THE ARCHIVE OF MECHANICAL ENGINEERING
Vol. LV 2008 Number 1
DOI: 10.24425/ame.2008.131613
Key words: metal matrix composite, thermal stresses, fracture

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HYPOTHETICAL FRACTURE AT FIBBER-MATRIX INTERFACE IN Cu-SiC COMPOSITE DUE TO THERMAL STRESSES

The Copper-SiC composite was investigated with the help of FEM. The authors modeled and analyzed the effect of relaxation of thermal stresses due to seasoning at room temperature after the manufacturing process together with the effect of thermal stresses induced by reheating the material to a service temperature. Especially, hypothetical fracture at interface was of interest. It was shown that, for a fixed temperature, a single crack emanating at 0° or 45° azimuth would develop only along a portion of fiber perimeter, and a further growth would require stress increase in the fiber surrounding.

1. Introduction

Due to high thermal conductivity of copper (401 $W \cdot m^{-1} \cdot K^{-1}$) Cu – SiC composites can be applied to some structure elements that drive away an excess of heat from parts of a structure to be protected.

Often, components of metal matrix composites (MMC) display different coefficients of thermal expansion (CTE). Therefore, in the course of manufacturing process, residual thermal stresses of significant level can develop. Also, thermal stresses can develop if the service temperature fluctuates with time. The thermal stress level depends on

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– mismatch of CTEs for Cu and SiC,
– gap between the stress-free and service temperatures and
– rate of cooling and stress relaxation process.

Therefore, the existing stresses appear as a result of competing phenomena of relaxation and thermal expansion.

For some MMC matrixes, CTE are higher than that for fibres. Such a relationship is often considered as a favourable one from composite strength point of view. In particular, it is beneficial for the interface strength, because the fibres are subjected to radial compression, and the fracture at fibre-matrix interface is unlikely [1]. However, the stresses decrease with time due to relaxation, and for sufficiently long relaxation time the reheating of such a composite can reverse the existing stress state. If so, the interfacial tensile stress will increase with temperature, and in the presence of interfacial flaws (weak or unbounded spots) interfacial cracks can be formed and increased in size.

In the case of copper-SiC composite, the mentioned relationship between the CTEs exists, see Fig.4. Therefore, in this case the described scenario can unfold.

In order to investigate such a phenomenon, the FE model of unidirectional Cu-SiC composite material has been developed. The composite was subjected to the temperature-time cycle shown in Fig.6. It was assumed that just after solidification the composite was stress free and that this free-stress state corresponded to 1400°K. Also, it was assumed that due to faults in the manufacturing process, micro cracks were formed at Cu-SiC interface. Two micro-crack locations were considered: at 0° and 45° azimuths, Fig.5. Hypothetical circumferential crack growth was of interest. It was assumed that at service temperature of 423°K a radial stress at the interface reached its maximum before the matrix plasticized. For the monitoring of the crack growth, the changes of the Strain Energy Release Rate, G, with crack length, s were investigated. It was assumed that if criterion (1) was met, the crack would stop, and a further growth would be possible only at stress increase.

$$dG/ds \leq 0 \tag{1}$$

2. Finite Element micromechanical model of the composite material

2.1. Geometry

For the purpose of the analysis, a representative volume of composite material was selected. A geometry of its cross-section perpendicular to the fibre direction is depicted in Fig.1. Existence of an interfacial crack did not allow for taking an advantage of a symmetry otherwise existing. Therefore, it was difficult to define a unite cell containing a fraction of a fibre surrounded by a matrix with appropriate symmetry and boundary conditions. Instead, a brick of composite material 1.5mm x 1.5mm x 0.002 mm containing several fibres had to be considered, as shown in Fig.1. The assumed fibre diameter d_f was equal to 0.14mm and fibre volume fraction v_f=0.2.

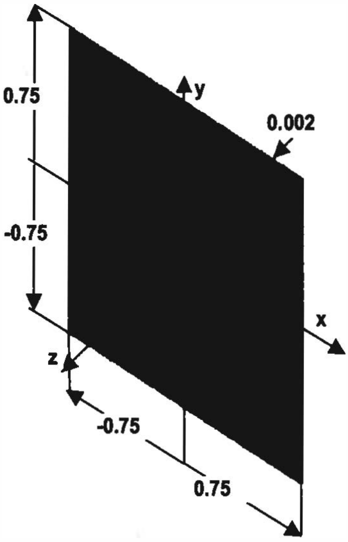

Fig. 1. Geometry of the composite specimen under consideration (dimensions in mm)

2.2. Mechanical properties of components

Mechanical properties of copper matrix and SiC fibres are shown in Figs. 2–4.

