THERMAL FATIGUE OF MMC INDUCED BY LASER HEATING

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Summary The thermal fatigue of particle reinforced metal matrix composites (MMC) induced by laser heating and applied mechanical load was experimentally and numerically studied. It was found that the initial fatigue damage took place near the edge of laser-irradiated region. The initial damage was the form of the void nucleation, growth and subsequent coalescence in the matrix or the interface separation. The fatigue damage parameters were determined by ultrasonic method. The plane of mechanical load with the times of pulsed laser heating could be divided into three regions, i.e. non-damage region, damage region and failure region. The damage processing was numerically investigated by finite element method. The fields of temperature, macroscopical stress and microscopical stress induced by the laser heating and tensile load were numerically obtained. The simulative results were good agreement with the experimental results.

INTRODUCTION

MMC are excellent candidates for structural components in the aerospace and automotive industries due to their high specific modulus, strength, and thermal stability [1]. The structural components applied for those industries are often subjected to thermal and mechanical loads simultaneously [2]. The thermal and mechanical loads are usually cycled. Thermal load will lead to intense thermal stress concentration in the components of MMC because of the mismatch of thermal and mechanical properties between the metal matrix and ceramic reinforced particle. Such a concentration of thermal stress around defects often results in catastrophic failure of components. Therefore, it is necessary to study the properties of MMC subjected to the combined loads with thermal and mechanical cycled loads.

Generally, the thermal fatigue is produced by quenching method. Here, a new method of multi-pulsed laser beam heating the specimen was used to produce thermal fatigue. In the new method, the rate of temperature rise, i.e. the thermal fatigue intensity, could be easily controlled by adjusting the laser intensity and laser heating region.

EXPERIMENTAL PROCEDURE

SiC particle/6061 aluminum alloy composites was chosen as a model MMC system for this study. The composite with 15-vol. pct SiC was fabricated by melt casting route, and as-cast ingots of the composite were subsequently extruded. The average size of the reinforced particle is $10\mu m$. Fig.1 is the schematic of the specimen configuration. In the figure, the geometrical parameter, a, is the radius of the multi-pulsed laser irradiation region. When the multi-pulsed laser irradiated on the specimen, the mechanical load, i.e. the applied tensile mechanical stress, σ, was applied on the two end of the specimen simultaneously. The frequency, f, of the laser is $10Hz$. The full width, FW, of one pulse laser was $4ms$. The spatial distribution of the laser intensity was non-Gaussian, which was roughly uniform within the laser-irradiated region and declined very sharply toward the edge where the laser spot terminated. The total energy, E, of one pulsed laser is $20J$.

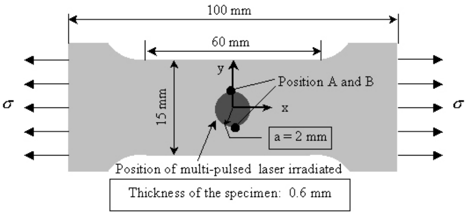

Fig. 1 The schematic of the specimen configuration and loads model

In order to study the evolution of the damage on the surface of the specimen, when the pulsed laser heating times were up to the designed times, the pulsed laser heating was paused. Then the surface of the specimen was observed by SEM and the time of an ultrasonic traveled in the specimen was measured to determine the damage of the specimen. After that, the specimen was again heated and loaded. The surface of the specimen was again observed and the damage was again measured. In this case, the damage evolution of the specimen due to the pulsed laser thermal fatigue and mechanical load could be understood.

EXPERIMENTAL RESULTS

For the thermal load induced by the laser with above parameters and the mechanical load of $\sigma = 100MPa$, after 600 times laser heated, Fig.2(a) shows the microstructure on the surface of the specimen at position A, where the position A is near the edge of laser-heating region as shown in Fig.1. One could find that the damage had taken place and the damage form was the voids in matrix and the debonding of interface. There was no fractured particles. Through much observations, we could have the conclusions that the damage initially took place at the positions A and B as shown in Fig.1, wherein, the initial damage was induced by void nucleation, growth and subsequent coalescence in the matrix or separation of interface. Fig.2(b) shows the microstructure on the surface of the specimen at position A after 1200 times laser heated. One could find that the damage forms were the voids in matrix, the debonding at interface as well as the fracture of particles.

