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# High temperature deformation behavior and optimal hot processing parameters of Al–Si eutectic alloy

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*Abstract:* High temperature deformation behavior of Al–Si eutectic alloy was investigated by compression tests conducted at various temperatures (563, 603, 643, 683, 723, and 763 K) with various strain rates of 0.001, 0.01, 0.05 and 1 $s^{-1}$. Hot processing map and extrusion test were used to optimize hot processing parameters. The results that are obtained show that the main high temperature deformation mechanism of the Al–Si eutectic alloy is dislocation movement. The difference between the maximum deformation activation energy of 178 kJ/mol and self-diffusion activation energy of pure aluminum results from rupture of eutectic silicon crystals. The deformation activation energy and instable domain decrease with increasing strain. Then the effects of strain on deformation activation energy and instable domain are negligible at higher stain than 0.4. The optimal hot processing parameters of the Al–Si eutectic allFoy are deformation temperature ranging from 660 K to 723 K, lower strain rate than $10^{-1.5}$ $s^{-1}$, and strain of 0.51–1.20.



## 1. Introduction

Al–Si eutectic alloys with good mechanical properties, excellent wear resistance and low coefficient of thermal expansion have been used widely in aerospace and automotive industry [1–4]. Furthermore, Al–Si eutectic alloys are some of the most commercially important casting alloys because of excellent castability. So numerous parts of Al–Si eutectic alloy were manufactured by die-casting [5–7]. However, the disadvantages of parts manufactured by die-casting, e.g. poor airtightness and ordinary mechanical properties resulting from coarse microstructures, limit their application [8,9]. Hot forging technology that enable a dense material structure performing better mechanical properties is thought to be one way to solve the problem [10,11].

During hot forging of Al–Si eutectic alloys, people pay more attention to hot workability and final mechanical properties of the parts. The hot workability is usually defined as the amount of deformation that a material can undergo without cracking and reach desirable deformed microstructures and service performance at a given temperature and strain rate. Generally, the hot workability of Al–Si eutectic alloy is attributed to the size, distribution and morphology of eutectic-Si particles [12–17]. Up to now, there were many work focused upon the effects of hot processing parameters on high temperature deformation behavior and microstructures of Al–Si alloys. Haghshenas et al. [14] has investigated hot deformation behavior of thixocast Al–Si–Mg alloy during hot compression and concluded that increasing the deformation temperature and decreasing the strain rate are in favor of hot workability. Haghdadi et al. [15] have studied the effect of thermomechanical parameters on the eutectic silicon characteristics in a non-modified cast A356 aluminum alloy. The results indicated that the Si refinement was more pronounced at lower deformation temperature and higher strain rates, while the highest degrees of spheroidization were achieved at higher temperatures and lower strain rates. Haghdadi et al. [16] reported the flow behavior modeling of cast A356 aluminum alloy at elevated temperatures considering the effect of strain. However, to the best of our knowledge, there are a few researches reported on optimal hot processing parameters of Al–Si eutectic alloys. Besides, final mechanical properties of the parts manufactured by hot forging are greatly affected by hot processing parameters (deformation temperature, strain rate, and strain that stands for deformation amount of the material underwent from billet to part) too [18]. So study of high temperature deformation behavior of Al–Si eutectic alloys and optimization hot processing parameters are necessary.

Prasad et al. [19] developed the dynamic material model (DMM) to enhance our understanding of workability parameters. Workability can be evaluated by means of processing maps, constructed from experimentally generated flow stress variation with respect to strain, strain rate, and deformation temperature. Processing map shows in the processing space, i.e. on the axes of temperature and strain rate, the processing conditions for stable

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and unstable workability deformation. This methodology has been used to optimize hot processing parameters of various materials [20–23]. Generally, hot processing maps were constructed to optimize deformation temperature and strain rate, which cannot be used to optimize strain. The previous investigations also did not reach a uniform conclusion about relationship between hot processing map and strain. Luo et al. [24] reported that the instability domains in instability maps in the isothermal compression of 7A09 aluminum alloy at the strains of 0.3, 0.5, and 0.7 vary with increasing strain. Sagar et al. [25] constructed hot processing map of Ti–24Al–20Nb alloy at the strains of 0.3 and 0.5 and found that the instability region reduced with the increment of strain. Cai et al. [26] proposed that the strain had a slight effect on the processing map of a Ni-based superalloy. So some other method such as extrusion test should be introduced in order to optimize strain during hot forging besides hot processing map.

In this research, the effect of strain on deformation activation energy of an Al–Si eutectic alloy during high temperature compression was presented to investigate high temperature deformation behavior of the Al–Si eutectic alloy. Hot processing map was used to optimize deformation temperature and strain rate, and extrusion test was used to optimize strain of the Al–Si eutectic alloy. During extrusion tests, the billets cut from the Al–Si eutectic alloy bar were extruded with different reduction ratios that represented different strains. Then elongation and strength results of the extruded specimens acquired by tensile tests were utilized to optimize strain.