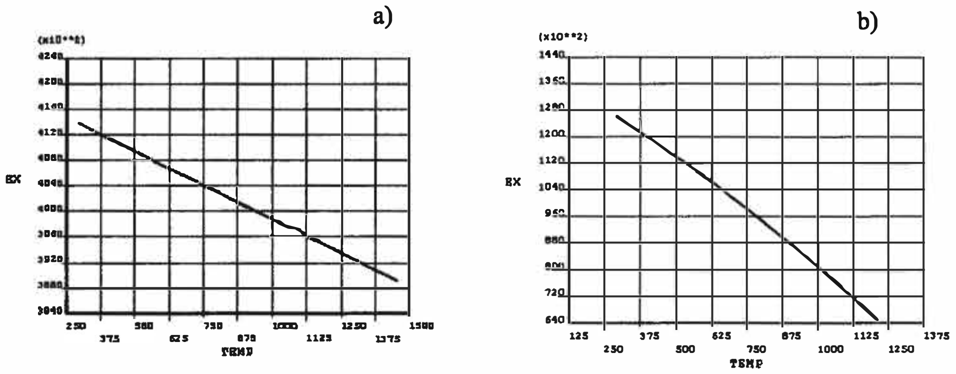

Fig. 2. Variation of Young's Moduli for Cu (a) and SiC (b)

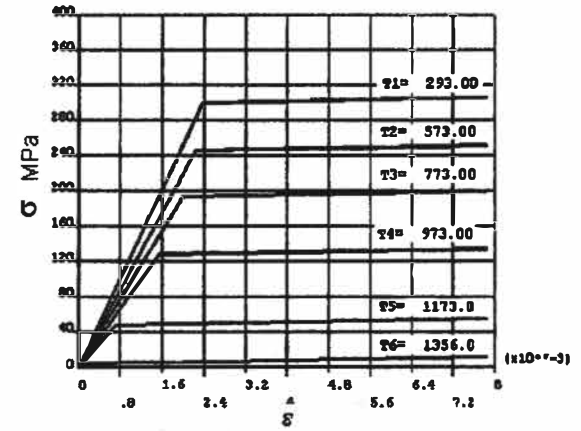

Fig. 3. Stress-strain curves for Cu for the temperature range under consideration

Creep of copper was defined with (2)

$$\varepsilon_{creep} = \frac{C_1}{C_3+1}\sigma^{C_2} t^{C_3+1} e^{\frac{-C_4}{T}} \tag{3}$$

in which

$$C_1 = 0.31\times10^{-13} \quad C_2 = 1.1 \quad C_3 = -0.8 \quad C_4 = 140$$

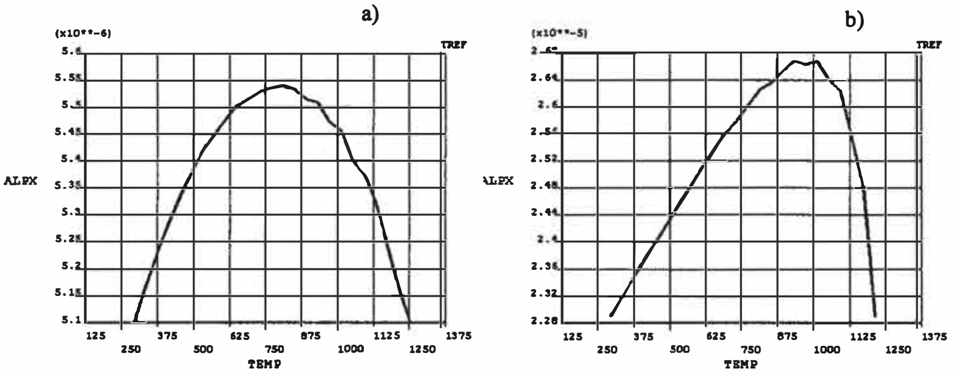

Fig. 4. Variation of the thermal expansion coefficients with temperature for Cu (a) and SiC (b)

2.3. Finite element representati

2.3.1. Finite element mesh

The analysis was performed with the use of ANSYS v.10 code [3]. Finite element mesh generated is shown in Fig.5 for the small region containing a fibre with an initial, interfacial flaw. The mash geometry shown is typical for the rest of the structure.

