Characterization of tensile fracture in heavily alloyed Al–Si piston alloy

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Abstract: This paper focuses on a typical automotive piston material to characterize its fractographic appearance after tensile rupture. The fracture of this heavily alloyed Al–Si alloy takes place in a brittle manner. The consecutive eutectic zone is found to break by debonding of Si platelets from the Al matrix or by fracturing of Si platelets. The various intermetallic particles break up complicatedly under the stress field of the propagating crack. The fracture tends to pass through or approach to the boundary between the eutectic Al matrix and Si platelets and there is a strong interaction between the propagating crack and the obstructing intermetallic compound. A tensile fracture mechanism in the heavily alloyed Al–Si alloy is elucidated.

Key words: tension test; aluminum alloys; facets; fracture

1 Introduction

Al–Si alloys are widely used in industry. This is related to their excellent castability, wear resistance and other good technological properties practically for potential applications [1]. Due to an increasing requirement for reducing fuel consumption and CO₂ emission, higher service temperatures will allow more efficient operation [2, 3]. Typically pistons are cast from near eutectic Al–Si alloys due to their high strength over weight ratio and good thermal conductivity [4–7]. This class of alloy exhibits complex multiphase microstructures, comprising primary and eutectic Si, Al, and numerous intermetallic particles [8]. It is therefore important to characterize the microstructural features controlling alloy mechanical performance such that improved alloys may be developed for this application. In the past decades, a lot of mechanical tests and microstructural investigations have been carried out for various Al alloys and the related theories of strength and fracture of Al alloys have also been built up [9–12]. Al–Si alloys as important cast alloys have been studied extensively, but most of the previous researches on Al–Si alloys are focused on the hypoeutectic alloys such as A356, slightly different from the modern automotive piston materials [13–15]. Near eutectic Al–Si piston alloys strengthened by Cu, Ni and several other elements possess hard Si particles and intermetallic phases and are known to have excellent mechanical properties such as high level of strength at elevated temperatures and low value of the thermal expansion coefficient [4, 6]. These materials have complex heterogeneous microstructure, and a significant number of phases could be present [1]. So far, few investigations have been carried out for the fractographic characteristics and mechanisms of the fracture in the near eutectic Al–Si piston alloys.

In order to develop alloys that can better withstand the harsh operating conditions in an engine, it is necessary to assess the fundamental mechanical properties of the piston alloys properly. As one part of our systematic study for a commercial piston alloy, in this paper, an Al–Si alloy specimen directly taken from a piston was tensile tested and characterized to supply exact information for future piston development.

2 Experimental

The piston was cast in the temperature range of 790–810 °C and then aged at 230 °C for 7 h. The composition of the alloy studied is listed in Table 1 after being examined with optical emission spectroscopy. Besides Si, the basic alloying elements in this alloy are Cu and Ni. All of the principal alloying elements increase...
strength and hardness, but somewhat reduce alloy relative elongation. According to the Al–Si phase diagram, the present alloy corresponds to eutectic or near eutectic alloy.

Smooth cylindrical test specimens (5.0 mm gage diameter and 45.0 mm gage length) were machined directly from as-cast piston to ensure representative microstructures. The specimens were soaked at 350 °C for 100 h before testing to provide a practical simulation for the effect of long-term high temperature service environment. Tensile test was performed at room temperature on a fully automated servohydraulic test machine (Instron 8801) equipped with a load of 29.4 kN at a cross-head displacement rate of 1 mm/min. The strain in the specimen gauge length was monitored directly by a clip-gauge extensometer. Additionally, the etching treatment was carried out by immersing a metallographic sample in a solution of 10% NaOH for 600 s.

Post failure analysis was conducted on the fracture surface using a JEOL JSM–6610LV scanning electron microscope (SEM) with energy dispersive X-ray spectrometer microanalysis (EDS). The microstructure was examined using SEM and optical microscopy.

3 Results and discussion

3.1 Microstructure

The micrographs illustrating the microstructure of the piston alloy are shown in Fig. 1. Both primary "blocky" Si and eutectic plate-like Si phases mounted in the aluminium matrix were observed in the optical micrograph (Fig. 1(a)). Due to the existence of excessive alloying elements (Cu, Ni, etc.), a large amount of intermetallic compounds (Fig. 1(b)) occurred in the form of complex conglomerate together with the eutectic. Using image analysis based on the backscattered electron (BSE) mode in a scanning electron microscope, the intermetallic particles were presented in good contrast (since the Si phase almost merges with the background). An intermetallic clustering or agglomeration at a high magnification revealed that there existed several kinds of intermetallics according to their different contrast. Al₅NiFe phase, Al₅CuNi phase, Al₅CuNi phase, and Al₅Cu₂Mg₆Si₆ phase were identified in this alloy with the aid of EDS analysis shown in Fig. 1(c).

