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Compressive behavior of high particle content B_4C/Al composite at elevated temperature

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Abstract: The compressive properties of the aluminum matrix composite reinforced with 55% B_4C (volume fraction) particles were characterized using Gleeble 3500 thermal-mechanical testing machine. The compressive stress—strain curves were obtained at the temperature ranging from 298 to 773 K and strain rate ranging from 1×10^{-3} to 5 s^{-1}. The results showed that the dynamic compressive strength decreased more slowly than the quasi-static compressive strength at elevated temperatures, which was attributed to the different failure modes of the composite under dynamic and quasi-static load. The strain rate sensitivity increased from 0.02 to 0.13 when the temperature increased from room temperature to 773 K, suggesting that the strain rate sensitivity of this type of composite is a function of temperature.

Key words: B_4C; composite; compressive properties; strain rate; high temperature

1 Introduction

The high particle content (particle content greater than 50% in volume fraction) aluminum composite (including Al_2O_3/Al, B_4C/Al, SiC/Al and etc.) is a kind of promising material for the combination of good structural properties (i.e., high hardness, high modulus and low specific gravity) and excellent functional properties (e.g., low thermal expansion coefficient and high heat conductivity). These composites can be potentially applied to structural components in auto/aerospace industry, and functional substrates in the electronic packaging field.

There are three types of high ceramic content composites including discontinuously reinforced composites (DRCs), interpenetrating phase composites (IPCs) and concrete-like composites [1−6]. In DRCs, metal matrix is continuous and ceramic particles are separated with each other. The deformation behavior is dominated by the enhanced matrix. In IPCs, both metal and ceramic phases are continuous and interpenetrating throughout the microstructure. Both the metal phase and the ceramic phase can singly bear the external load. The concrete-like composite is such named due to its peculiar microstructures. The microstructures are similar to those of geologically derived cemented granular materials. Differing from the DRCs and IPCs, the solid particles are densely packed and the molten alloy is injected into the gap to stick to the particles in this composite. The metal matrix is continuous but the ceramic phase should be taken as semi-continuous since particles contact with each other but no molecular association occurs. The concrete-like composite is mainly fabricated by injecting the molten liquid metal into the particle preform. The mechanical behavior of the matrix can directly affect the load carrying capacity of the particle skeleton and thus to the performance of the composite.

In the last decades, the mechanical behaviors of concrete-like composites at room temperature have been widely investigated. KOUZELI and MORTENSEN [7] studied the tensile behaviors of 46%−58% (volume fraction) Al_2O_3/Al and B_4C/Al composites. They found that the tensile properties of the composite were significantly influenced by geometrically necessary dislocations. MARCHI et al [8] measured the compressive properties of 40%−55% Al_2O_3/Al composites under quasi-static and dynamic loading. It was reported that the composite showed significant strain-rate sensitivity due to the strain-rate sensitive matrix. TAN et al [9,10] and ZHU et al [11] investigated the dynamic mechanical responses of composites with particle content varying from 45% to 60% by split Hopkinson pressure bar (SHPB). They discovered that

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the material failure was significantly affected by the heat generated during adiabatic compression. LIU et al [12] reported that the composite with smaller particles was less sensitive to the heat generation than that with larger particles under impact load when the particle volume fraction was the same. However, to the best of our knowledge, the deformation behavior and failure mechanism of this concrete-like composite at elevated temperatures have yet been investigated.

In the present work, the compressive tests of 55% B_4C/Al composite at elevated temperatures were carried out using a Gleeble 3500 thermal-mechanical testing machine. The effect of temperature on the deformation behavior and strain rate sensitivity of the composite was investigated. Corresponding mechanisms were elucidated in the present work.

2 Experimental

B_4C particles with average diameter of 20 μm were selected as reinforcements and high purity aluminum (99.99%) was used to fabricate the MMCs via the squeeze casting method. Initially, B_4C particles were dry pressed to a preform with particle volume fraction to 55%. Then, the molten Al (1023 K) was poured onto the pre-heated preform (823 K) in a steel die. A pressure of 40 MPa was applied subsequently. Finally, the as-made B_4C/Al composites were air-cooled to room temperature for compressive tests.

