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# Mechanical Properties of Several Magnesium and Aluminum Composites

Nikos Tsangarakis and  
Barmac Taleghani

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## Introduction

Metal matrix composites (MMC) are used to improve the strength-to-weight ratio of structural members. The selection of a MMC for a specific application depends on its mechanical characteristics which, in turn, should fulfill certain design requirements. During the past few years, a number of lightweight MMCs have been tested and characterized for potential U.S. Army applications. These applications include helicopter transmission, landing skid, track pads, and portable bridge elements. This report aims to consolidate the MMC database available at the U.S. Army Materials Technology Laboratory (MTL) for public reference. Some of the data presented in this report such as the magnesium composites have been released previously [1,2].

Two magnesium alloy composites (AZ91C, ZE41A) and a commercially pure magnesium (CP Mg) composite were examined. These matrices were reinforced with 40% by volume continuous graphite fibers. Mechanical property data were also generated for several aluminum composites. The aluminum composites were 2124-T6, 6061-T4, 2124-T4, and 2219-T4 alloys reinforced discontinuously with silicon carbide or boron carbide. The reinforcements were either whiskers or particulate. Tensile, compressive, and fatigue properties, as well as fracture toughness and impact fracture energy, were examined and correlated with the reinforcement volume content and quality of the metal-to-reinforcement bonding.

The system proposed by the Technical Committee on Product Standards of the Aluminum Association was adopted for the designation of the composites discussed herein. The designation consists of the following three parts, each separated from the others by a slash mark: the matrix alloy designation (per American National Standard), the composition of the reinforcement (e.g., SiC), and the volume percent of the reinforcement followed by the type of the reinforcement. The type of the reinforcement is indicated by a lower case letter (f = continuous fiber, p = particulate, w = whisker, and c = cut fibers).

## Materials, Specimens, and Test Procedures

The magnesium composites contained 40% by volume continuous P-55 graphite (Gr) fibers. The P-55 Gr fiber was manufactured by AMOCO (Union Carbide). Typical fiber properties (provided by Union Carbide) are shown in Table 1. The average fiber diameter was 10  $\mu\text{m}$ . Prior to consolidation with magnesium, the fibers were immersed in a proprietary organometallic solution and then baked to form a silicon oxide coating. This coating was intended to promote bonding of the fibers with the magnesium matrix. The unidirectionally-reinforced magnesium plates were consolidated by Materials Concept, Inc. using proprietary methods. The chemical composition of the matrix materials is given in Table 2 [1].

Table 1. Properties of Thornel P-55 AMOCO carbon fiber

|                     |   |                         |
|---------------------|---|-------------------------|
| Tensile strength    | = | 2,100 MPa               |
| Elastic modulus (E) | = | 380 GPa                 |
| Density             | = | 2 (gr/cm <sup>3</sup> ) |
| Fiber diameter      | = | 10 $\mu\text{m}$        |

Table 2. Composition of matrix magnesium alloys

| Alloy | Al  | Mn   | Zn   | Zr   | Ce   | Fe   | Si   | Mg  |
|-------|-----|------|------|------|------|------|------|-----|
| AZ91C | 8.8 | 0.22 | 0.48 | —    | —    | 0.06 | 0.50 | Bal |
| ZE41A | —   | —    | 4.20 | 0.70 | 1.20 | —    | —    | Bal |
| CP Mg | —   | —    | —    | —    | —    | 0.60 | 0.53 | Bal |

Plates of 2124-T6 aluminum composites were purchased from AVCO (presently TEXTRON). The size of the particulate silicon carbide (SiC) was  $8\text{ }\mu\text{m}$  to  $36\text{ }\mu\text{m}$  (as estimated metallographically). The silicon carbide whiskers were  $12\text{ }\mu\text{m}$  to  $36\text{ }\mu\text{m}$ . Plates of 6061-T4, 2124-T4, and 2219-T4 aluminum composites were purchased from DWA. These composites were reinforced with silicon carbide and boron carbide ( $\text{B}_4\text{C}$ ) particulates. The respective particle diameters were  $8\text{ }\mu\text{m}$  to  $24\text{ }\mu\text{m}$  and  $16\text{ }\mu\text{m}$  to  $88\text{ }\mu\text{m}$ . The volume content of these reinforcements was 15% to 30%.