Since the concentration of Si is around 12%, the alloy should possess microstructure close to eutectic. Due to the existence of primary Si particles, the alloy should be precisely classified to be hypereutectic. In the process of solidification, the Si phase was presumed to form first, followed by the Al+Si eutectic. Therefore, the primary Si blocks, Al+Si eutectic colonies, and various intermetallic clusters are the main structure components in the present Al–Si alloy, as shown in Fig. 1.

3.2 Tensile property

The tensile stress—strain curve of the piston alloy was measured and is shown in Fig. 2. The measured tensile properties of the alloy are listed in Table 2. It can be seen from the figure and the data that the tensile
properties were lower than those of some Al alloys, which had tensile strength of 306.5 MPa and 428.1 MPa, and elongation of 7.21% and 23.8% for an A356 (Al–7.0Si–0.15Mg–0.2Fe–0.02Ti–0.02Mn–0.05Cr–0.01V) (mass fraction, %) aluminum alloy and a 2017–T351 (Al–0.52Si–4.29Cu–0.60Mg–0.58Mn–0.02Ti–0.08Zn–0.02Cr) (mass fraction, %) aluminum alloy, respectively [16, 17]. Especially, the tensile elongation of the alloy was about 2.7%, which was far lower than the normal value (25%–55%) for commercial Al alloys [18].

There are several factors that should be considered for the brittleness of Al–Si piston alloy: (1) massive alloying elements lead to an increased concentration in Al matrix; (2) there are a great deal of boundaries between the Al matrix and the Si particles or among the intermetallic compounds; (3) there is a high volume fraction of brittle Si particles as well as intermetallics.

### 3.3 Fractography

Figure 3 shows the fracture appearance of a tensile specimen. The overall fracture morphology (Fig. 3(a)) at first glance was similar to that in common Al alloys [19–20]. The overall fracture surface was perpendicular to the tensile axis. The fracture was initiated from the inclusion close to the specimen surface as marked by an arrow in Fig. 3(a). There were a lot of small black spots, which might be distinguished difficultly at such a low magnification. These small spots glittered when examined by the unaided eye. This fact showed that these spots were small planes which could reflect light. At a slightly high magnification (Fig. 3(b)), a large proportion of the fracture surface revealed a brittle manner with a very large number of smooth planar facets.

Two typical fracture characteristics in this Al–Si piston alloy are presented in Figs. 4(a) and (b). The areas “A” and “B” in Fig. 4(a) show a cleavage pattern with flat facets representing Al–Si eutectic zone as confirmed by EDS analysis. In these flat areas, the Si platelet might be torn off from the Al matrix, leaving a terrace with a smooth facet. These facets were more probably formed as a result of fracture of brittle Si phase crystals. On the other hand, some broken intermetallics might be found in this micrograph as the circled area or along the dashed line. The area “C” in Fig. 4(b) represented characteristics of the broken intermetallics. Severe breakup occurred at these intermetallics, which presented a flower-like morphology with no obvious cleavage facets. This means that the stress field of the main crack broke up the intermetallics due to their poor deformation properties. That is to say, the crack propagated by the breaking of the intermetallic itself, not by destroying the boundaries among the intermetallic particles or the boundaries between the intermetallic phases and the Al–Si eutectic. Sometimes Al–Si eutectic zone might be mixed with the broken intermetallics, as marked by “D” in Fig. 4(b).

Figure 5(a) shows the details of the facets in the Al–Si eutectic after fracture. Between the facet “A” and the facet “B”, there is a sharp ridge indicated by arrows.
Fig. 4 Typical fracture morphologies: (a) Cleavage fracture surface in Al–Si eutectic zone; (b) Breakup of obstructing intermetallics

Fig. 5 Further magnification of fracture surface: (a) Tear ridges in Al matrix; (b) Microscopic cracks in Al–Si eutectic

These ridges were formed by Al matrix separating Si platelets. As shown in Fig. 5(b), a lot of microscopic cracks were introduced in the Si-platelet or Al–matrix during the tensile test. As to the microcracks in the eutectic, two possible introduction processes should be considered: (1) the applied tensile loading; and (2) the stress field at the tip of the main crack. After tensile testing, there were few typical microcracks in the Al–Si eutectic or intermetallics along the longitudinal section of the specimen. This fact suggested that the microcracks observed in the fracture surface were mainly introduced during the propagation of the main crack. In the eutectic zone, coarse Si particles were the main sources of stress concentration and the Si particles were very brittle [1]. The fracture of Si particles were also found in other Al–Si alloys [16]. Another two typical characteristics in Fig. 5(b) should also be mentioned: one was the tear ridges along the bright ribbon and the other was the brittle layer-to-layer fracture as indicated by the dashed circle. The tear ridges were caused by the significant plastic deformation and fracture of the Al matrix, and these circled traces were the fracture evidence of Si particle in a brittle manner.

