Constitutive behavior of $\text{Al}_2\text{O}_{3\text{np}}$ /Al7075 composites with a high solid fraction for thixoforming

Xiao-Hui Chen ^{a, b}, Hong Yan ^{a, *}

ABSTRACT

The thixotropic compression tests of nano- Al_2O_3 ($\text{Al}_2\text{O}_{3\text{np}}$) /Al7075 composites with different particle sizes and contents and containing a high fraction of solid, were conducted under conditions of 560-590 °C and 0.01-5 s^{-1} , and the microstructures were observed. A visco-plastic constitutive model of nanoparticle reinforced composites for thixoforming was proposed, considering the coupling effects of strain, strain rate, deformation temperature and liquid fraction and presence of nanoparticles, to describe constitutive behavior of the composites under various deformation conditions. Furthermore, the influence of deformation parameters on thixoforming was investigated. It could be shown that the predictions by the developed model were consistent with experimental results. Fracture analysis of the thixotropic compression samples revealed that high deformation temperature or/and high strain rate could prompt continuous uniform distribution of the liquid phase along the grain boundary, causing the formation of a thin liquid film around an approximately spherical grain, accordingly improving thixoformability of the

composites with a high solid fraction. Moreover, deformation mechanisms of the composites during thixotropic compression process were discussed.

Keywords: Metal matrix composites; Nanoparticles; Semisolid; Constitutive model; Thixoforming.

1. Introduction

Nano-particles reinforced aluminum matrix composites have been used for structural components of automobile, high speed train and aircraft due to their high specific strength, high abrasive resistance, and superior high-temperature creep resistance [1-3]. Due to their lower plasticity, it is difficult to secondarily process the composites into the required parts with complex geometry, indicating limited application of such composites in industry. Thixoforming is one of semisolid processes, involving feedstock preparing, reheating, and subsequent forming in the semisolid region [4,5]. When thixoforming the composites with a high solid fraction, low liquid phases distributed in the composites can serve as a lubricant at the interface to reduce the deformation forces and to improve the reinforcement redistribution [6]. However, large liquid fraction may lead to the liquid flow and low cohesion of interface, hence resulting in a rapid decrease in thixoformability [7].

The process exhibits lower deforming forces, less thermo-mechanical impact on mould, fewer product defects, and higher capability for near net shaping compared to conventional hot forging [8,9]. Thus, the use of this technology enables production of complex nanocomposite parts. Moreover, obtaining the desired microstructures and good mechanical properties for the parts depends on appropriate deformation

conditions. Furthermore, the material flow becomes significantly complicated due to a change of deformation mechanisms by the forming conditions, short-time characteristics of deformation, and inhomogeneity of microstructure. Thus, establishing a constitutive model, comprehensively reflecting the response of composites to external actions such as strain, strain rate, and deformation temperature, will provide a strong foundation for the optimization of forming processes, design of dies, and control of microstructures. In addition, during simulation modeling, the constitutive relationship of materials can generally be used as an input code to describe forming features. Thus, whether the mechanical behavior of the composites can accurately be predicted via finite element modeling depends on the reliability of the developed constitutive relationship.

Several constitutive equations of composites with a high solid fraction for thixoforming are summarized in Table 1. According to the power-law strain hardening of the Ramberg-Osgood type, the power-law strain rate hardening, and the coupling effects of strain rate and Al_2O_3 volume fraction, Bao and Lin [10] investigated the rate-dependent plastic flow behavior of $\text{Al}_2\text{O}_3/\text{Al}$ composites. Li et al. [11] then simplified the constitutive model developed by Bao and Lin and considered the effect of SiC particle damage within the $\text{SiC}_p/\text{A359}$ composites on stress. However, the utilized models ignore the effects of heat softening and liquid phase. Semisolid materials are made of a combination of liquid and solid phases. The solid skeleton can be regarded as a viscous and compressive medium, saturated with liquid. However, each phase has its own behavior, which due to interfacial action can be

influenced by the presence of the other phase. Thus, two-phase finite element modeling is particularly important to reliably predict the behavior of thixoformed composites. Qi et al. [12] introduced the fraction of interface wetted by the liquid phase into the constitutive model, but ignored the effects resulting from the presence of short carbon fibers (including fiber size, reinforcement content, and distribution). Spigarelli et al. [15], Gangolu et al. [16], and Zhou et al. [17] developed constitutive models of composites during hot deformation, according to the sine hyperbolic law by Sellars and Mc-Tegart [18] and strain compensation. Nguyen et al. [19] and Kang et al. [20] established a two-phase constitutive model via the hybrid theory to describe the thixotropic behavior of alloys, where the stress of the solid region is a function of the Zener–Hollomon parameter (Z). Based on both models, Luo et al. [13] introduced a two-phase constitutive model with micro-rheological characteristics for thixoforming of SiC_p/A356, in which however, the effect of reinforcements is only characterized by a change in apparent activation energy due to addition of high volume particle fraction. Thus, a constitutive model with the ability to reflect the effect of microstructures as well as that of deformation parameters needs to be established.

The presence of nano-particles can cause significant improvement in the mechanical properties of composites due to the resulting strengthening effect [3,21,22]. For semisolid composites, nano-particles or aggregates of nano-particles that are distributed within grains and along grain boundaries, have an impact on the plastic deformation of solid particles, sliding between solid particles and fluid flow during

thixoforming. Based on previous studies, Yan et al. [14] developed a constitutive equation of micro-sized particle-reinforced metal matrix composites with a high solid fraction for thixoforming, mainly focusing on the effects of strain, strain rate, deformation temperature, and particle volume fraction, but ignoring the effects of particle size and particle distribution. So far, the coupling effects of deformation parameters and microstructures of composites (including liquid distribution, size and content of particles, and particle distribution in semisolid materials), have been rarely considered when establishing of the constitutive model of composites with a high solid fraction for thixoforming. In addition, the constitutive models for alloys or composites presented in previous publications can only capture some aspect of the semisolid deformation behavior. Thus, to achieve a consensus in theoretical and experimental research, a constitutive model needs to be developed, comprehensively reflecting the thixotropic behavior of nano-composites with a high solid fraction.

In this paper, the thixotropic compression deformation behaviors of the nano-composites with different particle sizes and contents and containing a high fraction of solid were tested at varying deformation temperatures and strain rates. A constitutive model was developed to determine thixotropic behaviors of the nano-composites with a high solid fraction under various deformation conditions and the accuracy of the model was validated by experimental results. Based on fracture analysis of the thixotropic compression samples, the influence of deformation parameters on thixoforming was investigated. Moreover, deformation mechanism of the composites during the thixotropic compression process was discussed.

