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ScienceDirect
Trans. Nonferrous Met. Soc. China 20(2010) 1555−1560
Transactions of Nonferrous Metals Society of China
www.tnmsc.cn

Effect of Si, Cu and Fe on mechanical properties of cast semi-solid 206 alloys

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Received 13 May 2010; accepted 25 June 2010

Abstract: The development of a modified 206 alloy whose composition was optimized to minimize hot tearing during semi-solid forming was reported. The effect of varying silicon, copper and iron contents was investigated using a design of experiment (DOE) approach. Semi-solid slurries were prepared using the SEED process and injected into a high pressure die casting press. The hot tearing sensitivity results were reported for different alloy variants. The microstructure evolution during the semi-solid preparation was presented along with actual die cast components. The effects of silicon, copper and iron on mechanical properties in the T7 condition were also analyzed. Beyond the benefit of reducing hot tearing, it is shown that the tensile and fatigue properties remain compatible with the automotive industry requirements.
Key words: semi-solid forming; 206 aluminum alloy; SEED process; hot tearing; mechanical properties

1 Introduction

The 206 alloy belongs to the Al-Cu family that includes some of the strongest and toughest alloys currently available for use as aluminum foundry products. The B206 variant has the potential to contribute to light weighting efforts due to its cast-iron like properties and this has generated the current interest in its use for components such as automotive suspension arms or knuckles[1−2]. Consequently, this material could be used in a number of applications in the automotive industry, where the minimum elongation requirement is typically 7% to respect the safety needs in suspension part applications[3−4]. In addition, casting processes for lightweight materials must be in constant evolution to face the increasing challenges for better fuel economy in transportation applications[5].

These challenges can be addressed from different avenues including the use of innovative and reliable processes as well as new alloys. Rheocasting offers many advantages in the fabrication of high integrity near-net-shape components[6−7]. Semi-solid processing offers greater flexibility to cast certain alloys that are more susceptible to hot tearing because of their higher solid fraction. However, this advantage is not sufficient to process alloy compositions in traditional 206 alloys because they are generally very prone to hot tearing. Semi-solid processing, however, offers new opportunities for these difficult-to-cast alloys due to the distinctive globular structure of the slurry and the lower amount of contractions that the castings undergo upon solidification. A previous study reported a reduction of hot tearing with semi-solid gravity casting with a solid fraction as low as 5%[8]. In that respect, a higher solid fraction is more likely to minimize hot tearing susceptibility in this alloy system.

The objective of the present study was to adopt a 206 alloy for semi-solid die casting applications while offering low hot tearing susceptibility and competitive mechanical properties. A preliminary series of tests, using the constrained rod casting (CRC) method, was first performed to evaluate the hot tearing susceptibility of liquid alloys[9]. Alloy compositions considered the most promising were selected for semi-solid processing. In this work the results of casting trials with semi-solid slurries produced using the Rio Tinto Alcan process, dubbed SEED[11], are reported.

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DOI: 10.1016/S1003-6326(09)60338-1

2 Experimental

2.1 SEED process and die casting

The rheocasting SEED process is described in Fig.1, where liquid metal is poured into a metallic container followed by a mechanical mixing (swirling) and an optional drainage of the excess eutectic liquid[6, 11]. The semi-solid slurry is then transferred to the high-pressure die-casting (HPDC) press (Bühler SC N/53) and injected into the mold. In this work, all tests were performed without drainage.

The parts were cast using two different shapes. The first mold had a "U" shape to better assess the filling behavior as well as the hot tearing sensitivity. Indeed, this geometry was selected because it contained features such as corner radii and section changes that promote stress concentration and hot tearing[10]. The second series of castings was carried out using a rectangular wedge mold that was designed to optimize the number of test bars for mechanical property evaluations. All process parameters of the slurry preparation and die casting were fixed.

2.2 Hot tearing assessment

Table 1 lists the alloys that were assessed using the SEED process and cast in the "U" shape mold for hot tearing assessment[12]. The contents of silicon and copper are shown. The content of the remaining chemical elements conformed to a standard B206 alloy composition. The hot tearing susceptibility (HTS) index on the castings was determined using a liquid dye penetrant. The index was based on the number of hot tears and their respective lengths[6].