Microstructures and the fracture surfaces of the composite were observed by a JSM−6460 scanning electron microscope (SEM). The compressive tests were carried out on a Gleeble 3500 thermal-mechanical testing machine under displacement control. The specimens of each group were placed into the machine, where the specimens were heated to the temperature of 473, 573, 673 and 773 K respectively by induction heating. The temperature was kept constant for 5 min to homogenize the temperature in the specimens. In order to investigate the different deformation behaviors under quasi-static and dynamic load condition, three strain rates including 1×10^{-3}, 1×10^{-1} and 5 s^{-1} were employed for the study. The dimensions of cylindrical compressive specimens were d10 mm×15 mm. In addition, the different failure modes under different temperature and loading rate were observed and compared by a Cannon camera.

3 Results

3.1 Microstructure

The SEM microstructure of the B_4C/Al composite reinforced with 20 μm particles is shown in Fig. 1. B_4C particles are distributed uniformly in the composite. There are not any obvious cast defects such as porosity and shrinkage cavities in the composite. It is seen that the contact point retains after the infiltration of the melted aluminum.

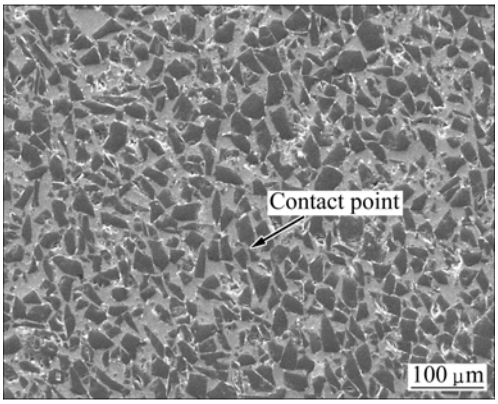

Fig. 1 SEM image of B_4C/Al composite

3.2 Stress—strain curves

Figure 2 gives the compressive engineering stress—strain curves of B_4C/Al composite obtained at elevated temperatures with strain rate ranging from 1×10^{-3} to 5 s^{-1}. It can be seen that the ultimate compressive strength, whatever the strain rate is, decreases when the temperature of the specimen increases from 298 to 773 K. When the strain rate is 1×10^{-3} s^{-1}, the ultimate compressive strength decreases from 420 to 68 MPa. When the strain rate is 5 s^{-1}, the ultimate compressive strength decreases from 490 to 155 MPa. The ultimate strain of all tested specimens increases with increasing deformation temperature due to the softening of the matrix. In addition, the flow stress of the composite increases as the strain rate increases from 1×10^{-3} to 5 s^{-1} at all temperature levels. However, the increasing amplitude is different at various temperatures.

4 Discussion

4.1 Stress and strain behaviors at elevated temperatures

Figure 3 shows the variation of ultimate compressive strength of the composite with elevated temperature. The temperature has little effect on the compressive strength of the composite when it is below 473 K. However, the quasi-static compressive strength and dynamic compressive strength decrease with increasing temperature from 473 to 773 K.

In order to facilitate the comparison, Fig. 4 gives the decreased ratio of ultimate quasi-static to dynamic compressive strength of B_4C/Al composite when the temperature increases from 298 to 773 K. The decreased ratio of compressive strength is defined as follows:

