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Energy absorption capacity of pseudoelastic fiber-reinforced composites

Abstract: Pseudoelastic fiber-reinforced metal matrix composite with enhanced ductility and energy absorption capacity was developed. This composite system relies on the distributed nature of large pseudoelastic strains to mitigate localization of inelastic deformation and failure, and thus mobilizes a major fraction of volume for effective energy absorption. The pseudoelastic fibers were made of Ni-Ti-Cr alloy used in conjunction with two different matrices, aluminum and copper. Tension and pull-out tests were performed to evaluate the ductility and energy absorption capacity of control and pseudoelastic fiber-reinforced composites. Experimental results confirmed the ability of pseudoelastic fibers to induce distributed inelastic deformation within metal matrix composites for realizing major gains in ductility and energy absorption capacity.

Keywords: ductility; energy absorption capacity; metal matrix composite; Ni-Ti-Cr fibers; pseudoelastic fibers.

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1 Introduction

Energy absorption capacity is a governing criterion for selection of materials and structural systems in diverse fields of application, including crashworthy guardrails and vehicles [1–4], ballistic impact-resistant armored vehicles [5], and seismic-resistant structures [6–8].

Metal matrix composites (MMCs) have received growing attention in recent years due to their advantages over polymer matrix composites (PMCs) in terms of thermal stability, fire resistance, transverse stiffness and strength, moisture barrier qualities, electrical and thermal conductivity, and radiation resistance [9–12]. The properties of MMCs depend strongly on the selection of matrix and reinforcement materials [8, 11, 13]. In fiber-reinforced composites, the potential to absorb substantial mechanical energy is largely untapped due to localization of failure in the matrix (e.g., metal matrix), which induces localized rupture of fibers (Figure 1A). Such localized failure phenomena prevent activation of frictional fiber pull-out (Figure 1B) as an effective means of energy dissipation. With metal fibers, localized yielding of fibers further prevent a major fraction of the MMC volume from contributing toward plastic energy absorption [6]. Pseudoelasticity, as an alternative to plasticity, offers the potential for substantially improved energy absorption capacity; as an inherently elastic mode of behavior, pseudoelastic behavior does not experience localization [14]. Pseudoelastic alloys can be strained 10 times more than ordinary metals without being plastically deformed [15–18]. Pseudoelasticity is caused by a stress-induced martensitic transformation (which also renders shape memory effect) [15]. A typical pseudoelastic stress-strain curve (Figure 2A) includes a loading (upper) plateau where stress-induced martensite formation takes place and an unloading (lower) plateau where reverse transformation to the austenite phase occurs. The total pseudoelastic energy storage in the system during loading (the area under the loading stress-strain curve) is, unlike plasticity (Figure 2B), distributed in nature and thus mobilizes a large volume of the material for effective energy absorption (Figure 2C).

MMCs comprising pseudoelastic fibers embedded in a metal matrix are expected to exhibit more energy absorption capacity, with the distributed nature of pseudoelasticity inducing distributed yielding of the matrix and encouraging random rupture of pseudoelastic fibers along their length for effective energy dissipation via frictional pull-out. Past experience with the use of pseudoelastic fibers in composites was largely concerned with improvement of the toughness characterization of PMCs [19].

In this investigation, MMCs reinforced with pseudoelastic fibers were experimentally evaluated. Tension and pull-out tests were performed in order to evaluate the effect of pseudoelastic fibers on the mechanical performance of aluminum matrix composites. The approach relies on distributed plasticity within the matrix to increase total energy absorption of the system by mobilizing a larger
volume of the material for plastic energy absorption and also inducing extensive frictional pullout of fibers.

2 Materials and methods

2.1 Selection of pseudoelastic fibers

The investigation focused on the Ni-Ti family of shape memory alloys, which offer attractive technical attributes. Chromium-doped Ni-Ti alloy with 55.7 wt% Ni and 0.3 wt% chromium was selected. This alloy was cold-worked to 64% and then annealed at a temperature of 510°C for 5 min; the annealing condition was chosen to be compatible with the processing condition of MMCs. Preliminary tests on the fibers showed that the ultimate strength in monotonic loading to failure was 1000 MPa, and the pseudoelastic fibers exhibited a stable behavior under repeated loading to a constant maximum tensile strain of 5%.

2.2 Processing

The processing method involved use of a heated press under vacuum. In this approach (Figure 3), the

Figure 1 Local and distributed yielding of the matrix in composite.

Figure 2 Pseudoelastic constitutive behavior, and the localized nature of plasticity versus the distributed nature of pseudoelasticity.
reinforcement and matrix (in the form of foil) were stacked and consolidated under vacuum through the application of heat and pressure. The combination of elevated temperature and pressure caused the metal matrix to flow, as shown in Figure 3. The temperature can be selected to cause either complete or partial melting of the metal matrix. As the metal flows around fibers, the void area between fibers was filled, and the adjacent foils came in contact. Diffusion bonding then occurred between metal foils during the consolidation process.

