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Strengthening mechanism and thermal deformation behavior of Al-12Si/Fe piston composite

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Abstract

The present paper aims the investigation on the influence of Fe based amorphous on strength of aluminum alloy (Al-12Si), and the thermal deformation behavior of new Al-12Si/Fe base amorphous composites. On this foundation, a heat flow stress model of the sample was proposed by a Zener-Hollomon parameter and microstructural studies were carried out on Al-12Si/Fe base amorphous composite by many means. Microstructural study reveals dynamic recovery and dynamic recrystallization of Al-12Si/Fe base amorphous composite at thermal compression test. In addition, the deformation activation energy of Al-12Si/Fe-based amorphous composites is as high as 211.29 kJ mol \(^{-1}\), compared with Al-12Si alloy (170.51 kJ mol \(^{-1}\)). Importantly, the flow stress equation of the new composite is \(\dot{\varepsilon} = 4.42 \times 10^{14} \sinh (0.0166\sigma)/6.13\exp(-211290/RT)\), and the linear regression coefficient is 0.99. This study constitutes a significant advance in strengthening the Al-12Si engine piston and controlling the thermal deformation behavior and opens new directions for the development of piston material.

1. Introduction

At the Al alloys, Al-Si alloys such as Al-12Si are widely used in engine piston for their excellent wear resistance and dimensional stability at elevated temperatures [1–3]. However, thermal deformation behavior for this alloy may vary with temperature, and can lead to piston eccentric wear and failure [4–6]. Some researchers have reported the hot deformation behavior and constitutive equation of Al-12Si alloys, whose results show that the strength and linear correlation coefficients are low, the hot deformation behavior has not been described in detail and the performance has not been improved [7, 8]. Therefore, it needs to be further studied systematically. Such requirements of material properties for applications can be obtained by use of particle reinforced composites (PRC) with the alloy as matrix [9].

Recently, a large number of enhanced aluminum base composites studies have reported (such as SiC, Al\(_2\)O\(_3\), B\(_2\)C, TiB\(_2\) ceramic particles) [10–12]; whereas the thermal diffusivity of ceramic particles and matrixes are quite different, which lead to enhanced phase decomposition or brittle fracture for interfacial edge between enhanced phase and substrate [13–15]. Fe based amorphous is preferred as these composites exhibit relatively low lattice defects, similar thermal expansion coefficient and excellent mechanical properties compared to composites reinforced with the various types of particulate reinforcements such as SiC, Al\(_2\)O\(_3\), B\(_2\)C and TiB\(_2\) [16, 17]. Some researchers have reported that the use of Fe-based amorphous particles as reinforcement in the Al matrix composites leads to a remarkable combination of high strength and plasticity, but the crystallization temperature of amorphous Fe in composite materials was not discussed in detail [18, 19]. The crystallization temperature of Fe base amorphous particle in Al-12Si/Fe base amorphous composite needs to be considered [20]. Moreover, our group found that few studies the thermal deformation behavior of amorphous particle reinforced composites. In view of the potential applications of Al-12Si/Fe base amorphous composite engine piston, the thermal deformation behavior of this composite is of interest in the present work.
Herein, a novel composite of engine piston materials has been prepared using stronger Fe based amorphous reinforcement in an Al-12Si matrix alloy. The thermal deformation behavior under different strain rates and temperatures could be tested by thermal compression test. Based on this, a heat flow stress model of this composite can be proposed by a Zener-Hollomon parameter in the hyperbolic-sine equation. Our group hope that this study can provide a theoretical basis for strengthening and controlling the thermal deformation behavior of Al-12Si engine pistons and practical applications.

2. Materials and methods

2.1. Preparation of Al-12Si/Fe base amorphous composite

In this work, the commercial Al-12Si alloy with 40 μm size (chemical composition is listed in table 1, Alibaba, Shanghai) was chosen to be the matrix material. To mix the powders evenly, Fe base amorphous particles (chemical composition is listed in table 2, ~37 μm size, Alibaba, Shanghai) and Al-12Si particle (90 wt%) was mixed by high energy ball-milling (QXQM-2, Tian chuang, China) in nitrogen atmosphere: the weight ratio of ball to powder is 6.67, the speed is 360 revolutions per minute (rpm) and the run times is 12 h. The microstructure and element distribution of powders are shows in figure 1. As can be seen, the diameter of Fe base amorphous powder did not change drastically (~35 μm size) by planetary ball mill, which helpful to improve the strengthening characteristics of composites [21]. Subsequently, Al-12Si/10%wt. Fe base amorphous composite with diameter of ~14 mm was prepared in continuous extruder (JL-350) at 440 °C under an extrusion ratio of 1:26 and extrusion speed of

![Figure 1](image_url)
0.5 mm s\(^{-1}\) [22]. Finally, all cylindrical samples with height with 12 mm and diameter of 8 mm can be processed by numerical control lathe and wire cutting.