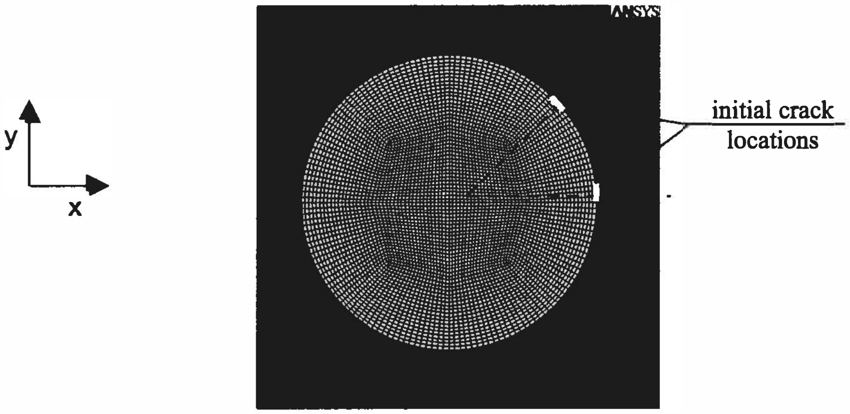

Fig. 5. Geometry of the finite element mesh in the region of the fiber with interfacial flaws

To obtain σ v. (*T,t*) relationship resulting from the temperature changes with time according to the temperature profile shown in Fig.6 the SOLID45 elements were used for the matrix and fibres representations. Provision for the crack development was done with the application of LINK14 elements "sewing" the matrix and fibre along an appropriate portion of the fibre perimeter.

2.3.2. Boundary conditions

Assuming that the planes parallel to xz and yz that bound the selected volume in x and y directions are far enough from the interfacial crack, the following boundary conditions were set for the bonding planes, Fig.1:

- symmetry conditions are set for planes x=-0.75, y=-0.57 and z=0
- for all the nodes at plane x=0.75 u_x degrees of freedom are coupled
- for all the nodes at plane y=0.57 u_y degrees of freedom are coupled
- for all the nodes at plane z=0.002 u_z degrees of freedom are coupled

3. Temperature variation

The variation of temperature with time is shown in Fig.6. One assumed that at 1400K the composite was stress free. The composite was cooled down from this temperature to RT with an approximate cooling rate of 10K/min. Next, it was kept at RT for 360 days, (from t_1 to t_2), to release the thermal stresses. Finally, it was heated up to 423K (assumed operating temperature) with an approximate heating rate of 5K/min.

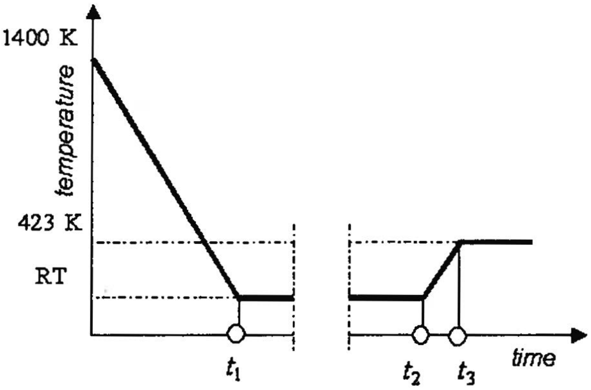

Fig. 6. Time-temperature history.

After the composite reached the service temperature, the Strain Energy Release Rate, G, was calculated with the use of the Modified Crack Closure Integral Method [2] for several cracks of increasing length. The initial interfacial crack (interfacial flaw) was 0.006mm long. For each calculation the crack length was increased by Δa= 0.003mm along the fibre perimeter.

4. Results and discussion

The results of the numerical analysis have been separated into two groups. The first one contains results for the selected time points t_1 and t_3 of the cooling and seasoning processes respectively. They are:

- t_1= 120 min, and corresponding to time at which RT was reached and the begin of seasoning
- t_3=360 days, corresponding to the and of seasoning and the start of heating up to the service temperature.

The second group of results presents the hypothetical development of interfacial flaws at 0° and 45° initial locations that could be produced by the induced thermal stresses resulting from a fast temperature increase from RT to the service temperature.

4.1. Elastic- plastic response of the composite due to cooling and seasoning

Figure 7 presents radial and longitudinal stresses (in the fibre direction) in the fibre and surrounding matrix. It can be seen that both the fibre and the matrix adjacent to it are under compression. Therefore, development of interfacial cracks is unlikely.

