Improvement of Thermal and Mechanical Properties of Graphite/Copper Composites Through Interfacial Modification

S.M. DeVincent and G.M. Michal

Unidirectionally reinforced graphite/copper composites have been fabricated using a pressure infiltration casting procedure. T300 and T650 graphite fibers have been used to reinforce copper and copper-chromium alloys. The effects of the chromium level in the copper matrix on the tensile strength, stiffness, and thermal expansion behavior of the composites have been evaluated through tensile and three-point bend testing, and thermal cycling. At the 0.5 wt% alloying level, chromium increases the stiffness and optimizes the thermal expansion behavior of graphite/copper composites. The longitudinal tensile strengths of these composites are above 1606 MPa, whereas the transverse tensile strengths are lower than 40 MPa due to incomplete infiltration during processing. Scanning electron microscopy analyses reveal that the unalloyed copper matrix composites experienced extensive fiber/matrix debonding under tensile loading. The addition of chromium to the copper increases the level of matrix bonding to the graphite fibers, as evidenced by observations of fractured tensile specimens. Auger electron spectroscopy analyses indicate that a chromium carbide phase present at the interface is responsible for the improved bonding.

Keywords
composites, copper, graphite fibers, metal matrix

1. Introduction

HIGH heat flux structures such as combustion heat exchangers are currently under design consideration for the National Aerospace Plane (NASP). The actively cooled heat exchangers have an expected service life of 100 h. Life of these structures generally is limited by thermally induced low-cycle fatigue. High conductivity composites are effective in these applications due to their reducing thermal gradients, which in turn minimizes the thermal strains in the components.

Graphite fiber-reinforced copper matrix (Gr/Cu) composites are candidate materials for such systems, which demand a material with low thermal expansion, high thermal conductivity, low density, high stiffness, and high strength. These composites offer the potential to achieve each of these goals. Elemental Cu has one of the highest thermal conductivities of any material, but density and mechanical properties are lacking. The addition of a high volume fraction of graphite fibers to Cu increases the stiffness and strength while lowering the overall density of the composite material. Materials competitive with Gr/Cu composites include Mo-24Re and NARloy-Z.*

2. Background

The fabrication and performance of composite materials designed for elevated temperature applications are strongly influenced by the fiber/matrix interface. A key aspect of fiber/matrix interfaces is the fiber/matrix interfacial energy. However, often the ideal fiber/matrix combinations, based on their mechanical and physical properties, have high interfacial energies.[1] High interfacial energies relative to the surface energies of the graphite fibers result in a lack of wetting between the fibers and their Cu metal matrix. This intrinsic lack of wetting causes difficulties in production of Gr/Cu composites. More importantly, the lack of wetting can lead to fiber/matrix debonding and pore formation during the service life of the composites at elevated temperatures.[2]

To overcome the fact that pure Cu does not wet graphite, alloyed matrices of Cu, containing approximately 1 at.% Cr or more, have been developed that suitably wet and adhere to graphite during conventional sessile drop tests.[3] The interface formed between the Cu-Cr bulk and the graphite surface has been found to contain a chromium carbide reaction layer that forms at elevated temperatures. Layers as thick as 10 μm have been observed to form in 3600 s (1 h) at 1130 °C for a Cu-0.1 at.% Cr alloy in contact with a graphite substrate. Considerations of the thermodynamics and kinetics of mass transport suggest that the same alloy matrix, with a 50 vol% continuous graphite fiber reinforcement, will produce a composite that has a chromium carbide reaction layer on the order of tens of nanometers about each fiber.

The thermomechanical behavior of fiber-reinforced composites depends on the fiber/matrix interaction. The load transfer from the matrix to the fiber occurs through a complex interfacial shear mechanism.[4] When fiber/matrix debonding occurs, transfer of load to the fiber reinforcement is reduced, or in extreme cases, eliminated. Under these circumstances, the composites tend to exhibit behavior resembling that of the matrix. A strong fiber/matrix bond, however, is not the simple solution to this problem. Residual strain present from fabrication, caused by thermal expansion mismatch, has been shown to lead to cracking in composite materials. In fiber/matrix bonded systems, this cracking can occur in the reinforcement if $\alpha_{fiber} <$

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* NARloy-Z® is a registered trademark of North American Rocketdyne, Canoga Park, CA.

α_{matrix} or along the interface if $\alpha_{fiber} > \alpha_{matrix}$ (where α is thermal expansion.[5] Plastic flow in the metal, and elastic mismatch between the fiber and the matrix due to the creation of a reaction layer phase at the fiber/matrix interface, also can induce fracture.[6]

The presence of a stable, continuous interfacial reaction layer is necessary for improved properties in Gr/Cu composites. Creation of a continuous reaction layer at the fiber/metal interface can ensure load transfer and increased mechanical properties. Conversely, a source of inadequate performance of the composites is loss of strength due to reaction layers.[7] If the chemical reaction is extensive, a significant percentage of the fiber reinforcement can be consumed in the formation of the reaction layer phase.

The extent of the reaction between the fibers and matrix in a composite is one of the main factors that determine the level of operating properties attained in the material during its production. On the one hand, the extent of reaction reached during the fabrication of the composite should be sufficient to ensure the required bond strength at the fiber/matrix interface. However, the reaction must not lead to a substantial loss of fiber strength.