2. Experimental procedure

2.1. Production of thixotropic compression specimens

Fig. 1 shows the graphite crucible and mould. The obtained nano- Al_2O_3 ($\text{Al}_2\text{O}_{3\text{np}}$)/Al7075 composite slurries were poured into the graphite crucible, which was preheated to 550-600 °C in a holder. The nano-composites with different particle sizes and contents were fabricated by combining sub-type multi-frequency ultrasonic vibration with wetting reaction. The detailed process was described in our previous studies [3]. When the composite slurries held in the crucible were cooled in a quiescent fashion to a temperature of 700 °C, they were ultrasonically vibrated at 1 kW and a frequency of 20 kHz and simultaneously cooled at a cooling rate of 10 °C/min to 620 °C. After ultrasonic treatment, the graphite mould preheated to 620 °C was forced into semisolid composite slurries and these slurries were then rapidly cooled via cold air to obtain cylindrical ingots with a fine globular microstructure. The compression specimens with a diameter of 8 mm and a height of 12 mm were machined from the composite ingot according to ASTM: E209.

2.2. Thixotropic compression tests

The thixotropic compression tests were conducted using a Gleeble3500 thermo-mechanical simulator. Thin graphite sheets were used in the compression tests so as to reduce the friction between anvils and sample. A thermoelectric couple was placed on the surface of sample to precisely measure and control the experimental temperature. Based on the DSC date, the solidus and liquidus temperatures of the as cast Al7075 were 471.54 and 637.37 °C, respectively. For the deformation

temperatures of 560, 570, 580, and 590 °C, the corresponding liquid fractions (f_L) were 2.94%, 4.78%, 8.94%, and 15.34%, respectively. A variation of liquid fractions could be obtained via controlling the temperatures. To precisely reach the preset temperature and to ensure a uniform temperature distribution within the specimens before the compression tests, two-step heating was used. Fig. 2 shows the heating procedure during compression testing. Each specimen was held for 4 min at the target deformation temperature to obtain the temperature equilibrium. The experimental conditions used in the different experiments are listed in Table 2. All the specimens were quenched into water immediately afterwards in order to preserve the deformation microstructures and the liquid.

2.3 Microstructures

Fig. 3a shows the semisolid microstructures of specimen after holding for 4 min at a deformation temperature of 580 °C. Fig. 3b shows the microstructures in the mid section of deformed specimen. As shown in Fig. 3a, the sample before deformation consisted of solid and liquid phases, and the approximately spherical grains were uniformly distributed within the matrix. The grains could roll over each other while the fluid surrounding them acted as a lubricant, thus reducing the deformation forces. However, the plastic deformation of solid grains occurred after thixoforming (Fig. 3b).

3. Results and discussion

3.1. Flow stress curves

Fig. 4 shows the typical true stress-true strain curves of the $\text{Al}_2\text{O}_{3\text{np}}/\text{Al7075}$

composites at different deformation temperatures. It could be found that the true stress decreased with increasing deformation temperature. This means that deformation temperature sensitivity of the stress existed. At lower deformation temperatures, high true stress during deformation was induced via pile-up of dislocations due to the presence of nano-particles and the glide and plastic deformation of solid grains. The volume of liquid phases surrounding solid grains increases with increasing deformation temperature. Consequently, the morphology of the grains ultimately trends toward a near-sphere [12,23,24], and the globular particles move far easier over each other than dendritic grains in liquid phases. It should be noted that the hard particles distributed along grain boundaries could act as a barrier against grain boundary sliding. Nevertheless, more liquid phases cause a release of the stress concentration or pile-up of dislocations [25], leading to reduced resistance to deformation.

Fig. 5 shows the typical true stress-true strain curves of the $\text{Al}_2\text{O}_{3\text{np}}/\text{Al7075}$ composites at various strain rates. It can be clearly observed in Fig. 5 that the true stress increases with increasing strain rate. For lower strain rates, the resistance to deformation could be reduced as there was sufficient time for liquid phases remaining suspended nano-particles to flow through gaps among solid grains [23,24]. At higher strain rates, the dislocation pileups around nano-particles easily take place, which can be attributed to inadequate proceeding of dislocation motion. In addition, the liquid phases after collapse of the solid skeleton rapidly flowed from the inner portion to the marginal region of specimen [26,27], indicating the rapid compaction of solid phases,

and consequently resulting in enhanced deformation forces.

Fig. 6 shows the typical true stress-true strain curves of the $\text{Al}_2\text{O}_{3\text{np}}/\text{Al7075}$ composites with different nano-particle sizes and contents under various conditions. The true stress increases with increasing nano-particle content, as shown in Fig. 6a. The improvement of the mechanical properties of nano-particles reinforced composites is related to the load-bearing effect, dislocation multiplication induced by the thermal mismatch between the matrix and the nano-particles, and Orowan strengthening effect [2]. The first two improvement factors were ignored, since the volume fraction of nano-particles was relatively low and the compression tests were conducted in the semisolid temperature range [28]. Adding more nano-particles induces a stronger Orowan strengthening effect. On the other hand, agglomerates of nano-particles in the liquid phases increase with increasing nano-particle content, which hinders the movement of globular solid grains. Thus, a high addition amount of nano-particles can cause increased true stress. Furthermore, the true stress decreases with increasing nano-particle size, as shown in Fig. 6b. At given volume fraction of nano-particles, the amount of nano-particles will reduce when the nano-particle size increases, ultimately causing a weakened strengthening effect. This result is in agreement with the report by Zhang et al. [28].

3.2. Constitutive modeling

3.2.1. Constitutive relationship of nanocomposites

When the strain rate and deformation temperature are constant, the relation of strain to stress is given as:

$$\sigma = k_1 \varepsilon^n \quad (1)$$

where, σ is the stress, ε is the strain, n is the strain hardening index and k_1 is the constant related to strain.

When the strain and deformation temperature are constant, materials obey the power-law strain rate hardening behavior under a lower strain rate. The relationship between the strain rate and stress can be written as [24,29]:

$$\sigma = k_2 \dot{\varepsilon}^m \quad (2)$$

where, $\dot{\varepsilon}$ is the strain rate, m is the strain rate sensitivity parameter, k_2 is the material constant reflecting the effect of material structure and temperature. The strain rate sensitivity can be obtained by taking the logarithm on both sides of Eq. (2). The double logarithmic relationship between the peak stress and strain rate at each deformation temperature and nano-particle content level is plotted in Fig. 7. The relationships between the peak stress and strain rate are linear on a log-log scale. The strain rate sensitivity (m) and the coefficient of multiple correlation (R^2) at all deformation temperature and nano-particle content levels are listed in Table 3. As shown in Table 3, the value of m is independent of the volume fraction of nano-particles. This is consistent with the result reported by Nguyen-Thanh and Suéry [30]. Furthermore, the value of m increases with increasing deformation temperature, which may be related to the increased liquid phases.