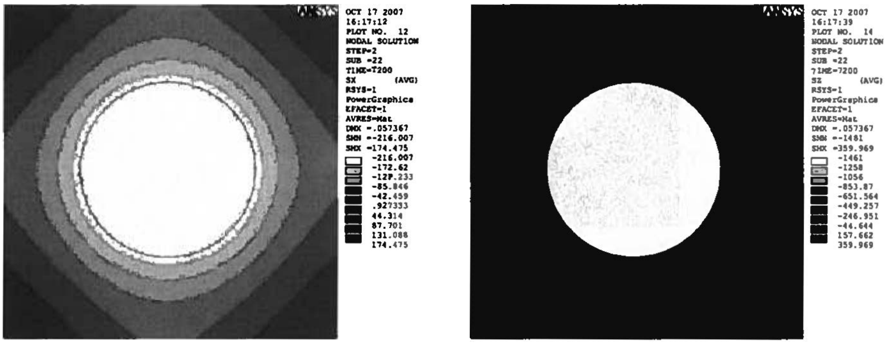

Fig. 7. Radial and axial stresses expressed in cylindrical coordinate system with the origin at the centre of the fibre for t_1; a – radial stress, b- longitudinal stress

One year seasoning at RT resulted in a dramatic decrease of residual stresses in the matrix, Fig.8, however, compressive radial stress was still present at the locations vital from possible crack formation point of view.

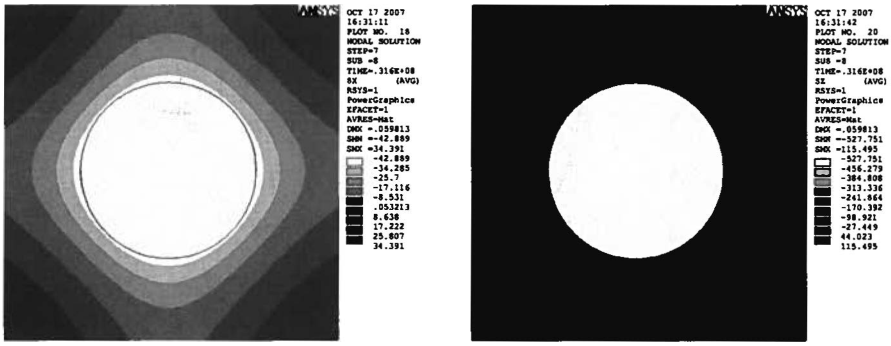

Fig. 8. Radial and axial stresses expressed in cylindrical coordinate system with the origin at the centre of the fibre for t_2; a – radial stress, b- longitudinal stress

Some residual circumferential tensile stress existed in the matrix adhering to the fibre surface, Fig.9, however, the stress was relatively low, and a crack development in the matrix in this region should not be expected.

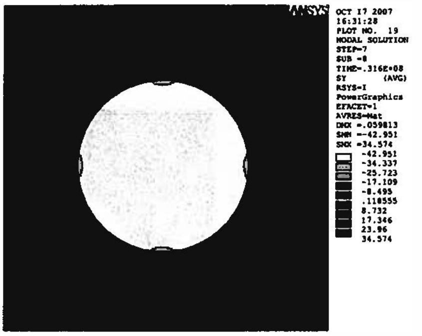

Fig. 9. Circumferential stresses expressed in cylindrical coordinate system with the origin at the centre of the fibre for t_2

4.2. Hypothetical development of interfacial crack

Heating to 430°K resulted in the interfacial stresses, σ_r, and, $\tau_{r\theta}$, presented in Fig.10.

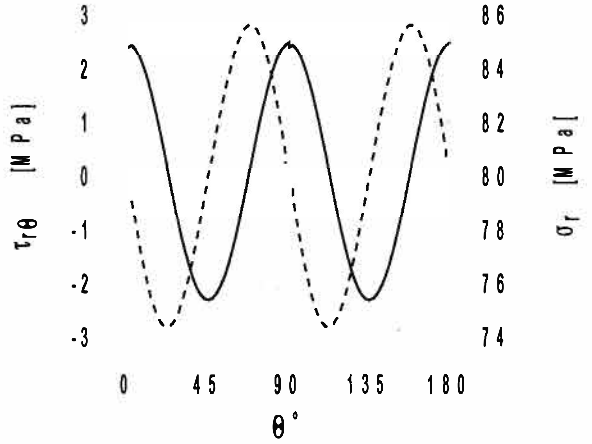

Fig. 10. Radial, σ_r, and shear, $\tau_{r\theta}$, (dashed line) interfacial stresses

For both considered initial locations, the Strain Energy Release Rate initially increased with increasing crack length, Fig.11. However, after reaching by the crack tips certain perimeter locations: approximately ±60° for 0° initial location and -12° and 102° for 45° initial location, the SERR reached maximum and a further increase in crack length did not resulted in the increase of SERR. It suggests possibility of cracks arrest.

