Improvement of formability of silicon-containing recycled wrought aluminum alloy by hot stamping after rapid heating

KAWANA Ryohei[1,a *], HIROSAWA Shoichi[1,b *], OOTAKI Mitsuhiro[1,c], MAENO Tomoyoshi[1,d], SUZUKI Yasushi[2,e] and YABUKI Yuuji[2,f]

[1]Graduate School of Engineering Science, Yokohama National University, 79-5 Tokiwadai, Hodogaya-ku, Yokohama, Kanagawa 240-8501, Japan

[2]R&D Division, G-TEKT Corporation, 4-7-28 Shinmeidai, Hamura, Tokyo 205-0023, Japan

[a]kawana-ryohei-fv@ynu.jp, [b]hirosawa@ynu.ac.jp, [c]ootaki-mitsuhiro-kb@ynu.ac.jp, [d]maeno-tomoyoshi-yf@ynu.ac.jp, [e]yasushi_suzuki.nv@g-tekt.jp, [f]yuuji_yabuki@g-tekt.jp

Keywords: Al-Si Alloy, Recycled Aluminum, Rolling, Hot Stamping, Formability, V-Bending

Abstract. To clarify the detrimental effect of Si content on the fabrication of wrought products with recycled aluminum ingots, the formability of cold-rolled Al-Si alloy sheets with different Si contents was evaluated and improved by a V-bending test after rapid heating. It was shown that rapid heating to a certain temperature can improve the formability of Al-Si alloy sheets, and the higher heating temperatures, the more severe forming can be accomplished even for difficult-to-process Al-12%Si alloy sheet. High temperature tensile tests after rapid heating and observation of fracture surfaces indicated that rapid heating improves the ductility of aluminum matrix, and relieves stress accumulation around Si particles, resulting in the suppressed initiation of cracks.

Introduction

To improve fuel efficiency of automobiles, light-weight Al-Si alloy (die)castings are utilized for engine parts, while 5000 series (Al-Mg) and 6000 series (Al-Mg-Si) alloy sheets have been adapted for panel components. However, when the vehicles are disposed, the (die)castings and alloy sheets are mechanically crushed and melted together without sorting, resulting in the production of secondary ingots with various alloy compositions of Si, Mg, Cu, Fe, Mn and so on [1, 2]. In the present recycling system, such recycled ingots are exclusively utilized for fabricating low-purity casting materials (i.e. cascade recycling), but electrification of automobiles forecasts the decreased demand of engine parts. Therefore, application of secondary ingots to wrought products (i.e. upgrade recycle) is highly anticipated by improving their formability.

Recently, the authors successfully improved the formability of difficult-to-process A7075-T6 alloy sheets by hot stamping after rapid heating to medium temperatures [3]. The proposed forming method appears to be applicable to recycled wrought aluminum because short heating time of 10-20 s decreases the deformation resistance but increases the elongation to fracture at the temperatures. In this study, rapid heating to 200, 250 or 300°C was applied to cold-rolled Al-Si alloy sheets with different Si contents, and then their formability was evaluated by 90° V-bending test with punch radii $R = 2$ and 9 mm. The purpose of this study is to optimize heating temperatures for applying recycled aluminum sheets with various Si contents (3, 7 and 12%Si) to wrought materials.

Experiment

Al-3, 7 and 12%Si binary alloys prepared from 99.7%-purity aluminum and Al-19.5%Si mother ingot were melted in a graphite molten crucible by a resistance furnace below 720°C, degasified by Ar gas flow, and then casted into an iron mold preheated to 150°C. The compositions of the fabricated alloys were evaluated by a handheld XRF analyzer (HITACHI X-MET range) and listed in Table 1. The ingots with a dimension of 200×80×20 mm^3 were subjected to surface milling, homogenization treatment at 540°C for 4 h, hot rolling to 10 mm thickness and cold rolling to 2 mm thickness (i.e. reduction ratio of cold rolling is 80%).

Table 1. Compositions of the fabricated Al-Si binary alloys [%].

	Si	Fe	Al
Al-3%Si	3.43	0.22	Bal.
Al-7%Si	6.78	0.22	Bal.
Al-12%Si	12.73	0.28	Bal.

