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Plastic Deformation Behavior of a Uniaxial Metal Matrix Composite Under Transverse Compression

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Plastic deformation behavior of a stainless-steel/Sn-Bi composite was examined using transverse compression tests on rectangular specimens under plane strain loadings. Based on the anisotropic yield criterion proposed by Hill, a theoretical analysis on the relationship between the yield strength of the matrix material and the yield strength of the composite was developed and compared to experimental results. Experiments were carried out to investigate the effects of the forming parameters such as yield strength of the matrix material, fiber packing patterns, fiber volume fraction, and lubrication of the compression platens, on the plastic deformation behavior of the metal matrix composite. Failure modes of the composite included shear band formation and eye formation at the fiber-matrix interface. Low deformability in the transverse directions was found for the metal matrix composite specimen. The theoretical and experimental results on the effects of the forming parameters provide basic information for further research on the transverse compression of metal matrix composite materials.

Key Words: Metal Matrix Composite, Plastic Deformation, Transverse Loading, Failure Modes, Anisotropic Yield Criterion

1. Introduction

Fiber reinforced materials have demonstrated significant advantages over conventional materials, especially on their high strength-to-weight ratio and stiffness-to-weight ratio. Since 1960's, metal matrix composites(MMC) have been used extensively in aerospace industries. MMC, compared to traditional polymer matrix composites, provide additional advantages, such as good environmental resistance, excellent toughness, and better service temperature capability. Although MMC exhibit a wide range of plastic deformation, current manufacturing process shows some limitations in forming and sizing of MMC(Kennedy, 1989). The determination of successful forming parameters requires an understanding of the process and knowledge of the material's capability to deform.

So far, little attention has been paid to the behavior of unidirectional MMC under transverse compressive loading. This is because such loading is not usually of primary concern in structural applications of MMC. Nevertheless, it can be important under certain circumstances such as secondary formings, i. e., forging, rolling and extrusion, of unidirectional MMC(Collings, 1974). For the analysis of these kinds of plastic forming processes, a yield criterion in the plane perpendicular to the fibers and the effects of the various forming parameters should be obtained.

The transverse normal loading problem was considered by Foye(Foye, 1975). Foye defined the stress concentration factor as the ratio of the maximum microscopic effective stress to the macroscopic effective stress. The effective stress is taken as proportional to the square root of the second deviated stress invariant(Lin, 1968 ; Hill, 1960). Hoffman(Hoffman, 1974) used a contin-

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uum model to represent the mechanical behavior of metal matrix composites in the elastic-plastic range. As a more practical approach to secondary formings of unidirectional MMC, Erturk and Kuhn(Erturk and Kuhn, 1979) examined the large-scale plastic deformation behavior of stainless-steel/aluminum fiber composites. They provided experimental guidelines for development of a process for forging of an airfoil shape from the composites. Off-axis uniaxial testing was used to characterize the nonlinear behavior of a boron/aluminum composite by Kenaga *et al*(Kenaga *et al*, 1987). Hung conducted a finite element analysis to investigate the nonlinear behavior of MMC based on Hill's yield criterion for anisotropic materials(Hung, 1990).

Although these studies have focused on macroscopic deformation in the plastic region for MMC, there have been little efforts to clarify the effects of the microscopic factors on the plastic behavior of MMC. These factors, including the yield strength of matrix material, fiber array types, fiber volume fractions, and the frictional conditions between the loading head and the specimens, can serve as the forming parameters for processing MMC under transverse compression.

This paper presents an experimental investigation on the effects of the forming parameters for Sn-Bi MMC under plane strain condition. Based on the Hill's yield criterion for anisotropic materials, the relationship between the yield strength of composites and yield strength of matrix materials was derived to clarify the role of the matrix yield strength on the plastic deformation of the composite. Experimental stress-strain behavior of the composite specimen verifies the theoretical analysis. The experimental observation has identified shear band formation and eye creation at the fiber-matrix interface as the major failure modes.