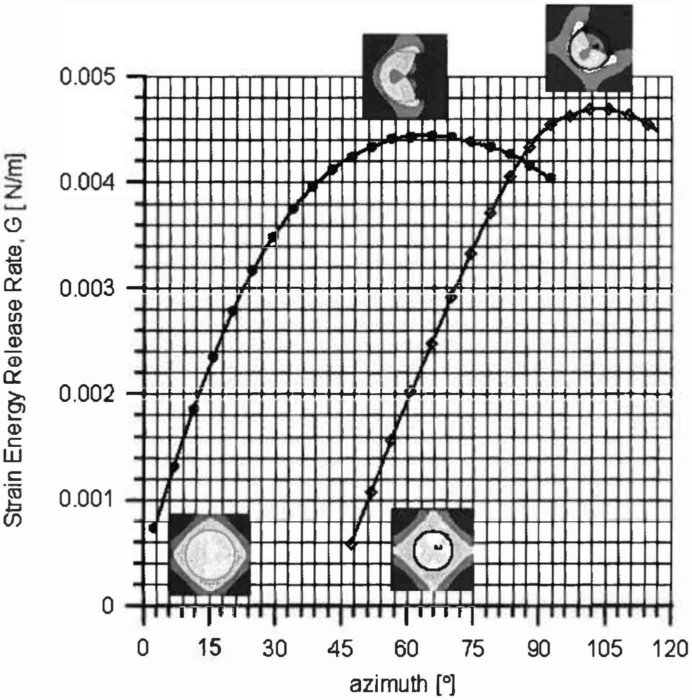

Fig. 11. Variation of G v. crack length, for 0° (●) and 45° (◇) initial crack locations

5. Conclusions

The results presented allow one to conclude that:

1. The cooling resulting from manufacturing process produced substantial residual stresses. Compressive stresses in a matrix adjacent to a fibre surface prevented formation and development of an interfacial crack.
2. At RT stress relaxation process was present, and after sufficiently long period of time, (in this case one year), dramatic changes of stress state occurred. Radial compressive stress in matrix adjacent to fibres that prevented interfacial crack formation decreased approximately five times, and the axial compressive stress was alternated to tensile stress allowing for crack formation in the matrix adhered to fibre surface.
3. The first reheating up to the service temperature following the seasoning alternated radial compressive stress at fibre – matrix interface into tensile stress which was in favour for interfacial crack formation and propagation of such cracks along fibre-matrix interface. It must be stressed that the considered scenario of crack propagation was a hypothetical one. It could

or could not take place depending on the critical value of the SERR which defines resistance against interfacial fracture, and that must be determined experimentally.

4. To prevent formation of stress state favourable for interfacial crack formation and growth, one should consider seasoning and precisely adjust seasoning period.

It is a part of research project 3T08A 068 28 supported by the Ministry of Science and Higher Education.

Manuscript received by Editorial Board, December 30, 2007

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Hipotetyczny rozwój pęknięcia na granicy włókna i spoiwa, powodowany naprężeniami cieplnymi, w kompozycie Cu-SiC

Streszczenie

W pracy analizowano stan naprężeń cieplnych w kompozycie Cu-SiC, wynikających ze spadku temperatury od temperatury wytwarzania do temperatury pokojowej oraz relaksacji naprężeń w okresie sezonowania w tej temperaturze a następnie podgrzaniu kompozytu do temperatury przewidywanej pracy. Szczególna uwagę zwrócono na możliwości rozwoju pęknięć na granicy włókna i spoiwa w temperaturze pracy. Rozpatrywano dwie lokalizacje 0 i 45 stopni. Stwierdzono, iż w obu przypadkach, w ustalonej temperaturze hipotetyczna propagacja pęknięć będzie stabilna w tym sensie, iż rozwiną się one jedynie na pewnej długości obwodu włókna a ewentualny dalszy ich rozwój będzie wymagał wzrostu naprężeń w jego otoczeniu.