## 2. Experimental

A commercial Al–Si eutectic alloy bar with 40 mm in diameter and T6 temper was used in the present work. The composition is Al–12Si–0.8Cu–1.1Mg–0.7Ni–0.5Fe (wt%). Fig. 1 is the optical micrograph showing the initial microstructures of the Al–Si eutectic alloy consists of coarse massive primary Si, dentritic eutectic Si and Al matrix. Compression specimens with a diameter of 8 mm and a height of 12 mm were machined with the compression axis parallel to the extrusion direction. Compression tests were conducted to a predetermined strain of 0.69 on a thermal–mechanical simulator (Zwick/Roell 20) at 563, 603, 643, 683, 723 and 763 K and the strain rates of 0.001, 0.01, 0.05 and 1 $s^{-1}$, respectively. Generally, the deformation temperatures of Al–Si eutectic alloy during hot deformation is lower than that of the solidus temperature of the equilibrium phase diagram of Al–Si binary alloy exceeds 70 K to avoid the effect of partial melting on hot deformation. The six compression temperatures were chosen according to the solidus temperature (850 K) of Al–Si eutectic alloy in equilibrium phase diagram of Al–Si binary alloy shown in literature [27]. Graphite was used as lubricant during compression to reduce the friction between the flat ends of the specimens and die interfaces. The billets with 30 mm in diameter were cut from the Al–Si eutectic alloy bar before extrusion tests. Then extrusion tests were conducted at YK28-800 double-action press. The billets were extruded along longitudinal direction with ram speed of 20 mm/s and 120°extrusion angle of female die. The extrusion temperature and section reduction ratio were 573, 623, 673, 723, and 773 K and 25%, 40%, 55%, 70%, and 85%, respectively. The section reduction ratio is represented as $A/A_0$, where $A$ is the section area of extruded sample and $A_0$ the section area of billet. The corresponding strain values during extrusion were 0.29, 0.51, 0.80, 1.21 and 1.90, respectively. Tensile specimens with a gage diameter of 5 mm and a gage length of 20 mm were cut from the extruded bar with the tensile axis parallel to the extrusion direction. Tensile tests were conducted on a 100 kN universal material testing machine (WDW3200) at ambient temperature. The displacement rate for each specimen was chosen about 1 mm/s. Samples were mounted, polished and etched by 0.5% HF for optical microscopy (OM) observation by Axiovert 200Mat. A Quanta 200 scanning electron microscope (SEM) and Energy-dispersive X-ray spectroscopy (EDS) were applied to observe microstructure and distinguish the main phases of the Al–Si eutectic alloy.

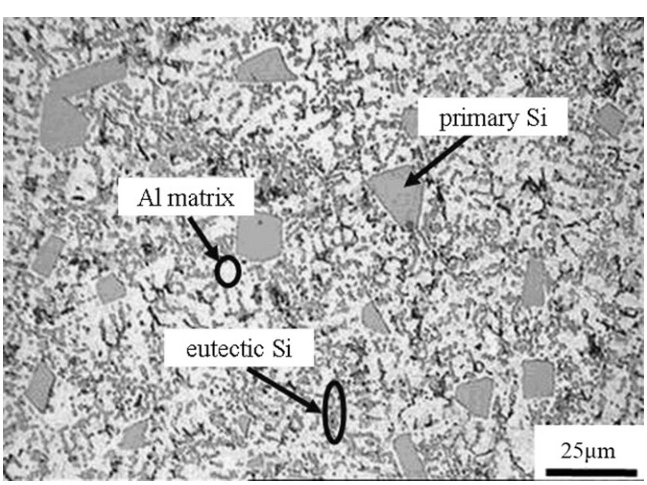


**Fig. 1.** Optical micrograph showing the microstructure of the Al–Si eutectic alloy.

The processing map was constructed using the principles of the dynamic material model [28]. The strain rate sensitivity index ($m$) was calculated at each temperature using Eq. $m=\partial\log\sigma/\partial\log\dot{\varepsilon}$, where $\sigma$/(MPa) is the flow stress and $\dot{\varepsilon}/s^{-1}$ is the strain rate. The efficiency of power dissipation ($\eta$) is then calculated using Eq. $\eta=2m/(m+1)$ from a set of $m$ values at a constant strain as a function of strain rate and deformation temperature, and plotted as three-dimensional map. The region of microstructure instability was evaluated using the criterion $\xi(\dot{\varepsilon})=\partial\ln[m/(m+1)]/\partial\ln\dot{\varepsilon}+m<0$ [29]. The dimensionless parameter ($\xi(\dot{\varepsilon})$) is evaluated as a function of strain rate and temperature to obtain an instability map, where metallurgical instability during plastic flow occurs in region where the instability parameter $\xi(\dot{\varepsilon})$ is negative [30–32].

## 3. Results

### 3.1. Mechanical behavior

The true stress–strain curves of the Al–Si eutectic alloy compressed at different deformation conditions are presented in Fig. 2, which shows the effects of deformation temperature and strain rate on flow behavior of the experimental alloy. It is shown that all the curves exhibit the same trend: the flow stresses increase quickly to the peak values and then decrease slowly. The peak stress increases with increasing strain rate and decreasing deformation temperature.

Following constitutive equations have commonly been applied in high temperature deformation of crystal materials:

$$\dot{\varepsilon}=A'\sigma^{n'}\exp\left(-\frac{Q}{RT}\right) \tag{1}$$

$$\dot{\varepsilon}=A''\exp(\beta\sigma)\exp\left(-\frac{Q}{RT}\right) \tag{2}$$

$$\dot{\varepsilon}=A(\sin h\alpha\sigma)^{n}\exp\left(-\frac{Q}{RT}\right) \tag{3}$$

where $A$, $A'$, $A''$, $n$, $n'$, $\alpha$ and $\beta(=\alpha n)$ are constants, $Q$ is an activation energy for deformation, and $R$ is the gas constant.