From knowledge of the kinetics of the strength loss encountered by the reinforcing fibers in a composite as a result of their reaction with the matrix it is possible to determine the temperature range of stability of its mechanical characteristics.[6] A study directed at understanding the effects of the presence of a reaction layer phase on the thermal and mechanical properties of continuously reinforced Gr/Cu composites has been undertaken. Composite plates have been pressure infiltration cast using combinations of T300 or T650 graphite fibers and matrices of pure Cu and Cu alloys containing 0.1, 0.5, and 0.9 at.% Cr. Testing focused on evaluating the performance of the Gr/Cu composites as a function of Cr addition to the Cu matrix and includes the evaluation of room-temperature tensile and three-point bend (3PB) properties, and thermal cycling behavior. The composites were evaluated in the as-cast condition.

3. Experimental Procedures

3.1 *Materials and Processing*

A fairly new technique for fabricating Gr/Cu composites involving pressure infiltration casting (PIC) Cu or a Cu alloy into a mold containing graphite fibers has been used. The PIC process is conducted within a single vessel containing the mold and the preform, the mold furnace, the melt furnace, and solidification controls. Details regarding this processing method have been reported elsewhere.[9] The main advantages of this technique include cost effectiveness, the ability to produce near-net and net-shape parts, and the opportunity to introduce an engineered interface. This is produced by the reaction of Cr from the Cu alloy matrix with the graphite fibers to form chromium carbide at the interface.

Eight Gr/Cu composites were cast at PCast Equipment Corporation (Pittsburgh, PA) under contract to NASA Lewis Research Center. Plates approximately 7.5 × 15.2 × 0.15 cm (3 × 6 × 0.060 in.) in size were produced. Matrices of oxygen-free high-conductivity (OFHC) Cu and OFHC Cu with 0.1, 0.5, and 0.9 wt% Cr additions were used. The reinforcement consisted of high-strength T300 or T650 graphite fibers. These polyacrilonitrile (PAN) precursor fibers were purchased from Amoco Performance Products (Atlanta, GA). The unidirectional graphite fiber reinforcement was nominally 50 vol% for each plate and was in the longitudinal direction (parallel to the 15.2 cm length). The densities of the Gr/Cu composites were calculated to be 5.4 g/cm^3. The individual properties of as-cast OFHC Cu and the graphite fibers are given in Table 1.

3.2 *Optical Microscopy*

Optical micrographs were obtained for each composite plate. Investigation of a transverse cross section allowed for the evaluation of the homogeneity of the composite and the quality of the casting. Using optical metallography, fiber distribution can be monitored. The presence of fiber clusters, incomplete infiltration, and Cu channeling (areas containing no fiber reinforcement) have been investigated.

3.3 *Tensile Testing*

Room-temperature tensile testing was conducted on longitudinal and transverse test specimens 7.62 × 1.27 × 0.15 cm (3 × 0.5 × 0.060 in.) in size. The specimens were wire electro-discharge machined (EDM) from the T300 and T650 graphite fiber-reinforced plates. Two specimens from each plate were tested. Tapered steel tabs were affixed to the ends of the specimens using epoxy, resulting in a total sample length of 10.2 cm (4 in.). The specimens were tested in an Instron® load frame* equipped with MTS® hydraulic grips.** An extensometer having a 1.27 cm (0.5 in.) gage length was used for accurate measurement of the elongation. Load and elongation were recorded by a computer and subsequently converted to stress-strain curves.

3.4 *Three-Point Bend Testing*

Test specimens 7.62 × 1.27 × 0.15 cm (3 × 0.5 × 0.060 in.) in size were wire EDMed from the various composite plates. The tests were conducted in a similar manner to that of ASTM

* Instron® is a registered trade name of Instron Corp., Canton, MA.
** MTS® is a registered trade name of MTS Systems Corp., Minneapolis, MN.

Table 1 Selected properties of OFHC copper and graphite fibers

Material	Density, g/cm^3 (lb/in.^{3})	UTS, GPa (ksi)	*E*, GPa (Msi)	Elongation, %
OFHC Cu	8.94 (0.323)	0.17 (25)	117 (17)	40
T300 Gr	1.76 (0.064)	3.65 (530)	230 (33)	1.40
T650 Gr	1.77 (0.064)	5.05 (732)	290 (42)	1.70

D 2344.[10] Test specimens were mounted in an Instron® machine and loaded at a cross head speed of 0.01 cm/min. A maximum load of 9.09 kg (20 lb) was used to ensure loading in the elastic range only. The specimens were then unloaded. A linear variable differential transducer (LVDT) was used to measure the midspan deflections. The LVDT was mounted inside the support stand and aligned so that the transducer core rod touched the center of the lower surface of the specimen. During the test, the midpoint displacement and applied load were continuously monitored on a chart recorder and collected by a computer. Each specimen was tested using a 4.5-cm and a 7.0-cm span length. Four replicate tests were run for each plate composition and span length.

