International Journal of Thermophysics, Vol. 27, No. 4, July 2006 (© 2006)
DOI: 10.1007/s10765-006-0075-9

Influence of Thermal Strain on Thermal Properties of Composites[1]

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The temperature dependence of the thermal expansion characteristics of the AS21 magnesium alloy, AS21–25 vol% Saffil fiber composite and the Mg-10 vol% Saffil fiber composite has been measured in the temperature range from 20 to 380°C. The expansion characteristics were influenced by the residual and thermal strains. The residual strain was removed within the first thermal cycle. The relative elongation of the tensile pre-deformed AS21–25 vol% Saffil fiber composite is lower than that for the sample without deformation and for the composite pre-deformed in compression. The anisotropy of the thermal expansion is demonstrated on the Mg-10 vol% Saffil fiber composite. The coefficient of thermal expansion (CTE) in the transverse direction (TD) (the planes of the short Saffil fibers are laid perpendicular to the axis of the sample) is higher than the CTE in the longitudinal direction (LD) (the planes of the short Saffil fibers are laid parallel to the axis of the sample). The anisotropy and the thermal strain influence the thermal diffusivity for AS21 composites investigated at temperatures between 20 and 380°C.

KEY WORDS: Mg composites; thermal properties; thermal strain.

1. INTRODUCTION

The origin of thermal stresses and accompanying thermal strains consists of differences in the thermal expansion of various components of a material or parts of a body under such a condition such that free expansion

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[1] Paper presented at the Seventeenth European Conference on Thermophysical Properties, September 5-8, 2005, Bratislava, Slovak Republic.

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of each small volume unit cannot take place. Metal-matrix composites (MMC) are frequently reinforced with ceramic fibers and/or particles to improve their mechanical properties. Ceramic reinforcements have a low thermal expansion coefficient usually in the range of 5 to 10×10^{-6} K^{-1}. Magnesium and magnesium alloys studied in this work exhibit much higher CTE values (about $26 \times 10^{-6} K^{-1}$).

In the literature we find various analyses dealing with a release of thermal stresses by elastic mechanisms, e.g., the frequently used relation of Careno–Moreli [1]. It can be seen from our previous measurements [2, 3] that in (MMC) only a small part of the thermal strain is released by purely elastic mechanisms. After reaching a certain temperature, the elastic thermal stress is influenced by variations of plastic deformation in the matrix near the interface and relations based on the only elastic presumption cannot be used. Relaxation of thermal stresses by a plastic mechanism in MMCs was analyzed by Dunan and Mortensen in Ref. 4. They defined "the total mismatch strain" ε_m between the matrix and reinforcement as

$$\varepsilon_m = \Delta\alpha\Delta T, \tag{1}$$

where

$$\Delta T = T_c - T. \tag{2}$$

Here $\Delta\alpha$ is the absolute value of the difference between the CTE values of the matrix and the ceramic reinforcement, and T_c is the temperature at which the reinforcements and the matrix are assumed to be stress-free. The results of their work indicate the existence of plastic zones along particles and/or fibers. Elastic–plastic stress transfer in short fiber-reinforced MMCs was also analyzed by Jiang et al. [5]. These authors showed that the local matrix plastic deformation due to thermal stresses resulted in asymmetric tensile and compressive stress–strain responses.

The aim of this work is to investigate the influence of the thermal stress and the accompanying thermal strain on the thermal expansion behavior of the Mg-10 vol% Saffil fiber composite and AS21 25 vol% Saffil fiber composite with parallel and longitudinal orientations of fibers with respect to the sample axis, respectively. The results are analyzed using an elastic–plastic conception of the release of the thermal strain in the temperature range from room temperature up to 380°C. Moreover, the effect of thermal stresses on the thermal diffusivity for an AS21 composite was also studied.

2. EXPERIMENTAL

The composite based on the AS21 alloy (Mg-2 mass% Al-1 mass% Si-0.5 mass% Mn) reinforced with 25 vol% Saffil fibers was produced by squeeze casting at Zentrum für Funktionwerkstoffe, gGmbH, Clausthal. The Mg-matrix composite reinforced with 10 vol% Saffil fibers was prepared by the gas pressure infiltration of fibrous preform in an autoclave at 695°C/6 MPa at the Institute of Materials and Machine Mechanics in Bratislava (Slovakia).