2.2. Test method
The scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) were tested using S-4800FE to observations microstructure and element distribution of samples. The transmission electron microscopy (TEM) were tested using FEI Tecnai G2 F20. For SEM, a sample was cut from the middle of the compress samples and then manual polished using 220\#, 500\#, 1200\# and 2000\# SiC paper and finely polished with 6000\# diamond polishing paste. To prepare TEM sample, 1.5 mm thick discs were first cut from the middle of the compress samples, where most of the deformation took place. The discs were further mechanically ground to thicknesses of about 50 μm. The final electro-polishing step to reach thicknesses suitable for TEM investigations was done in a Tenupol-3 machine. The electrolyte, consisting of 1/3 H\(_3\)NO\(_3\) and 2/3 methanol. The crystallization temperature of Fe base amorphous particle in composite was conﬁrmed using a differential scanning calorimetry (DSC, Mettler Toledo) with a heating/cooling rate of 10 K min\(^{-1}\) under argon atmosphere in a temperature range of 210 °C–570 °C. Then, the phase structure of the particles was recorded via x-ray diffraction (XRD, Siemens equipped with Cu-K\(_\alpha\) radiation (λ = 1.5406 Å), using a continuous \(θ–2θ\) scans mode at a tube power of 40 kV/40 mA in a range of 10–100° (2\(θ\)) with step=0.02° (2\(θ\)) and 0.15s per step) spectra.

Afterwards, the hot compression tests were tests using a Gleeble-3500 thermomechanical simulator: the experimental temperature is from 350 to 450 °C, the strain rates is 0.001 to 1 s\(^{-1}\). To ensure uniform sample temperatures, all samples were heated to tests temperature with a heating speed of 10 °C s\(^{-1}\) and insulation for 300 s. Then, graphite was filled between the samples and crossheads to minimize the friction. It is important to note that the true strain of 0.9 was employed in the tests, at this moment the specimens were quenched by cold water immediately to keep the microstructures.

3. Results and discussion
3.1. The crystallization temperature of Fe base amorphous particle
The crystallization temperature of Fe base amorphous particle in composite is an important performance. Here, the DSC thermograms of Al-12Si alloy particle, Fe base amorphous particle and mixed powder was displayed in figure 2(a). It can be clearly seen that the exothermic peak of mixed powder correspond to the crystallization event of Fe base amorphous particle, illustrating that the crystallization temperature (\(T_x\)) of amorphous Fe particle is 496 °C and the Fe base amorphous transition temperature (\(T_g\)) of this alloy is 464 °C. The machining temperation and meet the needs completely due to the supercooled liquid region of the Fe base amorphous about 32 °C [6, 21].

Afterwards, the XRD patterns of Al-12Si/Fe composite final prepared at 490 °C and Fe base amorphous at room temperature are showed in figure 2(b). It is noteworthy that the diffuse peak was observed in the XRD pattern of the composite around 2\(θ\) = 45° concur with Fe base amorphous, which indicated that the existence of the Fe base amorphous phase in the composite [21]. It can be understood that the XRD pattern of Al-12Si/Fe...
composites is the combination of amorphous Fe powder and Al-12Si alloy. The result is consistent with the DSC thermograms. Therefore, the extrusion temperature of composites can be confirmed at 440 °C due to the temperature may increases 50 °C during extrusion [23].

The Fe base amorphous exhibits an excellence bonding strength and superplasticity at supercooled liquid region [16, 17]. Based on this, the thermal deformation behavior of composites can be well analyzed by constitutive equation.

