DOI 10.1007/s11223-016-9753-4
Strength of Materials, Vol. 48, No. 1, January, 2016

THE SOURCES AND AFFECTING FACTORS OF CREEP THRESHOLD STRESS OF MAGNESIUM-BASED COMPOSITES

J. Tian UDC 539.4

Tensile creep experiments were carried on AZ91D magnesium alloy and aluminum silicate short fiber-reinforced AZ91D magnesium matrix composite. The creep threshold stress of AZ91D composite depends on the Al atoms solute atmosphere, the bearing and transferring force of short fiber. Threshold stress decreases with temperature and increases with the short fiber volume fraction and the load transfer coefficient α*, but the extent of increase drops with the amount of* β*-*$Mg_{17}Al_{12}$ *precipitation phase. The load transfer coefficient* α *characterizes the bearing and transferring capabilities of short fibers. As a result, the mathematical model of threshold stress in the magnesium matrix composite has been developed.*

Keywords: magnesium matrix composite, creep, threshold stress, AZ91D, load transfer coefficient.

Introduction. Currently, a lot of research has been conducted on the high-temperature creep properties and behavior of metal matrix composites [1, 2]. Many researchers underlined that there is a threshold stress and the creep is not generated when the applied stress is below that limit value [3, 4].

So far, there is no creep theory yet, which could explain all peculiarities of the creep process. The core research issues are the dislocation mechanisms at the second phase and the sources of threshold stress. The sources and physical meaning of creep threshold stress and the way of quantitative expression have not been determined yet. Some researchers believe that the creep threshold stress is due to interactions between mobile dislocations and precipitated phase in he matrix [5, 6]. A one-dimensional micromechanical model, which is based on the law for interfacial sliding, has been developed for thermomechanical deformation of continuous fiber-reinforced metal matrix composites [7]. Based on the recent studies on Al_3Sc coherent precipitates, non-coherent dispersion of Al_2O_3 reinforcing phase and aluminum alloy composite strengthening, the synergetic effect of the two constituents has been discovered. Furthermore, the total threshold stress is the sum of stress and back stress. The former is generated when mobile dislocations field is imposed by coherent precipitates to the mobile dislocation [8]. Dispersion-strengthened Al-Mg alloys are similar to pure ones from the standpoint that creep deformation is related to dislocation climb and dislocation – solute drag. The threshold stresses in the two materials are related to the function of mobile dislocation density, dislocation velocity and solute concentration in the dislocation core [9]. However, the creep studies focus on the dispersion strengthening, particle reinforcement or long fiber reinforced metal matrix composites. There are few studies of high-temperature creep in short fiber-reinforced metal matrix composites. For example, the assessment of back stress and load transfer approaches for rationalizing creep of short fiber-reinforced aluminum alloys has been demonstrated [5]. Chmelik et al. [2] studied the creep properties and behavior of unreinforced AZ91 magnesium alloy and a similar alloy reinforced with short alumina fibers, and has revealed that addition of short alumina fibers to an AZ91 magnesium alloy improved the creep resistance due to introduction of a threshold stress reducing the effective stress acting on the material [10]. Sklenička et al. [1] conducted creep tests on an AZ91–20 vol.% Al_2O_3 short fiber composite and unreinforced AZ91 matrix alloy, and the results obtained showed that creep resistance of

School of Mechanical Engineering, Dongguan University of Technology, Dongguan, China (841608534@qq.com). Translated from Problemy Prochnosti, No. 1, pp. 197 – 208, January – February, 2016. Original article submitted August 3, 2015.

the reinforced material was considerably improved, as compared with the matrix alloy, while the creep strengthening arose mainly from the effective load transfer between plastic flow in the matrix and the fibers. However, the sources of threshold stress of metal matrix composites reinforced with short fibers have not been explained. Nowadays, the research and development of magnesium matrix composites play an increasinly important role in automotive and aerospace industries. Therefore, it is necessary to conduct a systematic, experimental and theoretical analysis on the creep behavior and mechanism of short fiber-reinforced magnesium matrix composites. Here, the constant stress tensile creep tests are conducted on two kinds of metal materials for different temperatures and stresses. One is aluminum silicate short fiber-reinforced AZ91D composite with different fiber volume fractions, the other being AZ91D magnesium alloy. The nature of the threshold stress and the affecting factors of aluminum silicate short fiber-reinforced AZ91D composite are investigated intensively to obtain a reasonable explanation and insights of the source of creep threshold stress in aluminum silicate short fiber-reinforced AZ91D composite, which is yet a controversial issue. The aim of this study is to promote practical application of the material and enrich the creep theory of short fiber-reinforced magnesium matrix composites through the original findings.

Experimental Procedure. The materials were prepared by squeeze casting method with aluminum silicate short fiber and AZ91D magnesium matrix alloy (Mg-9%Al-1%Zn-0.3%Mn, the percentage is mass fraction). The AZ91D magnesium matrix composite has proved to possess good bonding interface and mechanical properties and thus to provide effective reinforcement of composites. The preform of aluminum silicate short fiber is composed of randomly distributed aluminum silicate short fiber Al_2O_3-SiO_2, its diameter being no more than 5 μm and the length being less than 80 μm. The volume fractions of short fiber in the three metal materials after squeeze casting are 20, 25, and 30%, respectively. For the convenience of expression, the reinforced AZ91D magnesium matrix composite with 25% aluminum silicate short fiber is depicted as 25%Al_2O_3-SiO_2(sf)/AZ91D, where *sf* indicates a short fiber. AZ91D magnesium matrix composites and AZ91D alloy were both subjected to the tensile creep tests until the final creep rupture. The experiments were conducted using the GWT105 lasting test machine at 473, 523, and 573K, with the applied stresses of 30 to 100 MPa. The creep curves was constructed through linear variable displacement transducer (LVDT) data acquisition system.

