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THERMAL FAILURE MECHANISM AND THRESHOLD OF SiC PARTICULATE REINFORCED METAL MATRIX COMPOSITES

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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 damage threshold and completely failure threshold.

KEYWORDS

Thermal failure, Particulate-reinforced metal matrix composites, Laser beam, Damage and failure mechanism, Failure threshold

INTRODUCTION

Metal matrix composites (MMCs) 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 [2-4]. At the same time, there are mechanical loads acting on the structural components. The concentration of thermal stresses around defects often results in catastrophic failure. The damage analysis for these structures exposed to intense thermal shock and mechanical load will be required for MMC design and reliability analysis. In the present paper, the thermal failure mechanism and failure threshold of particulate-reinforced metal matrix composites were experimentally and theoretically investigated.

EXPERIMENTAL METHOD

SiC particulate/6061 Al composite was chosen as a model MMC system for this study. The composites with

15 wt pct SiC were fabricated by melt casting route, and as-cast ingots of the composite were subsequently extruded. Thermal shock is generated by an incident laser beam, which impinges normally to a single-edge notched specimen. The energy *E* of the laser beam ranges from 1 to 40J, with a power intensity of the order of 1.0×10^4 to $18.0\times10^4 W/cm^2$. It is a single pulse Nd:glass laser with a wavelength of 1.06μm. Laser beam was pulsed Nd:glass laser with a wave length of 1.06μm and a full width at half of the maximum (FWHM) of 250μs. 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.

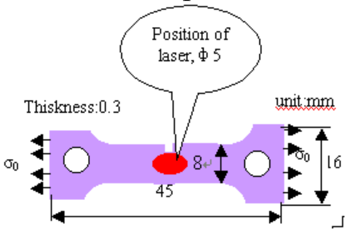


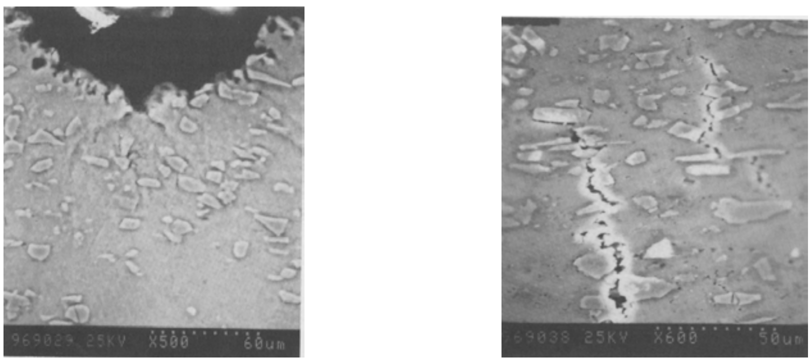
Figure 1: Schematic of the specimen configuration and dimensions

The shape of the notch is U-like. As well known, the maximum stress is located in notched tip with a coefficient of stresses concentration of α_σ=3.2 [3]. Therefore, the maximum stresses at the tip of the notch are $\sigma_{max} = \alpha_\sigma \sigma$. In experiment, the samples were subjected to the different coupled loads of mechanical load and laser shock intensity (σ_{max}, E_J).

EXPERIMENTAL RESULTS

Damage mechanism

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 phenomena could be observed by scanning electron microscopy. Figure 2 shows the typical SEM of damage characterization. Figure 2(a) is the micro-voids in the notched-tip region. It is observed that the voids occur in the form of interfacial debonding between the particles and the matrix and the micro-cracks occur in the matrix and interface. When the



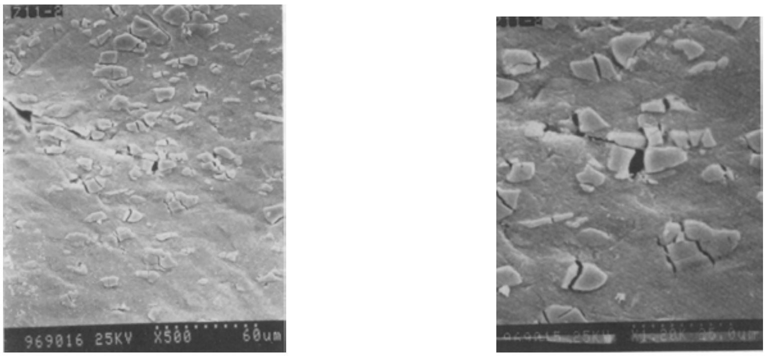
(a) (b)

