Thermal failure mechanism and threshold of particulate reinforced metal matrix composites induced by laser beam

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ABSTRACT Thermal failure of Al/SiC composites induced by coupled loads of laser thermal shock and mechanical load is experimentally and theoretically studied. It is found that the initial crack is occurred in the notched-tip region, wherein the initial crack was induced by void nucleation, growth and subsequent coalescence in the matrix materials or separation of the interface. It is further found that the process of the crack propagation occurred by fracture of the SiC particulate. The damage threshold and completely failure threshold could be described with a plane of far-field load σ_{max} with laser beam energy density E_J. A simple theoretical model was proposed to explain the damage/failure mechanism and to calculate the thresholds.

KEYWORDS: Thermal failure, particulate-reinforced metal matrix composites, laser beam, failure threshold

1. INTRODUCTION

Metal matrix composites (MMC) are excellent candidates for structural components in the aerospace and automotive industries due to the high specific modulus, strength, and thermal stability[1]. However in aerospace and automotive industries the structural components are often subjected to sever thermal loads that may be produced by aerodynamic heating, by laser irradiation, or by localized intense fire[2]. In the present paper, the thermal failure mechanism and failure threshold of particulate-reinforced metal matrix composites were experimentally and theoretically investigated.

2. EXPERIMENTAL METHOD

SiC particulate/6061 Al composite was chosen as a model MMC system for this study. The composites with 15wt pct SiC were fabricated by melt casting route. Thermal shock is generated by an incident laser beam, which impinges normally to a single-edge notched specimen. Laser beam was pulsed Nd:glass laser with a wave length of $1.06\mu m$. The single-edge notched specimen was radiated by laser beam and loaded by a static tensile machine. In this case, the thermal damage and fracture are induced by both laser thermal shock and far-field mechanical load. Figure 1 is a schematic of the specimen configuration and dimensions. The shape of the notch is U-like. Therefore, the maximum stresses at the tip of the notch are $\sigma_{max} = \alpha_\sigma \sigma$ [2]. In experiment, the samples were subjected to different coupled loads of mechanical load and laser shock intensity (σ_{max}, E_J).

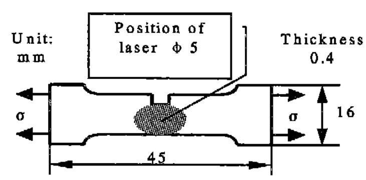

Figure 1. Schematic of the specimen.

3. EXPERIMENTAL RESULTS

When the intensity of the coupled loads (σ_{max}, E_J) were low (i.e. σ_{max} and E_J were lower than critical thresholds), there were not any visible damage and failure phenomenon. However, when the coupled loads were increased to critical thresholds, some visible damage

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phenomena could be observed by scanning electron microscopy. Figure 2 shows the typical SEM of damage characterization. It is observed that the voids occur in the form of interfacial debond and the micro-cracks occur in matrix and interface. When the particle is at the crack tip, the SiC particle does not fracture and resist crack propagation. When the thermal shock and mechanical loads were gradually increased, the damage became more and more serious. When coupled loads (σ_{max} , E_J) were up to critical threshold, micro-cracks formed in the notched region would grow into macroscopic cracks. The SEM micrograph of macroscopic crack tip is shown in figure 3. As shown in the figure, the particle fracture is the dominant damage mechanism for macro-crack propagation. Note that the SEM in figure 3 is distinct from the SEM in figure 2 for damage mechanism. It is very interesting that although the particles were broken near macro-crack tip region, there was not damage in matrix and the interfaces.

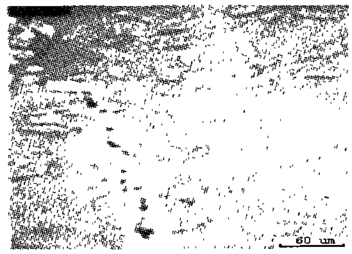

Figure 2. Radial cracking showing voids in matrix and the separation between SiC particle and matrix.