Results and Discussion.

High-Temperature Creep Curve. The curves of strain ε and strain rate $\dot{\varepsilon}$ of AZ91D alloy versus time t at $T = 473$ K, $\sigma = 60$ MPa are depicted in Fig. 1. The respective curves of 25%Al_2O_3-SiO_2(sf)/AZ91D composite versus time t at $T = 473$ K, $\sigma = 70$ MPa are shown in Fig. 2. It is evident that these two creep curves involve three stages of typical metal creep process: after generation of an initial deformation in an instant at the first phase, strain increases rapidly, while strain rate decreases gradually. The first stage is deceleration creep stage. When the strain rate decreases gradually to a stable value, the second stage of creep or the so-called steady creep stage starts. The peculiarity of this stage is that the creep strain increases almost linearly with time. The creep time of the steady creep stage accounts for a large share of the entire creep time. The third stage is creep damage stage, where the strain rate increases significantly until the material fracture. Temperature and load are the two main factors affecting the creep process. The steady-state creep time of AZ91D alloy at $T = 473$ K and $\sigma = 60$ MPa is about 12 h, while that of AZ91D composite at $T = 473$ K and $\sigma = 70$ MPa is about 100 h. The steady-state strain rate of the composite is lower than that of the alloy by one order of magnitude. It is clear that the creep resistance of the composite is much higher than that of the alloy at the same temperature and similar external stress.

Indexes of Creep Threshold Stress and True Stress. If there is creep threshold stress σ_{th} in a metal material at fixed temperature, the strain rate equation of the metal material can be expressed with Eq. (1) derived in [11]. Formula (1) can be reduced to Eq. (2):

$$\dot{\varepsilon} = A(\sigma - \sigma_{th})^n, \tag{1}$$

$$\dot{\varepsilon}^{1/n} = A_1(\sigma - \sigma_{th}), \tag{2}$$

where A and A_1 are constants related to the material and temperature, n is the creep exponent, σ is the applied stress, σ_{th} is the threshold stress, and $\sigma - \sigma_{th}$ is referred to as the effective stress of the metal material. For the

TABLE 1. Creep Threshold Stress Values of Materials

Material	T, K	Threshold stress σ_{th}, MPa
AZ91D	473	41
	523	33
	573	31
20%Al_2O_3-SiO_2(sf)/AZ91D	473	50
	523	46
	573	37
25%Al_2O_3-SiO_2(sf)/AZ91D	473	53
	523	49
	573	39
30%Al_2O_3-SiO_2(sf)/AZ91D	473	57
	523	53
	573	42