When the strain and stress were constant, Qi et al. [12], Kang et al. [29] and Chen et al. [31] reported the relationship between the deformation temperature and stress as:

$$\sigma = A \exp(Q / RT) \quad (3)$$

where, A is the material constant, Q is the apparent activation energy, R is the gas constant, and T is the absolute temperature. The equation can be simplified to:

$$\sigma = k_3 \exp\left(\frac{a_1}{T}\right) \quad (4)$$

where, k_3 and a_1 are the material constants related to deformation temperature. Wang et al. [24] reported that the modified constitutive model of AA6061 alloy for thixoforming, considering the effect of liquid phases, could be applied for a viable prediction of experimental results. Some research also investigated the effect of liquid phases on compression behavior [12,29,32]. Based on previous studies, it has been proposed to incorporate the liquid fraction factor into a constitutive model for thixoforming to precisely reflect the effect of liquid phase on compression behavior, as described below:

$$g_1 = k_4 (1 - \beta f_L)^{a_2} \quad (5)$$

where, k_4 and a_2 are the material constants related to liquid fraction, β is the geometric parameter ($\beta = 1.5$ [19,24,29]), and f_L is the liquid fraction.

According to the above-mentioned relationships, a constitutive relationship can be proposed via the following equation:

$$\sigma = \exp\left(a'_0 + \frac{a_1}{T}\right) \cdot \varepsilon^n \cdot \dot{\varepsilon}^m \cdot (1 - \beta f_L)^{a_2} \quad (6)$$

where, a'_0 is the material constant ($a'_0 = \ln(k_1 k_2 k_3 k_4)$). Eq. (6) represents only a coupling effects of strain, strain rate, deformation temperature, and liquid fraction. Thus, the model for explaining the constitutive behavior of nano-composites for thixoforming is naturally limited. This is crucial to precisely predict the constitutive

behavior of composites and to develop a model that can comprehensively capture the behavior of thixoforming at different conditions. The thixotropic deformation behavior of the resulting composites is significantly affected by nano-particle size (d_p), particle volume fraction (f_p), and particle distribution, as well as by the already mentioned influences.

Bao and Lin [10] and Li et al. [11] investigated the constitutive behavior of aluminum matrix composites, and a polynomial function containing particle volume fraction was used as a strengthening factor in the developed model. Thus, based on the typical true stress-true strain curves in Fig. 6a, the effect of particle volume fraction on stress can be presented as:

$$g_2 = e^{a+bf_p+cf_p^2} \quad (7)$$

where a , b , and c are the material constants related to particle volume fraction.

Fig. 8 shows a comparison among the peak stresses of the nano-composites obtained after deformation at 580 °C and different strain rates. The peak stress values of point 1 to 6 reveal that the peak stress increases with increasing particle content and strain rate. Note that the peak stress values from points 7 to 10 seem to not depend on the particle content or strain rate. Large shear stress is easily induced in semisolid materials due to rapid deformation. When the shear stress is larger than the bond between nano-particles and solid grains or liquid phases, voids are formed within grains, along grain boundaries, or in the liquid phase. During thixoforming, these will coarsen and then propagate, finally resulting in cleavage fracture of solid grain, collapse of solid skeleton, and tearing of liquid phase, which indicates less

deformation resistance. Thus, the effect of particle volume fraction is relatively complex and may depend on strain rate. Bao and Lin [10], and Li et al. [11] also discussed direct coupling effect of the strain rate and particle volume fraction. Thus, the coupling effect can be described by:

$$g_3 = \left[1 + (a_3 \dot{\varepsilon})^m f_p \right]^{a_4} \quad (8)$$

where, a_3 is the correction factor and a_4 is the material constant.

Sajjadi et al. [2] reported that for the A356 alloy with 1.0 wt.% $\text{Al}_2\text{O}_{3\text{np}}$ (50 nm), the compressive strength is 2.13 times larger than that obtained by adding the same amounts of micro-sized Al_2O_3 particles (20 μm), suggesting that particle size greatly affects the mechanical properties of composites. In our previous study on particle pushing [33], we reported the agglomerates of $\text{Al}_2\text{O}_{3\text{np}}$ were easily pushed toward eutectic regions. The presence of agglomerates hindered the flow of liquid phases, thus causing the difficulties in feeding shrinkage porosity. Thus, based on the typical true stress-true strain curves in Fig. 6b, the effect of particle size can be given by:

$$g_4 = k_5 d_p^{a_5} \quad (9)$$

where, k_5 and a_5 are the material constants related to particle size.

Fig. 9 shows a comparison among the peak stresses of the nano-composites obtained after deformation at 560 °C and a strain rate of 0.1 s^{-1} . The peak stresses of the composites with 1.5 and 2.5 wt.% $\text{Al}_2\text{O}_{3\text{np}}$ (80 nm) obtained after thixoforming were significantly increased compared to those of other composites. At given particle content, the smaller the particle size, the higher the amount of particles will be. As a result, many dislocation loops are induced around nano-particles, consequently

causing dislocation pileups in the matrix, finally increasing the resistance to deformation. The increased deformation forces are mainly a result of the dispersed distribution of the nano-particles. Thus, the effect of the distribution state is given by:

$$g_5 = (1 + \lambda f_p^{\frac{1}{3}} d_p^{-1} \ln k d_p)^{a_6} \quad (10)$$

where, $\lambda = \frac{0.16 G_m b}{\sigma_{ym}}$ and $k = \frac{1}{2b}$. In this study, G_m is the shear modulus of as cast Al7075 alloy ($G_m = 26.9$ GPa [34]), b is the magnitude of the Burgers vector for Al ($b = 0.286$ nm[34]), σ_{ym} is the compressive yield strength of as cast Al7075 alloy, and a_6 is the material constant.

Substituting Eqs. (7)-(10) into Eq. (6), the constitutive equation of the nano-particle reinforced composites with a high solid fraction for thixoforming can be modeled as follows:

$$\sigma = \exp\left(a_0 + b f_p + c f_p^2 + \frac{a_1}{T}\right) \cdot \varepsilon^n \cdot \dot{\varepsilon}^m \cdot (1 - \beta f_L)^{a_2} \cdot \left[1 + (a_3 \dot{\varepsilon})^m f_p\right]^{a_4} \cdot d_p^{a_5} \cdot (1 + \lambda f_p^{\frac{1}{3}} d_p^{-1} \ln k d_p)^{a_6} \quad (11)$$

where, $a_0 = \ln(k_1 k_2 k_3 k_4 k_5) + a$.