Mechanical properties of the as-cast, as-homogenized and cold-rolled samples were evaluated by room-temperature tensile tests. Tensile test specimens with a dimension shown in Fig. 1 were fabricated by punching with a die. Microstructural observation using optical microscopy (OM) and scanning electron microscopy (SEM) was conducted to clarify the relationship between microstructures and mechanical properties. Specimens for the microscopy observation were mechanically polished by waterproof papers, and then etched with a Keller solution. Size distribution and area fraction of Si particles were quantitively evaluated by analyzing OM images using ImageJ software.

To evaluate the formability of the fabricated Al-Si cold-rolled sheets, 90° V-bending test with punch radii $R = 2$ and 9 mm was conducted at room temperature or, if failed, after rapid heating to 200, 250 or 300°C as schematically illustrated in Fig. 2. A square blank with a dimension of 150×20×2 mm^3 was sandwiched between hot plates at 300°C maximum, and then heated to the target temperature within 10-20 s.

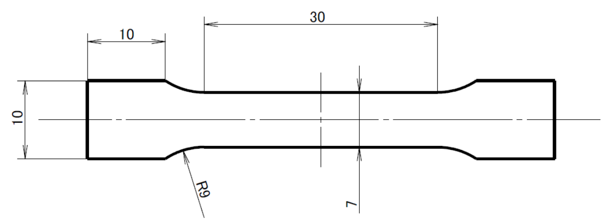

Fig. 1. The dimension of tensile test specimens.

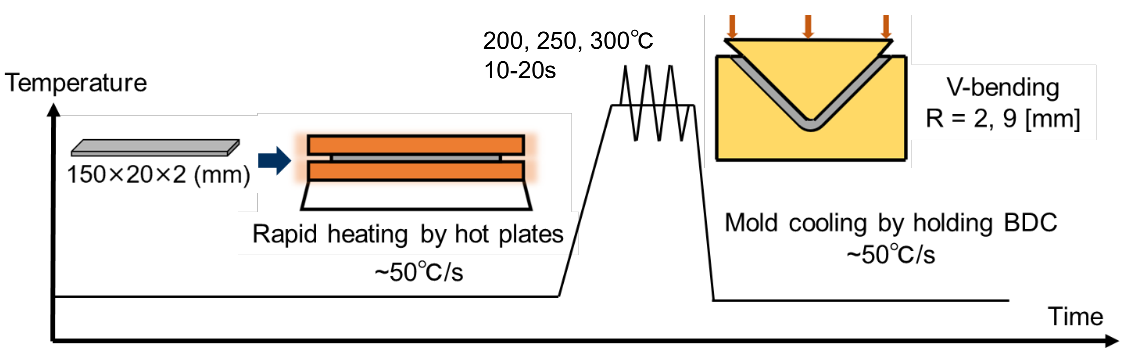

Fig. 2. Schematic illustration of procedure of rapid heating and V-bending.

Results

Relationship between mechanical properties and microstructures. Fig. 3 shows stress-strain curves of cold-rolled Al-Si alloy sheets subjected to reduction ratio of 80%. Irrespective of Si content, ultimate tensile stress (UTS) of the three alloys reached 200-210 MPa although the elongation to fracture decreased from 8% to 4% with increasing Si content. The corresponding OM and SEM microstructures are shown in Fig. 4. It was found from SEM images that Si particles are fractured through rolling process, and sharp edges cause stress concentration during tensile deformation, resulting in lower ductility. The decrease in ductility is greater in the highest Si-containing Al-12%Si alloy because Si particles are coarser and more angular as illustrated by the size distribution in Fig. 5.

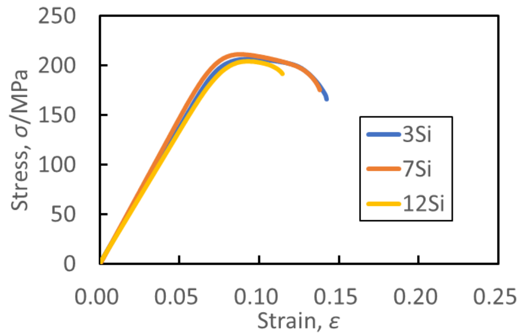

Fig. 3. Stress-strain curves of cold-rolled Al-Si alloy sheets.