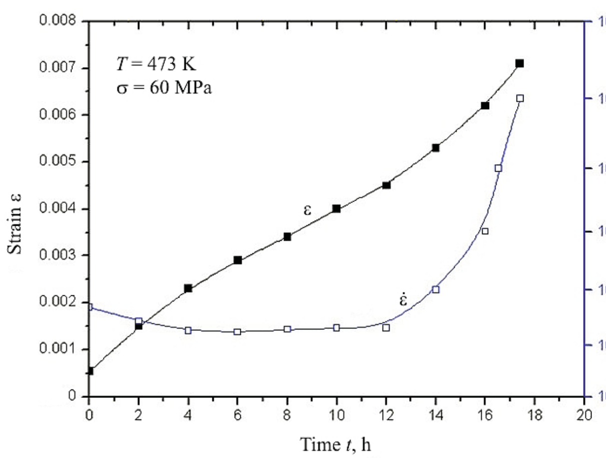


Fig. 1

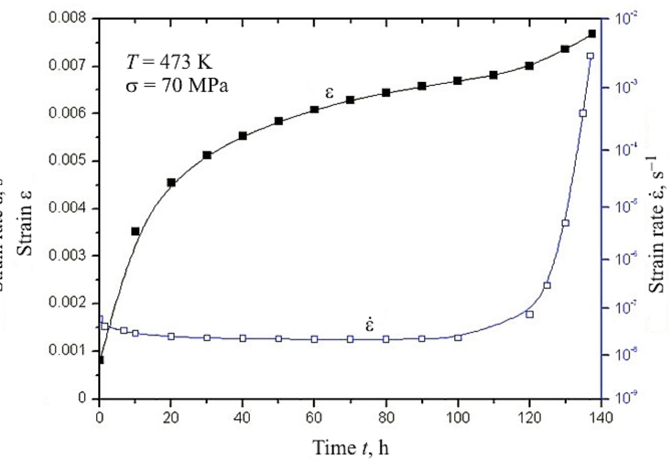
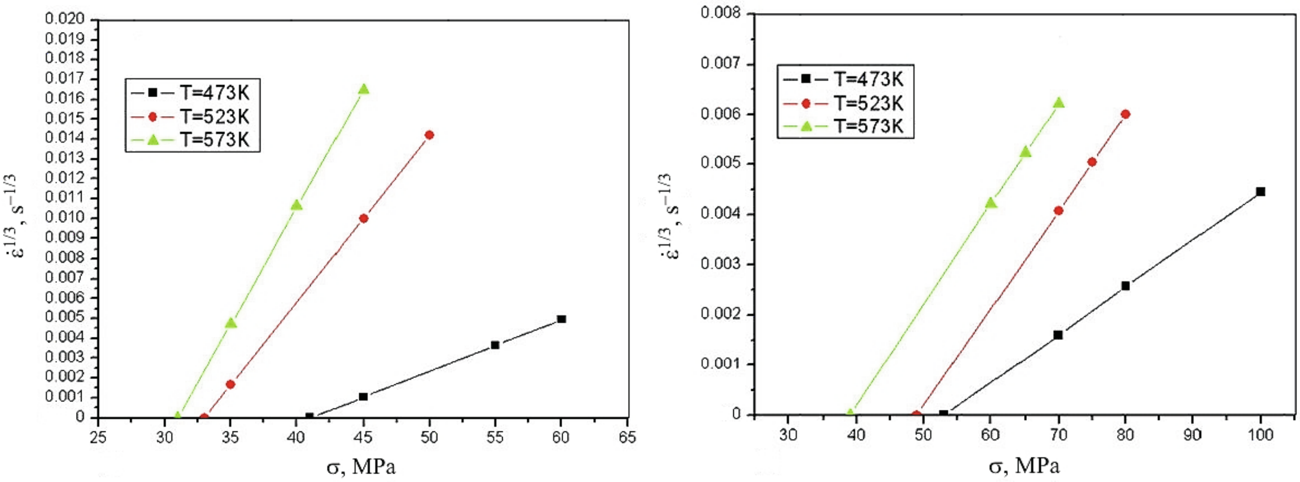


Fig. 2

Fig. 1. The creep and strain rate curves of AZ91D magnesium alloy at $T = 473$ K and $\sigma = 60$ MPa.
Fig. 2. The creep and strain rate curves of 25%Al_2O_3-SiO_2(sf)/AZ91D composite at $T = 473$ K and $\sigma = 70$ MPa.

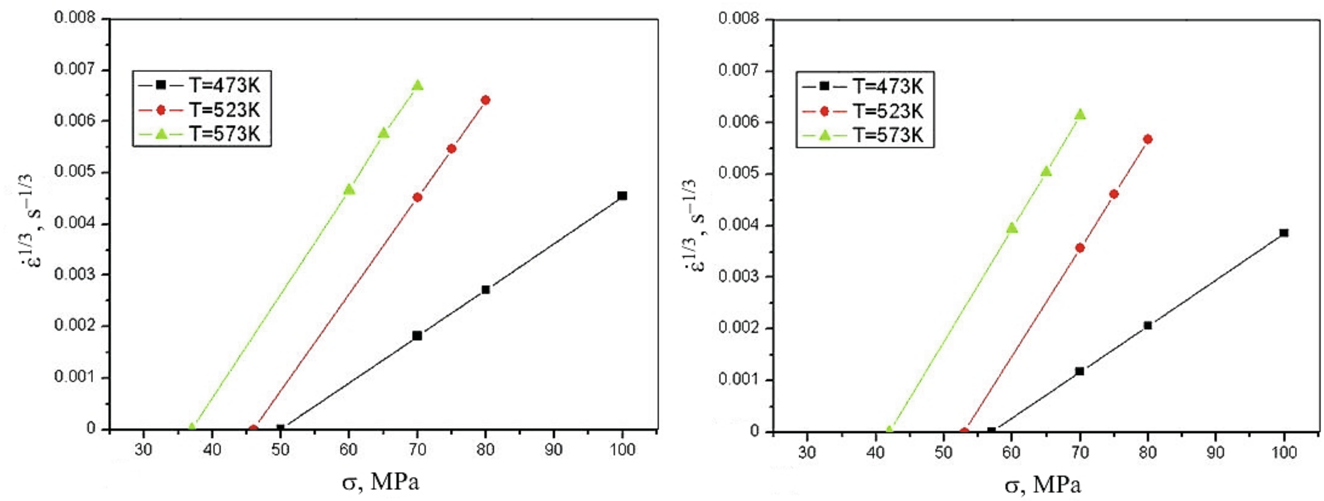
aluminum silicate short fiber-reinforced AZ91D magnesium matrix composite with different fiber volume fractions and AZ91D magnesium alloy, n values of 3, 5, and 8 are used to construct the best-fitting $\dot{\varepsilon}^{1/n} - \sigma$ diagram. In the diagrams with good linear relationships, where the corresponding values of n are the true stress indices, the true threshold stress can be assessed for different temperatures. The most close linear correlations between the composite and matrix alloy parameters are obtained when $n = 3$, as is shown in Figs. 3 and 4. The respective creep threshold stress σ_{th} values are given in Table 1.