Due to lower particle content in the developed nano-composites (0.5, 1.5, and 2.5 wt.% corresponding to 0.334, 1.006, and 1.682 vol.%, respectively), the term $c f_p^2$ in Eq. (11) can be ignored. Thus, the equation can be simplified to:

$$\sigma = \exp\left(a_0 + a_1 f_p + \frac{a_2}{T}\right) \cdot \varepsilon^{a_3} \cdot \dot{\varepsilon}^{a_4} \cdot (1 - \beta f_L)^{a_5} \cdot \left[1 + (E \dot{\varepsilon})^{a_4} f_p\right]^{a_6} \cdot d_p^{a_7} \cdot (1 + \lambda f_p^{\frac{1}{3}} d_p^{-1} \ln k d_p)^{a_8} \quad (12)$$

where, $a_0, a_1, a_2, a_3, a_4, a_5, a_6, a_7$, and a_8 are the material constants and E is the correction factor.

Based on the experimental data obtained from the compression tests and the commercial SPSS software, the material constants in Eq. (12) can be determined for semisolid nano-composites via multiple linear regression analyses. To adjust the value of a_4 via the software closer to that of average strain rate sensitivity parameter ($\bar{m}$) in Table 3, the E value in Eq. (12) was continually amended, finally choosing an E of 50.

The computational results are listed in Table 4. Thus, the constitutive model of nano-particle reinforced aluminum matrix composites with a high solid fraction for thixoforming is given:

$$\sigma = \exp\left(-6.575 + 26.212f_p + 6245.811/T\right) \cdot \varepsilon^{-0.365} \cdot \dot{\varepsilon}^{0.099} \cdot (1 - \beta f_L)^{1.883} \cdot \left[1 + (50\dot{\varepsilon})^{0.099} f_p\right]^{-1.601} \cdot d_p^{-0.378} \cdot (1 + \lambda f_p^{\frac{1}{3}} d_p^{-1} \ln k d_p)^{3.338} \quad (13)$$

In the empirical constitutive equations developed by traditional forging or fully solid deformation below the solidus temperature, n is a positive number due to strain hardening. It can be observed from Eq. (13) that a negative value of n (-0.365) is consistent with the strain-softening phenomenon observed in the typical true stress-true strain curves. This depends on the nature of material deformation in semisolid state.

3.2.2. Verification of constitutive equations

Fig. 10 shows the validation of the constitutive model for nano-composites against the experimental data obtained under different conditions. Whether the developed

constitutive model is accurate depends on appropriate fitting between the calculated and experimental results in a wider range of each parameter. Fig. 10 shows that the obtained constitutive model is already in good agreement with the experimental results.

The accuracy of the developed constitutive model was further determined by measuring the correlation coefficient (R) and the average absolute relative error ($AARE$). The equations for calculating R and $AARE$ values are given as [35]:

$$R = \frac{\sum_{i=1}^N (E_i - E)(P_i - P)}{\sqrt{\sum_{i=1}^N (E_i - E)^2 \sum_{i=1}^N (P_i - P)^2}} \quad (14)$$

$$AARE = \frac{1}{N} \sum_{i=1}^N \left| \frac{E_i - P_i}{E_i} \right| \times 100\% \quad (15)$$

where, E_i is the experimental data and P_i is the value predicted by the model. E and P are the mean values of E_i and P_i , respectively. N is the number of data used. The calculated values of R and $AARE$ are 0.948% and 8.54%, respectively. Thus, this developed constitutive model can be employed to adequately describe the behavior of the nano-composites for thixoforming. However, a difference can still be found between the predicted and experimental values, which may be due to interactive effects between the factors. The experimental results were also influenced by the dispersion and distribution of nano-particles, the size distribution and shape factor of primary α -Al solid grains, the different defects in samples, and the precise controlling of deformation parameters, consequently causing the occurrence of deviation. However, the improved prediction results indicate higher predictability of this model.

3.3. Influence of deformation parameters on thixoforming

Fig. 11 shows the fracture surfaces of 1.5 wt.% $\text{Al}_2\text{O}_{3\text{np}}$ (80 nm)/**Al7075** composite deformed to the true strain of 0.6 at 1.0 s^{-1} and different temperatures, and then quenched in water. As seen from Fig. 11a, the fracture surface **consists of** eutectic liquid **phases** and deformed solid grains. With the deformation temperature of 560°C corresponding to the lower liquid fraction of 0.0294, the deformation force is required to overcome the friction generated from the sliding and rotating between solid grains, and also to overcome the restriction of solid grain movement due to higher squeezing imposed by **surrounding solid grains**, finally resulting in **enhanced stress and reduced formability**. In Fig. 11b, many solid grains wrapped by a thick liquid film can be found as well as few eutectic liquid phases. With the deformation temperature of 590°C corresponding to the higher liquid fraction of 0.1534, the strain rate of 1.0 s^{-1} can produce a higher external shear force in the semisolid slurry, **consequently** leading to **the** de-agglomeration of solid grains and then to **the outflow of entrapped liquid**. As the force is continuously carried, the liquid phases diffuse into grain boundaries and then **become** uniformly distributed around solid grains, leading to effective lubrication action of the liquid during the sliding and rotation of solid grains and accordingly to **an** improved thixo-formability.

Fig. 12a shows that **the relationship between the strain rate and steady stress** at different deformation temperatures for the 1.5 wt.% $\text{Al}_2\text{O}_{3\text{np}}$ composite. Yan et al. [14], Iwasaki et al. [36], and Wang et al. [37] reported that the ratio of the stress to strain rate **can be approximated as** apparent viscosity of semisolid materials.

With the strain rate below 1.0 s^{-1} , the apparent viscosity decreases with increasing strain rate. Nevertheless, the apparent viscosity at low deformation temperature sharply decreases when the strain rate is above 1.0 s^{-1} . This may be related to the collapse of the solid skeleton. In addition, with high deformation temperature and high strain rate, the apparent viscosity shows no evident change because the velocity for the buildup of solid grains is faster than that for the breakdown due to the presence of more liquid phases, thus weakening the shear-thinning effect [38,39]. Fig. 12b shows that the relationship between the strain rate and steady stress at $570 \text{ }^{\circ}\text{C}$ for the composites with different $\text{Al}_2\text{O}_{3\text{np}}$ contents. Fig. 12b reveals that the changing trend of the apparent viscosity versus strain rate is similar to that in Fig. 12a. With the strain rate above 1.0 s^{-1} , the apparent viscosity of the semisolid composite with 2.5 wt.% $\text{Al}_2\text{O}_{3\text{np}}$ is higher than that with 0.5 and 1.5 wt.% $\text{Al}_2\text{O}_{3\text{np}}$. This can be attributed to the high content of nano-particle in the semisolid slurry. Thus, higher strain rates can make the apparent viscosity of semisolid composites decrease, resulting in enhanced thixotropic behavior.