$$R=\frac{\sigma_T}{\sigma_{298\text{K}}} \tag{1}$$

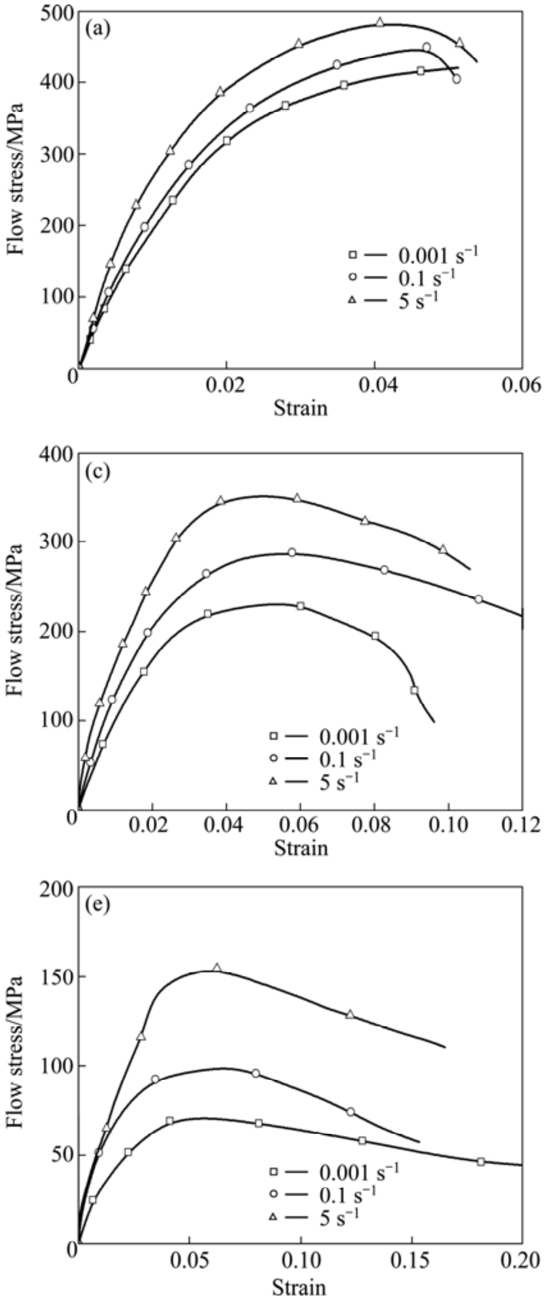

Fig. 2 Compressive stress—strain curves of B_4C/Al composite obtained at elevated temperatures and strain rates: (a) 298 K; (b) 473 K; (c) 573 K; (d) 673 K; (e) 773 K

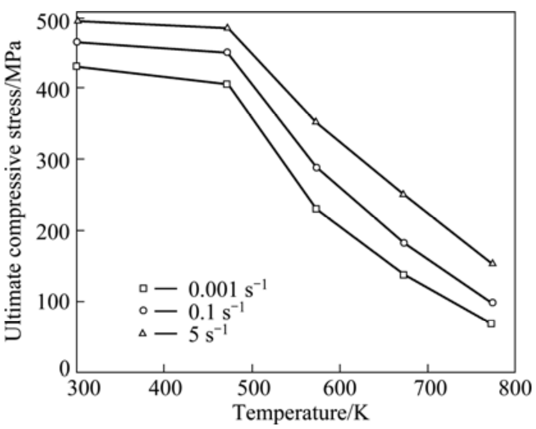

Fig. 3 Variation of ultimate compressive strength of composite with elevated temperature

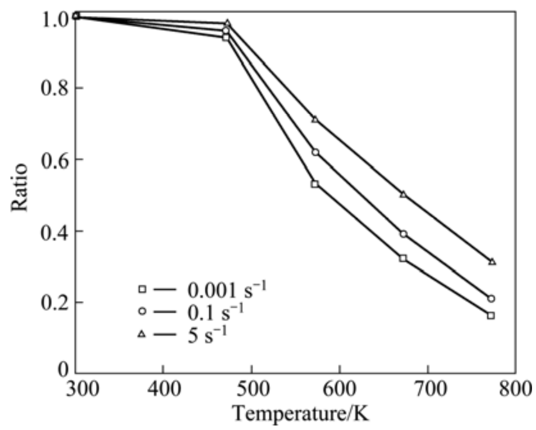

Fig. 4 Decreased ratio of quasi-static and dynamic compressive strength at various temperatures

where R is the strength ratio, σ_T is the compressive strength at temperature T and σ_{298K} is the compressive strength at 298 K. The decreased ratio is defined to 1 at 298 K. When the temperature increases from 473 to 773 K, the ratio decreases from 1 to 0.16 for 1×10^{-3} s^{-1}, and it decreases from 1 to 0.32 for 5 s^{-1}. This indicates that dynamic compressive strength decreases more slowly than the quasi-static compressive strength at elevated temperatures.

