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Dynamic properties and asymmetry of tension and compression of metal matrix composites under impact loading

H. Chenguang, Z. Rongjing, D. Zhuping and R.K.Y. Li*

LNM, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100080, P.R. China
** Department of Applied Physics and Material Sciences, City University of Hong Kong, Hong Kong, China*

Abstract. The mechanical behaviors of 2124, Al-5Cu, Al-Li and 6061 alloys reinforced by silicon carbide particulates, together with 15%SiCw/6061 alloy, were studied under the quasi-static and impact loading conditions, using the split Hopkinson tension / compression bars and Instron universal testing machine. The effect of strain rate on the ultra tensile strength (UTS), the hardening modulus and the failure strain was investigated. At the same time, the SEM observations of dynamic fracture surfaces of various MMC materials showed some distinguished microstructures and patterns. Some new characteristics of asymmetry of mechanical behaviors of MMCs under tension and compression loading were also presented and explained in details, and they could be considered as marks to indicate, to some degree, the mechanism of controlling damage and failure of MMCs under impact loading. The development of new constitutive laws about MMCs under impact loading should benefit from these experimental results and theoretical analysis.

1. INTRODUCTION

Metal matrix composite (MMC) has been considered as an important and promising material in the last three decades, because of its high specific stiffness and strength, as well as its perfect mechanical behaviors under high temperature. Especially, when the particulate or whisker is used as reinforcement, the MMC can be produced and processed by the traditional tools and techniques, and this kind of MMC is applied widely [1].

The research on dynamic properties of various MMCs under high strain rate has been very active and fruitful during the last several years in order to meet the demand of weapon development and other special industries. Bless *et al.* [2] found that some MMCs showed much stronger ability of withstanding the high velocity penetration up to 300% than that of the pure matrix. In the experimental results given by Marchand *et al.* [3], an interesting and useful phenomenon was that the critical stress intensity factor increased with the enlargement of strain rate for a part of MMCs. In 1988, Harding and his co-workers [4] presented that the tensile failure strain of SiC/2124 alloy raised obviously under impact loading obtained by Hopkinson bar testing devices. Many researchers, inspired by these important experimental results, turn to investigate the dynamic behaviors of MMCs from different directions and scales. Vaidya *et al.*, Hong and his co-workers [5,8,9] discussed and explained the effects of interface and microstructure on the dynamic properties of Al alloy reinforced by SiC and B_4C particles. Tvergarrd, Needleman, *et al.* [6,7] studied numerically the effects of volume content, shape, distribution of the reinforcement materials and mechanical properties of matrix on the macroscopic mechanical responses of MMCs by finite element method.

In this paper, a set of modified Hopkinson bar device was developed to investigate the dynamical behaviors of some Al alloys reinforced by SiC particulates and whiskers. New characteristics about the asymmetry of tension and compression properties (yielding, flow stresses and strength) were described in details and explained. It was put forward that the distribution of residual thermal stress, interface condition, strength of matrix and reinforcement jointly controlled the properties of the asymmetry.

2. EXPERIMENTAL SETUP AND RESULTS

2.1 Testing of macroscopic mechanical properties of MMCs

Fig.1 described the newly developed split Hopkinson devices, which was based on the 1-D elastic wave principle. The high-speed motion of the bullet was caused by the propulsion of high-pressure air in the chamber. The device was composed of tension section, compression section and a public air chamber, which was linked with a high-pressure container or an air pump with the pneumatically controlling system. Assorting to the progress of testing device, An advanced analysis software was developed, which was based on the traveling wave theory and included the acquisition and treating of signal waveforms from the strain gauges stuck on input and transmission bars.