The deflection of straight beams, elastically stressed and having a constant cross section throughout their length, is given by the formula:

$$\delta = \frac{k_b WL}{EI} + \frac{k_s WL}{GA} \quad [1]$$

where δ is the deflection; W is the total beam load acting perpendicular to the neutral axis; L is the beam span; k_b and k_s are constants depending on beam loading and the location of the point whose deflection is to be calculated; I is the beam moment of inertia; A is a modified beam area; E is the beam elastic modulus; and G is the beam shear modulus.[11] The first term on the right side of Eq 1 gives the bending deflection and the second term the shear deflection. For a simply supported rectangular beam with loading and deflection concentrated at the midspan, incorporating values for k_b, k_s, I, and A into the above equation yields the following:

$$\delta = \frac{1}{4}\frac{WL^3}{Ebh^3} + \frac{3}{10}\frac{WL}{Gbh} \quad [2]$$

where b is the specimen thickness (0.15 cm); h is the specimen width (1.27 cm); and E and G are the elastic and shear moduli in the longitudinal direction of the composite, respectively.

Once the data were collected, load versus displacement curves were generated for each of the tests. Slopes (load/displacement or W/δ) of the linear elastic portions of the curves were obtained. For each specimen, 1/slope (δ/W) values were inserted into Eq 2 for both the 4.5- and 7.0-cm span lengths (L). By doing this, a set of two simultaneous equations containing two unknowns (E and G) was generated for each plate composition. The systems of equations were then solved for E and G.

3.5 *Scanning Electron Microscopy*

Scanning electron microscopy (SEM) analyses were conducted on failed tensile specimens to qualify interfacial adherence and fracture modes. The presence of a reaction layer phase on the fracture surfaces was investigated.

3.6 *Auger Electron Spectroscopy*

Auger electron spectroscopy (AES) was used to investigate the graphite fiber surface in the as-cast condition. T650 graphite fibers were removed from a T650Gr/Cu-0.9wt% Cr plate using dilute nitric acid. Once the Cu alloy had completely dissolved, the fibers were cleaned and dried for AES evaluation. Various scans were obtained to determine the phase of the reaction product present on the fiber surface.

3.7 *Thermal Expansion Testing*

Longitudinal test specimens from each of the eight plates underwent thermal cycling. Specimens were cycled from 27 to 827 °C in an argon atmosphere, using an Orton® Model 1600D dilatometer.* One cycle consisted of heating from 27 to 827 °C and cooling back down to 27 °C at a rate of 3 °C/min. Each specimen was tested to six cycles. Transverse test specimens from each of the four T650 graphite fiber-reinforced plates were subjected to one thermal cycle, as indicated above. For each cycle, change in length was monitored at a data collection rate of one data point/°C change in temperature. Percent linear change versus temperature curves were generated from these data.

4. Results

4.1 *Optical Microscopy*

Each of the composite plates used in this study was investigated for fabrication quality. In general, the transverse sections revealed a fairly uniform distribution of graphite fibers throughout the cross section, with some difficulty in separating the 3K and 6K fiber tows. A few areas of Cu channeling were apparent in these plates. Some areas of fiber clustering and incomplete infiltration were also observed. A Cu layer of approximately 0.03 cm (0.01 in.) thickness was present on the front face of the composite plates, believed to arise from fiber layup or during solidification. These processing inconsisten-

* Orton® is a registered trade name of Orton Ceramic Foundation, Westerville, OH.

Table 2 Transverse tensile properties of T300Gr/Cu composites

Plate composition	Test No.	UTS, MPa (ksi)	0.2% YS, MPa (ksi)	Strain to failure, %
T300Gr/Cu	1	39.7 (5.75)	18.5 (2.68)	7.35
	2	26.1 (3.79)	14.9 (2.15)	5.44
T300Gr/Cu-0.1wt%Cr	1	20.3 (2.94)	19.2 (2.78)	1.85
	2	14.4 (2.08)	12.5 (1.81)	1.70
T300Gr/Cu-0.9wt%Cr	1	7.4 (1.07)	...	0.10

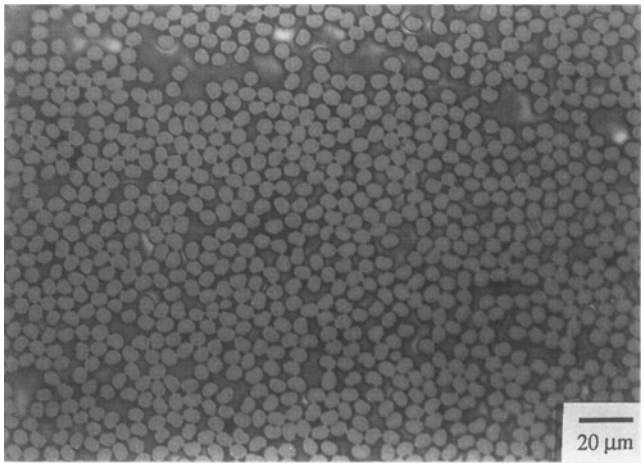

Fig. 1 Cross-sectional optical micrograph of the T300Gr/Cu plate.

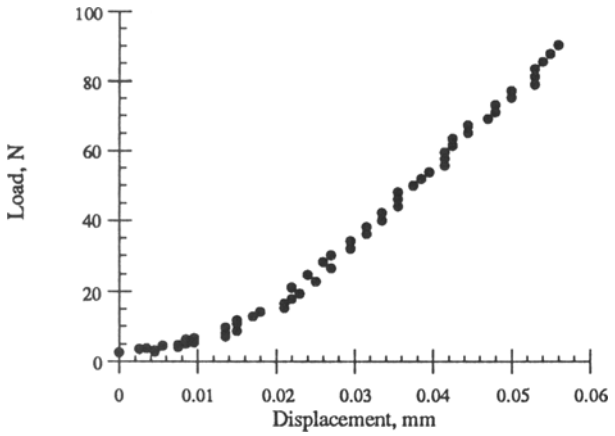

Fig. 2 Load versus displacement in three-point bending for T650Gr/Cu-0.1wt%Cr, span length 7 cm.