Tensile tests were conducted with specimens of the types shown in Figures 1 and 2. For the compression tests, cylindrical specimens were used. Fatigue tests were conducted with cylindrical specimens like the one depicted in Figure 2. Charpy bars (see Figure 3) were used for the determination of fracture toughness and impact fracture energy.

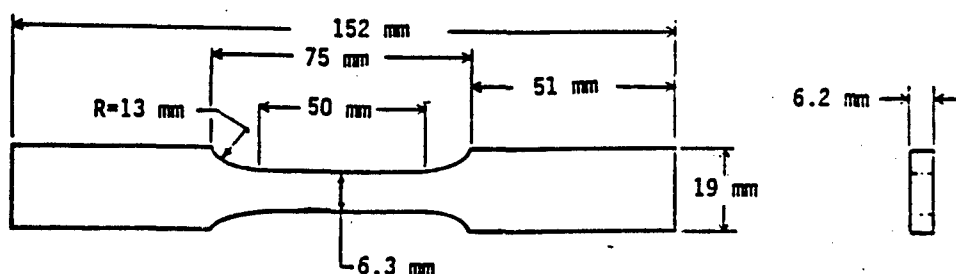


Figure 1. Tension specimen, flat.

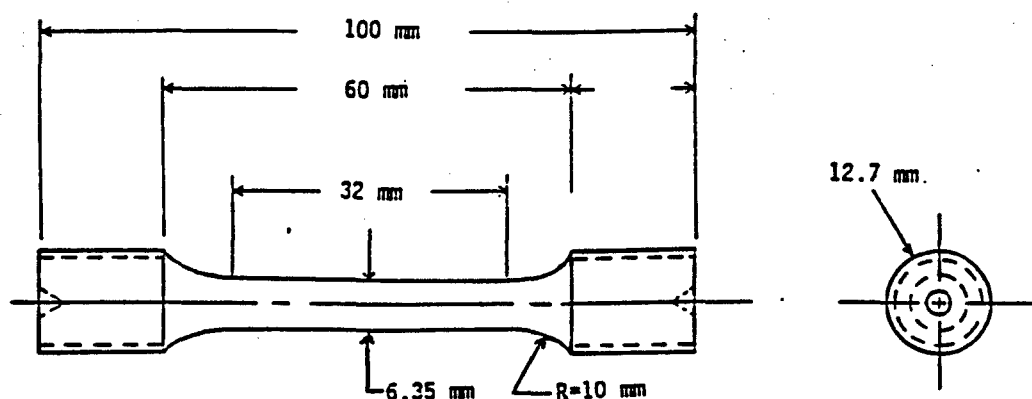


Figure 2. Tension specimen, round, threaded.

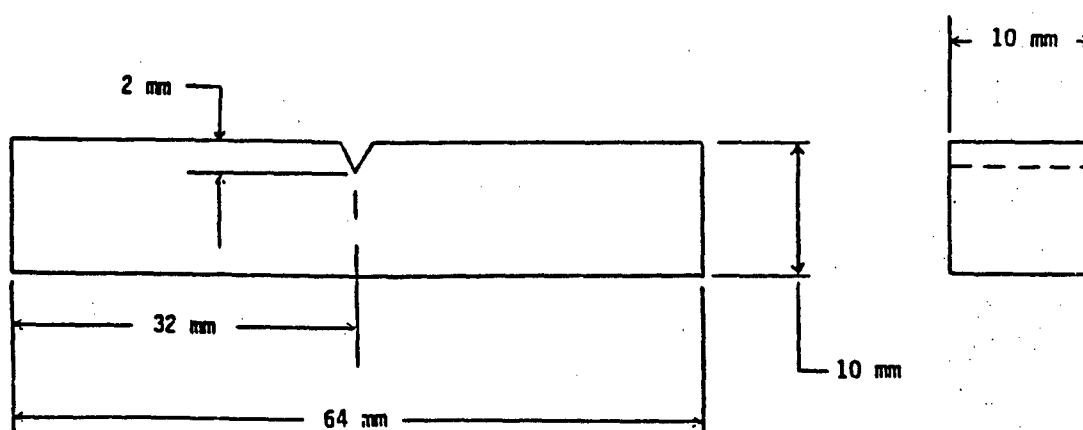


Figure 3. Charpy V-notch specimen.