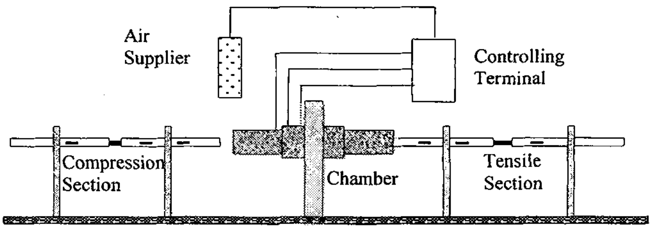


Figure 1. The set-up of new-type Hopkinson Bar

In the paper, the tested MMCs included the 15%SiC/Al-Li, provided by Goodfellow company, 15%SiC/Al-5Cu, 15%SiC/2124, 30%SiC/6061 and 20SiCw/6061 manufactured by the Research Institute of Metal, Chinese Academy of Sciences. The element constituents of various MMCs were shown in the Tab.1. And all the materials were heat-treated with T6 aging except for15%SiC/Al-Li.

Table 1. The elements constituent of various MMC materials

Number	Reinforcement, size	Matrix	Al(%)	Cu(%)	Mg(%)	Li(%)	Mn(%)
1	15%SiC_p(~20μm)	Al-Li	81	1.2	0.8	2.	/
2	14.8%SiC_p(3~5μm)	Al-5Cu	80.66	4.51	/	/	/
3	15%SiC_p(3~5μm)	2124	78.19	5.783	0.663	/	0.35
4	17%SiC_w(~μm)	6061	81.45	0.61	0.36	/	0.15
5	30%SiC_p(3~5μm)	6061	68.44	0.218	0.359	/	0.25

The compression sample was a cylinder with the dimension of $\phi 10\times 12mm$. The dumbbell-like tensile sample, was connected with the input bar and the transmission bar by screw threads at its two ends.

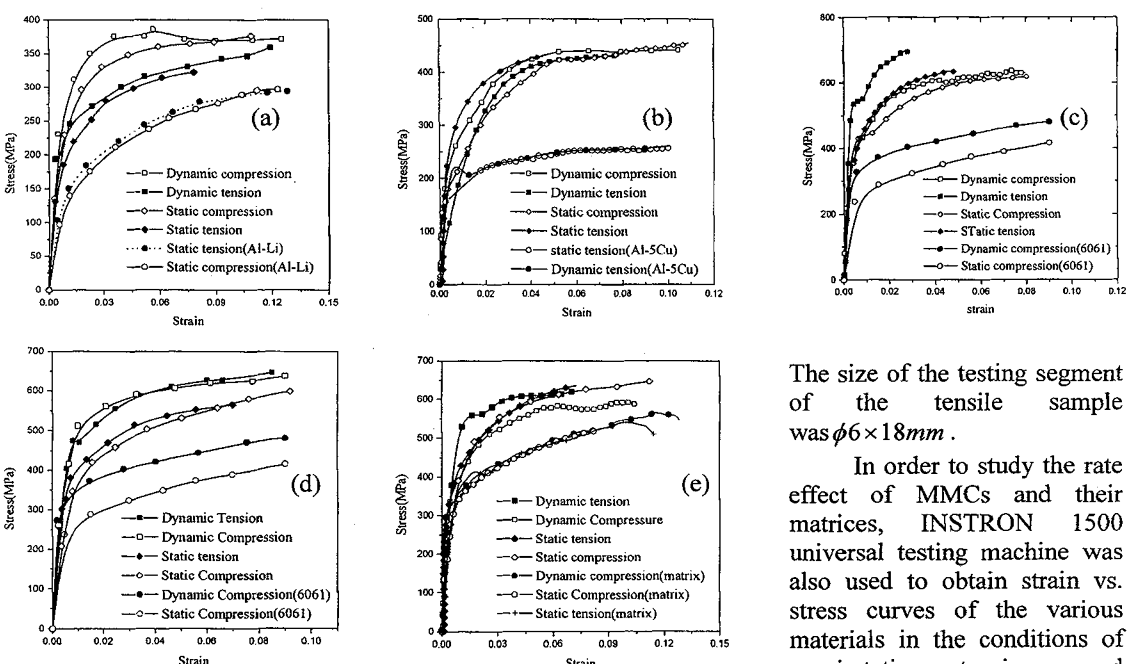


Figure 2. The curves of strain vs. stress of various metal matrix materials and their matrices(a) 15%SiCp/Al-Li (b) 15%SiCp/Al-5Cu (c) 15%SiCw/6061 (d) 30% SiCp/6061 (e) 15%SiCp/2124

The size of the testing segment of the tensile sample was $\phi 6\times 18mm$.