The MMCs processed in this investigation were composed of 0.2-mm-diameter Ni-Ti-Cr fibers that were cold-drawn to 64% of their original cross-sectional area. The matrix was 6061 aluminum in the form of 0.3-mm-thick foils. QQ-W-470B steel fibers of 0.22 mm were used as control fibers in the same metal matrix. Both the aluminum foil and the fibers were cleaned in a water-based acidic surface cleaner and neutralized in a water-based neutralizer. Subsequently, the fibers were spaced equally and stacked with aluminum foils. The stacked system was sandwiched between two BN powder-coated steel plates and consolidated using a heated press at 635°C under 10^{-5} mm Hg vacuum, using a consolidation pressure of 75 MPa for 15 min. This temperature and duration of exposure suits annealing of as-drawn pseudoelastic fibers. The vacuum application in the heated press facilitates a quintessential diffusion bonding process to form MMCs. The resulting composites had a total thickness of 0.9 mm with about 30% fiber volume fraction. Immediately after diffusion bonding in the heated press, composite plates were quenched in water at 20°C or 80°C and then heat treated at 170°C for 480 min in order to promote precipitation hardening [20].

### 2.3 Test methods

Pseudoelastic fiber-reinforced composites were subjected to tension tests using notched and unnotched specimens (Figure 4A and B, respectively). These specimens were all 20 mm wide, and their lengths were 100 mm. With the end grips used in tension tests (Figure 4C), the free lengths of specimens subjected to tension were 55 mm. The specimens were tested in tension using a servo-hydraulic test system with closed-loop control. The strain rate during tension tests was kept constant at 10^{-5}/s. The applied stress and strain over the gauge length and over full specimen length were monitored throughout the test period.

In order to better understand the pull-out behavior of pseudoelastic fibers from aluminum matrix, pull-out tests were performed on pseudoelastic Ni-Ti-Cr diffusion-bonded to aluminum and copper matrices in a heated press under vacuum. The pull-out test specimen is schematically shown in Figure 5. Diffusion bonding of the pull-out specimens was accomplished under a pressure of 75 MPa in 10^{-5} mm Hg vacuum over a period of 15 min. The fibers used here were 0.2 mm in diameter, and the aluminum and copper sheets were 0.3 mm in thickness. The diffusion-bonded specimens were immediately quenched in 80°C water and then annealed at 180°C for 480 min to promote precipitation hardening.

### 3 Results

#### 3.1 Tension

Tension tests were performed on notched and unnotched composite specimens. Figure 6A presents the stress-strain behavior of pseudoelastic fiber-reinforced aluminum matrix composites compared with that of some conventional metals as well as steel fiber-reinforced aluminum matrix composites. The tremendous ductility and energy absorption capacity of the composite system is shown in Figure 6A. At 30% fiber volume fraction, pseudoelastic fiber-reinforced aluminum has a density that is only half that of low-carbon steel. A picture depicting typical failure
of a notched specimen with pseudoelastic fiber reinforcement is shown in Figure 6B.

Figure 7 compares the tensile stress-strain behavior of pseudoelastic fiber-reinforced aluminum composites obtained through tension tests on unnotched specimens with those of other metals and composites. The results again confirmed the tremendous energy absorption capacity of pseudoelastic fiber-reinforced aluminum matrix composites.

Figure 8 compares the tensile stress-strain relationships of pseudoelastic fiber-reinforced aluminum matrix composites with 15% and 30% fiber volume fractions. The post-peak tensile resistance and energy absorption capacity are observed to increase proportionally with increasing fiber volume fraction.

### 3.2 Pull-out

Figure 9 shows pull-out load deflection curves produced at 25°C for pseudoelastic Ti-Ni-Cr fibers that were diffusion-bonded to aluminum and copper matrix. The pull-out process continued until the deformation capacity of the test system was exhausted. More than 60% of fibers underwent this extended pull-out process without rupture. Figure 9 also shows the stress levels corresponding to the ultimate strength and stress-induced martensite formation of individual fibers. Fibers undergoing an extended pull-out did so at a stress level corresponding to stress-induced martensite formation. This agrees with the hypothesis according to which pseudoelastic fibers avoid localized rupture and allow for fiber pull-out due
to the propagation of stress-induced martensite formation within fibers; the Poisson’s effect associated with the propagation of pseudoelasticity causes progressive debonding of fibers from matrix. The fact that fibers pulling out of the aluminum matrix retain the stress level corresponding to stress-induced martensite formation also agrees with our hypothesis that the friction along a very short fiber length suffices to induce martensite formation and allows
for fiber pull-out; hence, the pull-out load does not drop linearly with the reduction of embedded length during pull-out. Finally, the fact that fiber pull-out occurs at a relatively constant stress implies that the frictional pull-out process is not causing much damage to fiber surfaces, indicating that the reversible nature of pseudoelasticity helps fiber surfaces repeatedly recover their roughness as they pull through the tortuous path within the matrix.