## Test Results and Discussion

### Magnesium Composites

Tensile tests for the magnesium composites were conducted on flat specimens as that depicted in Figure 1. The tensile properties of the magnesium composites are listed in Table 3. The Gr/Cp Mg/40f composite exhibited the greatest ultimate tensile strength in the parallel to the fibers direction. The ZE41A matrix composite exhibited the highest elastic modulus  $E_{11}$ . The value of the  $E_{22}$  modulus, however, indicated some degradation when compared to that of pure magnesium (45 GPa).

Table 3. Tensile properties of Gr/Mg composites [1] (40% by volume graphite fiber, reinforced unidirectionally)

| Composite | UTS (MPa)<br>perpendicular<br>to the fibers | UTS (MPa)<br>parallel<br>to the fibers | $E_{11}$ (GPa) | $E_{22}$ (GPa) |
|-----------|---------------------------------------------|----------------------------------------|----------------|----------------|
| Gr/AZ91C  | 45 ± 10                                     | 586 ± 55                               | 184 ± 28       | 28 ± 2         |
| Gr/ZE41A  | 19 ± 5                                      | 279 ± 41                               | 204 ± 14       | 25 ± 7         |
| Gr/CP Mg  | 12 ± 7                                      | 658 ± 41                               | 159 ± 21       | 20 ± 2.7       |

For the determination of a conditional fracture toughness  $K_{IQ}$  of the magnesium composites Charpy bars (bend specimens) were used. These specimens are depicted in Figure 3. The selection of this specimen configuration was based on the findings of a previous study by Tsangarakis, et al [3]. Tsangarakis found that Charpy bars of a continuous fiber-reinforced MMC with a notch as a crack starter gave results comparable to Charpy bars with a saw cut as a crack starter. The former values were 5% to 10% higher than the latter. Fatigue cracking prior to testing for the determination of  $K_{IQ}$  was abandoned as it was a cumbersome task under reasonable laboratory conditions. The following crack planes and crack growth direction combinations were examined: LT, LS, TL, and TS (for the details of these designations see ASTM E-399 standard).

At least six Charpy bars were tested per composite, crack plane, and crack growth direction. For a description of the respective test procedure, the reader is referred to the ASTM standard procedures E-399. Fracture toughness values of the magnesium composites obtained from Charpy bars are shown in Table 4. For the LT and LS crack plane orientations the composite AZ91C/Gr/40f produced the highest  $K_{IQ}$  values, 2.50 and 1.60  $\text{MPa}\sqrt{\text{m}}$ , respectively. These values, however, are extremely small. Two specimens of this composite of the LT crack plane orientation produced even smaller values of  $K_{IQ}$ . The fracture toughness value for both specimens was 0.33  $\text{MPa}\sqrt{\text{m}}$ . Because both specimens exhibited numerous fiber pullouts on their fracture surfaces, it will be inferred that the low  $K_{IQ}$  values were the result of an inadequate bonding between matrix and fibers. The inadequate bonding between matrix and fibers produced an easy path for the growing cracks to follow (this easy path being the matrix/fiber interface) thus leading to low fracture toughness values. The same composite also produced low  $K_{IQ}$  values for crack plane orientations which were parallel to the graphite fibers. These values were 0.09  $\text{MPa}\sqrt{\text{m}}$  and 0.15  $\text{MPa}\sqrt{\text{m}}$  for the TL and TS crack plane orientations, respectively. The fracture toughness on planes parallel to the fibers was at least four times less than on planes perpendicular to the fibers. Although the methods used to produce these conditional fracture toughness values have not been approved by any organization; e.g., ASTM, their magnitudes are extremely small indicating property degradation and not improvement.

Table 4. Charpy fracture toughness  $K_{IQ}$  ( $\text{MPa}\sqrt{\text{m}}$ )<sup>2</sup> magnesium composites

| Crack plane orientation | Gr/AZ91C    | Gr/ZE41A    | Gr/CP Mg    |
|-------------------------|-------------|-------------|-------------|
| LT                      | 2.50 ± 0.15 | 1.32 ± 0.13 | 1.54 ± 0.18 |
| LS                      | 1.60 ± 0.69 | 1.21 ± 0.08 | 1.40 ± 0.19 |
| TL                      | 0.09 ± 0.08 | 0.24 ± 0.05 | 0.20 ± 0.08 |
| TS                      | 0.15 ± 0.09 | 0.31 ± 0.09 | 0.20 ± 0.04 |

Standard size Charpy V-notch bars of magnesium composites were tested in impact (ASTM E 23-86 test procedure) to assess their impact fracture energy, which is a measure of their toughness. The Charpy impact fracture energies are listed in Table 5. From these energy values it may be inferred that the CP Mg/Gr/40f is the superior composite. It should be noted that in all the magnesium composites the fracture energy along planes parallel to the fibers were at least one order of magnitude less than the fracture energy on planes perpendicular to the fibers.