Fig. 13 shows the fracture surfaces of 1.5 wt.% $\text{Al}_2\text{O}_{3\text{np}}$ (80 nm)/Al7075 composite deformed to the true strain of 0.6 at $560 \text{ }^{\circ}\text{C}$ and different strain rates, and then quenched in water. In Fig. 13a, the deformed solid grains present wrinkle-like features. Here, it is important to note that the grain boundary of the deformed solid grains appears to follow the shape of a straight-line, and the solid grains are wrapped by a thin liquid film, as shown in Fig. 13b. The lower strain rate (0.01 s^{-1}) provides sufficient time for solid grains to slide and rotate. Due to the lower strain rate and the

presence of high-temperature intermetallic compounds and nano-particles, a complicated stress field emerges in the sample, leading to the formation of wrinkle-like features. At higher strain rate (5 s^{-1}), solid grains or the high-temperature phases cannot rotate or slid in time to adapt to the external forces since the compression deformation is completed in a short time, during which the grains deform under the action of unidirectional stress similarly, representing the grain boundary perpendicular to the stress direction. In addition, the high-temperature phases, the eutectic liquid phases containing $\text{Al}_2\text{O}_{3\text{np}}$ agglomerates, and the uniformly distributed $\text{Al}_2\text{O}_{3\text{np}}$ inside solid grains hinder the movement of grain and the dislocation glide and climb. The occurrence of the liquid film wrapped around solid grains also verifies the shear-thinning behavior of high strain rate.

3.4. Deformation mechanism

Fig. 14 shows SEM-EDS image of the 1.5 wt.% $\text{Al}_2\text{O}_{3\text{np}}$ /A17075 composite deformed to 0.6 at $570\text{ }^\circ\text{C}$ and strain rate of 0.01 s^{-1} . Fig. 14a and the fracture surfaces obtained under other deformation conditions reveals that needle-like high-temperature intermetallic compounds are visible in the sample. According to the EDS results (at point 1: 6.11 at.% C, 49.78 at.% O, 1.84 at.% Mg, 33.73 at.% Al, 0.27 at.% Cr, 6.54 at.% Fe, 0.98 at.% Cu, 0.76 at.% Zn), the needle-like phase is Fe-rich intermetallic, to which AlZnMgCu eutectic phase and $\text{Al}_2\text{O}_{3\text{np}}$ adhere.

During thixoforming, the nano-composites undergo hardening, softening, and steady state deformation, as shown in Figs. 4-6. With the increase of true strain, the strengthening of composites firstly occurs, and the peak stress appears when the true

strain reaches a certain threshold. The true stress dramatically decreases upon further increase in the true strain. Subsequently, the true stress remains in dynamic balance. Fig. 14 also reveals that except for the needle-like Fe-rich phases, $\text{Al}_2\text{O}_{3\text{np}}$ aggregates were distributed at the grain boundary. Globular α -Al solid grains form a solid skeleton under the action of the needle-like phases and nano-particle aggregates, and this skeleton is saturated with liquid phases. In the initial stage of deformation, the deformation force mainly overcomes the interaction between and among the globular α -Al solid grains, Fe-rich phases, and $\text{Al}_2\text{O}_{3\text{np}}$ agglomerates, the yield strength of the grains, and the friction induced by sliding or rotation of the grains. During this initial deformation stage, the liquid phases flow laterally to accommodate the macroscopic deformation of the solid skeleton. During application of external force, the Fe-rich phases may be embedded into the globular α -Al solid grains due to their high hardness and high strength [40]. As the true stress peaks, the solid skeleton is destroyed due to brittle fracture of the Fe-rich phases. Subsequently, the liquid phases entrapped within the solid skeleton flow out. This softening phenomenon occurs due to the sudden decrease in stress. As a result, the liquid flow (FL) and flow of liquid cooperating with solid grains (FLS) mechanisms are dominant [41]. Rokni et al. [5] and Chen et al. [31] reported that with the hot deformation below solidus temperature, dynamic recrystallization could induce a softening of thixotropic strain. However, whether thixoforming in semisolid state is affected by dynamic recrystallization requires further investigation. After collapse of the solid skeleton, the liquid in the inner region decreases while that in the marginal region increases with increasing

strain. Sliding between solid grains will become increasingly difficult due to restrictions of high-temperature intermetallic compounds, agglomerates of nano-particles, and surrounding grains, finally resulting in plastic deformation of solid grains. On the other hand, the liquid phases distributed in the inner region provide a lubrication effect on the sliding and rotation of solid grains and release the stress concentration [25]. Finally, interactions between the above-mentioned two effects can be counterbalanced to a certain extent. At this deformation stage, the sliding between solid grains (SS) and plastic deformation of solid grains (PDS) mechanisms become dominant for thixoforming.

4. Conclusions

1) The deformation temperature, strain rate, and presence of nano-particles can affect the stress of nano-composites during thixoforming. The stress decreases with increasing deformation temperature and decreasing strain rate. The stress significantly increases when many nano-particles are well dispersed and uniformly distributed in the solid grains. The changes in the stress are mainly related to lubrication of liquid phases, motion state between dislocation and solid grain, and nanoparticle distribution.

2) For the thixoforming of nano-composites with a high solid fraction, the relationship between the stress and the deformation parameter can be characterized by a modified constitutive model, in which influences of content, size, and distribution of nano-particles are considered. The validity of the developed constitutive model was verified via the comparison between experimental and predicted results. It was found

that the model predictions were in good agreement with the experimental results.

3) High deformation temperatures or high strain rates could precipitate a uniform distribution of liquid phases along grain boundaries, which contributes to improving the thixotropic behavior of nano-composites. At low deformation temperatures, the resistance to deformation increases due to fewer liquid phases, while a complicated stress field is easily produced at low strain rates, indicating that the thixo-formability is deteriorated.

4) The nano-composites undergo hardening, softening and steady state deformation during thixoforming. The occurrence of dynamic balance of the stress is due to the coupling action of liquid relaxation and strain hardening. For the thixotropic deformation to proceed, the deformation mechanism is firstly the FL and FLS, and subsequently the SS and PDS.

Acknowledgments

Authors express their gratitude to the National Science Foundation of China (51364035), Ministry of Education Tied up with the Special Research Fund for the Doctoral Program for Higher School (20133601110001), and Production and Teaching and Research Cooperation Plan of Nanchang Non-party Experts and Doctor (2012-CYH-DW-XCL-002) for financial support.