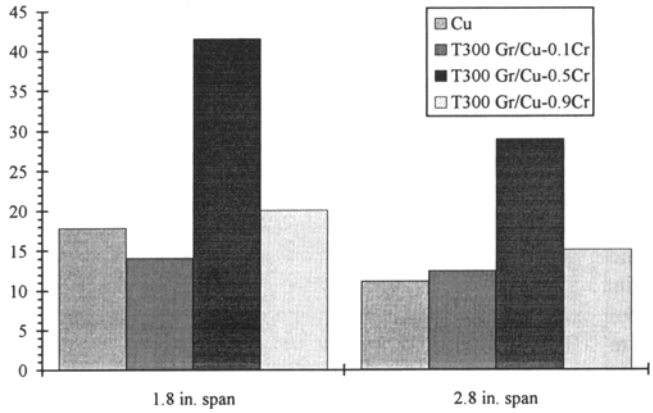

Fig. 3 Relative stiffness of T300 graphite composites with varying Cr additions.

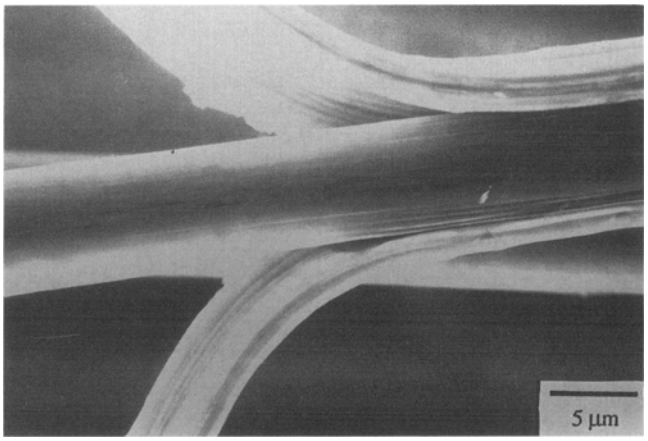

Fig. 4 SEM micrograph of T300Gr/Cu transverse tensile fracture surface indicating significant debonding at the fiber/matrix interface.

cies greatly affect the properties of these composites. Figure 1 is a representative optical micrograph taken from the cross section of the T300Gr/Cu plate.

4.2 *Tensile Properties*

The transverse tensile properties of the T300Gr composites are given in Table 2. Note that the T300Gr/Cu test specimens did not fracture within the 1.27 (0.5 in.) gage length of the extensometer so crosshead movement was used to determine final strain to failure. Considerable cracking and delamination between the fibers and the matrix, perpendicular to the loading axis, were observed prior to complete fracture. Final failure occurred near the specimen tabs in the Cu outer layer mentioned above. The fracture of the remaining specimens occurred within the gage length of the extensometer and without any excessive cracking or delamination.

Absolute values for the longitudinal tensile specimens could not be determined due to slipping that occurred between the Gr/Cu specimen and the steel tabs. At a value of 1.6 GPa (233 ksi) for the T300Gr/Cu specimen, the shear strength of the epoxy used to bond the tabs to the sample was exceeded. Rule of mixtures predicts a value of 1.9 GPa (281 ksi) for the ultimate tensile strength (UTS) of this composite. It is anticipated that the alloyed matrix composite plates will exhibit higher ultimate strengths due to improved bonding.

4.3 *Shear Properties*

A typical three-point bend loading curve is shown in Fig. 2 for T650Gr/Cu-0.1wt%Cr tested at a span length of 7.0 cm. The linear elastic portions of the loading curves were used to obtain displacement/load ratios for use in Eq 2. Solving the systems of equations resulted in values for the shear moduli of the composites in the range of 1.4 to 2.1 GPa (0.2 to 0.3 Msi). The value of G was so low that the bending deflection term was negligible compared to the shear deflection term in Eq 2. Because of this, values for the elastic moduli could not be determined.

To gain some understanding of the relative stiffnesses to the various plates as a function of alloying addition, the slopes of the load-displacement curves were compared. Figure 3 com-

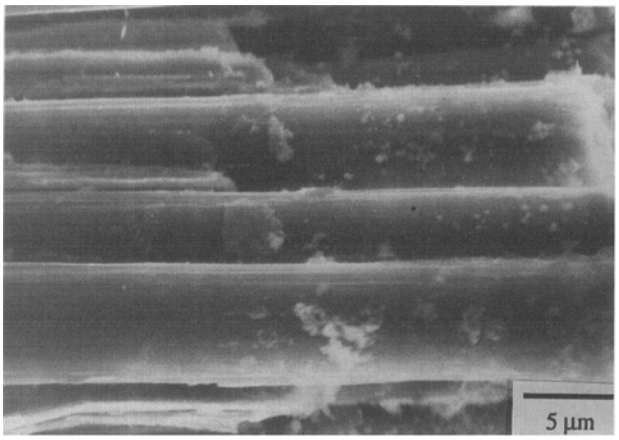

Fig. 5 SEM micrograph of T300Gr/Cu-0.1wt%Cr transverse tensile fracture surface indicating adherence of particles on the graphite fibers.