The external load must be equal to the load borne by the constituents, which gives rise to the condition:

$$(1-\varphi_p)\sigma^m+\varphi_p\sigma^p=\sigma \tag{2}$$

where φ_p is the volume fraction of the ceramic reinforcement; σ is the applied stress; σ^m and σ^p are the average stresses in the matrix and reinforcement, respectively. The temperature should have little effect on the load capability for ceramic particles because of the higher ceramic melting point. While, it can lead the metal matrix to be softened or even be melted. If the particles can bear the external load as much as possible, the composite will exhibit high compressive strength at high temperatures.

ZHAN [13] studied the rheological behavior of pure aluminum and found that the decreased ratio of the flow stress for pure aluminum will increase with increasing strain rate at high temperatures. Therefore, accounting for the different decreased compressive strength ratios, it can be deduced that the particles play a more important role under dynamic load than under quasi-static load at elevated temperatures. Figure 5 represents the typical failure modes of the composite at various loading rates. When the loading rate is 1×10^{-3} s^{-1}, the composite shows a shear failure mode at both 473 K and 673 K. The specimens are divided into two integrated parts when destroyed. However, when the loading rate is 5 s^{-1}, the composite shows a crush mode whatever the temperature is. The specimens are divided into multi-block once been destroyed. The failure modes exhibit a transition from creep phenomenon to multiple micro-cracking with the increase of the strain rate.

For the concrete-like materials, two different deformation mechanisms between quasi-static and dynamic load were investigated by former researchers [14−16]. Under quasi-static loading, the deviatoric stress field may cause the particles to move relatively to one another by slip, and the relative movements result in the onset of shear localization. Under dynamic loading, the local stress concentration near the particle contacts may be sufficiently high for particle skeleton crushing to occur. SONG and LU [17] studied the dynamic compressive behavior of concrete by a mesoscopic model. It was argued that the phenomenon of propagating damage under high rate loading enabled the mobilization of the strength of concrete, which was attributed to the increasingly higher stress in the particles as the strain rate increased. Therefore, the external load carried by the particles of the composite increases with the increase of strain rate, and the composite compressive strength at 5 s^{-1} decreases more slowly than that at 1×10^{-3} s^{-1} with elevated temperatures.