In both composites the short Saffil fibers (Al_2O_3) have dimensions of $\sim 3 \mu$m diameter and 87μm mean length. Fibrous preform consists of fibers randomly distributed in preferred parallel planes (planar–random orientation). If preferred fiber planes lie perpendicularly to the axis of the cylindrical sample, then we are concerned about the transverse direction (TD). If those are parallel with the sample axis, we are concerned about the longitudinal direction (LD).

The linear thermal expansion of the samples was measured in an argon atmosphere using the Netzsch 402E dilatometer in the temperature range from room temperature to 380°C at heating/cooling rates of $5^\circ C \cdot min^{-1}$. The samples were 6 mm in diameter and 50 mm in length. The thermal expansion curves for the composites were recorded during three heating/cooling cycles (runs). Materials were studied in an as-prepared state. The thermal diffusivity measurement was performed using the flash method described elsewhere [6] in the temperature range from 20 to 380°C in an argon atmosphere.

3. RESULTS

Figure 1 shows the temperature dependence of the relative elongation for the AS21 alloy and the corresponding composite in the longitudinal direction. Only very small hysteresis is perceptible with temperature for the AS21 alloy. The composite exhibits a larger hysteresis but still relatively small in comparison with the other fiber-reinforced composites as, for example, the Mg-10 vol% Saffil fibers [2] or the MgLi Saffil fibers composite [3]. The relative elongation in the first thermal cycle is smaller than in the second thermal cycle for both the alloy and corresponding composite.

In the next experiment, the AS21 composite was pre-deformed in compression and tension up to 1% and the thermal expansion was again measured. The results are presented in Fig. 2. The relative elongation of the compression pre-deformed sample is higher than the relative elongation of the sample without deformation (thermal cycle before deformation)

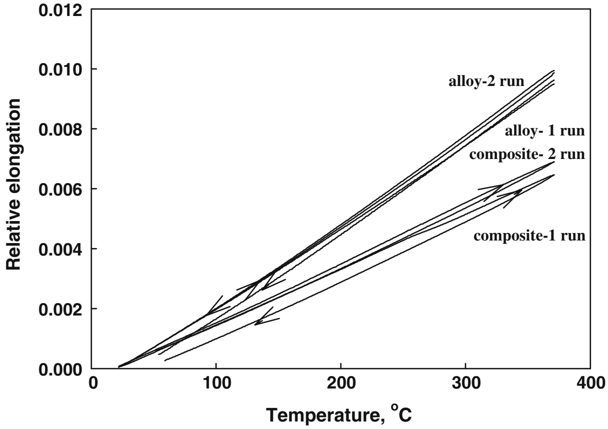

Fig. 1. Temperature dependence of the relative elongation for the AS21 alloy and AS21–25 vol% Saffil fiber composite in LD direction.

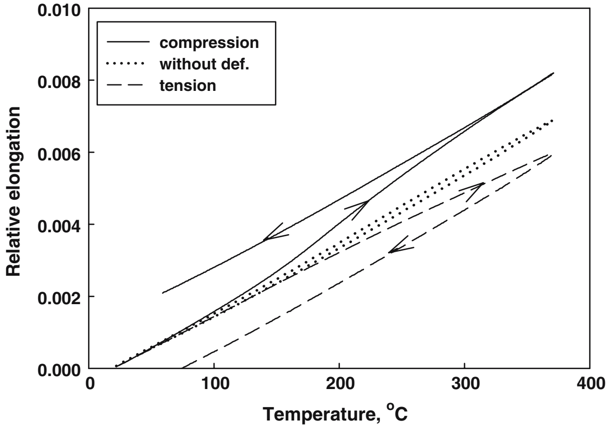

Fig. 2. Temperature dependence of the relative elongation for pre-deformed AS21–25. vol% Saffil fiber composites in LD direction.

over the whole experimental temperature range. In contrast, the relative elongation of the tensile pre-deformed sample is lower than that for the sample without deformation. Moreover, persistent length extension was found in a thermally cycled compression pre-deformed sample while a thermally cycled tensile pre-deformed sample exhibits persistent length reduction. The following thermal cycles deliver the same results as those obtained during measurements of the composite before pre-deformation. The deformation made by the mechanical pre-deformation and deformation due to thermal vibrations are additive. When subtracting the relative elongation of the pre-deformed sample from that of the sample without deformation, one obtains information about the development of the mechanical deformation during a single thermal cycle. For results, see Fig. 3. The deformation changes only during heating, and these changes are persistent. The remaining deformation is called the residual strain.