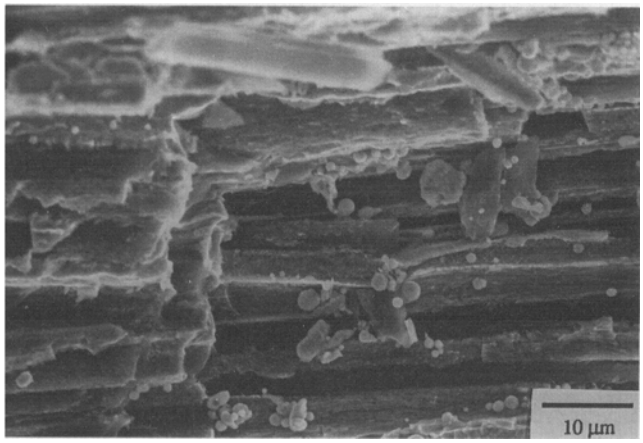

Fig. 6 SEM micrograph of T300Gr/Cu-0.9wt%Cr transverse tensile fracture surface indicating significant adherence of particles on the graphite fibers.

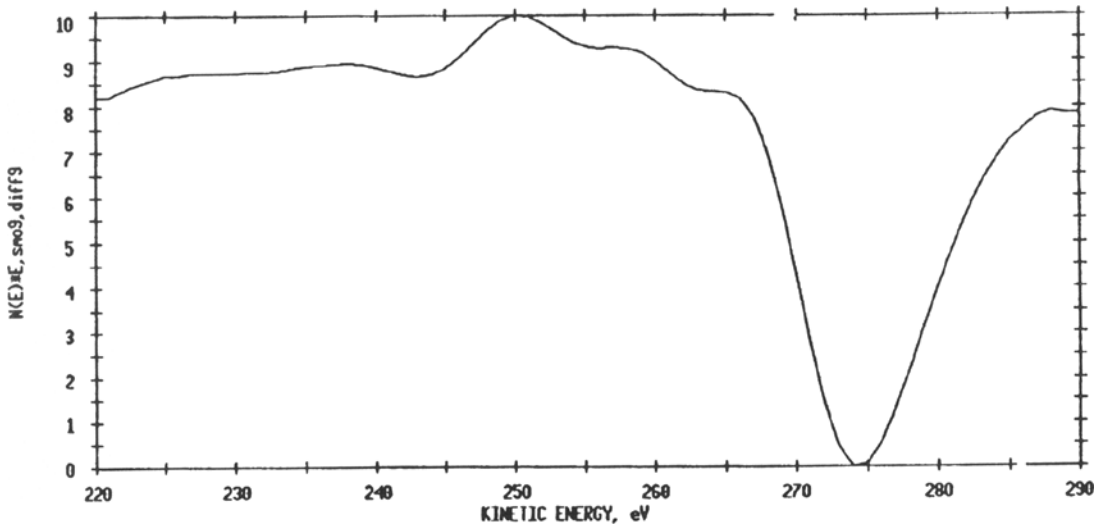

Fig. 7 AES multiplex scan for carbon taken from the reaction product on graphite fiber surface, after a 2.5-min sputter.

pares the results from this exercise. It was determined that the 0.5 wt% addition of Cr resulted in the greatest increase in the stiffness of the Gr/Cu composite compared to the pure Cu matrix plate.

4.4 *Scanning Electron Microscopy*

The SEM investigation of the fracture surfaces of the transverse tensile specimens showed significant fiber/matrix debonding at the Gr/Cu interface. An example of this debonding is depicted in Fig. 4 for the T300Gr/Cu composite. Some minor damage to the fiber surface was observed.

The fracture surfaces of the composite specimens fabricated with alloyed matrices revealed numerous particles adherent to the graphite fibers, as shown in Fig. 5 and 6. Energy dispersive spectroscopy (EDS) indicated the particles to be composed of Cr and C, suggesting a chromium carbide phase formed by the reaction of the Cr alloying addition with the graphite fibers. In general, these specimens contained minor fiber surface damage.

4.5 *Auger Electron Spectroscopy*

Auger electron spectroscopy was used to identify the reaction layer phase that formed at the Gr/Cu-Cr alloy interface. A multiplex scan was obtained from the particles adherent to the graphite fiber surface to verify the presence of Cr and C. Data were gathered from the 220 to 290 eV range for C, as indicated in Fig. 7. The shape of the C peak is indicative of that of a carbitic phase. In a similar manner, data for Cr were taken in the 470 to 540 eV range. The Cr peak shown in Fig. 8 is quite distinct and free of oxygen contamination. The composition of the reaction phase is believed to be Cr_3C_2 based on prior thermodynamic and kinetic calculations.[12]