Sources of the Creep Threshold Stress. Non-equilibrium solidification, the segregations of Mg solid-solution Al-poor (magnesium dendritic crystals) and Al-rich (solidification of remaining liquid) regions are formed in the casting-state structure of AZ91 alloy. Al-rich area is composed of white intermediate phase β-$Mg_{17}Al_{12}$ or black β-$Mg_{17}Al_{12}$+α-Mg eutectic phase. The phase of AZ91D in cast state is mainly composed of α-Mg and β-$Mg_{17}Al_{12}$ [12]. When creep occurs at high temperature, the solute Al in supersaturated α-Mg solid solution will firstly segregate in the grain boundary to form the Al atoms' air mass. Next, the non-continuous precipitation of lamellar or rod-like β-$Mg_{17}Al_{12}$ phase will occur in the form of particles. The coarsening-induced softening of β-$Mg_{17}Al_{12}$ will decline creep resistance of AZ91D alloy. At the moment, only α-Mg matrix will continue to prevent the creep



a b

Fig. 3. The $\dot{\varepsilon}^{1/3}-\sigma$ plots of AZ91D alloy (a) and 25%Al_2O_3-SiO_2(sf)/AZ91D composite (b).



a b

Fig. 4. The $\dot{\varepsilon}^{1/3}-\sigma$ plots of 20%Al_2O_3-SiO_2(sf)/AZ91D (a) and 30%Al_2O_3-SiO_2(sf)/AZ91D (b) composites.

process. α-Mg matrix is solid solution, so the solute Al atoms' atmosphere, which is formed by the segregation of solute Al in the α-Mg solid solution in the grain boundary, is followed by dislocation motion through diffusion. Because the diffusion rate is lower than slip rate of dislocation, the solute Al atoms' atmosphere will drag the movement of dislocation. The drag attraction of mobile dislocation generates the threshold stress. The threshold stress of AZ91D magnesium alloy is 41 MPa at $T = 473$ K. It is visible that solute Al atoms' atmosphere generates a strong pinning on mobile dislocation, which is the source of threshold stress of AZ91D alloy.

Most of the nanoparticles in the surface of aluminum silicate short fiber-reinforced AZ91D composite are MgO particles, while a small share $MgAl_2O_4$ particles is also available [12]. It is obvious that there is a layer of nanoparticles on the fiber surface of the composite under high-temperature creep conditions. Most of the nanoparticles are uniform MgO particles with a layer thickness of about 0.2 μm [12]. The reinforcement of the composite is achieved, i.e., the bearing and mass loading capabilities of short fibers are enhanced. The threshold stresses of AZ91D alloy at $T = 473$ and 573 K are 41 and 31 MPa, respectively. Meanwhile, at the same temperature the threshold stresses of 25%Al_2O_3-SiO_2/AZ91D composite are 53 and 39 MPa, respectively. It can be seen that the threshold stresses of 25%Al_2O_3-SiO_2/AZ91D composite at $T = 473$ and 573 K are higher than those in the matrix by

12 and 8 MPa, i.e., by 29.3 and 25.8% respectively. The improvement can be attributed strictly to the effect of aluminum silicate short-fiber reinforcement.

In addition to α-Mg and β-$Mg_{17}Al_{12}$ phases, which can be observed in the matrix, there are $AlPO_4$, MgO, and $Al_2O_3 \cdot SiO_2$ phases in AZ91D composite [12]. Here α-Mg and $Al_2O_3 \cdot SiO_2$ are two major phases in AZ91D composite, and the mobile dislocation movement is mainly affected by these two phases. Other phases can be assumed to act through $Al_2O_3 \cdot SiO_2$. It can be considered that mobile dislocation motion is only affected by these two factors, provided a certain influence coefficient is introduced to describe the effects of other phases. Creep is generated when mobile dislocations overcome these two effects and start to move, and hereinafter the sum of the two forces is the threshold stress. During the process of high-temperature creep, solute atmosphere will attract the mobile dislocation, which is part of the sources of the threshold stress of AZ91D composite. The solute atmosphere is formed by the segregation of Al atoms at the grain boundary in the supersaturated α-Mg solid solution. Because the elastic modulus of AZ91D matrix is smaller than that of aluminum silicate short fiber, the strain of matrix is larger than that of short fiber under external loads, and dislocations in the matrix will undoubtedly be dragged by the short fiber. The drag force on mobile dislocation, which is generated from the inconsistency of the strains of matrix and short fiber, is the bearing and transferring force of the short fiber, i.e., another constituent of the source of the threshold stress in AZ91D composite.

The Impacts of Load Transfer Factor and Material Impacting Factor. When creep is generated in AZ91D alloy and mobile dislocations leave the solute atmosphere, a kind of stress will form. Friedel [13] called the threshold stress that exists in alloy as breakaway stress σ_b, and the stresses at creep in the alloy can be expressed by means of the following expressions:

$$\sigma_b = \frac{W_m^2 c}{5b^3 kT}, \tag{3}$$

$$W_m = -\frac{1}{2\pi}\left(\frac{1+\mu}{1-\mu}\right) G |\Delta V_a|, \tag{4}$$