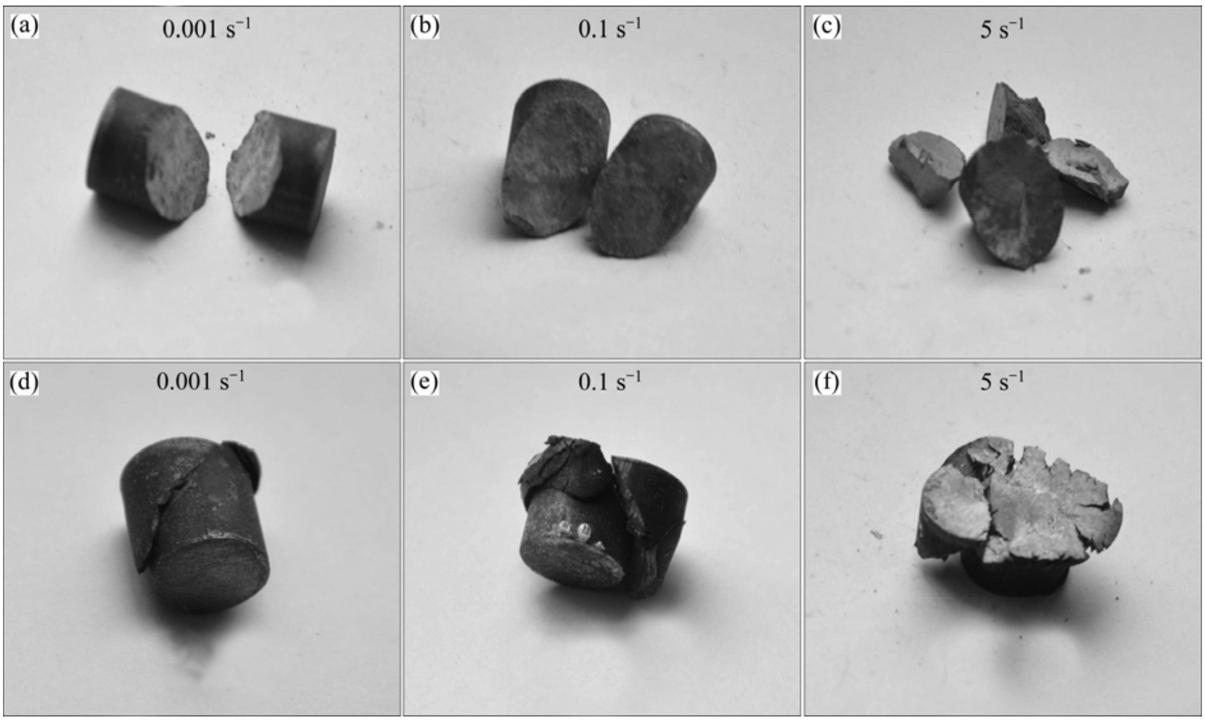

Fig. 5 Failure modes of composite at various strain rates: (a−c) 473 K; (d−f) 673 K

In addition, it can be seen in Fig. 2 that the fracture strain increases with increasing deformation temperature at all strain rate levels. Figure 6 shows the typical fracture surfaces of the composites at 473 and 673 K. Sliding trace of the particles can be observed on the fracture surface of the composite at 473 K. However, the particles are wrapped up by the matrix on the fracture surface of the composite at 673 K and no sliding traces are observed. When the temperature is low, the matrix is strong, and the deformation compatibility between the matrix and the particle skeleton is poor, which results in the higher flow stress and lower fracture strain. When the temperature is high, the matrix is softened and the particles in the composite can slide or roll easily. The particle skeleton is unstable and the deformation behavior is dominated by the matrix, which results in the lower flow stress and higher fracture strain.

4.2 Strain rate sensitivity at elevated temperature

The high particle content B_4C/Al composite shows an increasing tendency at strain rate ranging from 1×10^{-3} to 5 s^{-1}, as seen in Fig. 2. However, the increasing compressive strength amplitude at 298 K is increased by 18%, which is smaller than that at 773 K whose increasing amplitude is increased by 113%. This indicates that the strain rate sensitivity increases at elevated temperatures. The strain rate sensitivity proposed by HONG et al [18] is defined as follows:

$$S=\frac{\sigma_{\mathrm{d}}-\sigma_{\mathrm{s}}}{\sigma_{\mathrm{s}}}\frac{1}{\ln(\dot{\varepsilon}_{\mathrm{d}}/\dot{\varepsilon}_{\mathrm{s}})} \quad (3)$$

where S is the strain rate sensitivity; σ_d and σ_s are the dynamic and quasi-static flow stress at a constant strain respectively; $\dot{\varepsilon}_d$ and $\dot{\varepsilon}_s$ are the corresponding strain rates for dynamic and quasi-static loading. In this work, the strain of 5% and the corresponding flow stress as in Ref. [8] are chosen to calculate the strain rate sensitivity of the composite.