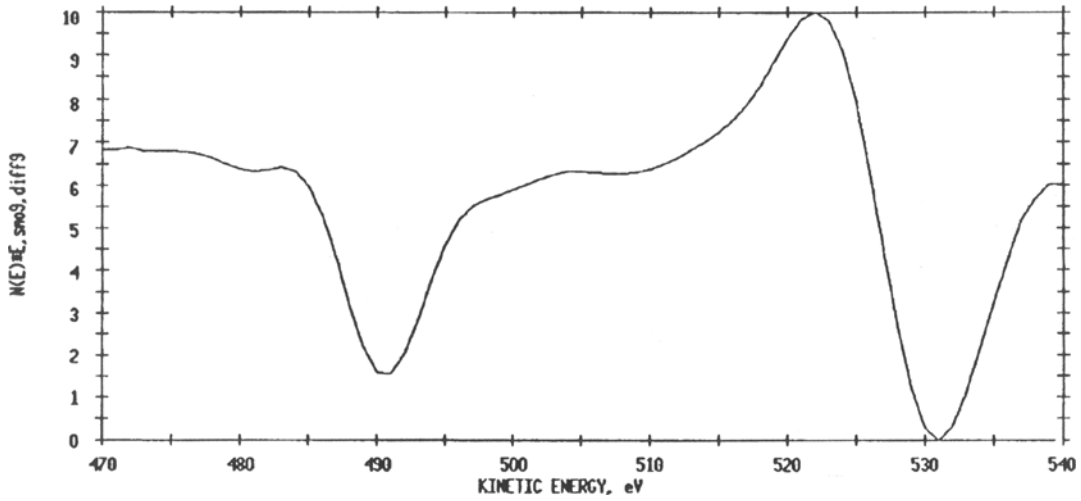

Fig. 8 AES multiplex scan for chromium taken from the reaction product present on graphite fiber surface, after a 2.5-min sputter.

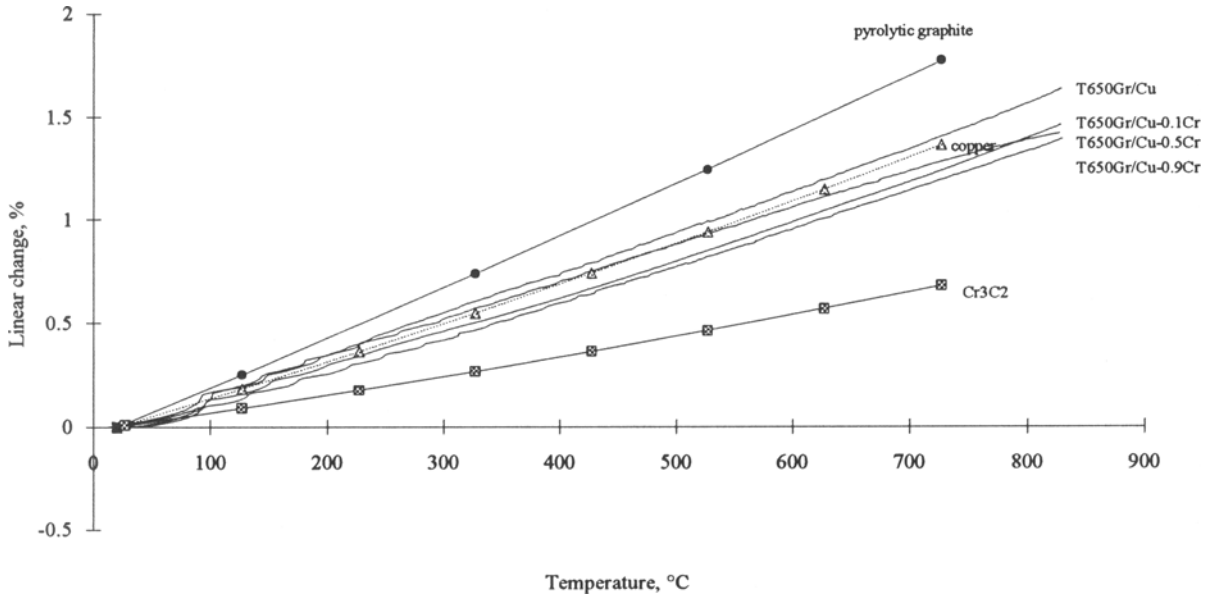

Fig. 9 Transverse thermal expansion behavior of T650 graphite composites compared to those of Cu, pyrolytic graphite, and Cr_3C_2.

4.6 *Thermal Expansion*

The transverse thermal expansion behavior of the T650Gr/Cu composites was assessed by subjecting composite specimens representing each of the four matrix alloys to one thermal cycle of 27 °C to 827 °C to 27 °C. Figure 9 contains the heating portion of the cycle for each composite. The thermal expansion behavior of Cu and pyrolytic graphite in the transverse direction are included for comparative purposes.[13] The thermal expansion responses of the four composites are linear and vary only slightly with alloying addition. In general, the behavior resembles that of unconstrained Cu. The increase in alloying addition appears to decrease the thermal expansion of the composites slightly. This is due to the presence of Cr_3C_2 at the Gr/Cu interface. As shown in Fig. 9, the thermal expansion of Cr_3C_2 is less than that of the composites and of Cu.[14] The enhanced bonding at the Gr/Cu interface due to the presence of the Cr_3C_2 prevents some of the free expansion of the composite specimens. More specifically, the radial expansion of the graphite fibers is restricted by the presence of the carbide at the interface. The presence of a chemical bond at the Gr/Cu interface restricts the longitudinal contraction of the Gr and therefore, in turn, restricts its transverse expansion. Although the Cu still expands in the transverse direction, without the contribution of the graphite, the overall expansion of the specimen is lower.