where W_m is the binding energy of dislocations and solute, c is the solute concentration (Al atom concentration, $c = 0.08$), b is the Burgers vector of dislocation, $b = 3.2 \cdot 10^{-10}$ m, G is the shear modulus of Mg, $G = 1.92 \cdot 10^4 - 8.6T$, k is the Boltzmann constant, $k = 1.3806505 \cdot 10^{-23}$ J/K, T is the absolute temperature, ΔV_a is the volume difference caused by the difference of Mg and Al atomic radius, $\Delta V_a = 8.2 \cdot 10^{-30}$ m^3, and μ is Poisson's ratio of Mg, $\mu = 0.34$. However, Eq. (3) overestimates the value of stress σ_b and fails to estimate the variations of the elastic interaction energies of dislocations and solute atmosphere. The variations of the energies are caused by the variations of solute atoms concentrations, while the latter are caused by variations of the distances between line dislocations and solute atoms. Therefore, the value of σ_b calculated by Eq. (3) exhibits more than a 2-fold increase. Hence, both the concentration of Al atom and the coefficient c in Eq. (3) will be reduced. If the concentration of aluminum atom changes from 0.08 to 0.06 and the value in Eq. (3) is multiplied by a factor of 1/2, it can be obtained that $\sigma_b = 42$ MPa, at $T = 473$ K. The result is close to the experimental stress of AZ91D alloy, $\sigma_b = 41$ MPa. Therefore, Eq. (3) can be rewritten as Eq. (5) to obtain the empirical formula of threshold stress of AZ91D alloy (breakaway stress):

$$\sigma_b = \frac{1}{2}\frac{W_m^2 c_1}{5b^3 kT}, \tag{5}$$

where c_1 is the reduced solute concentration (Al atom concentration, $c_1 = 0.06$).

With Eq. (5), the creep threshold stresses of AZ91D alloy at $T = 523$ and 573 K are obtained as 35 and 32 MPa. The results are very similar to the experimental results of $\sigma_{th} = 33$ MPa ($T = 523$ K) and $\sigma_{th} = 31$ MPa ($T = 573$ K), which confirms that formula (5) possesses a good accuracy.

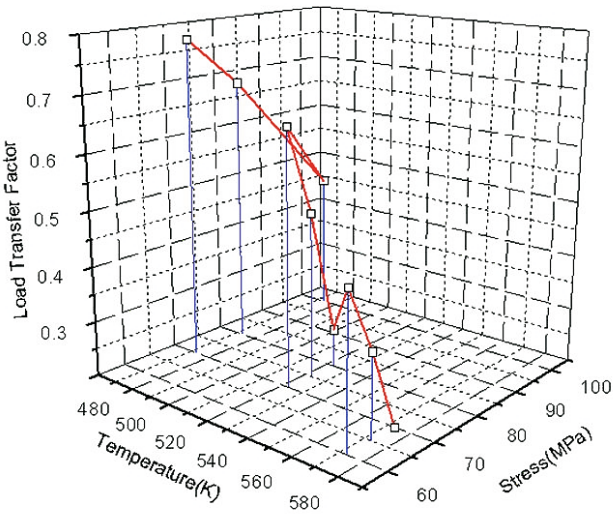


Fig. 5. The $\alpha - T - \sigma$ plot for 25%Al_2O_3-SiO_2(sf)/AZ91D composite.

The other part of the threshold stress in AZ91D metal materials is the loading and transferring force of short fibers, which is affected by many internal factors such as orientation, aspect ratio and distribution of short fibers, the availability of MgO particles on surfaces and the interface of short fibers and matrix. Thus, the calculation of force is quite complicated. In order to estimate the force, one can simply calculate it by multiplying the load transfer capacity by the material influence coefficient H, which comprehensively reflects the internal factors, which affect the force, and can be obtained through the experimental data.

When AZ91D composite creeps under certain temperature T and certain stress σ, the load transfer capacity of aluminum silicate short fiber reinforcement is equal to the product of the load transfer factor α and the external stress σ, which is $\alpha\sigma$. The loading and transferring forces of short fibers are equal to the product of load transfer capacity and material influence coefficients H. Thus, the mathematical model of threshold stress of AZ91D metal materials can be expressed with Eq. (6):

$$\sigma_{th} = \frac{1}{2}\frac{W_m^2 c_1}{5b^3 kT} + H\alpha\sigma. \tag{6}$$

Because of the varying lengths, fibers are randomly distributed in an approximately two-dimensional form. Strict dealing with load transfer is a highly complex issue in mechanics. As a simplified experimental method, a load transfer factor α has been introduced, which varies from 0 to 1: $\alpha = 0$ indicates no load transfer, while $\alpha = 1$ indicates that load is fully transferred to the short fiber. Thus, load transfer coefficient α characterizes the bearing and transferring load capacity of a short fiber. The empirical formula of composite strain rate can be expressed as Eq. (7) [11]:

$$\frac{\dot{\varepsilon}_c}{\dot{\varepsilon}_b} = (1-\alpha)^n, \tag{7}$$

where $\dot{\varepsilon}_c$ is the composite strain rate and $\dot{\varepsilon}_b$ is the martix strain rate.