2. Theoretical Background

For anisotropic materials, the yield criterion proposed by Hill(Hill, 1960) is given by,

$$2f(\sigma_{ij})=F(\sigma_y-\sigma_z)^2+g(\sigma_z-\sigma_x)^2+H(\sigma_x-\sigma_y)^2+2L\tau_{yz}^2+2M\tau_{zx}^2+2N\tau_{xy}^2=1 \quad (1)$$

where F, G, H, L, M and N are the material's characteristic parameters of the current state of anisotropy and $f(\sigma_{ij})$ is the yield function. This criterion assumes that there is no Bauschinger effect and principal axes are chosen as Cartesian axes, (x, y, z). Fig. 1 shows the schematic view of transverse compression of MMC.

The yield strength under uniaxial loading, Y_u, can be expressed as

$$Y_u=\left(\frac{1}{F+H}\right)^{1/2}. \quad (2)$$

From the associate rule(Hill, 1960), the stress in the z direction assuming plane strain condition($\varepsilon_z=0$) is obtained by

$$\sigma_z=\frac{G\sigma_x+F\sigma_y}{F+G}. \quad (3)$$

Substituting Eq. (3) into Eq. (1) with $\tau_{xz}=\tau_{yz}=0$ gives,

$$2f(\sigma_{ij})=\frac{FG+GH+HF}{F+G}(\sigma_x-\sigma_y)^2+2N\tau_{xy}^2=1. \quad (4)$$

Therefore, the yield strength under plane strain condition, Y_p, is defined by

$$Y_p=\left(\frac{F+G}{FG+GH+HF}\right)^{1/2} \quad (5)$$

where, denoting X, Y and Z as the tensile yield stresses in the principal directions of anisotropy,

$$2F=\frac{1}{Y^2}+\frac{1}{Z^2}-\frac{1}{X^2}, \quad (6)$$

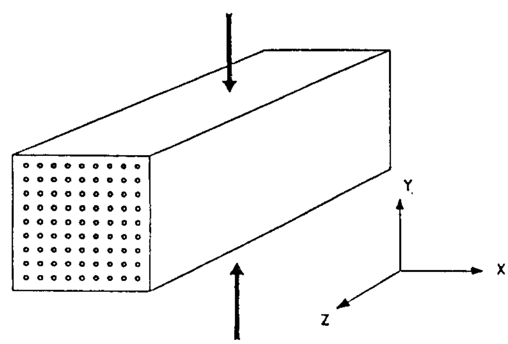


Fig. 1 A schematic view of transverse compression of MMC

$$2G=\frac{1}{X^2}+\frac{1}{Z^2}-\frac{1}{Y^2}, \tag{7}$$

$$2H=\frac{1}{X^2}+\frac{1}{Y^2}-\frac{1}{Z^2}, \tag{8}$$

From material symmetry with respect to the z axis, one has

$$X=Y \text{ and } F=G. \tag{9}$$

Then, Eq. (5) becomes

$$Y_p=\left(\frac{2}{F+2H}\right)^{1/2}. \tag{10}$$

By combining Eq. (10) and Eq. (2), the ratio of two yield strengths becomes

$$\frac{Y_p}{Y_u}=\left[1-\frac{1}{4}\left(\frac{Y}{Z}\right)^2\right]^{1/2}. \tag{11}$$

Eq. (11) indicates that, for metal matrix composites, the yield strength under plane strain conditions is almost the same as yield strength under uniaxial conditions, assuming $Y/Z \ll 1.0$.

Since the matrix material carries most of the load for composites under transverse compression, it is interesting to investigate the relationship between the yield strength of the matrix and of its composites reinforced by fibers. Assuming no stress concentrations created by fibers and a strong fiber-matrix interface, one simply says

$$X=Y=Y_u^m \tag{12}$$

where Y_u^m is the yield strength of the matrix material. Eq. (12) is a upper bound for the yield strength of MMC. The actual yield strength of the composite should be smaller than Y_u^m due to premature failure caused by the stress concentration at the fiber-matrix interface.