Figure 7 gives the reported strain rate sensitivity of 55%Al_2O_3/Al and B_4C/Al composites at room temperature [8,10] and the calculated strain rate sensitivity of 55%B_4C/Al composite at elevated temperature. It is observed that the reported strain rate sensitivity for Al_2O_3/Al or B_4C/Al composites is between 0.02 and 0.03 at room temperature. The strain rate sensitivity of 55% B_4C/Al composite is 0.02 at the temperature of 298 K, and it increases to 0.13 with increasing temperature to 773 K. Obviously, it can be concluded that the strain rate sensitivity at high temperature is larger than that at low temperature for the concrete-like composite.

MARCHI et al [8] and LI et al [19] suggested that the strain rate sensitivity of composite was correlated to the rate sensitivity of matrix alloy, and this effect would be enlarged by the increase of particle content. The pure aluminum was reported to have a rate sensitivity parameter of about 0.02 in the strain rate ranging 1×10^{-4} to 1×10^{3} s^{-1} [8]. The reported strain rate sensitivities for Al_2O_3/Al and B_4C/Al composites at room temperature are all around 0.02. However, the strain rate sensitivities of B_4C/Al composite at 573, 673 and 773 K are much

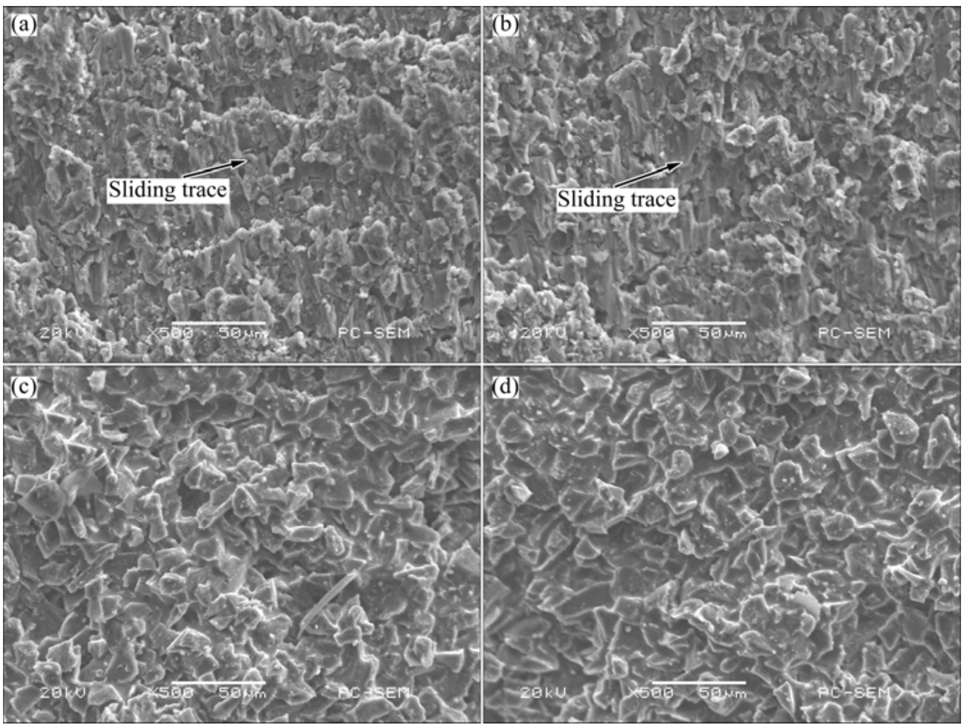

Fig. 6 Typical fracture surfaces at elevated temperatures: (a) 473 K, 0.001 s^{-1}; (b) 473 K, 5 s^{-1}; (c) 673 K, 0.001 s^{-1}; (d) 673 K, 5 s^{-1}