In order to study the rate effect of MMCs and their matrices, INSTRON 1500 universal testing machine was also used to obtain strain vs. stress curves of the various materials in the conditions of quasi-static tension and compression.

Fig.2 (a)~(e) showed the

tension/compression strain-stress curves of MMC materials listed in the Tab.1, and their matrices under impact loading and quasi-static loading. The effects of strain rate on the strength, failure strain and the strain hardening could be concluded from these curves.

It was found that the dynamic tensile strength of 6061 alloy reinforced by SiC whiskers and particles increased with the increment of strain rate. While, the strength of other MMC materials was not sensitive to the loading rate in the region of the strain rate involved in the paper.

In general, the strain rate sensitivity of MMC materials depended on the sensitivity of matrices, because the reinforcement could be considered of rate-independence. And though the interface phase played a very important role in the damage and failure of MMC materials, its effect on the rate sensitivity was very weak because of its low percentage in composition. The proposition was testified by our experimental results. Fig.2 showed that only 6061 aluminum alloy expressed higher strength with the increases of the loading rate.

Fig.3 described the failure strain of various MMCs under quasi-static and impact loadings. Two different and paradoxical tendencies about the effect of strain rate on the elongation of MMC samples were obtained. For 15%SiC/Al-Li, 15%SiC/Al-5Cu and 30%SiC/6061, the failure strain enlarged with the increment of strain rate, but for 15%SiCw/6061 and 15%SiC/2124 alloy, the conclusion was opposite. The former was almost the same as the observations presented by J. Harding and his co-workers [4]. The increment of failure strain meant that the voids in matrices grew and coalesced in more stable manner under high strain rate, rather than the plastic deformation ability enhanced. The TEM observations of dislocation density in deformed matrices showed that the dislocation density was independent on the strain rate [10]. However, when the breakage of whiskers and particles turned into controlling mechanism of MMC failure, as 15%SiC/6061 and 15%SiC/2124, the effect of strain rate on the failure strain would not follow the explanation given by Harding.

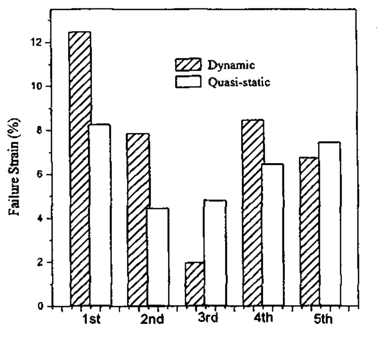


Figure 3. The effect of loading rate on the failure strain of MMCs materials.
1st: 15%SiC/Al-Li 2nd: 15SiC/Al-5Cu 3rd: 15%SiC_w/6061 4th: 30%SiC/6061 5th: 15%SiC/2124

As to the strain hardening of the above MMC materials, our experiments indicated that under impact loading the strain hardening of MMC increased more rapidly in the early stage of plastic flow, as compared with the low strain rate condition. However, the strain hardening modulus of MMCs decreased fleetly after certain plastic deformation under high strain rate. The effect of reinforcement on the strain hardening modulus of MMC materials could be described with the following equation,

$$\Theta = \eta(\Theta_h - \Theta_r - \Theta_{ad} + \Theta_{str}) \tag{1}$$

where Θ_r represents softening effect resulting from the dynamic recovery, Θ_{ad} and softening owing to the damage and temperature rising, Θ_{str} denotes the pure structural effect and can be depicted with the inclusion theory, which is neglected by many researchers. η is the modifying coefficient, including the some complex factors, Θ_h denotes the effect of increment of dislocation density in matrix and plays the controlling role in rate sensitivity of hardening modulus of MMC materials.