The ratio between the plane strain yield strength of composite and the uniaxial yield strength of matrix material can be expressed as

$$\frac{Y_p}{Y_u^m}=\left[1-\frac{1}{4}\left(\frac{Y}{Z}\right)^2\right]^{1/2}. \tag{13}$$

Expanding Eq. (14) by Taylor's formula yields

$$\frac{Y_p}{Y_u^m}=1+\frac{1}{8}\left(\frac{Y}{Z}\right)^2+\frac{3}{128}\left(\frac{Y}{Z}\right)^4+\cdots \tag{14}$$

Therefore, $Y_p \geq Y_u^m$ and Y_p becomes closer to Y_u^m as Y/Z becomes smaller than 1.0, which is generally true for fiber reinforced composite materials.

3. Experiments

A eutectic tin-bismuth(Sn-Bi) alloy(Cerrotru) was used for the matrix materials for the current study. It is a non-work hardening material having a low melting temperature and low coefficient of thermal expansion(Lewis, 1949). 0.9 mm diameter stainless steel wires were used for the reinforcements. Aluminum fibers with a large stiffness compared to the matrix material bond well with the matrix material(ASM, 1983). The mechanical properties of the matrix and the fibers are presented in Tables 1 and 2.

The stainless steel wires were cut and cleaned with acetone to improve interfacial properties. Copper mesh(20 mesh/2.45 cm) was used to hold the fibers inside the mold. A mold release agent was sprayed into the mold for easy removing of the specimen after curing. The matrix material was melted in an electric oven. The mold was also heated to the same temperature to avoid sudden cooling of the matrix. The melted Sn-Bi was poured inside the mold slowly to minimize possible void creation. The whole structure was heated up again for 10～15 minutes. After turning

Table 1 Mechanical properties of matrix material(Sn-Bi alloy)

Material	Tensile strength(MPa)	Yield temp.(℃)	Compressive strength*(MPa)
Sn-Bi Alloy	55	138	58

* given by experiment

Table 2 Mechanical properties of fiber material(stainless-steel)

Material	Tensile strength(MPa)	Yield strength(0.2%)(MPa)
Stainless-steel	550	207

Table 3 Specimen specification

Specimen type	V_f (%)	No. of fibers	Width (mm)	Height (mm)	Length (mm)
0° square	38.5	49	10.2	10.2	25.4
0° square	9.62	16	10.2	10.2	25.4
0° square	4.28	9	10.2	10.2	25.4
45° square	30.0	41	10.2	10.2	25.4
neat matrix	0	0	10.2	10.2	10.2

the oven off, the mold was cooled in the oven. The specimens were removed from the mold and both ends of specimens were removed by a saw tooth cutter to obtain flat surfaces. Due to the specimen dimensions (length/width=2.5) and strong fibers in the z direction, the deformation under transverse loading can be assumed as plane strain deformation.

The transverse compression tests of the MMC specimens were divided into three categories to investigate the effects of the fiber packing types, fiber volume fraction, and frictional conditions during the tests. To investigate the effects of the packing methods on the compressive behavior of the MMC, two different types of fiber arrays were employed : 0° square and 45° square packing of the fibers. The effects of the fiber volume fraction on the compressive behavior were examined by choosing three different fiber volume fractions : 4.28%, 9.62% and 35.8% for the specimens with the 0° square fiber packing. The volume fraction of the 45° square array was 30%. Lubrication was applied between the loading head and the specimen surfaces for the selected test configurations to investigate the effects of the frictional conditions. All other tests were conducted without lubrication. Table 3 presents the specimen specifications.

An Instron testing machine with a chart recorder was used to obtain the compressive data of the various specimens. The chart recorder gave load-displacement curves which were converted to stress-strain curves by volume constancy. The transverse compression tests of the composites were conducted until the height reduction reached about 20%. For every one percent reduction, the end surfaces of the specimens were photographed to see the deformed profile, and checked the crack initiation. The photographs were enlarged and digitized by a Calcomp 9100 digitizer to generate the enlarged graphic profiles. The graphic profiles were overraped by Autocad to investigate the metal flow of the composites during the transverse compression tests.

