integrity of the fibers could be jeopardized due to the concentration of loads at points of fiber-fiber contact, Figure (10). This critical strain is a function of the volume fraction, stacking arrangement and cross section of fibers. In the present composite material, this critical strain was shown to be 0.34 and forming of the composites should therefore be limited to strains lower than this level (Kandeil and Wallace, 1984).

It was also observed that the flow stresses for the composites are always substantially higher than those observed for the nonreinforced matrix material when the tests are carried out under nominally similar conditions (Kandeil et al., 1982). Several factors are thought to make up for these differences. These include consolidation temperature of matrix and composite, presence of the rigid tungsten fibers in the composite and deformation mode in both materials. These differences have been incorporated in a simple model describing the forging stress of the composite (Kandeil et al., 1984). By comparing values of peak flow stress for a series of compacts and composites forged under identical conditions of temperature and strain rate, it was possible to define regions of temperature and strain rate where early void formation may be avoided, as shown in Figure (11).

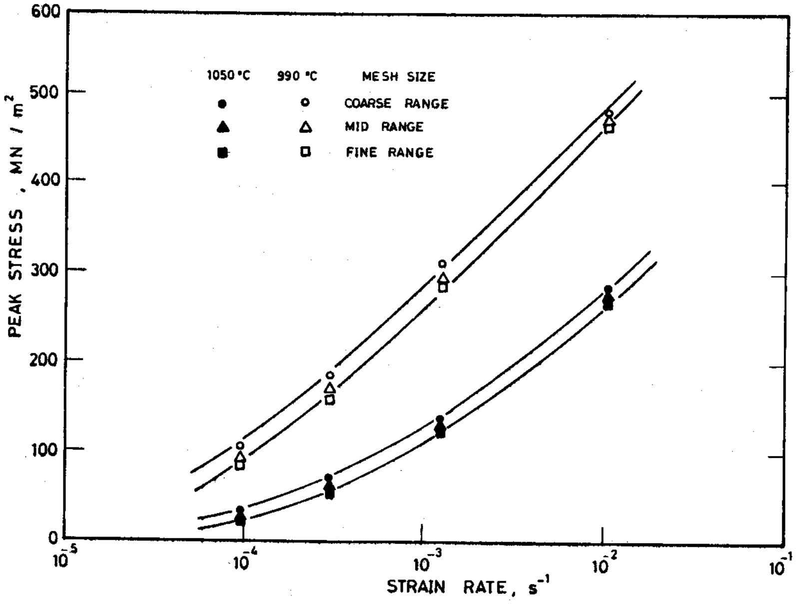

Fig. 9 : Effects of mesh size on peak flow stress of Mar M200 matrix.

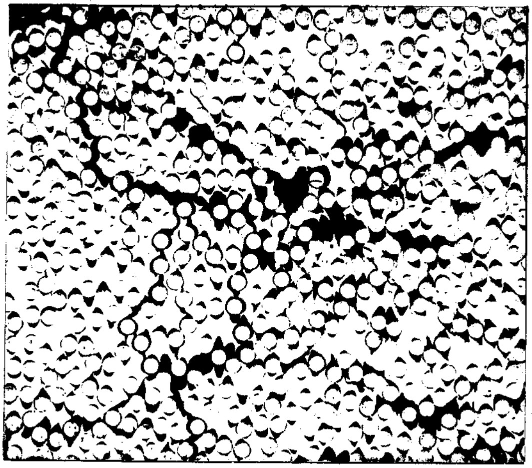

Fig. 10 : Extensive damage in composite forged beyond the critical strain.

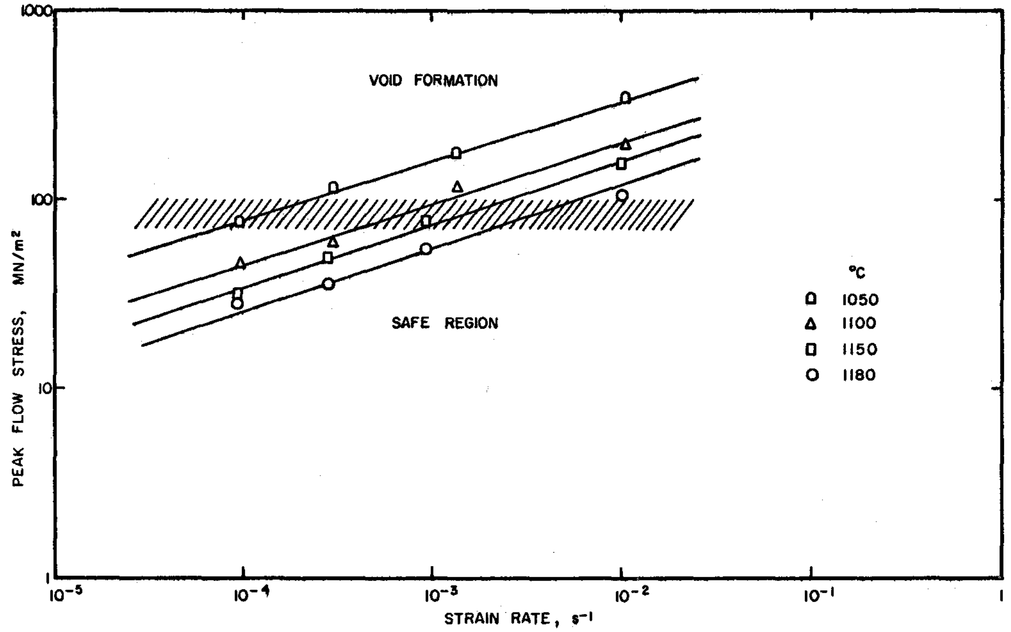

Fig. 11 : Forging limit diagram showing the safe region where early void formation in composite could be avoided.

Geometry of Forged Composites. The nature, extent and distribution of damage in forged composites as a function of the aspect ratio (initial width to height of specimen) was examined by Kandeil (1987). Results of this work indicated that the fracture pattern and void distribution as well as the flow stress of the composit are greatly influenced by the width to height ratio of the specimens. Most damage occured in intense shear bands inclined at about 45° to the loading direction for aspect ratios between 0.67 and 1.5. For lower values of the aspect ratio, extensive damage occured in the central region of the specimen while no damage was observed at the middle region near the die/billet interface. It was concluded from this work that void formation may be reduced by increasing the aspect ratio of the forged composite billet or increasing the friction at the die/billet interface. It was further suggested that void formation could be avoided by the addition of extra matrix material in the critical areas. These extra material will exert back pressure on the composite and help retard void formation.

6. CONCLUSIONS

Formability of fiber reinforced composites is limited to low strains by 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. Means of decreasing the flow resistance of the matrix should retard void formation and improve formability of the composites. These include forging at high temperatures and slow strain rates, selection of fine mesh powders and proper consolidation procedure. Furthermore, void formation could be reduced by the application of back pressure on the composite blanks.

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