Figure 2: Damage characterizations: (a) SEM of micro-voids in the notched-tip region, (b) radial cracking showing voids in matrix and the separation between SiC particle and matrix

reinforcement SiC particle is at the crack tip, the SiC particle does not fracture and resist the crack propagation. In order to understand the initial damage behavior of SiC particulate reinforced aluminum alloy matrix composite induced by laser beam thermal shock, the laser beam irradiated region was moved away from the notched-tip region. In this case, the radial crack appeared around the periphery of the laser beam as shown in figure 2(b). The radial crack occurred by the same mechanism as in figure 2(a). Therefore, one can conclude that the initial damage should be produced in the form of the separation of the SiC particle-matrix interface or in the form of void nucleation and growth within the matrix.

Crack propagation

When the thermal shock and mechanical loads were gradually increased, the damage became more and more serious. When the coupled loads (σ_{max}, E_J) were up to critical threshold, the micro-cracks formed in the notched region would grow into macroscopic cracks. The higher magnification SEM micrographs of macroscopic crack tip are shown in figure 3. As shown in the figure, the reinforcement SiC particle fracture is the dominant damage mechanism for macro-crack propagation. The reinforcements are broken by cracks perpendicular to the loading axis, and the fraction of broken reinforcements increases near the crack tip zone as shown in figure 3(b). 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 the macro-crack tip region, there was not damage in matrix and between the interfaces of matrix/particle.



(a) (b)

Figure 3: The failure characterizations in crack-tip: (a) macro-crack showing the cracked SiC particles, (b) phenomenon of SiC particles broken and no-damage of matrix in the crack-tip region

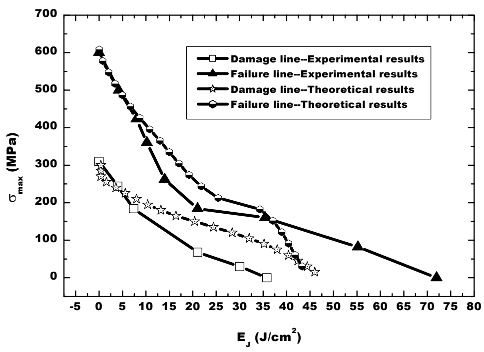


Figure 4: Damage and failure threshold plane

Damage and failure threshold

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 occurred in two forms, which were matrix failure as in the form of voids, and particle/matrix interface de-cohesion. 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 failure region, respectively. 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 MMCs 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. On the other hand, when the laser energy density is high enough, additional little mechanical load also makes the samples completely failure.

DISCUSSIONS

Theoretical model

As previously described, the mechanism of initial damage was void formation in matrix and separation of SiC particle-matrix interface. However, the mechanism of crack propagation was dominated by SiC particle fracture. Why is there the difference between the damage mechanism and crack propagation. 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 and Zok[5].The secant Young's modulus E^c of MMC was defined by the ratio of tensile stress to the tensile strain,

$$E^c = \frac{E^m}{1+\frac{3}{7}\left(\frac{\sigma^m}{\sigma_0^m}\right)^{\frac{1}{N}-1}} \left\{ \bar{\rho}(\varepsilon)(1-\gamma f - \xi f^2) + [1-\bar{\rho}(\varepsilon)][1+\bar{\alpha}\tan(3\pi f/4) + \bar{\beta} f^3] \right\} \tag{1}$$

where the superscript m indicate matrix, σ^m and ε are the axial stress and strain of matrix, respectively; σ_0^m is its yield stress; N is the hardening exponent, f is particle volume fraction, other variables are coefficients and they are given in [5].