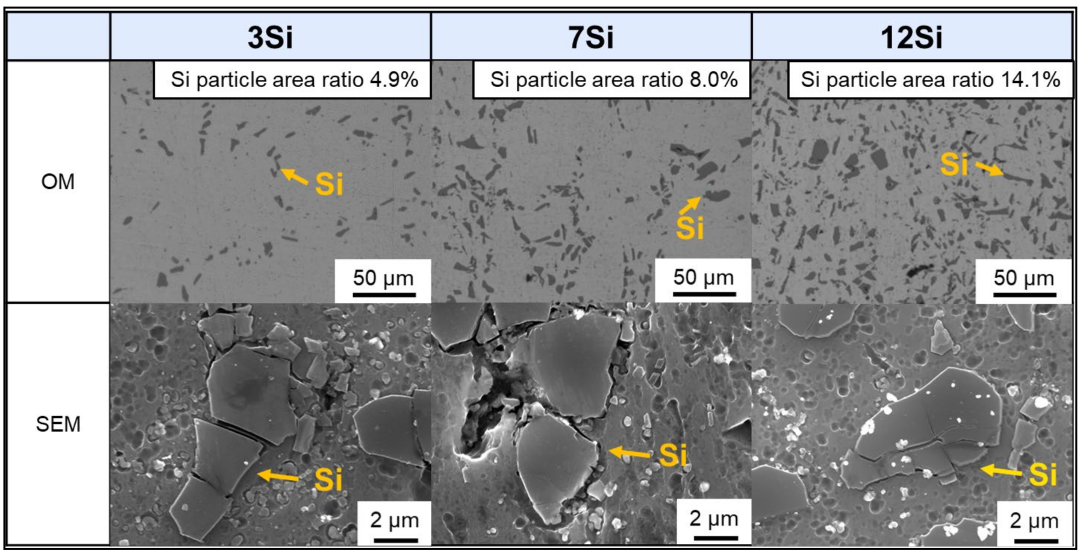

Fig. 4. OM and SEM microstructures of cold-rolled Al-Si alloy sheets.

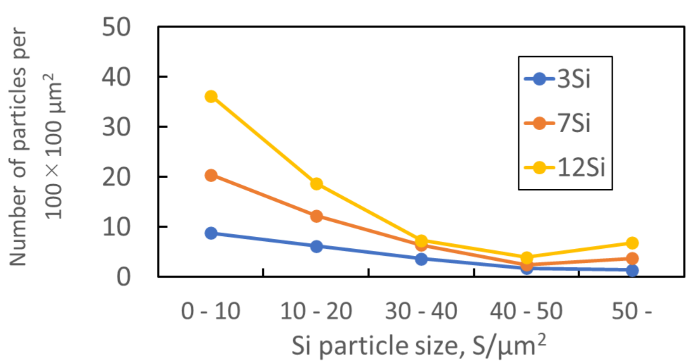

Fig. 5. Size distribution of Si particles in cold-rolled Al-Si alloy sheets.

V-bending tests. Results of 90° V-bending tests with punch radii of $R = 9$ mm and 2 mm are shown in Fig. 6. At $R = 9$ mm, V-bending of Al-3%Si and Al-7%Si alloy sheets was successful even without rapid heating, indicating that the amount of Si particles has less influence on the degradation of their formability (Fig. 6(a)). In V-bending of more Si containing Al-12%Si alloy, on the other hand, V-bending could not be accomplished at room temperature, and therefore rapid heating to 250°C became quite effective for improving the formability of Al-12%Si alloy.

The effectiveness of such a hot stamping method was clarified even in the case of R = 2 mm (Fig. 6(b)); Al-3%Si alloy could be V-bent at room temperature, whereas rapid heating to 250 and 300 °C was required for Al-7%Si and Al-12%Si alloys, respectively. Therefore, it was revealed that higher Si content degrades the formability of the Al-Si alloy sheets, but rapid heating to a certain temperature can improve the formability of recycled wrought aluminum.