After removing residual strains (due to both mechanical and thermal loadings), the thermal strains always exist in composites. These thermal strains reflect the anisotropy of the fiber composite. Figure 4 shows the influence of the thermal strain on the relative elongation in a Mg-10 vol% Saffil fiber composite together with the relative elongation calculated using the rule of mixtures. The latter represents a hypothetical case when no thermal strain occurs in the composite. The relative elongation of the TD (LD) composite is higher (lower) than the relative elongation obtained by the rule of mixtures. The hysteresis is larger for the TD composite than for the LD composite. Let us calculate the thermal strain as a difference between the experimentally measured relative elongation and the relative elongation calculated using the rule of mixtures. The temperature dependences of the thermal strain values for both the LD and TD composites are shown in Fig. 5.

Figure 6 shows temperature dependences of the thermal diffusivity for both the TD and LD AS21 composites. The curve for the AS21 alloy normalized to the thermal diffusivity at room temperature is also plotted. The

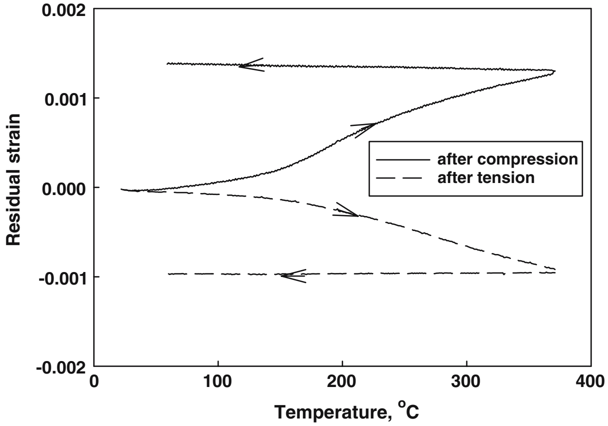

Fig. 3. Temperature dependence of the residual strain for AS21–25 vol% Saffil fiber composite in LD direction.

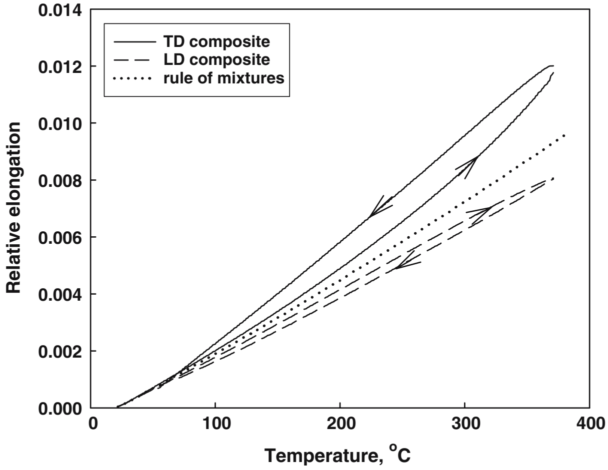

Fig. 4. Temperature dependence of the relative elongation for LD and TD Mg-10 vol% Saffil fiber composites (the second runs).