Table 1 Chemical composition for hot tearing assessment (mass fraction, %)

Alloy	Si	Cu
Standard B206	0.05	4.2−5.0
Alloy-I	1.0	5.5
Alloy-II	1.0	5.0
Alloy-III	1.2	4.1−4.6

2.3 Metallographic, tensile and fatigue evaluation

A series of wedge shape castings were produced from which test specimens were cut for metallographic examination as well as tensile and fatigue testing. The chemical composition of alloys that were rheocast are shown in Table 2, and the contents of silicon, iron and copper were varied according to a design of experiment (DOE) approach. Once more, the chemical composition of remaining elements conformed to a standard B206 alloy composition for permanent mold casting.

Table 2 Chemical composition based on statistical design matrix (mass fraction, %)

Alloy	Si	Fe	Cu
Alloy-1	1.2	0.07	3.8
Alloy-2	0.8	0.07	4.4
Alloy-3	1.2	0.15	4.4
Alloy-4	0.8	0.15	3.8

The castings for tensile and fatigue testing were heat-treated to the T7 condition as follows: solution heating at 500 °C for 10 h, water quenching at 65 °C, natural ageing for 24 h and artificial aging at 195 °C for 4 h. The tensile evaluation was carried out according to the ASTM standard B557-06.

Two alloys (Alloy-2 and Alloy-3) were investigated for the unnotched axial fatigue testing at room temperature according to the ASTM standard E466-07. The reduced section had a length of 34.8 mm and a diameter of 6.35 mm. Ten bars were machined for each alloy and the tests were performed with a standard servo-hydraulic machine (MTS model 810) under an axial load with a stress ratio of 0.1 and a load frequency of 30 Hz. The tests were performed at the following maximum stress levels: 200, 220, 240, 260 and 280 MPa. Each test was repeated once.

3 Results and discussion

3.1 Hot tearing sensitivity

The hot tearing sensitivity results were compiled as

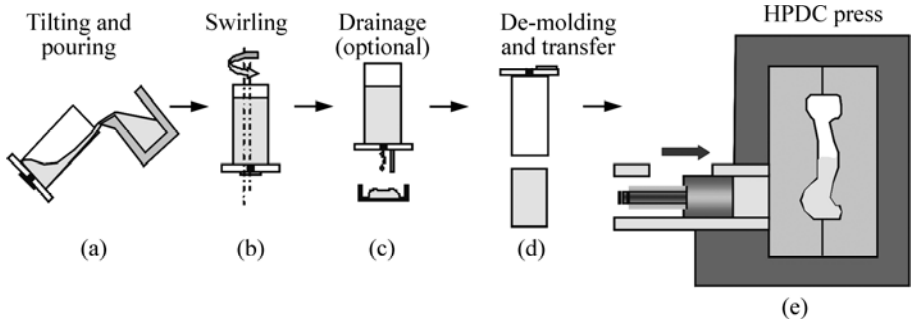

Fig.1 Diagram of SEED process (a−d) and HPDC press (e)

the HTS index for alloys presented in Table 1. Fig.2 illustrates that it is possible to significantly reduce the HTS index from 9 to 2.5 with a silicon level of 1.2%. The beneficial effect of silicon to reduce hot tearing is known[13]. On the other hand, the addition of copper above 4.6% could be detrimental to hot tearing. In the present case, the fine globular microstructure obtained using the SEED process combined with the silicon addition provided a microstructure that reduced hot tearing sensitivity. Moreover, the partially solidified metal resulted in less solidification contraction to compensate for strains by movement of both liquid and solid[8]. Consequently, the mechanical property study was based on Alloy-II and Alloy-III variants using a silicon level of approximately 1% and a copper level below 5%.

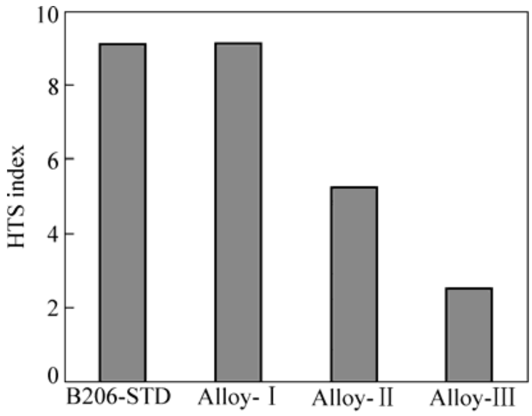

Fig.2 Comparison of hot tearing sensitivity for various Cu and Si contents

3.2 Microstructure

The semi-solid slurries produced using the SEED process had the following characteristics: 1) stable mass, 2) ease of demoulding, 3) uniform surface and 4) good consistency for die filling. The process conditions were sufficiently robust to produce sound castings with all tested alloys. The typical microstructures of the semi-solid castings are shown in Fig.3. The uniform fine globular grains provided the desirable die filling behavior.