Table 5. Charpy fracture energy (Joules) magnesium composites

| Orientation | Gr/AZ91C      | Gr/ZE41A      | Gr/CP Mg      |
|-------------|---------------|---------------|---------------|
| LT          | 1.65 ± 0.42   | 0.96 ± 0.25   | 3.86 ± 0.82   |
| LS          | 2.60 ± 0.86   | 1.39 ± 0.28   | 3.24 ± 0.36   |
| TL          | 0.008 ± 0.013 | 0.030 ± 0.013 | 0.194 ± 0.147 |
| TS          | 0.026 ± 0.019 | 0.031 ± 0.009 | 0.116 ± 0.022 |

## Aluminum Composites

All the tensile tests on the aluminum composites and matrices were conducted with cylindrical specimens with threaded ends. These tensile specimens are depicted in Figure 2. Results of the tensile tests on the aluminum matrix and its composites are given in Table 6. The addition of 30 v/o SiC whiskers and 15 v/o SiC particulate to the 2124-T6 aluminum caused little or no improvement of the 0.2% yield stress and ultimate tensile stress (UTS). However, the addition of 30 v/o SiC particulate caused a 22% improvement of the matrix yield and ultimate tensile stresses. Ali reinforcements caused noticeable improvement of the matrix elastic modulus. The 30 v/o SiC particulate addition produced a 71% increase of the modulus value. One should notice, however, the drop in the value of the strain to failure. The latter is a measure of the composite's machinability and formability. The 2124-T4/B<sub>4</sub>C/25p composite exhibited an excellent strength improvement over the 2124-T6/SiC/30p. Because the UTS improvement in 2124-T4/B<sub>4</sub>C/25p was 39%, it is recommended that this composite should be examined more closely.

Table 6. Tensile properties (aluminum and composites)

| Material                     | 0.2% YS (MPa) | UTS (MPa) | E (GPa)   | Strain |
|------------------------------|---------------|-----------|-----------|--------|
| 2124-T6/SiC/15p              | 199 ± 2.0     | 259 ± 2.4 | 84 ± 6.2  | 0.053  |
| 2124-T6/SiC/30p              | 254 ± 5.0     | 367 ± 3.6 | 120 ± 9.0 | 0.040  |
| 2124-T6/SiC/30w              | 212 ± 3.3     | 323 ± 4.6 | 81 ± 6.6  | 0.095  |
| 2124-T6/SiC/30w              | 179 ± 1.6     | 283 ± 1.7 | 91 ± 9.0  | 0.098  |
| 2124-T6 aluminum             | 208 ± 3.0     | 305 ± 4.5 | 70 ± 4.1  | 0.145  |
| 6061-T4/SiC/15p              | 341 ± 8.0     | 434 ± 10  | 94 ± 1.0  | 0.050  |
| 6061-T4/B <sub>4</sub> C/20p | 369 ± 2.0     | 416 ± 2.0 | 104 ± 4.0 | 0.034  |
| 2124-T4/B <sub>4</sub> C/25p | 381 ± 5.0     | 511 ± 13  | 119 ± 3.0 | 0.022  |
| 2219-T4/B <sub>4</sub> C/15p | 315 ± 25      | 421 ± 27  | 98 ± 3.0  | 0.021  |

NOTE: 0.2% YS = Yield stress  
UTS = Ultimate tensile stress  
E = Young's modulus  
Strain = Strain at failure