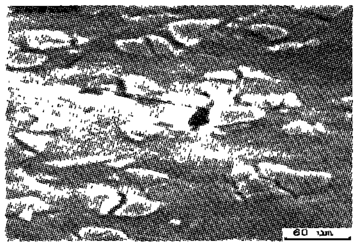

Figure 3. Failure characterization in crack-tip: phenomenon of particles oken and no-damage of matrix.

The damage threshold and completely failure threshold could be described with a plane of far-field load with laser beam energy density, i.e., a plane of σ_{max}-E_J. In the plane, σ_{max} is the maximum stress at notched-tip and E_J is the energy density of incident laser beam. The damage threshold was defined as that one could observe voids in matrix or between matrix/particle interfaces for analyzing the SEM micrographs with 500 magnifications. The failure threshold was defined as that when the sample with single-notched was completely fractured. Figure 4 is the experimental results for the plane of σ_{max}-E_J. The damage threshold for mechanical load with no laser beam heating E_J is σ_{max}=300MPa. The complete failure threshold for mechanical load is σ_{max}=600MPa. According to the level of damage and failure, three regions are divided. They are non-damaged region, damaged region and complete failure region. The non-damage region is located on the down left of damage line. The damage region is on the region between damage line and failure line. The failure is located on the upper right of failure line. One can see that the contribution of far-field mechanical load and laser beam thermal load to the damage and failure of MMC is non-linear. In other word, their contributions are coupled. If the mechanical load is between damage thresholds σ_{max}^{Dth} and complete failure thresholds σ_{max}^{Fth} , an additional thermal load with a little laser energy density will make the samples completely failure. This region is called a laser beam sensitive region.

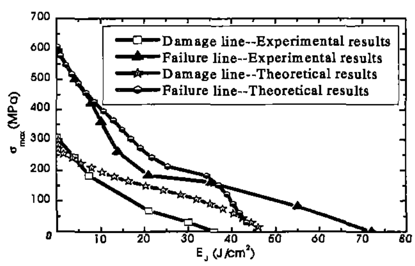

Figure 4. Damage and failure threshold plane.

4. DISCUSSIONS

In this section, a simple theoretical model is proposed to explain the interesting experimental phenomenon and to predict the damage threshold and failure threshold. In the model, the temperature rise and thermal stress was first obtained. The stress-strain relation of MMC is assumed to follow the numerical results obtained by Brockenbrough[3]. The secant Young's modulus E^c of MMC was defined by the ratio of tensile stress to the tensile strain. The idea of stress transfer for a hard elastic particulate with (E^p,ν^p) embedded in an infinite elastic matrix with (E^c,ν^c) is adopted in the model. The complete solution to this problem was given by Eshelby[4]. The largest normal stress in the particle and largest shear stress along the interface can easily obtained from Eshelby solution[4]. The above ideas can be easily explain the damage and failure mechanism, and predict the damage threshold. In order to predict the failure threshold, the stress intensity for a single edge crack in a finite rectangular plate should be calculated. The weight function method is used to calculate the stress intensity factor K_I as,

$$K_I = K_I^m + K_I^T \tag{1}$$

where K_I^m is the stress intensity factor induced by the far-field mechanical loading and it is given by the following expression

$$K_I^m = F_I(\varsigma)\frac{\sigma_{max}}{\alpha_\sigma}\sqrt{\pi c} \tag{2}$$

Here c is the crack length, $\varsigma = c/w$ and w is the width of the sample, the coefficient $F_I(\varsigma)$ was given in [5]. One can obtain the thermal stress intensity factor K_I^T by using Wu's weight function as,

$$K_I^T = \Phi\sigma_0\sqrt{\pi c} \tag{3}$$

with $\sigma_0 = \frac{1}{2}\alpha E^c \vartheta$ and $\Phi = \frac{1}{\sqrt{2\pi\beta_0(\varsigma)}}\frac{1}{\varsigma}H(\varsigma)$. In the equation, α is thermal expansion coefficient of MMC, ϑ is temperature rise induced by laser beam thermal shock. The coefficient $\beta_0(\varsigma)$ is given in [6] and the coefficient $H(\varsigma)$ can easily be obtained by integrating Wu's weight function [6] and thermal stress. The stress intensity factors can be used to predict the completely failure threshold.