3.3 Tensile properties

The partial factorial design presented in Table 2 was used to study the effect of silicon, iron and copper on the mechanical properties. It should be noted that this design had a resolution level of 3, which excluded the analysis of two-factor interactions. Accordingly, only the main effects were considered in the analysis.

The mechanical properties obtained from four alloys are illustrated in Fig.4. For comparison, the figure also includes a line that represents the low specification limits (LSL) which are typically required in the structure

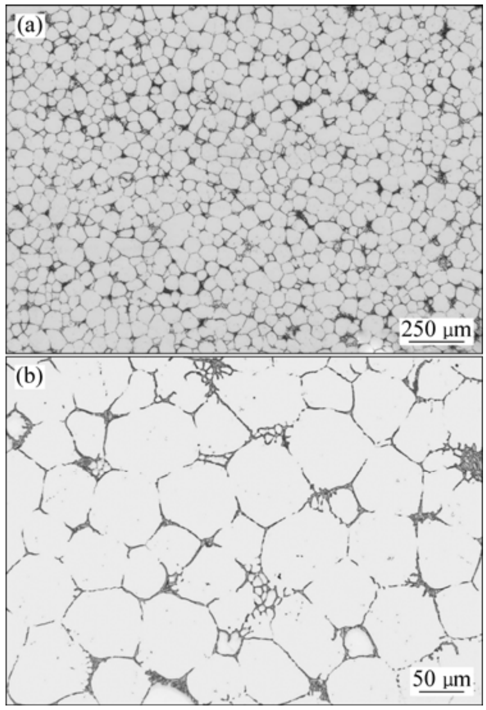

Fig.3 Representative microstructures of casting produced by SEED process (Alloy-2 as-cast): (a) In low magnification; (b) In high magnification

components for automotive applications[3, 14]. The best performance for the ultimate tensile strength (UTS) and yield strength (YS) were obtained with Alloy-2 and Alloy-3. These two alloys were not the best in terms of elongation, but their values were well above the minimum requirement of 7%. It should also be noticed that Alloy-2 and Alloy-3 had both a copper content of 4.4% but different iron contents, 0.07% and 0.15%, respectively. This indicates that the impact of iron content on the mechanical properties is low and thus could bring a great advantage for production and recycling.

Fig.5 provides an illustration of the mechanical property domains for the four alloys with respect to the ultimate tensile strength and elongation. It can be clearly seen that Alloy-2 and Alloy-3 provide the best performance. A domain for AA6082-T6 forged material is also shown on the graph[14]. The properties of Alloy-2 and Alloy-3 are significantly above those of the 6061-T6 forged material.

Normalized Pareto diagrams for the effect of silicon, iron and copper on tensile properties are shown in Fig.6. The normalized value is represented by the line at 2.03. The diagrams illustrate that the strongest positive effect on the ultimate tensile strength (UTS) and on the yield strength (YS) is provided by copper (increasing from 3.8% to 4.4% in this study). This is due to an increase of the volume fraction of fine $CuAl_2$ precipitate particles in