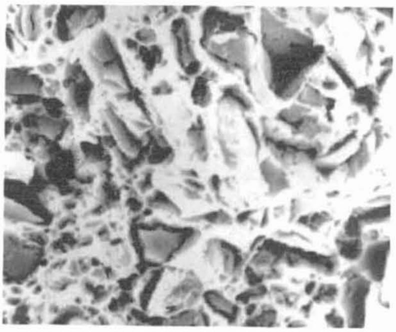
In general, the dislocation density can be written as [11],

$$\rho_d = M(\dot{\varepsilon}) \tag{2}$$

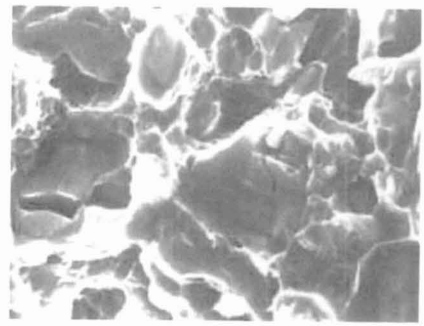
where ρ_d denotes the dislocation density, $M(\dot{\varepsilon})$ is a monotone increasing function of $\dot{\varepsilon}$. Then, this was the reason why hardening modulus of MMCs increased in higher speed in the condition of high strain rate in the early stage of plastic flow.

2.2 SEM observations of fracture surfaces

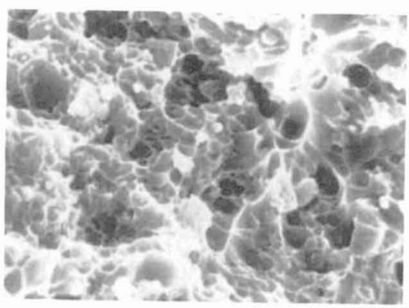
The SEM observations about the fracture surfaces of dynamic tensile samples showed several different microscopic textures and characteristics. Fig.4 (a) displayed the representative debonding of interface, with a small amount of breakage of large particulates in the 15%SiCp/Al-Li. Fig.4(b) indicated that the controlling failure mechanism of 15%SiCp/2124 alloy should be the cracking of small size reinforcement ($\sim 3\mu m$), and the large plastic deformation occurred in the matrix with the fine dimple texture and without the interface damage. For the 15%SiCw/6061 alloy, an important matter that resulted in the failure was the breaking of whiskers, shown in Fig.4(c), that was very rare in the condition of relatively low strain rate. Under quasi-static loading, the failure mechanism of 6061 alloy reinforced by SiC whiskers was thought as the nucleation and evolution of damage of interface and matrix near the angular points. Fig.4(d)~(e) presented that the failure of matrices was the direct factor causing integral fracture of composites when the strength of matrix materials was very low or the volume content of reinforcement was high enough, as 15%SiCp/Al-5Cu and 30%SiCp/6061 alloy.



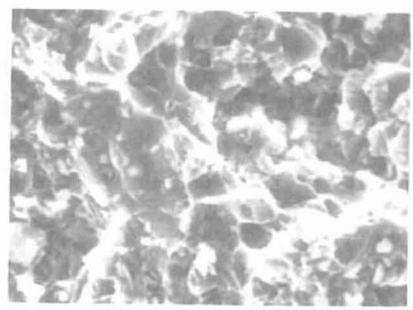
30μm, 4(a)



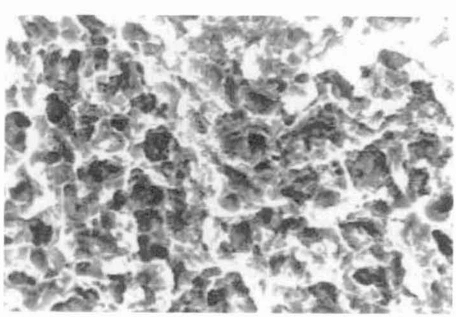
10μm, 4(b)



5μm, 4(c)



15μm, 4(d)



10μm, 4(e)

Figure 4. The SEM photographs of fracture surface of MMCs samples. (a) 15%SiCp/Al-Li (b) 15%SiCp/2124 (c) SiCw/6061 (d) 30%SiCp/6061 (e) 15%SiCp/Al-5C

The SEM observations reported in our paper exhibited four typical failure mechanisms, which were determined by matching mechanical characteristics of different phases and interfaces, as well as the content, distribution, shape and size of the reinforcement. In the next section, the effect of different failure mechanisms on the asymmetry of tension/compression strength of MMCs would be discussed in some details.