The thermal cycling behavior of a longitudinal T650Gr/Cu composite specimen is compared to that of pure Cu and experimental data obtained for a T650 graphite fiber in Fig. 10. As indicated, there is a large difference in the longitudinal thermal

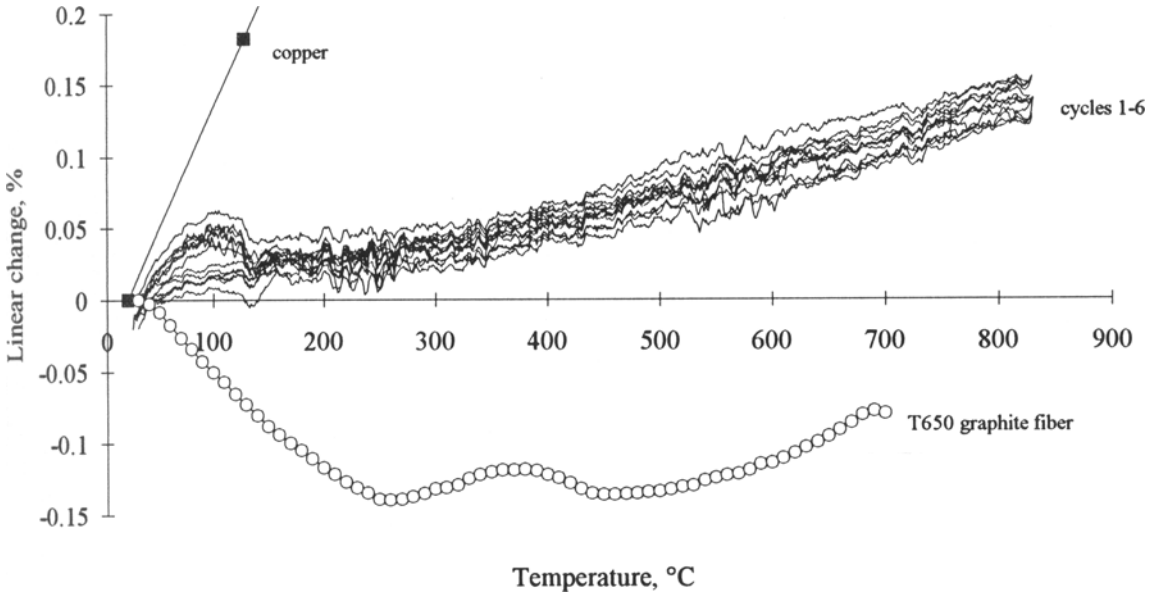

Fig. 10 Longitudinal thermal expansion behavior of T650Gr/Cu composite compared to those of Cu and T650 graphite fiber.

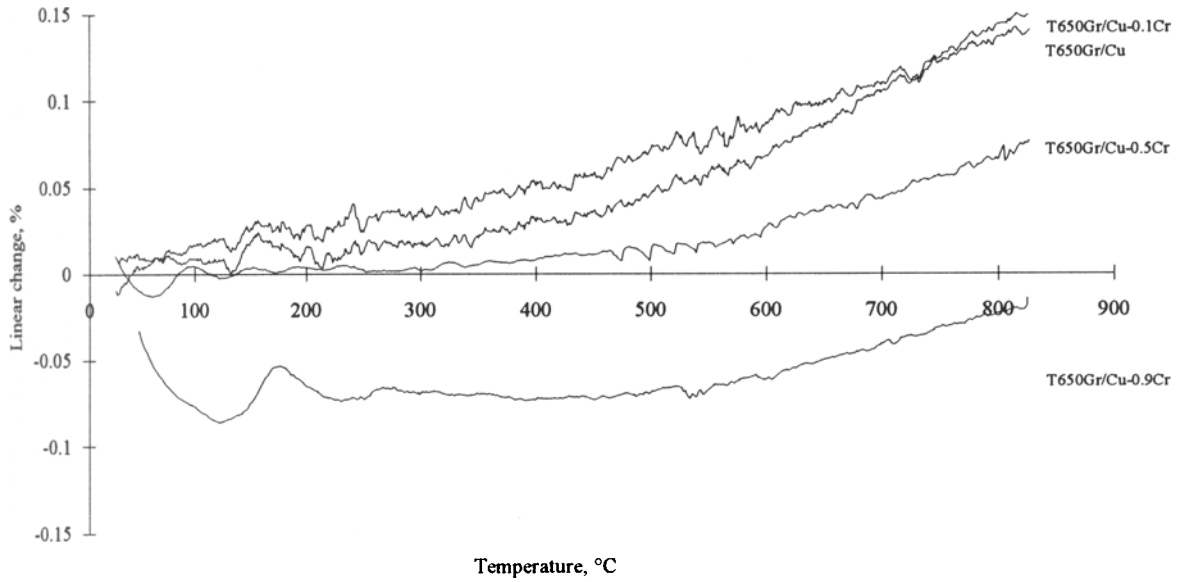

Fig. 11 Longitudinal thermal expansion behavior of T650Gr/Cu composites as a function of Cr alloying addition.