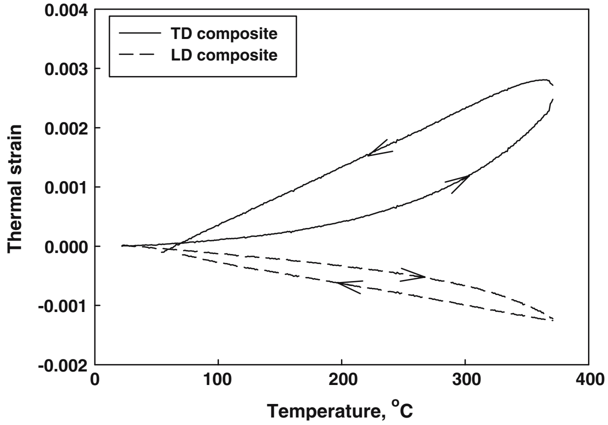

Fig. 5. Temperature dependence of the thermal strain for LD and TD Mg-10 vol% Saffil fiber composites.

thermal diffusivity of the LD composite is higher than that of the TD composite over the entire temperature range.

4. DISCUSSION

We principally distinguish between the residual strain and thermal strain. The residual strain is a macroscopic plastic deformation of the

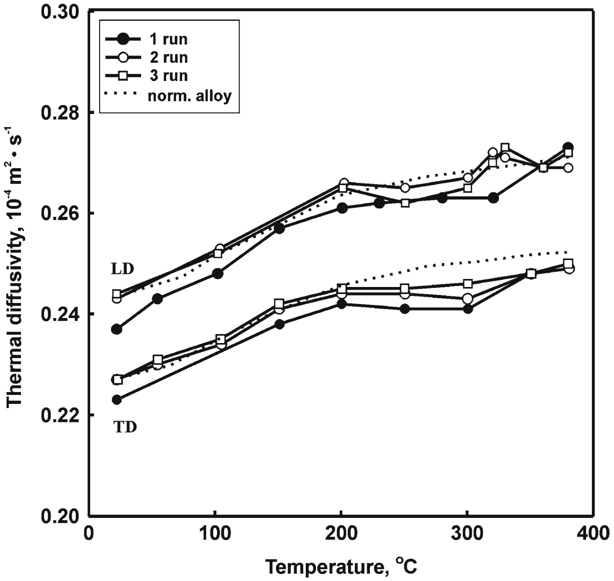

Fig. 6. Temperature dependence of the thermal diffusivity for LD and TD AS21–25 vol% Saffil fiber composites.

sample, and it may be entirely removed by heating. The thermal strain is an elastic–plastic deformation of the composite, which cannot be removed by any process. It is a fundamental property of a composite material, which depends on the CTE‘s difference of composite components and temperature. The thermal strain in aligned fibrous, composites shows considerable anisotropy when the tensile thermal strain is in the direction of the fibers, and the compressive strain is in the perpendicular direction. We also observed that the manufacturing-caused residual strain is isotropic (this result will be published elsewhere).

The samples of the as-prepared alloys and composites nearly always show some persistent deformation after the first thermal cycle (Fig. 1), which is related to the thermal and mechanical history. To obtain relevant information about this behavior, the expansion characteristics of the AS21 composite were determined for pre-deformed samples. From Fig. 2 one can see that the pre-deformation in compression (tension) leads to an increase (decrease) of relative elongation in comparison to the expansion characteristics of non-deformed material. From Fig. 3 it can be deduced that the plastic compression and tension strain changes only during heating. These results allow us to assume that the as-prepared alloy and composite samples are deformed in tension (reduction of the sample length after the first thermal cycle). This may be a consequence of the volume changes at the liquid–solid transition during the processing. If deformation due to manufacturing is not removed by the thermal treatment before the measurement, this residual strain may change all results where the strain can influence the given physical parameter, e.g., the thermal expansion.

Thermal stresses and residual stresses and with them connected strains have been the subject of recent papers of Kainer et al. [7, 8]. Their results are similar to those reported in a present paper, i.e., the CTE increases for TD composites and decreases for LD composites above a certain temperature. Kainer et al. explained these results as an attribute of plastic deformation. They assume that thermal stresses first relax elastically with increasing temperature, and after the yield strength of the matrix alloy is reached, the plastic deformation under compressive stresses occurs. However, this hypothesis as well as a hypothesis used in later studies (e.g., Ref. 9), do not take into account that investigated composites are already plastically deformed at room temperature. In the as-prepared composite, we can observe the macroscopic plastic residual strain of the entire sample and the microscopic plastic strain in the matrix region adjacent to the fiber/matrix interface. Both these strains first occur during cooling from the manufacturing temperature. In accordance with the relation (Eq. (1)), all of our results show that the residual and thermal strains have the highest values at room temperature if this is the lowest experimental temperature. Any heating of the samples leads to a decrease (release) of the residual and thermal strains towards the stress-free state. Plastic deformation due to the thermal or residual strain cannot occur during heating. This can be demonstrated by the results obtained from pre-deformed composites where the extent of plastic deformation decreases with increasing temperature (Fig. 3). The reduction of the compressive (tensile) stress yields a sample expansion (contraction).