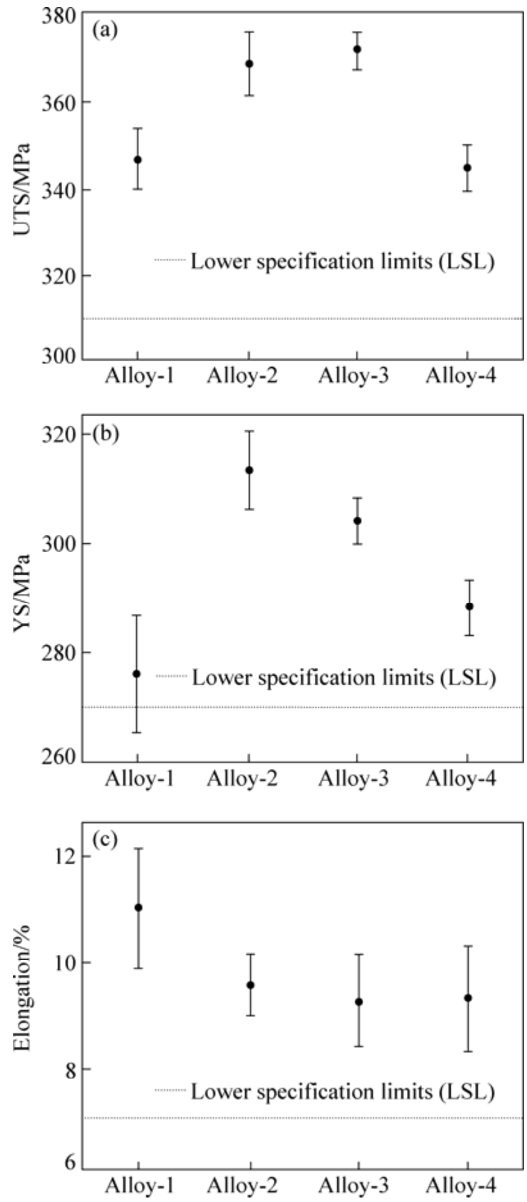

Fig.4 Comparison of mechanical proprieties of alloys in T7 condition

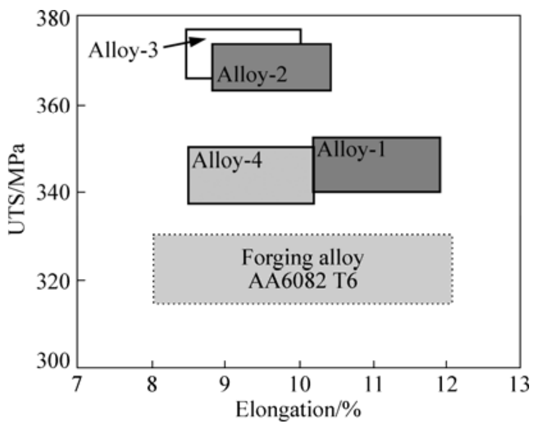

Fig.5 Static mechanical property domains based on 95% confidence intervals for four tested alloys in comparison with AA6082 T6 forging parts[14]

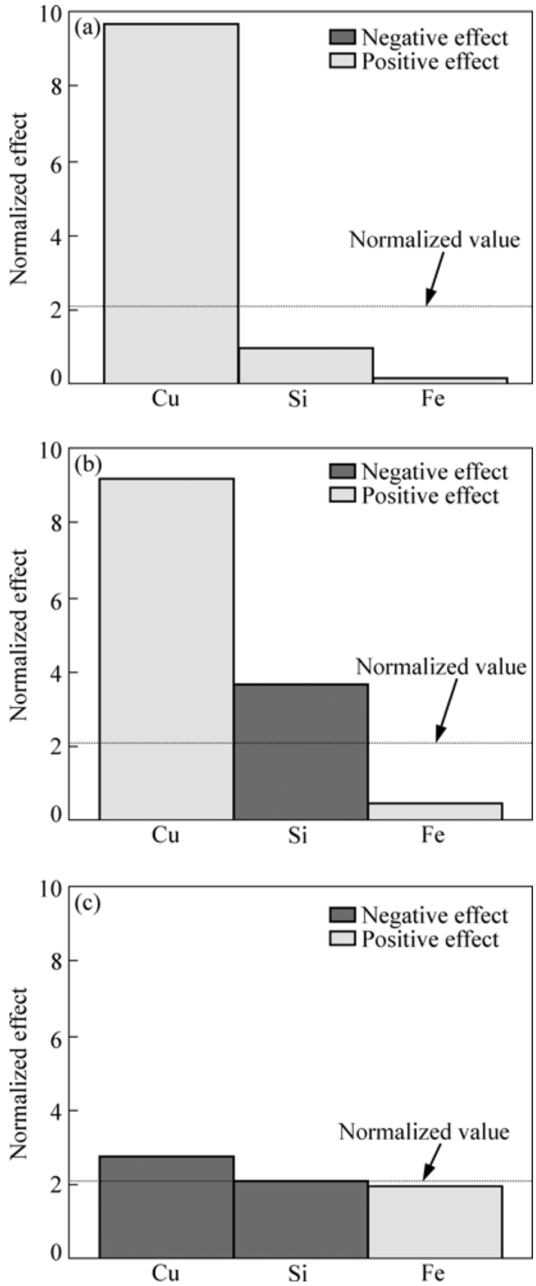

Fig.6 Pareto diagrams of normalized effect of Cu, Si and Fe on UTS (a), YS (b) and elongation (c)

the aluminum matrix at a higher copper level. The typical micrographs of semi-solid castings after a T7 treatment are shown in Fig.7 for Alloy-3 and Alloy-4. It can be seen that Alloy-3 with 4.4% copper has a higher volume fraction and more uniform distribution of these precipitates than Alloy-4 with 3.8% copper. Note that a copper level of 3.8% is also below the specification limit for standard 204 and 206 alloys.