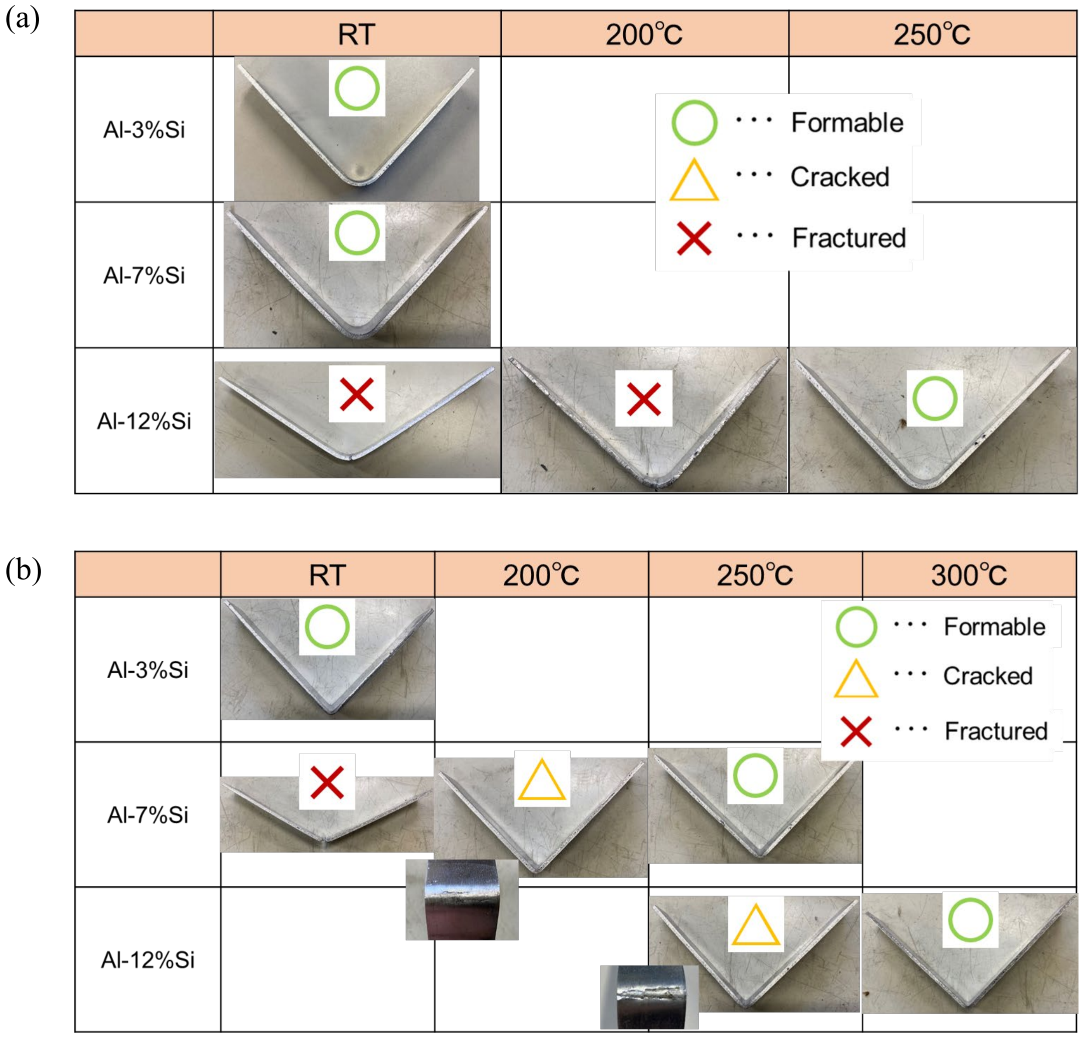

Fig. 6. Results of 90° V-bending tests of cold-rolled Al-Si alloy sheets with punch radii of (a) 9 mm and (b) 2 mm.

Discussion

To discuss the reason why rapid heating before forming improves the formability of cold-rolled Al-Si alloy sheets, the influence of rapid heating on mechanical properties of Al-12%Si alloy was evaluated by high-temperature tensile tests after rapid heating (Fig. 7(a)). The obtained stress-strain curves confirmed that heating to 300°C decreases deformation resistance to ~50 MPa, but improves the elongation to fracture above 20% (Fig. 7(b)).

The corresponding tensile fracture surfaces of cold-rolled Al-12%Si alloy sheets are shown in Fig. 8. It was revealed from the SEM images that coarse Si particles are exposed from the matrix with fine dimples at room temperature, but larger dimples at higher temperatures. This suggests that cracks were propagated along Si particles, but the fracture was retarded by the deformation of the surrounding matrix with increasing heating temperatures. Therefore, rapid heating before forming can improve the formability of even difficult-to-process Al-12%Si alloy because relieved stress concentration between Si particles and Al matrix delays the propagation of cracks.