The scheme of the thermal strain release during the thermal cycle has been published elsewhere [10]. The thermal strain tensile (compressive) strain parallel (perpendicular) to the fiber direction is released during heating first only by elastic mechanism. Above a certain temperature, the extent of the micro-plastic strain in the matrix near the interface diminishes (the yield stress decreases with increasing temperature) when the yield stress is reached. Above this temperature, the elastic stress in the matrix is modulated by changed plastic deformation in the interface and the total thermal strain is released faster than if the micro-plastic changes were absent. This result clearly demonstrates the strong dependence of the elastic stress in the matrix on the micro-plastic deformation in the interface. We can divide the experimental temperature range in two parts. First the micro-plastic strain in the matrix near the interface is invariable and the changes of the strain are only elastic; Second the extent of the micro-plastic strain diminishes and the reduction of the thermal strain has the elastic–plastic character. We assume that the elastic modulus of the composite matrix in the first temperature range differs from the elastic modulus of the monolithic alloy. The hysteresis of the temperature dependences of expansion characteristics points to the irreversible character of processes connected with the thermal strain release. We assume that during cooling the micro-plastic strain in the matrix near the interface reenters within a certain temperature range. The maximum value of the thermal strain is reached at the lowest temperature of the cycle (which is room temperature in our case). After finishing the thermal cycle, no persistent changes in the sample length occur in the composite. The thermal stresses released during the thermal cycle are connected with the positive strain in the case of compression stresses and the negative strain in the case of tensile stresses (see Fig. 5).

The shape of the temperature dependence of the thermal diffusivity for both composites is the same as that of a pure AS21 alloy. For the calculation of thermal diffusivity a, the following relation is used:

$$a = 0.139 \frac{l^2}{t_{1/2}} \tag{3}$$

where l is the sample thickness and $t_{1/2}$ is the half time (time when half of the maximum temperature rise is reached on the back side of the sample after its irradiation on the front side). Small departures observed above 200°C should be connected with the thermal strain. However, we assume that it is only due to variations of the sample thickness within the thermal cycle. The sample thickness is measured at room temperature. When the release of the thermal strain is due to an elastic–plastic mechanism, the sample thickness starts to increase considerably in the TD composites and decreases in the LD composites. The effect of these changes is larger in the TD composites (see Fig. 6).

5. CONCLUSIONS

Residual and thermal strains exist in short fiber MMCs with different CTEs of the components. These strains are changed during thermal cycling, which influences expansion characteristics of composites. The residual strain is released only during heating and does not change with cooling. The changes of the residual strain are persistent. The release of the thermal strain occurs by elastic and elastic–plastic mechanisms. No persistent length changes occur within the thermal cycle.

Planar–random fiber architecture in investigated MMCs is characterized by two basic directions of the fiber array: transverse (TD) and longitudinal (LD). The matrix is deformed in tension (compression) in the LD (TD) composites. The reduction of the thermal stresses in the LD samples leads to a decrease of the CTE, whereas an appreciable increase of the CTE is observed in TD samples.

The thermal diffusivity is influenced by the thermal strain by the "thickness effect," the sample thickness changes due to the release of the thermal strain. These changes are the highest in the elastic–plastic range, positive (negative) in the TD (LD) composites.

ACKNOWLEDGMENTS

This work is part of the research program MSM 0021620834 financed by the Ministry of Education of the Czech Republic. The authors acknowledge financial support from the Grant Agency of the Academy of Sciences under Grant A2112302 and from the Grant Agency of the Slovak Republic VEGA for financial support (Project VEGA No 2/5138/25).

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