The graphs in Fig.6 also illustrate that silicon (increasing from 0.8% to 1.2%) slightly decreases the yield strength (YS). The variation of iron (from 0.07% to 0.15%) has the lowest effect on the UTS and YS. The Pareto diagram for elongation shows that the influence of

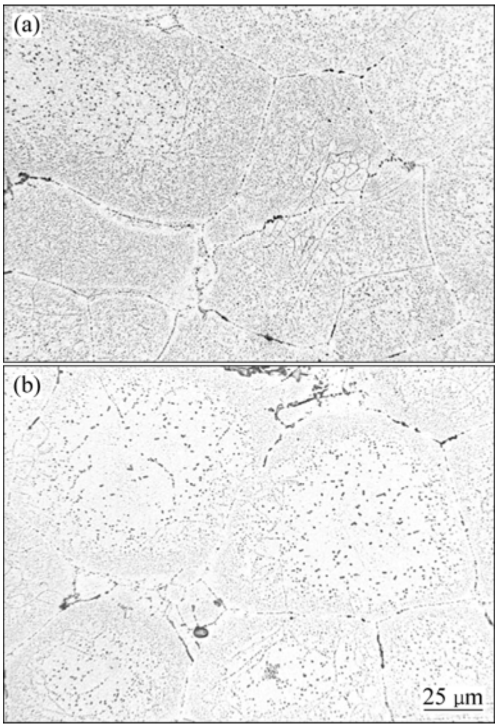

Fig.7 Typical micrographs of semi-solid castings after T7 showing $CuAl_2$ precipitate particles: (a) Fine and good distribution of precipitates in Alloy-3; (b) Poor distribution of precipitate in Alloy-4

copper, silicon and iron is relatively weak compared with the effect of these elements on the ultimate and yield strengths.

3.4 Fatigue evaluation

The fatigue results are presented in Fig.8. No significant correlation between fatigue and composition for Alloy-2 and Alloy-3 is observed. The tensile properties of these alloys also have a comparable behavior in terms of stress−strain relationship (see Fig.5). For comparison purposes, the graph also includes typical axial fatigue properties of an AA6061-T6 wrought alloy and an A357-T6 foundry alloy[15], both at a stress ratio of R=0. Although the stress ratio in the present investigation is slightly higher (R=0.1), it is obvious that the fatigue properties of the semi-solid castings from Alloy-2 and Alloy-3 are superior to those of the traditional A357 castings. Their values are also close to those of typical AA6061 wrought alloy.

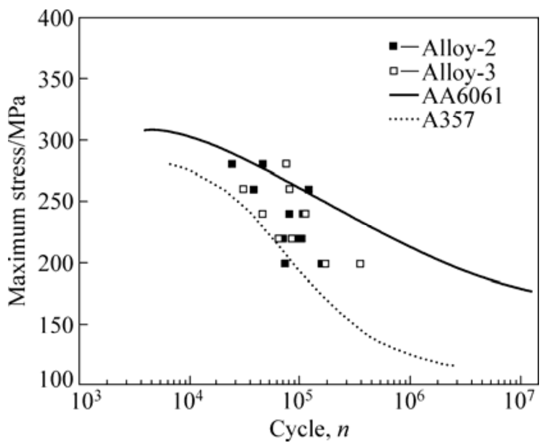

Fig.8 Unnotched axial fatigue at room temperature (R=0.1) for Alloy-2 and Alloy-3 in T7 condition and AA6061-T6 wrought alloy and A357-T6 foundry alloy[15]

4 Conclusions

1) The SEED process can accommodate fairly large compositional variations in the 206 alloy group to produce sound semi-solid castings.

2) The addition of silicon (Si) up to 1.2% and iron (Fe) up to 0.15% has no detrimental effect on the mechanical properties. Castings produced with the SEED process combined with modified 206 alloys can attain elevated mechanical properties compatible with automotive industry requirements.

3) Increasing the silicon content is beneficial to reducing hot tearing. A uniform and fine grain size obtained using the SEED process is also beneficial.

4) The fatigue properties of two best modified 206 alloys are superior to those of an A357 foundry alloy and approach those of an AA6061 wrought alloy.

Acknowledgements

The authors are grateful to Rio Tinto Alcan for allowing permission to publish this work. The authors wish to express special thanks to their colleagues at Rio Tinto Alcan, Mr. Clément Boudreault, at the National Research Council of Canada (NRC), Mr. Dany Drolet and Ms. Marie-Ève Larouche, at STAS, Mr. Stéphane Leclerc, as well as others who have contributed to the development of the SEED process.

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(Edited by YANG Bing)