References

- [1] A.A. Yar, M. Montazerian, H. Abdizadeh, H.R. Baharvandi, Microstructure and mechanical properties of aluminum alloy matrix composites reinforced with nano-particle MgO, J. Alloys Compd. 484 (1-2) (2009) 400-404.

- [2] S.A. Sajjadi, H.R. Ezatpour, M.T. Parizi, Comparison of microstructure and mechanical properties of A356 aluminum alloy/ Al_2O_3 composites fabricated by stir and compo-casting processes, *Mater. Des.* 34 (2012) 106-111.
- [3] X.H. Chen, H. Yan, Fabrication of nanosized Al_2O_3 reinforced aluminum matrix composites by subtype multifrequency ultrasonic vibration, *J. Mater. Res.* 30 (14) (2015) 2198-2209.
- [4] A. Bolouri, M. Shahmiri, C.G. Kang, Study on the effects of the compression ratio and mushy zone heating on the thixotropic microstructure of AA7075 aluminum alloy via SIMA process, *J. Alloys Compd.* 509 (2) (2011) 402-408.
- [5] M.R. Rokni, Z. Zarei-Hanzaki, H.R. Abedi, N. Haghdadi, Microstructure evolution, and mechanical properties of backwark thixoextruded 7075 aluminum alloy, *Mater. Des.* 36 (2012) 557-563.
- [6] S.J. Qu, A.H. Feng, L. Geng, Z.Y. Ma, J.C. Han, DSC analysis of liquid volume fraction and compressive behavior of the semi-solid $\text{Si}_3\text{N}_{4w}/\text{Al-Si}$ composite, *Scripta Mater.* 56 (11) (2007) 951-954.
- [7] G.S. Wang, L. Geng, Z.Z. Zheng, D.Z. Wang, Z.K. Yao, Investigation of compression of $\text{SiC}_w/6061\text{Al}$ composites around the solidus of the matrix alloy, *Mater. Chem. Phys.* 70(2) (2001) 164-167.
- [8] G.H. Fan, L. Geng, Z.Z. Zheng, G.S. Wang, Y.C. Feng, Hot extrusion deformation behavior of $\text{BaPbO}_3/2024\text{Al}$ composite containing a small volume of liquid phase, *Mater. Sci. Eng. A* 496 (1-2) (2008) 281-284.
- [9] Z.J. Wang, L.H. Qi, J.M. Zhou, 3D FE analysis on the product defects of composites formed by liquid–solid extrusion process, *J. Mater. Process. Technol.* 209 (4) (2009) 2068-2076.

- [10] G. Bao, Z. Lin, High strain rate deformation in particle reinforced metal matrix composites, *Acta Mater.* 44 (3) (1996) 1011-1019.
- [11] Y. Li, K.T. Ramesh, E.S.C. Chin, Viscoplastic deformations and compressive damage in an A359/SiC_p metal-matrix composite, *Acta Mater.* 48 (7) (2000) 1563-1573.
- [12] L.H. Qi, Z.J. Wang, J.M. Zhou, L.Z. Su, H.J. Li, Constitutive behavior of C_{sf}/AZ91D composites compressed at elevated temperature and containing a small fraction of liquid, *Compos. Sci. Technol.* 71 (7) 2011 955-961.
- [13] S.J. Luo, Y.S. Chen, W.W. Shan, Rheology of semi-solid metal, National Defense Industry Press, China, 2011. pp. 203-205.
- [14] H. Yan, J.J. Wang, F.Y. Zhang, A constitutive model for thixotropic plastic forming of composites, *Adv. Mater. Res.* 154-155 (2011) 690-693.
- [15] S. Spigarelli, E. Evangelista, E. Cerri, T.G. Langdon, Constitutive equations for hot deformation of an Al-6061/20% Al₂O₃ composite, *Mater. Sci. Eng. A* 319-321 (2001) 721-725.
- [16] S. Gangolu, A.G Rao, I. Sabirov, B.P. Kashyap, N. Prabhu, V.P. Deshmukh, Development of constitutive relationship and processing map for Al-6.65Si-0.44Mg alloy and its composite with B₄C particulates, *Mater. Sci. Eng. A* 655 (2016) 256-264.
- [17] L. Zhou, Z.Y. Huang, C.Z. Wang, X.X. Zhang, B.L. Xiao, Z.Y. Ma, Constitutive flow behavior and finite element simulation of hot rolling of SiC_p/2009Al composite, *Mech. Mater.* 93 (2016) 32-42.
- [18] C.M. Sellars, W.J. McTegart, On the mechanism of hot deformation, *Acta Metall.* 14 (9) (1966) 1136-1138.

- [19] T.G. Nguyen, D. Favier, M. Suery, Theoretical and experimental study of the isothermal mechanical behavior of alloys in the semi-solid state, *Int. J. Plast.* 10 (1994) 663-693.
- [20] C.G. Kang, P.K. Seo, S.W. Youn, Finite element analysis of thixoforming process with arbitrary shape die, *J. Mater. Process. Technol.* 159 (3) (2005) 321-329.
- [21] H.X. Qiu, H. Yan, Z. Hu, Effect of samarium (Sm) addition on the microstructures and mechanical properties of Al-7Si-0.7Mg alloys, *J. Alloys Compd.* 537 (2013) 77-81.
- [22] Z. Hu, X. Li, H. Yan, X.Q. Wu, H. Qun, J.W. Lin, Effects of ultrasonic vibration on microstructure evolution and elevated-temperature mechanical properties of hot-extruded Mg-6Al-0.8Zn-2.0Sm wrought magnesium alloys, *J. Alloys Compd.* 685 (2016) 58-64.
- [23] S.Z. Shang, G.M. Lu, X.L. Tang, Z.X. Zhao, C.M. Wu, Deformation mechanism and forming properties of 6061Al alloys during compression in semi-solid state, *Trans. Nonferrous Met. Soc. China* 20 (9) (2010) 1725-1730.
- [24] J.J. Wang, A.B. Phillion, G.M. Lu, Development of a visco-plastic constitutive modeling for thixoforming of AA6061 in semi-solid state, *J. Alloys Compd.* 609 (9) (2014) 290-295.
- [25] Y. Chino, M. Kobata, H. Iwasaki, M. Mabuchi, An investigation of compressive deformation behaviour for AZ91 Mg alloy containing a small volume of liquid, *Acta Mater.* 51 (11) (2003) 3309-3318.
- [26] M. Kiuchi, R. Kopp, Mushy/Semi-Solid Metal Forming Technology-Present and Future, *CIRP Ann.-Manuf. Techn.* 51 (2) (2002) 653-670.
- [27] W.Y. Kim, C.G. Kang, B.M. Kim, The effect of the solid fraction on rheological behavior of wrought aluminum alloys in incremental compression experiments with a closed die, *Mater. Sci. Eng. A* 447 (1-2) (2007) 1-10.