3. DISCUSSIONS ON ASYMMETRY

For the MMCs listed in Tab.1, the asymmetry of flow strength of tension and compression was very obvious in any range of strain rate from $10^3 s^{-1}$ to $10^{-3} s^{-1}$ as shown in Fig.2, which had been explained with the thermal residual stresses due to the mismatch of thermal expanding coefficients (CTEs). From these explanations and the inclusion theory, only one type of asymmetry characteristics could be approved, that was, tensile strength of MMC reinforced by whickers along the direction of loading should be lower than its compression strength.

Two new phenomena about the asymmetry were displayed, one was for 15%SiCp/Al-Li, the asymmetry characteristics of flow stresses and strength still existed; the other was that the tensile strength of 15%SiCw/6061 alloy was larger than its compression strength under impact condition.

The first phenomenon could not be explained by the thermal residual stresses theory because the effect of mismatch stresses in matrices and reinforcement on the deviated stress component could be neglected for MMCs reinforced by particulates. The main mechanism, which resulted in such a kind of asymmetry feature, was that relatively large size and a mass of interfaces vertical to the loading direction would reduce the threshold of damage and failure, when the sample withstood the tensile loading. However, when the fracture of matrices or particulates, rather than interface phase, controlled the failure of MMCs, this kind of asymmetry feature would vanish, which was proved by our experimental results about 30%SiCp/6061, 15%SiCp/Al-5Cu and 15%SiCp/2124 alloy.

The strange asymmetry of 15%SiCw/6061 alloy, which was reverse to the general knowledge, was caused by the relatively weak reinforcement. Under dynamic loading, the strength of 6061 alloy increased obviously, which was verified by our experiments. On the other hand, the interface between the reinforcements and matrix was perfect, which had been examined by the high-resolution TEM [10]. According to the reference [1], the compression residual stresses existed in reinforcements along the loading direction and tensile stresses occurred in the matrix. Then, when the failure mechanism was fracture of whisker in 15%SiCw/6061, the higher tensile strength and lower compression strength was reasonable and acceptable.

The asymmetry properties of MMCs have been summarized in Tab.2, which could be thought, to some degree, as a macroscopic symbol to get insight into the microscopic failure mechanism.

Table 2. The summary of asymmetry feature of tensile and compression properties of MMCs

Reinforcement shape	Basic failure region	Asymmetry characteristics
Particulates	Particulates or Matrix	$\sigma_{tensile} \approx \sigma_{comp}$
	Debonding	$\sigma_{tensile} < \sigma_{comp}$
Whiskers	Whisker	$\sigma_{tensile} > \sigma_{comp}$
	Matrix of interface	$\sigma_{tensile} < \sigma_{comp}$

4. CONCLUDING REMARKS

In this paper, five different MMCs were selected to experimentally investigate the effect of strain rate on the hardening, strength, failure and failure strain. And SEM observations of failure surfaces showed some microscopic fracture characteristics. The main conclusions are concluded as follows.

1. The strain rate sensitivity of MMCs was determined by the rate-dependent properties of their matrices, which was discussed in details with experimental data and theoretical analysis.
2. The increment of strain rate could accelerate the strain hardening in the early stage of plastic deformation. The relation between failure strain and strain rate was so complex that it could not be determined if the research did not aim at a given MMC.
3. Two new asymmetry features about the tension/compression properties of MMCs were reported and explained. It must be mentioned that the discussions about asymmetry must include not only the thermal mismatch stresses but also the characteristics of damage and failure.

Acknowledgments

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