The material properties of the neat matrix material were obtained by the uniaxial compression test of Sn-Bi block. The compressive yield strength of the matrix was calculated by the 0.2% offset method. Since the matrix material was relatively sensitive to strain rate, the slowest rate of cross-head speed(0.12 mm/min) was used.

Special care was given to the preparation of the parallel surfaces to minimize possible point contacts between dies and specimens. Since there was barreling of the sides of the specimens perpendicular to the loading direction, error resulted from conversion between the load-displacement curves and stress-strain curves. However, one can fine a better way to improve the results by taking the average measurements and plotting the load/length-displacement curves instead of load-displacement curve.

4. Results and Discussion

When the MMC specimens are compressed in plane strain condition, Poisson expansion is restrained by friction at the loading faces of the specimen. The non-uniform state of stress and strain caused by the friction produces a barreled specimen shape. For the sides of specimen perpendicular to the loading direction, wrinkling or roughening(orange peel cracking) occurs prior to compressive cracking(Papirno, 1985).

Shear failure occurs preferentially on the planes containing the fiber direction. This is because the shear stress on this plane will be higher than the shear stress parallel to the fibers. The shear strength is dominated by matrix properties because crack propagation can occur entirely by the shear of matrix without disturbing or fracturing the fibers. Shear cracks generally initiated on the outer surface of the specimen and propagated as the specimens deformed further. It is not certain that a valid crack-initiation stress could be calculated because of the barreling of the specimen. In addition to the shear failure, it was noted that eye formation occurred around fibers as the specimen was compressed.

The deformation process for 0° and 45° square array specimens showed that the localized shear failure started at 5% height reduction for the 0° square array specimen, and 6% height reduction for the 45° square array specimen. This observation represents very low deformability of the MMC specimens. While the 0° array specimen formed only one shear band, two shear bands crossing each other were created for 45° array specimen(Fig. 2). Note that more severe shear deformation occurred for the 0° square array specimen than for the 45° square array specimen.

The matrix-dominated shear failureoccurred at a higher strain as the fiber volume fraction of MMCdecreased. The increased surface area of the fiber-matrix interface, leading to more severe stress concentrations around the fibers for the specimens with higher volume fractions, resulted in earlier shear failure.

Figure 3 shows the uniaxial compression stress-strain curve. The calculated yield strength by 0.2% offset method was 58 MPa which is comparable to the tensile strength of the matrix material(55 MPa) given in the literature(Lewis, 1949). Note that the matrix material shows no work hardening in the strain range tested. In order to compare with the stress-strain curve of the composite, the uniaxial data were converted to plane strain according tothe following relations : $Y_p^m=2/\sqrt{3}\,Y_u^m$ and $\varepsilon_p^m=\sqrt{3}/2\varepsilon_u^m$ where the subscript, it p, stands for planestrain.

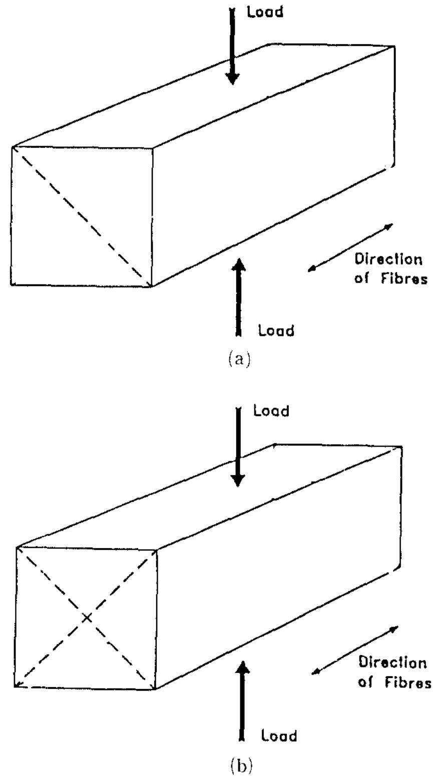


Fig. 2 The shear band(dotted lines) formation for (a) 0° and (b) 45° square array MMC under transverse compression