3.2. Organizational evolution

The TEM images of Al-12Si/Fe base amorphous composites under different compression temperatures and 0.1 s⁻¹ strain rates is presented in figure 3. First of all, we marked the grains at different temperatures with yellow dotted lines. It is obvious that the grains grow with the temperature. In addition, the dislocations are also marked at the corresponding positions in the figure (as shown by the yellow arrows). It was found that dislocations also decreased significantly during the heating process. With rising of temperature, the subgrain boundaries become more apparent which reduces the dislocations density and the grains size increases gradually show in figures 3(b) and (c). These trends can be explained as the deformation temperature increases, the thermal activation energy will be improved, which results in boundary migration and grain grow. This result explains the reason why the composites stress reduces with the increase of the hot deformation temperature.

The SEM images of the Al-12Si/Fe base amorphous composites deformed at temperatures 400 °C and strain rates of 0.001–1 s⁻¹ are shown in figure 4. The TEM of the figure 4(a) upper right corner shows the recrystallized grains grow and the subgrain boundaries are eliminated for the temperature of 400 °C and 0.001 s⁻¹, showing the happen of recrystallization for the hot deformation [24]. The subgrain boundaries spotted for tests at 400 °C and 0.001 s⁻¹ (figure 4(a)), hence, the subgrain boundaries are less compared to the strain rates 1 s⁻¹ (figure 4(d)). This results can be explain by both the recrystallized time and recrystallized grains grow are reduction with increasing the strain rate. Recrystallized structures can be found in all the images, however, recrystallization is more significant at lower strain rates. This result partly explains the reason why the composites stress increases with the increase of the strain rate.

To further investigate the effect of Fe base amorphous on the deformation behavior of the specimen, the TEM images of composites at 400 °C, 0.1 s⁻¹ (figure 5(a)) and 450 °C, 1 s⁻¹ (figure 5(b)). The doped amorphous Fe particles are pining at the grain boundaries of Al-12Si alloy, which resulting in an increase in the resistance to

![Figure 3. Microstructures of Al-12Si/Fe amorphous composites under different compression temperatures: (a) 350 °C; (b) 400 °C and (c) 450 °C.](image-url)
3.3. Flow stress analysis

The typical true stress–strain curves of Al-12Si/Fe base amorphous composites at different and strain rates and deformation temperatures were showed in figure 6. Obviously, the flow stress is mainly affected by the strain, temperature and strain rate [29]. In figure 6, the stress increase sharply with increasing strain and tends to be constant after a peak value, but the flow stress decreased with increasing strain when the strain rate is 1 s$^{-1}$ and...
strain values beyond of 0.8. Moreover, the flow stress increase with increasing strain rate and decreasing of temperature in each samples. The result is caused by competition procedure between dynamic softening and work hardening.

Before dynamic equilibrium, the stress increases linearly with increasing strain rate, this results can be caused by both the dislocation motion and climbing time are reduction with increasing the strain rate, work hardening is stronger than dynamic softening [30]. When the strain increases, both the dynamic recovery and dynamic recrystallization increase continuously; for instance the softening mechanism gradually takes effect, while the hardening effect weakens. Then, the flow stress reaches maximum, at this time, dynamic softening and work hardening remain at a dynamic equilibrium [31]. When the strain at 0.2–0.8, the stress curve flattens out which may be related to the recrystallization and dynamic recovery, as well as the accommodation ability of the Al-12Si/Fe amorphous composites. It is worth noting that at three different temperatures, from figure 3, a at 1s⁻¹ strain rate, the stress curves of the Al-12Si samples are under the composites. This means the strength of the sample is significantly improved after doping 10wt% amorphous Fe powder. Simultaneously, the amorphous doping material has a sensitivity to the positive strain rate. The hot deformation mechanisms and strengthening mechanism for the Al-12Si/Fe base amorphous composite will be analyzed based on microstructural observations and constitutive equation.

### 3.4. Constitutive analysis

In order to further study the correlation of various factors in the plastic deformation of the composites, the hyperbolic sine function raised by Sellars and Tegart was used for analysis [32]. For the flow stress,

\[
\dot{\varepsilon} = A [\sinh (\alpha \sigma)]^n \exp (-Q/RT)
\]  

where \( \dot{\varepsilon} \) refers to the strain rate (s⁻¹), \( R \) refers to the gas constant (8.31 J mol⁻¹ K⁻¹), \( \sigma \) refers to the flow stress (MPa), \( T \) refers to the absolute temperature (K), \( Q \) refers to the activation energy for hot deformation (kJ/mol), \( A, \alpha, \) and \( n \) are constants independent of temperature.
The relation among strain rate \( \dot{\varepsilon} \) and \( T \) can be obtained in terms of Zener-Hollomon parameters

\[
Z = \dot{\varepsilon} \exp \left( -\frac{Q}{RT} \right) = A \left( \sinh (\alpha \sigma) \right)^n
\]

(2)

where \( Z \) refers to the temperature compensated strain rate factor.