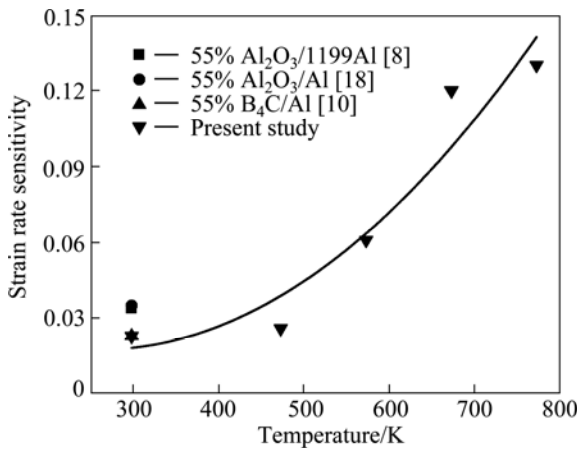

Fig. 7 Effect of temperature on strain rate sensitivity of aluminum composite

larger than 0.02. The strain rate effect of the metal matrix is well known to be caused by the dislocation blocking. Under dynamic loading, the deformation is so fast and the dislocations have not enough time to slip, which results in the increase of the flow stress. The increase of the temperature is benefited to the dislocation slipping and would decrease the strain rate sensitivity of the matrix alloy. However, the fact is that the strain rate sensitivity of the composite increases with decreasing strain rate sensitivity of the matrix. ZHU et al [11] pointed out that the strain rate sensitivity can be enhanced by the particle skeleton in the concrete-like composite because the external load can be transferred directly via particle skeleton. However, further detailed information needs to be discussed.

For the concrete-like materials, TOPIN et al [20] found that the matrix in the composite had not only a bulk effect with respect to load transfer but also a surface effect with bonding materials to inhibit the relative particle movements in the vicinity of particle contacts. At the same time, in the concrete-like composite, there are two ways for the particles to carry load in compressive behavior. One is caused by the elastic mismatch between the particles and matrix. The other one is due to the formed particle skeleton. The second way for the particles to carry external load depends strongly on inter-granular bond matrix material properties. Failure or sliding occurs when the shear stress across a bond exceeds the inherent matrix shear strength. Furthermore, under dynamic load, the stress distributed on the particles increases as the strain rate increases, which enhances the strain rate sensitivity of the composite [17]. When the temperature is low, the matrix is strong and the particles carry much load by aforementioned two ways under quasi-static load. When the temperature is high, the matrix is softened and the particles carry little load by aforementioned two ways under quasi-static load. The difference results in a greater number of particle failures under low temperature than that under high temperature [21]. Therefore, the proportionate increase in strength should be greater for the high temperature test when, at higher strain rate, the strength increase is gained partly by the propagation of cracks through the particles [21], as seen in Fig.5. In brief, the high temperature softens the metal matrix and results in larger proportionate increase of particle stress than that at low temperature, thus to affect the strain rate sensitivity of B_4C/Al composite.

5 Conclusions

1) The compressive strength of B_4C/Al composite at 5 s^{-1} decreases more slowly than that at 1×10^{-3} s^{-1} under elevated temperatures. The composite fails from creep phenomenon to multiple micro-cracking with the increase of the strain rate, which results in the increase stress of the particles.

2) The strain rate sensitivity of the composite increases from 0.02 to 0.13 when the temperature increases from 298 to 773 K. This is because the proportionate increased stress undertaken by particles should be greater under high temperatures than under low temperatures.

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高颗粒含量 B_4C/Al 复合材料的高温压缩力学行为

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摘 要：利用 Gleeble 3500 热模拟机对高颗粒含量 B_4C/Al 复合材料进行了温度范围为 298~773 K，应变率范围为 1×10^{-3}~5 s^{-1} 的单轴压缩力学行为测试。结果表明：由于高颗粒含量 B_4C/Al 复合材料在动态载荷和静态载荷作用下的破坏方式不同，导致了在高温条件下复合材料的动态强度随温度的下降速率要小于静态强度的下降速率。当温度从室温升高到 773 K 时，复合材料的应变率敏感指数从 0.02 增加到 0.13，该现象表明，该高颗粒含量复合材料的应变率敏感指数是温度的函数。

关键词：碳化硼；复合材料；压缩性能；应变速率；高温

(Edited by Hua YANG)