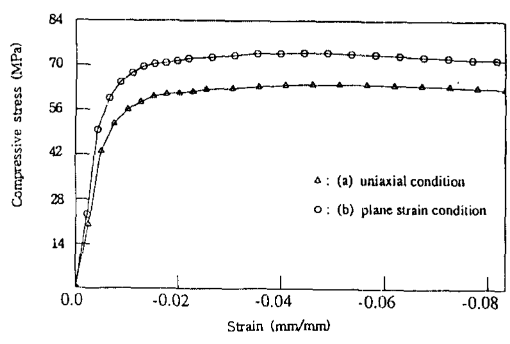


Fig. 3 The stress-strain curves for Sn-Bi alloy under (a) uniaxial condition and (b) plane strain condition

Figure 4 shows the stress-strain curves for the 0° and 45° square array specimens with 38.5% V_f and 30.0% V_f, respectively. The stress for the 0°

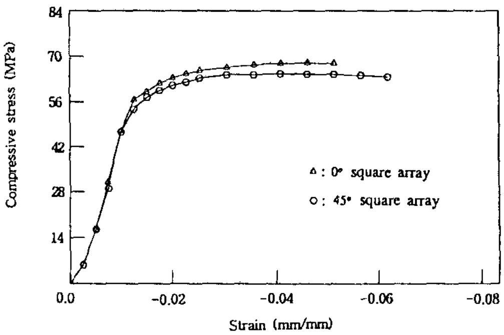


Fig. 4 The stress-strain curves for 0°(V_f=38.5%) and 45°(V_f=30.0%) square array MMC under transverse compression without lubrication

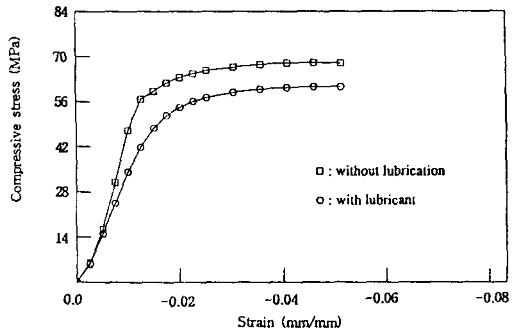


Fig. 5 The stress-strain curves of 0° square array MMC for different frictional conditions(V_f= 38.5%)

specimen is larger than that for the 45° specimen for the same strain. 1% more height reduction is observed for the 45° specimen before the oneset of shear band formation.

The effect of lubricating the surfaces during compression is shown in Figs. 5 and 6. For the same strain, the stresses in the specimens without lubrication are higher than those with lubrication, for both fiber array types. The stress state in the specimens with lubrication approaches uniaxiality. Figures 7～10 show the deformed(5% reduction) and the initial specimen configuration, taken from the photographs of the 0° and 45° specimens. Assuming that the metal flow of the center line maintained straight, the two configurations were superimposed to see how the material flowed. No significant differences in deformation with the lubrication were seen. However, slightly uniform deformation patterns were observed for the 45° square array specimen.

The stress-strain curves for 0° square array

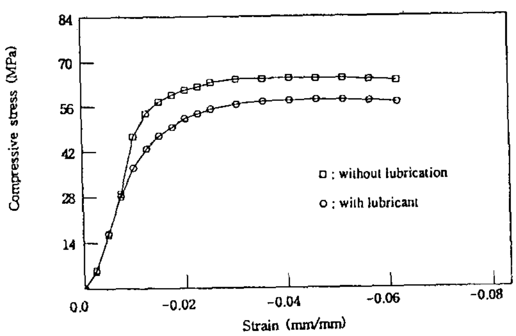
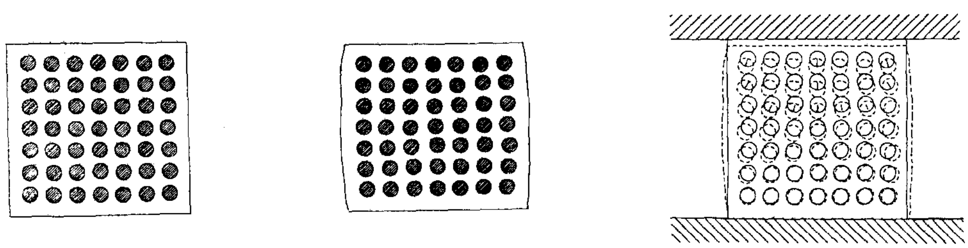