It is well known that the reinforcement of a hard ceramic in a soft metallic matrix produces composites with substantially higher yield strength compared to that of the matrix. 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 [6]. They found that then stress and strain fields inside the inclusion were uniform. For tensile loads the largest normal stress always occurs at the poles of the inclusion. The largest shear stress along the interface is always at 45 degrees off the tensile direction. The largest normal stress in the particle and largest shear stress along the interface can easily obtained. 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,

$$K_I = K_I^m + K_I^T \tag{2}$$

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

$$K_I^m = F_I(\varsigma)\frac{\sigma_{max}}{\alpha_\sigma}\sqrt{\pi c} \tag{3}$$

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 [7].

One can obtain the thermal stress intensity factor K_I^T by using Wu's weight function as,

$$K_I^T = \Phi \sigma_0 \sqrt{\pi c} \tag{4}$$

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 [8] and the coefficient $H(\varsigma)$ can easily obtained by integrating Wu's weight function [8] and thermal stress. The stress intensity factors can be used to predict the completely failure threshold.

Damage mechanism

For a pair of (σ_{max}, E_J), we can obtain the largest shear stress along the interface which is shown in figure 5. The laser beam thermal shock will make the yield strength and tensile strength of matrix degrade at high temperature. It is assumed that the degradation of the reinforcement is negligible and the strength of reinforcement/matrix and the strength of matrix is the same. The interface strength is also shown in the figure.

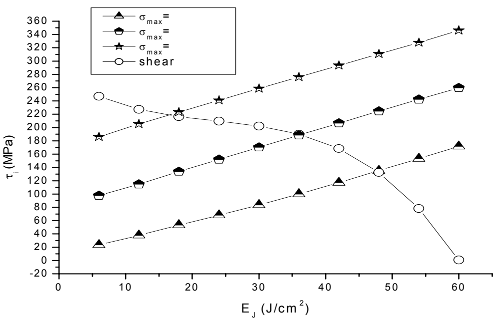


Figure 5: Largest shear stress along interface as a function of E_J for different σ_{max}

It is easily seen that the interfacial shear stresses τ_i may be 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 MMC is subjected to laser beam heating, the strength of the matrix will be degraded at elevated temperature. In other words, the matrix yield strength decreases. In this case, the particle loading through the interface is so low that the SiC particle cracking does not take place. But the localized thermal stresses due to the rapid changes in temperature may lead to the nucleation of micro-cracks within the matrix/reinforcing phase interface or in the matrix. More commonly, however, these thermal stresses lead to the growth of pre-existing cracks. If the applied stress is sufficiently large, these micro-cracks may grow into macroscopic cracks and lead to the propagation of the macro-crack.

Crack propagation mechanism

When the micro-cracks are formed in the notched region they may grow into macro-crack. As well known, the strain rate at the crack tip is very high in the case of macro-crack propagation. 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.

Damage and failure thresholds

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

$$K_I \geq K_{IC} \text{ or } G_I \geq G_{IC} \text{ and } \frac{\partial G_I}{\partial c} \geq \frac{\partial G_{IC}}{\partial c} \quad (5)$$

where the fracture toughness K_{IC} and crack-growth resistance G_{IC} of MMC at high temperature are taken from the [9]. 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 and higher, the difference of theoretical results and experimental results become larger and larger. It may be due to the neglect of visco-plastic deformation for MMC at high temperature. One can see the non-linear coupled effect of far-field mechanical load with laser beam thermal load on the MMC failure from the plane of $\sigma_{\max} - E_J$.

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, wherein the initial crack was induced by void nucleation, growth and subsequent coalescence in the matrix materials or separation of the interface. However, the process of the crack propagation occurred by fracture of the SiC particulate and it is very different from the crack initiation mechanism. 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. The model is based on the idea of stress transfer between reinforced-particle and matrix, and the calculation of far-field mechanical stress intensity factor and local thermal stress intensity factor. The theoretical model can explain the experimental phenomenon and predict the damage threshold and failure threshold. The failure of MMC induced by laser thermal shock and far-field mechanical load is non-linear coupled.

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