The compressive properties of several discontinuously reinforced aluminum composites and the aluminum matrix are listed in Table 7. Compression tests were conducted with solid cylinders 30 mm high and 20 mm in diameter. The ASTM E-9 test procedure was followed and TEFLON™ sheets were used between the specimens and the tungsten carbide loading plates to minimize friction. The crosshead displacement was monitored with a linear variable differential transducer (LVDT) and a longitudinally oriented strain gage (positioned in the middle of the height of the specimen) was used to monitor the strain. The specimens of each material were separated arbitrarily into two groups, each group containing at least three specimens. Calculation of the elastic modulus using the strain gages' output produced better values compared to LVDT. The maximum compressive stress (MCS) corresponds to the "reduction of height" presented in the last column of the table. This stress was calculated with the prior to testing cross-sectional area. The "reduction of height" listed in the last

column was estimated with a LVDT. No significant improvement of the MCS over that of the pure matrix was achieved by the reinforcements; on the contrary, the "reduction of height" to failure was significantly reduced. Failure of the cylinders was coincident with the drop in the load and the generation of lateral cracks in the specimens (see Figures 4 and 5). The modulus of elasticity was also reduced in the reinforced material by 9% to 41%. The degradation of the mechanical property values could be due to inadequate bonding of the reinforcements with the matrix. In this case, the presumably reinforced matrix areas acted like cavities which were deformed by, but did not contribute the appropriate resistance to the applied load.

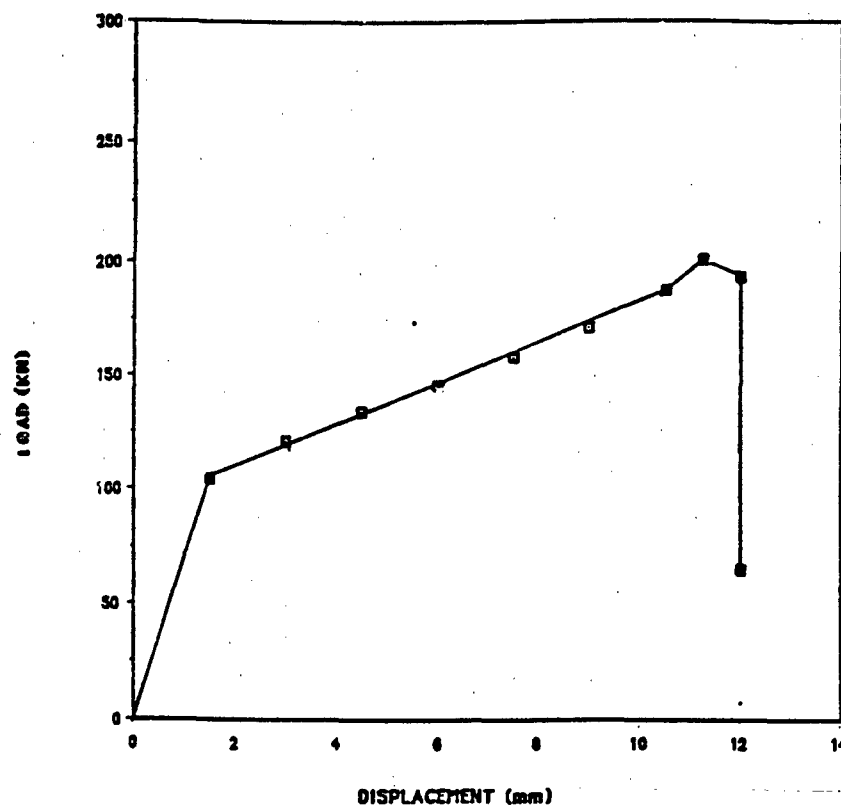


Figure 4. Load versus displacement curve for the 2124-T6/SiC-15w.



Figure 5. Compression cracks.

Table 7. Compressive properties of 2124-T6 reinforced aluminum

| Material        | 0.2% Yield stress (MPa) | Maximum stress (MPa) | Modulus E (GPa) | Reduction of height (mm) |
|-----------------|-------------------------|----------------------|-----------------|--------------------------|
| 2124-T6/SiC/15p | 205 ± 17                | 564 ± 24             | 56 ± 5.5        | -9.09                    |
|                 | 203 ± 21                | 565 ± 21             | 56 ± 2.8        | -9.09                    |
| 2124-T6/SiC/15w | 203 ± 3                 | 615 ± 10             | 43 ± 14         | -11.15                   |
|                 | 203 ± 1                 | 616 ± 11             | 44 ± 8          | -10.29                   |
| 2124-T6/SiC/30w | 265 ± 6                 | 655 ± 8              | 63 ± 13         | -8.13                    |
|                 | 265 ± 0                 | 649 ± 2              | 59 ± 8          | -7.92                    |
| 2124-T6         | 214 ± 3                 | 662 ± 1              | 75 ± 0          | -16.94                   |
| 2124-T6         | 216 ± 3                 | 660 ± 1              | 66 ± 3          | -16.51                   |

NOTE: The reduction of height listed in the last column corresponds to the onset of a visible specimen crack and a drop of the applied load.