With the strain rate values of matrix and 25%Al_2O_3-SiO_2(sf)/AZ91D composite within the experimental range, the diagram of load transfer factor corresponding to respective temperature and stress via Eq. (7) is plotted in Fig. 5, from which it is obvious that load transfer factor α is more sensitive to temperature than to stress. Fitting the space points with quadratic surface equation, the empirical formula of the load transfer factor α of Al_2O_3-SiO_2(sf)/AZ91D composite, which varies with temperature and stress, can be obtained as Eq. (8):

$$\alpha = 1.16\cdot 10^{-5} T^2 + 3\cdot 10^{-4}\sigma^2 - 2\cdot 10^{-4} T\sigma - 2\cdot 10^{-3} T + 4.06\cdot 10^{-2}\sigma + 1.441. \tag{8}$$

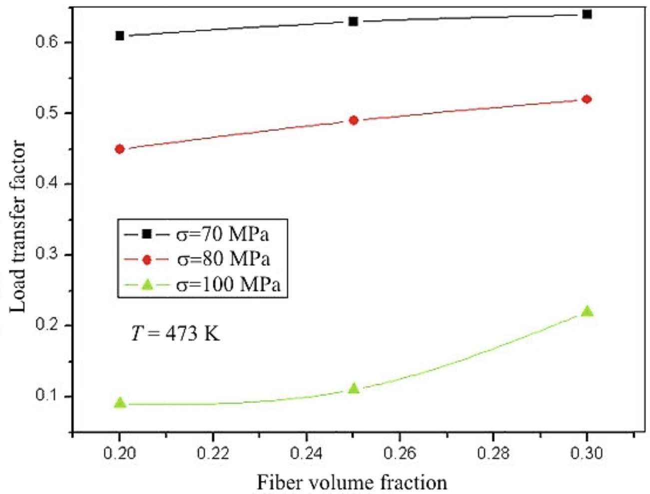


Fig. 6

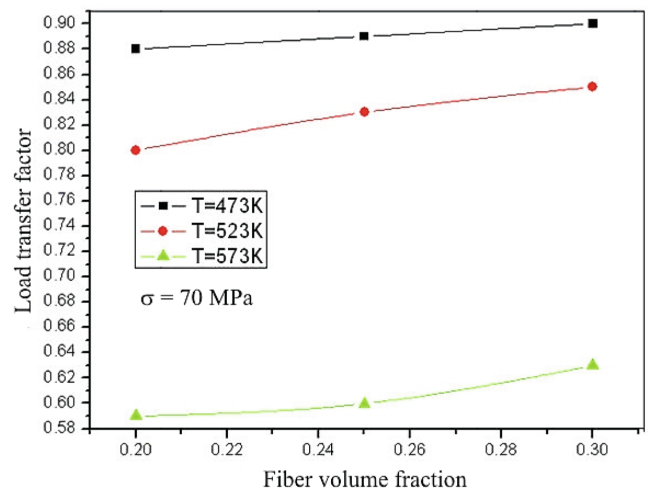


Fig. 7

Fig. 6. Load transfer factor dependence of fiber volume fraction for Al_2O_3-SiO_2(sf)/AZ91D composite at the same temperature and different loads.
Fig. 7. Load transfer factor dependence of fiber volume fraction for Al_2O_3-SiO_2(sf)/AZ91D composite at the same load and different temperatures.

Of course, as for the Al_2O_3-SiO_2(sf)/AZ91D composites with different volume fractions, the load transfer factors are also affected by the volume fractions. The diagrams of fiber volume fraction versus the load transfer factor of Al_2O_3-SiO_2(sf)/AZ91D composite are plotted at the same temperature and different loads in Fig. 6. At the same temperature and low external loads, the impact of fiber volume fraction on load transfer factor is not obvious. However, the effect becomes more manifested with the increase of external load. Similarly, at the same loads and lower temperatures, the impact of fiber volume fraction on load transfer factor is not strongly pronounced in Fig. 7, while the effect becomes more obvious as the temperature increases. The main reason is that the effects of temperature and load on the load transfer factor are stronger than the influence of volume fraction. Temperature and load affect the rate of increase of load transfer, which rises with the volume fraction.

With the creep threshold stresses of 25%Al_2O_3-SiO_2(sf)/AZ91D composite, which are obtained in the test range via formulas (6) and (8), the diagrams of material impact factor versus temperature and stress have been constructed in Fig. 8. Parameter H is more sensitive to temperature than to stress. Fitting the space points with quadratic surface equation yields the empirical formula of material impact factor of 25%Al_2O_3-SiO_2(sf)/AZ91D composite versus temperature and stress, which is expressed by Eq. (9):

$$H = 1.25 \cdot 10^{-4} T^2 + 6 \cdot 10^{-3} \sigma^2 - 3 \cdot 10^{-3} T\sigma - 3.5 \cdot 10^{-2} T + 2.06 \cdot 10^{-1} \sigma + 2.712. \quad (9)$$

The threshold stresses of 25%Al_2O_3-SiO_2(sf)/AZ91D composite can be determined by formulas (6), (8), and (9). The experimental values of threshold stresses are also listed in Table 2. The theoretical values of the threshold stresses are similar to the experimental ones, indicating that application of formula (6) as the empirical formula of threshold stress of composite yields highly accurate estimates.