Figure 10 compares the statistical distribution of stress levels corresponding to stress-induced martensite formation in our tension tests and also the statistical distribution of pull-out stress levels from two matrices: aluminum and copper. Figure 10 indicates that, at each probability level, pull-out stresses from different matrices considered exceed the tensile stress corresponding to stress-induced martensite formation. This suggests that pseudoelastic fibers pull out at high stress levels, which is quite significant for enhanced energy absorption in the pull-out process. Table 1 presents the means, standard deviation, and 95% confidence intervals of the stress levels corresponding to fiber pull-out from different matrices and also to stress-induced martensite formation in fiber tension tests. These results again confirmed the relatively high pull-out stresses developed in fibers during pull-out.

### Table 1

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Tension</th>
<th>Pull-out/Al</th>
<th>Pull-out/Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>421</td>
<td>620</td>
<td>483</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>172</td>
<td>212</td>
<td>132</td>
</tr>
<tr>
<td>95% Confidence interval</td>
<td>326–517</td>
<td>538–703</td>
<td>434–531</td>
</tr>
</tbody>
</table>

**3.3 Discussion**

The above results focused on tension and pull-out tests on fibers. In order to validate the first hypothesis, however, one needs to use the fiber pull-out tests to satisfactorily predict the energy absorption capacity of pseudoelastic fiber-reinforced MMCs. Figure 11 presents a typical stress-deflection relationship for a pseudoelastic fiber-reinforced aluminum specimen. The composite had 30% volume fraction of 0.2-mm-diameter pseudoelastic Ni-Ti-Cr fibers. Deflections were measured over a gauge length of 25 mm. The stress-deflection curve presented in Figure 11 suggests that the energy absorption capacity of the composite per unit area is close to 5000 N-mm/mm². Our hypothesis implies that, for the test specimen shown in Figure 11 with rigid end conditions, once the matrix fractures at the location of notch (in mid-height), fibers would rupture randomly within their length in between the mid-height and their rigidity-held ends. They would thus rupture, on the average, at a distance of 55/4 = 13.75 mm from mid-height, with the last fiber that pulls out rupturing at the rigidity-held end. Pull out of the fiber from the matrix thus occurs at a deflection of 55/2 = 22.5 mm; this corresponds well with the test results presented in Figure 11 where failure finally occurs at a deflection of about 25 mm.

As noted in Table 1, the average fiber stress during pull-out of pseudoelastic fibers from the aluminum matrix is 620 MPa. In the post-peak region, at 30% fiber volume fraction, the average load resistance of the composite would thus be 0.3×620 = 186 MPa, which compares reasonably well with the post-peak stress of about 210 MPa observed in Figure 11.

The pull-out process of each 0.2-mm-diameter fiber with 620 MPa pull-out stress over an average deflection of 13.75 mm absorbs an energy amount of 268 N-mm.
At 30% volume fraction of 0.2-mm-diameter fibers, the number of fibers per unit area of composite would be 9.5/\text{mm}^2. The total pull-out energy absorption per unit area of composite would thus be 9.5 \times 268 = 2546 \text{ N-mm/mm}^2. This pull-out energy absorption adds to the energy absorbed for the rupture of pseudoelastic fibers, which, based on our fiber tension tests, is about 200 N-mm per fiber, noting the distributed nature of pseudoelastic strains and their resistance to localization. The energy consumed for the rupture of fibers per unit area of the composite is thus 9.5 \times 200 = 1900 \text{ N-mm/mm}^2. The total energy absorption per unit area of the composite associated with the rupture and pull-out of pseudoelastic fibers is thus 2546 + 1900 = 4446 \text{ N-mm/mm}^2, which compares favorably well with the measured energy absorption capacity of 5000 \text{ N-mm/mm}^2. This further confirms the validity of the fundamental hypothesis based on which our approach has been developed.

4 Conclusion

Pseudoelastic fiber-reinforced MMCs of high ductility and energy absorption capacity were evaluated. This composite system relies on the large strain capacity of pseudoelastic fibers and the distributed nature of pseudoelasticity (as opposed to the localized nature of plasticity) to achieve high levels of ductility and energy absorption capacity. Pseudoelastic fibers used in this study were composed of Ni-Ti Cr alloy. Tension tests were performed on notched and unnotched pseudoelastic fiber-reinforced aluminum matrix composites. The results indicated that Ni-Ti-Cr pseudoelastic fibers provided substantially higher ductility when compared with conventional fiber-reinforced MMCs. Effects of pseudoelastic alloy composition on tensile stress-strain behavior on pseudoelastic fiber-reinforced aluminum matrix composites were also evaluated. Pull-out tests were conducted with pseudoelastic fiber-reinforced aluminum and copper matrix composites at ambient temperatures. The results confirmed that both pull-out and yielding of the fibers contributed to the energy absorption capacity of MMC significantly. This study confirmed that reinforcing the matrix with pseudoelastic fibers enhances the ductility and energy absorption capacity of MMCs.

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