All stresses were calculated with prior testing cross-sectional areas.

Fatigue test results for the aluminum 2124-T6 matrix and its composites are listed in Table 8. The fatigue test specimens were cylindrical with threaded ends, similar to those used for the tensile tests (see Figure 2). Fatigue tests were conducted with a frequency of 40 Hz and a stress ratio  $R = 0.1$  in a 45 KN Instron servohydraulic test machine. The matrix endurance limit for  $10^7$  cycles was 179 MPa. With 15% SiC<sub>w</sub> reinforcement the endurance limit was upgraded to just below 214 MPa. With 30% SiC<sub>w</sub> reinforcement the endurance limit remained at 214 MPa. Thus, a 15% reinforcement achieved full strengthening of the composite. The improvement was nearly 20% of the matrix endurance limit.

Table 8. Fatigue properties of aluminum and composites

| Material        | Maximum stress (MPa) | Cycles to failure |
|-----------------|----------------------|-------------------|
| 2124-T6/SiC/15p | 186                  | 11,430            |
|                 | 214                  | 10,170            |
|                 | 234                  | 3,000             |
| 2124-T6/SiC/15w | 214                  | 10,000,000        |
|                 | 214                  | 5,716,000         |
|                 | 234                  | 210,000           |
|                 | 255                  | 81,000            |
|                 | 269                  | 92,000            |
| 2124-T6/SiC/30w | 214                  | 10,000,000        |
|                 | 255                  | 272,000           |
|                 | 255                  | 6,214,000         |
|                 | 262                  | 86,679            |
|                 | 262                  | 206,000           |
|                 | 276                  | 113,310           |
|                 | 276                  | 262,000           |
|                 | 290                  | 83,300            |
| 2124-T6         | 303                  | 28,000            |
|                 | 179                  | 10,000,000        |
|                 | 200                  | 496,000           |
|                 | 207                  | 877,100           |
|                 | 221                  | 125,573           |
|                 | 227                  | 85,570            |

NOTE: Specimen diameter: 5.00 mm  
Specimen gage length: 25.00 mm  
Fatigue frequency: 40 Hz  
Stress ratio (min/max) = R: 0.1

For the determination of a conditional fracture toughness of aluminum composites reinforced discontinuously with SiC whiskers or particulates, the bend specimen was used. The length, width, thickness, and notch depth of these specimens were 86 mm, 19 mm, 9.6 mm, and 8 mm, respectively. These specimens were fatigue-cracked and tested per ASTM E-399 standard test procedure. Fracture toughness values for the discontinuously reinforced aluminum composites are given in Table 9. The majority of these test results did not satisfy the ASTM E-399 test criteria to produce  $K_{IQ}$  values qualifying for  $K_{IC}$ . Instead, the fracture toughness values shown represent conditional values only. As it can be inferred from the data in Table 8, the reinforcements did not improve the fracture toughness of the matrix alloy. The conditional fracture toughness values shown in the table are in agreement with those found by K. Salama, et al [4].

Table 9. Fracture toughness of aluminum composites

| Composite        | $K_{I0}$ (MPa $\sqrt{m}$ ) | Number of specimens |
|------------------|----------------------------|---------------------|
| 2124-T6/SiC/30w  | 16.65 $\pm$ 1.4            | 12                  |
| 2124-T6/SiC/15w  | 16.30 $\pm$ 0.5            | 5                   |
| 2124-T6/SiC/15p  | 16.72 $\pm$ 1.4            | 5                   |
| 2124-T6 aluminum | 16.42 $\pm$ 1.2            | 3                   |

### Summary

The Gr/CP Mg/40f composite exhibited the greatest ultimate tensile strength in the parallel to the fibers direction. In the discontinuous reinforced composites of aluminum, significant improvements were noted in the yield and ultimate tensile strengths and the tensile modulus by the 30 v/o SiC particulate. The 2124-T4/B<sub>4</sub>C/25p composite exhibited the highest ultimate tensile strength which was 511 MPa. Some improvement (20%) of the endurance limit was caused by the addition of 15% SiC whiskers.

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