At different stress levels, the relation among stress \( \sigma \) and strain rate \( \dot{\varepsilon} \) is obtained as follows

\[
\dot{\varepsilon} = A n \ln \left( \sigma + n \right)
\]

(3)

\[
\dot{\varepsilon} = A \beta \sigma
\]

(4)

where \( \beta = \alpha \times n \).

At a certain strain rate, the derivative of equation (1) can be obtained

\[
Q = R \frac{d (\ln \dot{\varepsilon})}{d \left( \ln \left( \sinh (\alpha \sigma) \right) \right)} = R n K
\]

(5)

The \( \sigma \) as the peak stress, the curves \( \ln \dot{\varepsilon} - \ln \sigma \) and \( \ln \dot{\varepsilon} - \sigma \) are obtained by equations (3) and (4). As shown in figure 7, the slope is obtained by least squares linear fitting \( n = 9.04, \beta = 0.15, \) and \( \alpha = 0.0166. \) The \( n \) and \( K \) are computed to be 7.845 and 3.241, from figures 7(c) and (d). The thermal compression activation energy \( Q = 211.29 \text{ kJ mol}^{-1} \) of Al-12Si/Fe base amorphous composites was obtained by equation (5).

The thermal compression activation energy \( Q = 170.51 \text{ kJ mol}^{-1} \) of Al-12Si was obtained by the same method. Plainly, the hot compression activation energy of the composites increased 40.78 kJ mol\(^{-1}\). And it is also higher 30.33 kJ mol\(^{-1}\) than the Al-15Si \( Q = 180.96 \text{ kJ mol}^{-1} \) calculated by Wang C X et al [33]. The activation energy increasing can be attributed to amorphous Fe powder pinning xdislocations and grain boundaries. The doping of amorphous Fe powder significantly improves the thermal compression deformation resistance of Al-12Si. The result is consistent with the thermal compression stress-strain curve.

Take the logarithm of the two sides of equation (2)

\[
\ln Z = \ln A + n \ln \left( \sinh (\alpha \sigma) \right)
\]

(6)
Linear fitting using least squares method is shown in figure 8. From equation (6), the slope of the line in figure 8 is the stress index of the composite material \( n = 6.13 \), the intercept \( \ln A = 33.72 \) and \( A = 4.42 \times 10^{14} \text{s}^{-1} \), the linear regression coefficient is as high as 0.99, which indicates that the constitutive equation is suitable for the flow stress behavior of Al-12Si/Fe base amorphous composites. This provides a theoretical basis for controlling strain rate, stress levels and process parameters during thermal processing and make possible for piston thermal deformation behavior controllable in service.

By substituting the \( A, \alpha, n, \text{ and } Q \) into the equation (1), the composites constitutive equation can be expressed as

\[
\dot{\varepsilon} = 4.42 \times 10^{14} \sinh(0.0166\sigma)^{0.13} \exp\left(-\frac{211290}{RT}\right)
\]

4. Conclusions

(1) The flow stress of Al-12Si/Fe base amorphous composites is mainly affected by the strain, temperature and strain rate. The flow stress increase with increasing strain rate and decreasing of temperature.

(2) The deformation activation energy of Al-12Si/Fe base amorphous composites was calculated to be 211.29 kJ mol\(^{-1}\) which is 40.78 kJ mol\(^{-1}\) higher than Al-12Si alloys and improve creep strength and service life of Al-12Si alloys.

(3) The constitutive equation of the flow stress obtained by the hyperbolic sine function is: \( \dot{\varepsilon} = 4.42 \times 10^{14} \sinh(0.0166\sigma)^{0.13} \exp\left(-\frac{211290}{RT}\right) \), the linear regression coefficient is as high as 0.99, it can provide a guidance for the safety of the high temperature piston material in service under high temperature environment.

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