For a pair of (σ_{max}, E_J), we can obtain the largest shear stress along the interface. It is assumed that the degradation of the reinforcement is negligible and the strength of interface and matrix is the same. It is easily calculated that the interfacial shear stresses τ_i are larger than the tensile strengths of matrix when the coupled loads (σ_{max}, E_J) are more than the thresholds. However, the largest normal stress in particle is lower than the strength of reinforcement SiC particle. The results explain that the initial crack is produced by the mechanism of void formation in the matrix and separation of void formation in the matrix and the reinforcement particles do not fracture. When the micro-cracks are formed in the notched region they may grow into macro-crack. It was found that the strain rate at crack tip is approximately $2.0\sim3.0\times10^3$/s. As a result of the high strain rates or the matrix hardening, the matrix yield stress increases significantly. Equivalently, the axial tensile stresses in reinforcement are so high that the stress intensity factor may exceed the SiC particle strength, i.e., the Griffith criterion.

The damage threshold is determined by the criterion that the largest shear stress is high than the interface strength. For a pair of (σ_{max}, E_J), we can obtain the largest shear stress along the interface. In this case, the damage threshold can easily determined and the results are shown in figure 4. For a pair of (σ_{max}, E_J), we can obtain the stress intensity factor K_I and energy release rate G_I. When the following condition is satisfied, the crack will propagate Δc

$$K_I \geq K_{IC} \text{ or } G_I \geq G_{IC} \quad \text{and} \quad \frac{\partial G_I}{\partial c} \geq \frac{\partial G_{IC}}{\partial c} \tag{4}$$

where the fracture toughness K_{IC} and crack-growth resistance G_{IC} of MMC at high temperature are taken from [7]. In this case, the failure threshold can be determined and the results are shown in figure 4. One can see that the theoretical results for both damage threshold and failure threshold are close their experimental results when the laser energy density E_J is low. When the laser energy density E_J is higher, the difference of theoretical results and experimental results become larger. It may be due to the neglect of visco-plastic deformation for MMC at high temperature.

5. CONCLUSIONS

The failure of particulate-reinforced metal matrix composites induced by laser beam thermal shock is experimentally and theoretically studied. It is found that the initial crack is occurred in the notched-tip region with the forms of void nucleation, growth and subsequent coalescence in the matrix or separation of the interface. It is further found that the process of the crack propagation occurred by fracture of particulate. The damage threshold and completely failure threshold could be described with a plane of far-field load σ_{max} with laser beam energy density E_J. A simple theoretical model was proposed to explain the damage/failure mechanism and to calculate the damage threshold and completely failure threshold.

ACKNOWLEDGEMENTS

Support for this research program was provided partly by the NNSF of China (No. 19772043) and the great research item (KJ951-1-201) of Chinese Academy of Sciences.

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Shiguo Long was born in Hunan Province, China on February 21, 1972. I am studying for Ph. D. degree in Xiangtan University now. I received my B. S. and M. S. degree at Xiangtan University in 1996 and 1999. During last five years I have taken part in the following projects as an important member: "Failure of Ceramic-Reinforced Metal Matrix Composites Induced by Laser Bean Thermal Shock" which was supported by the National Natural Science Foundation of China. Now my research areas are damage and fracture of particle reinforced metal matrix composite induced by coupled loads of mechanical and thermal load. I have published 10 papers within the domain of materials and mechanics.