expansion behavior of the Cu compared to the graphite fiber. The T650Gr/Cu composite exhibits behavior that incorporates the individual responses of both the Cu and the graphite. On heating, the composite expands in a linear manner, resulting in a 0.15% increase in length at 827 °C. Because of the mechanical bonds created during the casting process, the negative longitudinal thermal expansion behavior of the graphite limits the overall increase in length of the composite and prevents behavior that would resemble that of Cu. Also occurring during heating is the expansion of both the graphite and the copper in the radial or transverse direction. This creates additional mechanical bonds that "lock" the graphite and copper together to favor the longitudinal contraction behavior of the graphite fibers. As a result of this mechanical locking, when the composite is cooled from 827 °C to room temperature, it exhibits behavior similar to that of graphite. Once the temperature is below 300 to 350 °C, contraction of the composite stabilizes. At that point, the mechanical bonds created during heating have been reduced, and in some cases eliminated, by transverse or radial contraction of both the Cu and the graphite. Below 150 °C, radial expansion of the graphite, which actually begins at 300 °C, restores some of the mechanical bonding between the graphite

fibers and the Cu matrix. The specimen expands rapidly, mimicking the expansion of graphite. This again disturbs the mechanical locking at the Gr/Cu interface, and below 100 °C, the contraction behavior of Cu continues until the sample returns to its original length.

Some hysteresis is observed during cycling of Gr/Cu composites. In most cases, this is evident during the initial cycle and eliminated during subsequent cycling of specimens. As stated previously, degradation of the mechanical bonds formed during the casting process occurs during heating. This causes the cooling behavior of the composite to deviate from the heating behavior. On further cycling, the transverse expansion of both the graphite and the copper creates a mechanical locking effect. Although these new bonds eventually separate during cooling, the behavior continues during subsequent cycles.

The thermal expansion behavior of the T650Gr/Cu composites has been found to vary with Cr alloying addition to the Cu matrix. Figure 11 illustrates the longitudinal thermal expansion behavior during heating as it varies with matrix composition. As shown, the addition of 0.1 wt% Cr to the Cu matrix does not change the response significantly from that of the unalloyed matrix composite. Its behavior is dictated by the transverse thermal expansion behavior, as described above. The T650Gr/Cu-0.5wt%Cr composite exhibited considerably lower thermal expansion, about one half that of the unalloyed and 0.1 wt% Cr matrix composites. There is sufficient Cr available at that composition to allow for the formation of enough Cr_3C_2 at the Gr/Cu interface to create a chemical bonding effect. Improved bonding at the interface restricts extensive expansion of the Cu matrix and contraction of the graphite fibers. Some expansion is observed; however, it is on the order of 0.07% linear change. Increasing the level of Cr to 0.9 wt% enhances the bonding at the interface such that the composite exhibits the contraction behavior of the graphite fibers. The transverse and longitudinal behaviors of the T300Gr/Cu composites were found to follow those of the T650Gr/Cu composites presented here.

5. Discussion

As expected from previous studies of Gr/Cu composites, interfacial bonding was very limited in the composites containing pure Cu matrices. This was evident from the low values of transverse tensile strengths and shear moduli. The SEM analyses clearly indicated excessive fiber/matrix debonding at the interface under tensile loading. Although the addition of Cr to the Cu matrix facilitated the formation of Cr_3C_2 at the Gr/Cu interface and therefore increased the interfacial bonding, processing inconsistencies did not allow for an increase in the transverse tensile behavior of the composites. Preliminary testing showed that the longitudinal tensile strength of the Gr/Cu composites is greater than 1.6 GPa. Modification of the specimen preparation will allow for the determination of an absolute value for the ultimate tensile strength in the direction of the graphite fiber reinforcement.

Observations made during SEM analyses clearly indicate that the amount of Cr_3C_2 formed at the Gr/Cu interface increased with increasing Cr content. During three-point bend testing, the stiffnesses of the Gr/Cu composites were observed to increase as a result of the improved bonding. The T650Gr/Cu-0.5wt%Cr test specimen has a stiffness twice that of pure Cu.

Investigation of the thermal expansion behavior of the Gr/Cu composites revealed that, in spite of processing defects and incomplete bonding at the Gr/Cu interface, thermal expansion is minimal. The transverse thermal expansion resembles that of Cu and decreases slightly with increasing Cr addition to the Cu matrix. This is the result of the restraining action of the Cr_3C_2 at the interface. The longitudinal thermal expansion of the composites is very low, less than 0.15% at 827 °C. After six cycles, all of the composites measured an overall percent linear change in the range of –0.04 to 0.016. The T650Gr/Cu-0.5wt%Cr composite exhibited the least amount of linear change during thermal cycling and, when tested to ten cycles, showed no change in behavior.

6. Conclusions

Pressure infiltration casting has been shown to be a viable method for producing Gr/Cu composites. Additions of Cr to the Cu matrix improved the bonding at the Gr/Cu interface as evidenced by SEM analyses and three-point bend testing. Although variations in processing do not allow for favorable transverse tensile behavior, the longitudinal tensile strength of the Gr/Cu composites is superior to that of the competitive materials under consideration. Thermal cycling of the composites has shown that the thermal expansion is very low, near zero for the longitudinal thermal expansion of the T650Gr/Cu-0.5wt%Cr composite, and is retained after ten cycles.

The thermal and mechanical behavior of Gr/Cu composites is improved with the addition of Cr to the Cu matrix. At present, the T650Gr/Cu-0.5wt%Cr composite has the best combination of properties for the intended service application.

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