Influence of Volume Fraction of Short Fiber on Creep Threshold Stress. At the same temperature, the threshold stress increases with the aluminum silicate short fiber volume fraction, althoughe this increase is quite small (Table 1). The diagrams of fiber volume fraction versus threshold stress of Al_2O_3-SiO_2(sf)/AZ91D composite at different temperatures are depicted in Fig. 9. The increase rates of threshold stress versus fiber volume fraction are basically the same at different temperatures. Based on the above analysis, it may be concluded that the sources and affecting factors of threshold stresses of Al_2O_3-SiO_2(sf)/AZ91D metal materials with different fiber volume fractions are the same. With the increase in the number of aluminum silicate short fibers, the total drag forces increase. The

TABLE 2. Comparison of Theoretical and Experimental Values of Threshold Stress of 25%Al_2O_3-SiO_2(sf)/AZ91D Composite

T, K	Theoretical values of σ_{th}, MPa	Experimental values of σ_{th}, MPa
473	54.26	53
523	51.55	49
573	41.65	39

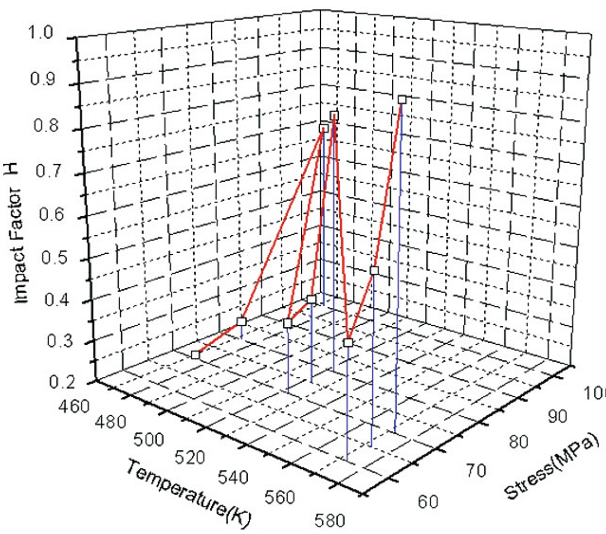


Fig. 8

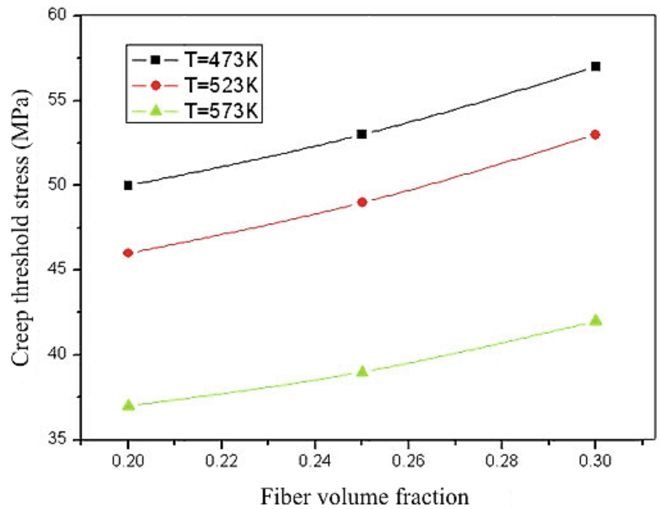


Fig. 9

Fig. 8. The $H-\sigma-T$ plot for 25%Al_2O_3-SiO_2(sf)/AZ91D composite.
Fig. 9. Creep threshold stress of Al_2O_3-SiO_2(sf)/AZ91D composite versus fiber volume fraction.

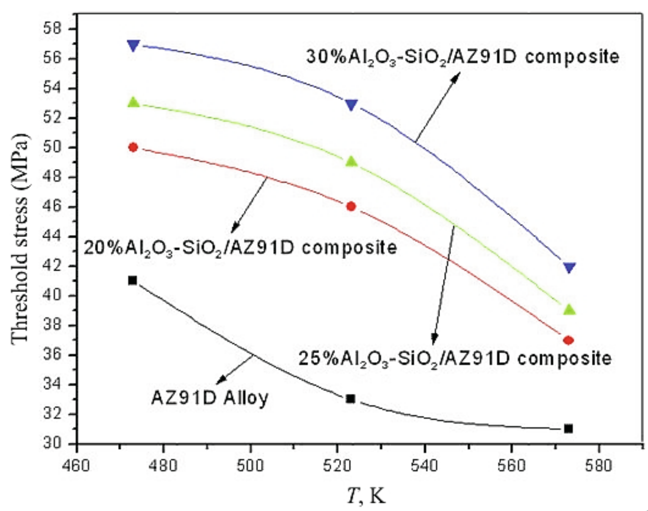


Fig. 10. Creep threshold stresses of AZ91D alloy and Al_2O_3-SiO_2(sf)/AZ91D composite versus temperature.

drag forces are generated from inconsistency of strains of matrix and short fiber on the mobile dislocation. The increase of bearing and transferring capacities of short fiber increases the creep threshold stresses of metal materials. However, with the increase in the amount of fiber and the density of dislocation, the precipitates easily precipitate at the dislocations. Therefore, with the increase of fiber volume fraction, the amount of precipitation of β-$Mg_{17}Al_{12}$ precipitates increase. The precipitates are easy to coarsen and soften, so that the threshold stress of the composite is not greatly improved with increased fiber volume fraction.