3.4 Fracture mechanisms

Figure 6 shows a typical morphology of brittle fracture with a lot of facets as analyzed above. SEM EDS microanalysis (as tabulated in Table 3) shows that the content of Al at location $A$ was 100% and the content of Si at location $E$ was 100%. In these two areas, Si particle and Al matrix might be torn off respectively during fracture. From the data at locations $B$, $C$ and $D$, the facet should be thin Si platelet. Analyzing with EDS in SEM, the electron beam can penetrate the specimen surface with a thickness of 1 μm and form a pear-like effective area. At the locations $B$ and $C$, the Si platelet was so thin that the Al matrix under the Si particle was also detected during EDS analysis. At the location $D$, the Si particle became thick and very little Al was detected. Certainly at the locations $A$ and $E$, the Al matrix and the Si platelet were very thick, and thus 100% Al and 100% Si have been detected respectively.

Fig. 6 SEM micrograph showing general fracture morphology in Al–Si eutectic to be further detected by EDS
To reveal the three dimensional structure of the silicon, the surface of a metallographic specimen was deep etched, as shown in Fig. 7. Close to the surface, the Al-matrix was etched off, the Si platelets and some intermetallic particles were left. It was very clear that the Si platelets including residual intermetallics connected each other. This observation for the Al–Si eutectic differed from our primary knowledge of the two-dimensional sections of Si particles in the Al–Si eutectic in Fig. 1. In fact, the Si platelets were not independent. The present knowledge of Si platelets was very helpful for understanding the tensile fracture of the Al–Si piston alloy.

From the microstructure, this piston alloy was mainly comprised of Al–Si eutectic, intermetallics, as well as a few primary blocky Si. In the Al–Si eutectic, the Si platelets were presumed to extend themselves consecutively. Thus the crack could propagate easily along the interface between the Si platelets and the Al matrix in the eutectic Al–Si alloy. That is why we could not find the obvious ductile dimples in the fracture appearance, which were very typical in the common Al alloys [21, 22].

In the eutectic, cracks were frequently found to nucleate at the interfaces between Si platelets and Al matrix, but some fractured Si platelets were also observed (Fig. 5). The possible mechanism may be explained as follows. The applied tensile stress initiates serious plastic deformation in the Al matrix around the Si platelet, which leads to occurrence of Al–Si debonding and formation of microvoids at the Al–Si interface. During tension, these microvoids at the Al–Si interface may connect each other and form a microscopic crack. The presence of the crack induces high stress concentration at its tip along the Al–Si interface, which may cause both fracture of the stiffer Si platelet and new crack nucleation inside the Al–Si interface. Therefore the crack propagates by the matrix microcracks coalescence along the Al–Si interface. As to the fracture of intermetallics, it is the stress field at the tip of a crack that breaks up the blocking intermetallic particles, as shown in Figs. 8(a) and (b).

**Table 3** SEM EDS compositions marked in Fig. 6

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass fraction/%</th>
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<tbody>
<tr>
<td>Al</td>
<td>A  B  C  D  E</td>
</tr>
<tr>
<td>100</td>
<td>50.58  40.28  5.76  0</td>
</tr>
<tr>
<td>Si</td>
<td>0  49.42  59.72  94.24  100</td>
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**Fig. 7** SEM micrographs showing microstructural characteristics of eutectic Si-plates in deep-etched undeformed sample: (a) Low magnification; (b) High magnification

**Fig. 8** Schematic illustration of tensile fracture mechanism of Al–Si piston alloy: (a) Microstructure of alloy mainly consisting of Al–Si eutectic and intermetallics; (b) Propagation of crack along Al–Si interfaces and breakup of blocking intermetallic particles

**4 Conclusions**

The microstructure of the present Al–Si piston alloy was mainly composed of primary and eutectic silicon particles together with numerous intermetallic compounds. During tension, this alloy presented a typically brittle fracture mode. Fracture of Si particles caused the formation of cleavage facets and a lot of
secondary cracks in the fracture surface. The tensile stress field at the crack tip caused the intermetallic compounds in front to break into various fragments. The continuous distribution of Al–Si eutectic with thin Si platelets in the alloy provided an easy path for crack propagation. The fracture proceeds preferentially along the boundaries between the Al matrix and the Si particles in the eutectic by the Al/Si interface debonding or fracture of Si particles, and breaks up the blocking intermetallic compounds.

References