- [28] Z. Zhang, D.L. Chen, Contribution of Orowan strengthening effect in particulate-reinforced metal matrix nanocomposites, *Mater. Sci. Eng. A* 483-484 (1) (2008) 148-152.
- [29] C.G. Kang, B.S. Kang, J.I. Kim, An investigation of the mushy state forging process by the finite element method, *J. Mater. Process. Technol.* 80-81(1998) 444-449.
- [30] L.N. Thanh, M. Suéry, Compressive behaviour of partially remelted A356 alloys reinforced with SiC particles, *Mater. Sci. Technol.* 10 (10) (1994) 894-902.
- [31] L. Chen, G.Q. Zhao, J.Q. Yu, W.D. Zhang, Constitutive analysis of homogenized 7005 aluminum alloy at evaluated temperature for extrusion process, *Mater. Des.* 66 (2015) 129-136.
- [32] W.M.V. Haafte, B. Magnin, W.H. Kool, L. Katgerman, Constitutive behavior of as cast AA1050, AA3104, and AA5182, *Metall. Mater. Trans. A* 33 (7) (2002) 1971-1980.
- [33] X.H. Chen, H. Yan, Solid-liquid interface dynamics during solidification of Al 7075-Al₂O_{3np} based metal matrix composites, *Mater. Des.* 94 (2016) 148-158.
- [34] K. Ma, H. Wen, T. Hu, T.D. Topping, D. Isheim, D.N. Seidman, E.J. Lavernia, J.M. Schoenung, Mechanical behavior and strengthening mechanisms in ultrafine grain precipitation-strengthened aluminum alloy, *Acta Mater.* 62 (5) (2014) 141-155.
- [35] H.L. Wei, G.Q. Liu, M.H. Zhang, Physically based constitutive analysis to predict flow stress of medium carbon and vanadium microalloyed steels, *Mater. Sci. Eng. A* 602 (25) (2014) 127-133.
- [36] H. Iwasaki, T. Mori, M. Mabuchi, K. Higashi, Shear deformation behavior of Al-0.5Mg in a semi-solid state, *Acta Mater.* 46 (18) (1998) 6351-6360.
- [37] N. Wang, G.J. Shu, H.G. Yang, Rheological study of partially solidified tin-lead and

aluminum-zinc alloys for stir-casting, *Mater. Trans.* 31 (8) (1990) 715-722.

- [38] R. Koeune, J.P. Ponthot, A one phase thermomechanical model for the numerical simulation of semi-solid material behavior. Application to thixoforming, *Int. J. Plast.* 58 (7) (2014) 120-153.
- [39] G.R. Burgos, A.N. Alexandrou, V. Entov, Thixotropic rheology of semisolid metal suspensions, *J. Mater. Process. Technol.* 110 (2) (2001) 164-176.
- [40] Y. Xue, R. Shen, S. Ni, M. Song, D. Xiao, Fabrication, microstructure and mechanical properties of Al-Fe intermetallic particle reinforced Al-based composites, *J. Alloys Compd.* 618 (2015) 537-544.
- [41] C.P. Chen, C.Y.A. Tsao. Semi-solid deformation of non-dendritic structures-I. Phenomenological behavior, *Acta Mater.* 45 (5) (1997) 1955-1968.

Figure captions

Fig. 1. Graphite die and crucible used to produce samples for thixotropic compression tests.

Fig. 2. Heating process of thixotropic compression tests.

Fig. 3. (a) Semisolid microstructure at 580 °C for the composite before thixotropic compression and (b) microstructure of the composite deformed to the true strain of 0.6 at 580 °C and a strain rate of 0.1 s^{-1} .

Fig. 4. True stress-strain curves of the 1.5 wt.% $\text{Al}_2\text{O}_{3\text{np}}$ (80 nm)/Al7075 composite compressed at various deformation temperatures with the strain rates of (a) 0.01 s^{-1} and (b) 0.1 s^{-1} .

Fig. 5. True stress-strain curves of the 1.5 wt.% $\text{Al}_2\text{O}_{3\text{np}}$ (80 nm)/Al7075 composite compressed with various strain rates at the deformation temperatures of (a) 560 °C; (b) 580 °C.

Fig. 6. True stress-strain curves of the composites compressed under different conditions: (a) 560 °C, 0.1 s^{-1} ; (b) 580 °C, 1 s^{-1} .

Fig. 7. Relationship between the logarithmic peak stresses and the logarithmic strain rate (a) for the composite with 1.5 wt.% $\text{Al}_2\text{O}_{3\text{np}}$ (80 nm) at different temperatures and (b) for the composites with different $\text{Al}_2\text{O}_{3\text{np}}$ contents at 570 °C, respectively.

Fig. 8. Comparison among the peak stresses of the composites obtained after deformation at 580 °C and different strain rates.

Fig. 9. Comparison among the peak stresses of the composites obtained after deformation at 560 °C and a strain rate of 0.1 s^{-1} .

Fig. 10. Validation of the constitutive model for thixoforming of composites with different Al_2O_3 contents and nanoparticle sizes against the experimental data obtained at different temperatures and strain rates: (a) 0.5 wt.% $\text{Al}_2\text{O}_{3\text{np}}$ /Al7075, 560 °C; (b) 1.5 wt.% $\text{Al}_2\text{O}_{3\text{np}}$ /Al7075, 570 °C.

Fig. 11. SEM fractographs of 1.5 wt.% $\text{Al}_2\text{O}_{3\text{np}}$ (80 nm)/Al7075 composite deformed to the true strain of 0.6 at 1s^{-1} and different temperatures: (a) 560 °C; (b) 590 °C, and then quenched in water.

Fig. 12. Variation in the steady stress as a function of the strain rate (a) for the 1.5 wt.% $\text{Al}_2\text{O}_{3\text{np}}$ (80 nm)/Al7075 composite at different temperatures and (b) for the composites with different $\text{Al}_2\text{O}_{3\text{np}}$ (80 nm) contents at 570 °C, respectively.

Fig. 13. SEM fractographs of 1.5 wt.% $\text{Al}_2\text{O}_{3\text{np}}$ (80 nm)/Al7075 composite deformed to the true strain of 0.6 at 560 °C and different strain rates: (a) 0.01 s^{-1} ; (b) 5 s^{-1} , and then quenched in water.

Fig. 14. SEM-EDS images of 1.5 wt.% $\text{Al}_2\text{O}_{3\text{np}}$ (80 nm)/Al7075 composite deformed to the true strain of 0.6 at 570 °C and a strain rate of 0.01 s^{-1} , and then quenched in water: (a) SEM fractographs of the composite; (b) EDS result of point 1 in (a).