Temperature Influence on Creep Threshold Stress. According to the previously obtained experimental data, the plot of threshold stress versus temperature has been constructed in Fig. 10. The threshold stresses of AZ91D alloy and AZ91D composite both decrease with temperature. The rates of threshold stresses decreasing with temperature for metal materials with different fiber volume fractions are basically the same. The tangent lines of the three curves are parallel at the same temperature, indicating that the sources and affecting factors of threshold stress are the same. However, the rate of threshold stress decreasing with temperature for composite is significantly lower than that of the alloy, indicating that the creep resistance of composite is significantly higher than that of the alloy. The curve of the composite is upward convex, while the curve of the matrix alloy is downward convex, which indicates that the sources and affecting factors of threshold stresses of the composite and alloy are different. The empirical formulas of threshold stresses of AZ91D alloy, 20%Al_2O_3-SiO_2(sf)/AZ91D, 25%Al_2O_3-SiO_2(sf)/AZ91D, and 30%Al_2O_3-SiO_2(sf)/AZ91D metal materials varying with temperature changes can be obtained by curve fitting, respectively, such as formulas (10), (11), (12), and (13):

$$\sigma_{th} = 1.2 \cdot 10^{-3} T^2 - 1.3552T + 413.5348, \tag{10}$$

$$\sigma_{th} = -1 \cdot 10^{-3} T^2 + 0.916T - 159.539, \tag{11}$$

$$\sigma_{th} = -1.2 \cdot 10^{-3} T^2 + 1.1152T - 206.0148, \tag{12}$$

$$\sigma_{th} = -1.4 \cdot 10^{-3} T^2 + 1.3144T - 251.4906. \tag{13}$$

The mathematical models of threshold stresses varying with temperature ensure a close fit with the experimental data. Compared with the previously derived mathematical models with the empirical formulas (6), (8), and (9), the calculation is simple and convenient. In engineering applications, the models can be employed to simply estimate the threshold stresses of metal materials at different temperatures. Therefore, the high-temperature creep properties of materials can be predicted.

CONCLUSIONS

1. The improvement of creep resistance of composites can be attributed to the effective load-bearing and transferring capabilities, and the load transfer coefficient α characterizes the bearing and transferring capabilities of short fibers, and α is more sensitive to temperature than to stress. Moreover, α increases with volume fraction of short fibers.

2. A portion of the creep threshold stress of Al_2O_3-SiO_2(sf)/AZ91D composite is a kind of drag force, which is generated by the Al atoms' atmosphere on mobile dislocation. The atoms' atmosphere is formed by the segregation of Al in α-Mg solid solution in the grain boundary. Another portion of the stress is another kind of drag force, which is generated by the inconsistent strains of matrix and short fiber on the dislocation, i.e., bearing and transferring force of the short fiber.

3. Temperature and the volume fraction of short fiber are two main factors, which affect the threshold stress. Threshold stress decreases with temperature and increases with volume fraction of short fibers, which are affected by the material impact factor H and load transfer coefficient α.

Acknowledgment. The work was supported by the National Science Foundation of Guangdong Province (Grant No. 10151170003000002).

REFERENCES

1. V. Sklenička, M. Svoboda, M. Pahutova, et al., "Microstructural processes in creep of an AZ91 magnesium-based composite and its matrix alloy," *Mater. Sci. Eng. A*, **319–321**, 741–745 (2001).

2. F. Chmelik, P. Lukáč, M. Janeček, et al., "An evaluation of the creep characteristics of an AZ91 magnesium alloy composite using acoustic emission," *Mater. Sci. Eng. A*, **338**, Issues 1–2, 1–7 (2002).
3. J. Olbricht, A. Yawny, M. L. Young, and G. Eggeler, "Mechanical and micro- structural observations during compression creep of a short fiber reinforced AlMg metal matrix composite," *Mater. Sci. Eng. A*, **510–511**, 407–412 (2009).
4. J. Čadek, H. Oikawa, and V. Šustek, "Threshold creep behaviour of discontinuous aluminum and aluminum alloy matrix composites: An overview," *Mater. Sci. Eng. A*, **190**, Issues 1–2, 9–23 (1995).
5. A. Yawny, G. Eggeler, "Assessment of back stress and load transfer approaches for rationalizing creep of short fiber reinforced aluminum alloys," *Mater. Sci. Eng. A*, **387–389**, 905–909 (2004).
6. T. L. Dragone, W. D. Nix, "Steady state and transient creep properties of an aluminum alloy reinforced with alumina fibers," *Acta Metall. Mater.*, **40**, No. 10, 2781–2791 (1992).
7. R. A. Karnesky, L. Meng, and D. C. Dunand, "Strengthening mechanisms in aluminum containing coherent Al_3Sc precipitates and incoherent Al_2O_3 dispersoids," *Acta. Mater.*, **55**, 1299–1308 (2007).
8. D. Sherby and E. M. Taleff, Influence of grain size, solute atoms, second-phase particles on creep behavior of polycrystalline solids, *Mater. Sci. Eng. A*, **322**, 89–99 (2002).
9. R. Fernández and G. Gonsález-Doncel, "Threshold stress and load partitioning during creep of metal matrix composites," *Acta Mater.*, **56**, No. 11, 2549–2562 (2008).
10. Y. Li and T. G. Langdon, "Creep behavior of an AZ91 magnesium alloy reinforced with alumina fibers," *Metall. Mater. Trans.*, **30**, No. 8, 2059–2066 (1999).
11. J. S. Zhang, *High Temperature Deformation and Fracture of Materials*, Science Press, Beijing (2007).
12. J. Tian, W. F. Li, L. F. Han, and J. H. Pen, "Microstructure, interface and fabricating process of Al_2O_3-SiO_2/AZ91D composites prepared by squeeze infiltration," *Hot Work. Technol. Sinica*, **38**, 53–56 (2009).
13. J. Friedel, *Dislocations*, Pergamon Press, Oxford (1964).