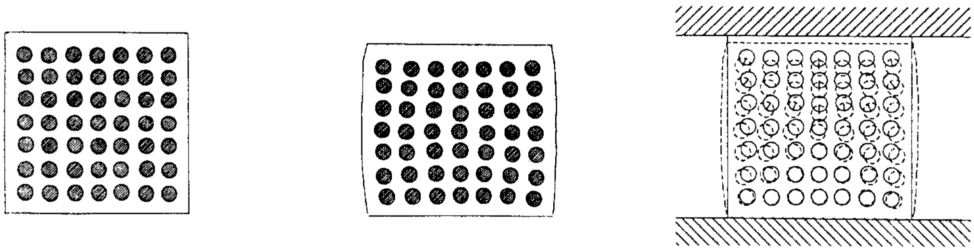
Fig. 6 The stress-strain curves of 45° square array MMC depending on different frictional conditions(V_f=30.0%)

specimens withdifferent fiber volume fraction are shown in Fig. 11. The specimens with low fiber volume fractions compressed further before the shear failure. As the fiber volume fraction increases, the stress flow becomes larger. It is clear that the transverse compressive strength isstrongly dependent on the fiber volume fraction



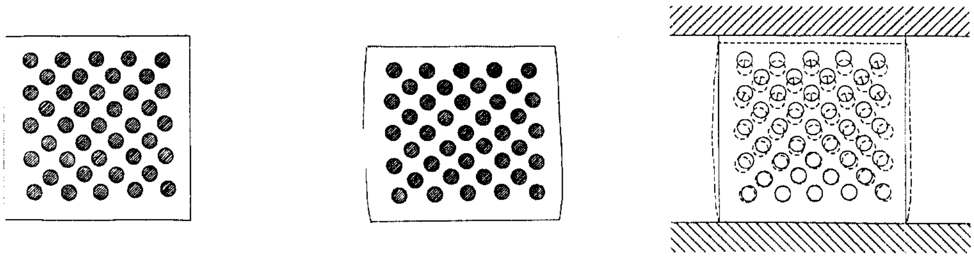
(a) Before deformation (b) After deformation (c) Metal flow in compression test

Fig. 7 The enlarged plot and metal flow diagram from the photograph of 0° square array MMC without lubrication(V_f=38.5%)



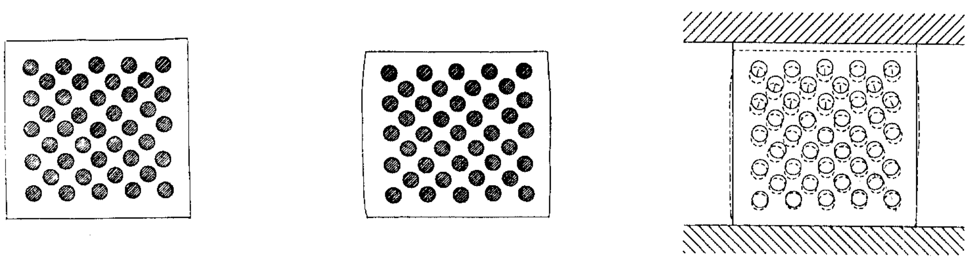
(a) Before deformation (b) After deformation (c) Metal flow in compression test

Fig. 8 The enlarged plot and metal flow diagram from the photograph of 0° square array MMC with lubrication(V_f=38.5%)



(a) Before deformation (b) After deformation (c) Metal flow in compression test

Fig. 9 The enlarged plot and metal flow diagram from the photograph of 45° square array MMC without lubrication(V_f=30.0%)



(a) Before deformation (b) After deformation (c) Metal flow in compression test

Fig. 10 The enlarged plot and metal flow diagram from the photograph of 45° square array MMC with lubrication(V_f=30.0%)

in the MMC. Thus, there existsan optimal fiber volume fraction to transversely process the Sn-Bi composite. While a low fiber volume fraction is desirable to obtain high deformability, the high stiffness requirements of the structural applications of MMC require increased fiber volume fraction.