Table 1. Summary of the constitutive models used to describe thixotropic behavior of composites

Authors	Models	Types
Bao and Lin [10]	$\sigma_N = \phi(f_p, N) \left[1 + \left(\frac{\dot{\varepsilon}}{\varepsilon_0} \right)^m \right] \left[1 + \psi(m, N) f_p^{3/2} \left(\frac{\dot{\varepsilon}}{\varepsilon_0} \right)^{\beta m} \right]$ <p>where f_p is particle volume fraction</p> <p>and N is the inverse of the stress exponent</p>	One-phase model
Li et al. [11]	$\sigma(f_p, \varepsilon, \dot{\varepsilon}) = \sigma_0(\varepsilon) g(f_p) \left(1 + \left(\frac{\dot{\varepsilon}}{\varepsilon_0} \right)^m \right) \left(1 + \left(\frac{\dot{\varepsilon}}{\varepsilon_0} \right)^m f_p \right)$ <p>where $g(f_p) = 1 + 1.17f_p + 2.28f_p^2 + 21.0f_p^3$</p>	One-phase model
Qi et al. [12]	$A \left(\frac{\sigma}{1 - f_{IWL}} \right)^{1/m} = \dot{\varepsilon} \exp \left(\frac{Q}{RT} \right)$ <p>where f_{IWL} is the fraction of interface wetted by liquid phase and Q is the activation energy</p>	Two-phase model
Luo et al. [13]	$\sigma = \sigma_s + \sigma_L$ $\dot{\varepsilon} = \frac{\varepsilon_{eq}}{\sigma_{eq}} \left[\frac{A}{2} \sigma_s + \frac{6B - A}{6} I_1 \right]$ $u_1 f_L = \frac{k \partial p}{\eta_1 \partial x}$ <p>where $\dot{\varepsilon}_{eq} = \beta \exp \left(-\frac{Q}{RT} \right) \left[\sinh(\alpha \sigma_{eq}) \right]^n$</p>	Two-phase model
Yan et al. [14]	$\sigma = g(f_p) \exp \left(\frac{d}{T} \right) \varepsilon^n \dot{\varepsilon}^m (1 - \beta f_L)^{a_1} \left(1 + \left(a \dot{\varepsilon} \right)^m f_p \right)^{a_2}$	Two-phase model

Table 2. Experimental conditions used in different experiments.

Composites	Strain rate (s ⁻¹)	Temperature (°C)	Nanoparticles content (f_p , wt.%)	Particle size (nm)	Maximal strain
Al ₂ O _{3np} /Al707 5	0.01	560	0.5	80 nm	0.6
	0.1	570	1.5	200 nm	
	1	580	2.5	500 nm	
	5	590			

Table 3. Values of strain rate sensitivity in the semisolid state

Nanoparticle content (wt. %)	0.5	1.5	2.5		1.5	
Temperature (°C)		570		560	580	590
m	0.112	0.090	0.111	0.081	0.109	0.122
R^2	0.990	0.981	0.996	0.970	0.974	0.984
$\bar{m}$	0.1042					

Table 4. Parameter values in the constitutive equation for composites

a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	Multiple correlation coefficient
-6.575	26.212	6245.811	-0.365	0.099	1.883	-1.601	-0.378	3.338	0.956

Fig. 1. Graphite die and crucible used to produce samples for thixotropic compression tests.

Fig. 2. Heating process of thixotropic compression tests.

Fig. 3. (a) Semisolid microstructure at 580 °C for the composite before thixotropic compression and (b) microstructure of the **composite** deformed to the true strain of 0.6 at 580 °C and a strain rate of 0.1 s^{-1} .

Fig. 4. True stress-strain curves of the 1.5 wt.% $\text{Al}_2\text{O}_{3\text{np}}$ (80 nm)/Al7075 composite compressed at various deformation temperatures with the strain rates of (a) 0.01 s^{-1} and (b) 0.1 s^{-1} .

Fig. 5. True stress-strain curves of the 1.5 wt.% $\text{Al}_2\text{O}_{3\text{np}}$ (80 nm)/Al7075 composite compressed with various strain rates at the deformation temperatures of (a) 560 °C; (b) 580 °C.

Fig. 6. True stress-strain curves of the composites **compressed** under different conditions: (a) 560 °C, 0.1 s⁻¹; (b) 580 °C, 1 s⁻¹.

Fig. 7. Relationship between the logarithmic peak stresses and the logarithmic strain rate (a) for the composite with 1.5 wt.% $\text{Al}_2\text{O}_{3\text{np}}$ (80 nm) at different temperatures and (b) for the composites with different $\text{Al}_2\text{O}_{3\text{np}}$ contents at 570 °C, respectively.

Fig. 8. Comparison among the peak stresses of the composites obtained after deformation at 580 °C and different strain rates.

Fig. 9. Comparison among the peak stresses of the composites obtained after deformation at 560 °C and a strain rate of 0.1 s⁻¹.

Fig. 10. Validation of the constitutive model for **thixoforming of composites** with different Al_2O_3 contents and nanoparticle sizes against the experimental data obtained at different temperatures and strain rates: (a) 0.5 wt.% $\text{Al}_2\text{O}_{3\text{np}}$ /Al7075, 560 °C; (b) 1.5 wt.% $\text{Al}_2\text{O}_{3\text{np}}$ /Al7075, 570 °C.

Fig. 11. SEM fractographs of 1.5 wt.% $\text{Al}_2\text{O}_{3\text{np}}$ (80 nm)/Al7075 composite deformed to the true strain of 0.6 at 1 s^{-1} and different temperatures: (a) 560 °C; (b) 590 °C, and then quenched in water.

Fig. 12. Variation in the steady stress as a function of the strain rate (a) for the 1.5 wt.% Al_2O_{3np} (80 nm)/**Al7075** composite at different temperatures and (b) for the composites with different Al_2O_{3np} (80 nm) contents at 570 °C, respectively.

Fig. 13. SEM fractographs of 1.5 wt.% $\text{Al}_2\text{O}_{3\text{np}}$ (80 nm) / Al7075 composite deformed to the true strain of 0.6 at 560 °C and different strain rates: (a) 0.01 s^{-1} ; (b) 5 s^{-1} , and then quenched in water.

Fig. 14. SEM-EDS images of 1.5 wt.% Al₂O_{3np} (80 nm)/Al7075 composite deformed to the true strain of 0.6 at 570 °C and a strain rate of 0.01 s⁻¹, and then quenched in water: (a) SEM fractographs of the composite; (b) EDS result of point 1 in (a).