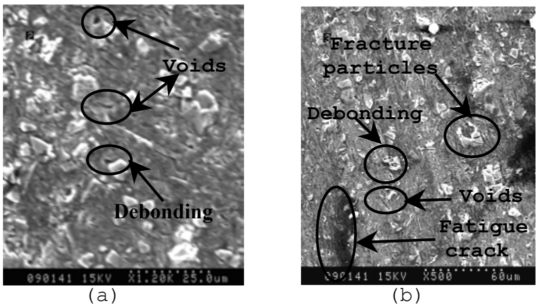

Fig.2 The microstructure on the surface at position A, (a) 600 times laser heating, (b) 1200 times laser heating

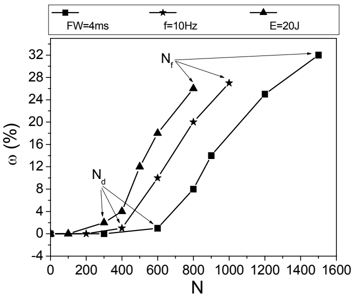

Fig.3 The fatigue damage parameters determined by ultrasonic method

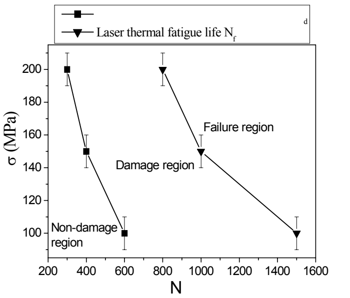

Fig.4 The plane of mechanical load and times of pulsed laser heating

The fatigue damage parameters, ω, were determined by ultrasonic method as shown in Fig.3. It was found that the varied level of the damage parameters was very different for different fatigue stage. According to the fatigue damage curves, the parameters of laser thermal fatigue damage threshold, N_d, and laser thermal fatigue life, N_f, were defined as shown in Fig.3. The plane of mechanical load and times of pulsed laser heating could be divided into three regions, i.e. non-damage region, damage region and failure region as shown in Fig.4.

FINITE ELEMENT SIMULATION

In the simulation, it was assumed that the particle was elastic and the matrix was elastic-plastic. The stress-strain relationships of MMC were dependent on the temperature. Fig.5 shows the stress fields, σ_{xx}, on the laser heating surface at the time of $3ms$. The figure shows that the maximum tensile stress occurred at positions A and B(as shown in Fig.1). Therefore, the damage would initially take place at position A and B. The results are good agreement with the experimental results.

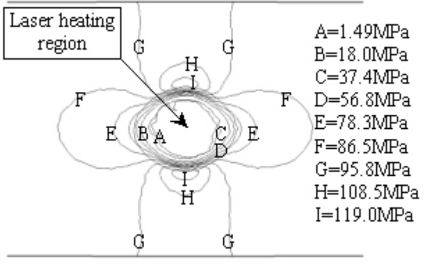

Fig.5 The stress field, σ_{xx}, on the laser heating surface

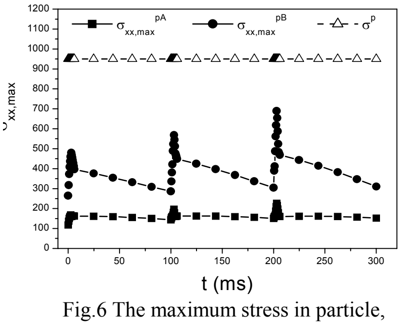

Fig.6 The maximum stress in particle, $\sigma^{p}_{xx,\max}$, and particle strength, σ^{p}

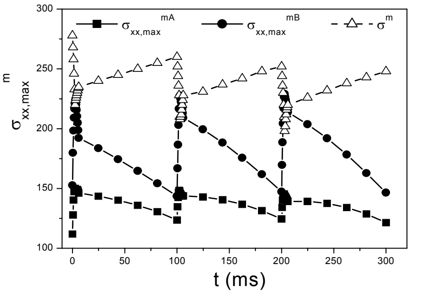

Fig.7 The maximum stress in matrix, $\sigma^{m}_{xx,\max}$ and matrix strength, σ^{m}

Fig.6 is the histories of the maximum stress, $\sigma^{pA}_{xx,\max}$, in the round particle and $\sigma^{pB}_{xx,\max}$, in the square particle as well as the particle strength, σ^{p}. Fig.7 is the histories of the maximum stress, $\sigma^{mA}_{xx,\max}$, in the matrix for round particle model and $\sigma^{mB}_{xx,\max}$, in the matrix for the square particle model as well as the matrix strength, σ^{m}. The figures show that the matrix is more easily damage than particles induced by thermal fatigue and mechanical load and the square particle is more easily fractured than round particle.

CONCLUSIONS

The thermal fatigue of MMC induced by laser heating and applied mechanical load was experimentally and numerically studied. The initial fatigue damage position and form were found. The fatigue damage parameters were determined by ultrasonic method. The plane of mechanical load with the times of pulsed laser heating could be divided into three regions, i.e. non-damage region, damage region and failure region. The damage processing was numerically investigated by finite element method. The simulative results were good agreement with the experimental results.

References

[1] Llorca J.: Fatigue of particle and whisker-reinforced metal matrix composites. Progress Mater Sci 47: 283-353, 2002

[2] Long S. G.: Determination of damage parameter in particle reinforced metal matrix composite by ultrasonic method. J. Mater Sci Lett 22: 911-913, 2003