Comparison with the analysis in Sec. 2 is graphically presented in Fig. 12. While the stress-strain curves of the MMC lie above the curve of matrix material under uniaxial loading, they lie below the curveof the matrix material under plane strain condition as predicted. The ratio between the plane strain yield strength of the composite and that of the matrix material under uniaxial loading is close to 1.0 as predicted by the analysis in Sec. 2, assuming the strong fiber-matrix interface. When the end portion of specimen is in perfect plane strain condition(Y_p/Y_u=1.154) and the middle portion is not(Y_p/Y_u=1.0), the ratio, Y_p/Y_u^m is between 1.0 and 1.154, as seen from Fig. 12. Since there is no perfect bonding in the fiber-matrix interface in reality, the analysis is acceptable.

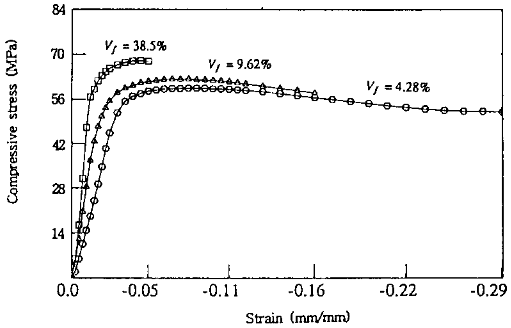


Fig. 11 The stress-strain curves for 0° square array MMC depending on different fiber volume fractions without lubrication

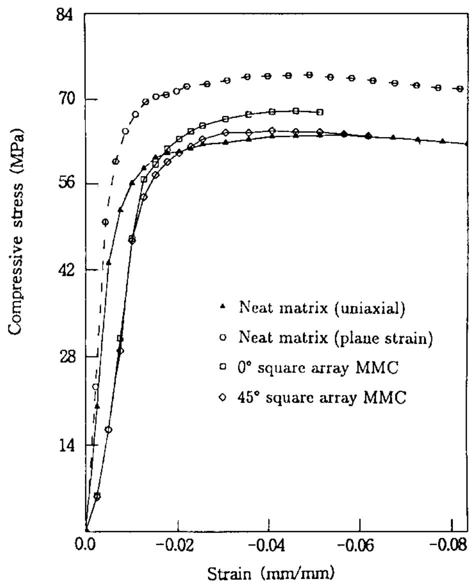


Fig. 12 The comparison of the stress-strain curves of the matrix material and MMC with different array types(V_f = 38.5% for 0° square array, V_f = 30.0% for 45° square array and under no lubrication for both array types)

5. Concluding Remarks

MMC specimens were fabricated with Sn-Bi as the matrix material and stainless steel as the reinforcement. The yield criterion proposed by Hill was utilized to see how the yield strength ofthe matrix material governs the yield behavior of the composite under transverse loading, and the theoretical analysis was verified by experiments. Transverse compression tests were conducted to characterize the effects of the yield strength of the matrix material, the fiber array types, the fiber volume fraction, and the frictional conditions. Since the matrix material was relatively sensitive to strain rate, the slowest rate of cross-head speed(0.12 mm/min) was used. It has been shown that these forming parameters significantly influence the plastic deformation of theSn-Bi composite.

In general, the MMC showed lower deformability and needed higher stresses to deform than the metal matrix only. The 0° square array specimen showed a higher stress flow and less height reduction before shear failure than the 45° square array specimen. Proper lubrication of the specimen provided a more uniaxial loading condition, resulting in less stress being needed to deform for a given strain. The stress to deform for the specimen with low volume fraction was smaller than that with high volume fractions. The deformation with low volume fraction flowed longer before the shear failure. This information on the Sn-Bi composite undertransverse compression can be utilized to serve as basic data for forming of MMC.

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