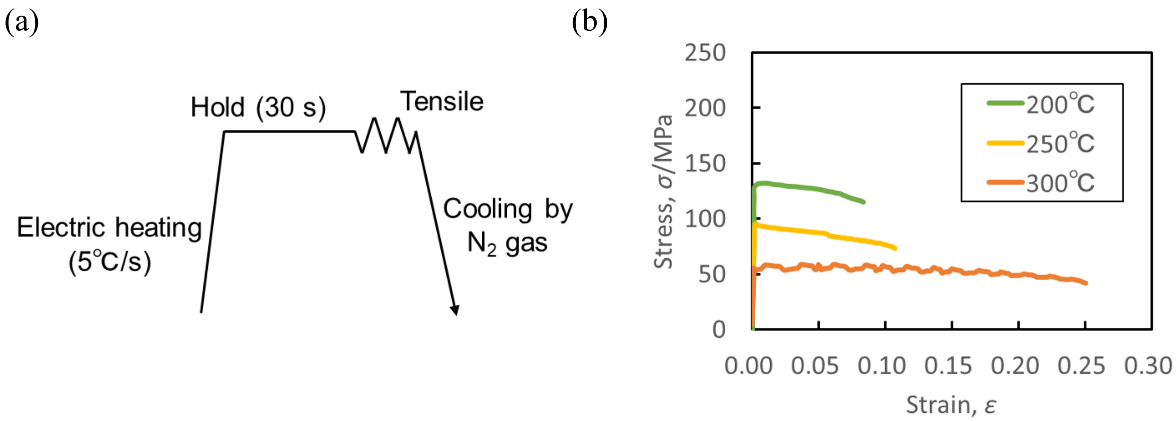

Fig. 7. Schematic illustration of procedure of high-temperature tensile test after rapid heating (a). The obtained stress-strain curves at 200, 250 or 300°C was also shown in (b) for cold-rolled Al-12%Si alloy.

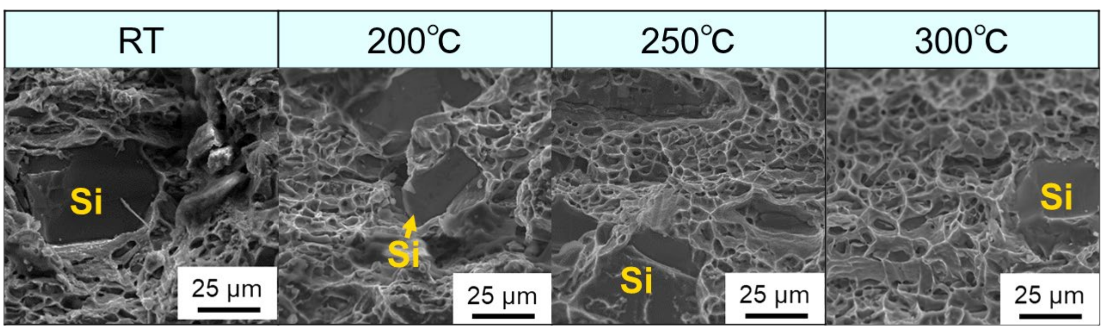

Fig. 8. Tensile fracture surfaces of cold-rolled Al-12%Si alloy at different temperatures.

Summary

Al-3, 7 and Al-12%Si binary alloys were subjected to cold rolling by 80%, and then V-bent at room temperature or, if failed, after rapid heating to 200, 250 or 300°C for evaluating their formability. The obtained results are summarized below.

1. Irrespective of Si content, higher ultimate tensile stress (UTS) of 200-210 MPa were obtained, but the elongation to fracture decreased from 8% to 4% with increasing Si content, resulting from stress concentration caused by sharp edges of fractured Si particles.
2. From the results of 90° V-bending tests, it was found that the formability of cold-rolled Al-Si alloys is degraded with increasing Si content, but improved by rapid heating to a certain temperature. In the case of punch radius R = 9 mm, for example, Al-3%Si and Al-7%Si alloy sheets were successfully V-bent at room temperature, but V-bending of more Si containing Al-12%Si alloy could not be accomplished at room temperature. Therefore, rapid heating to 250 °C become quite effective for improving the formability of Al-12%Si alloy.
3. The effectiveness of rapid heating was clarified even in more severe case of R = 2 mm. Al-3%Si alloy could be V-bent at room temperature, but rapid heating to 250 and 300 °C was required for Al-7%Si and Al-12%Si alloys, respectively. Therefore, rapid heating before

forming can improve the formability of even difficult-to-process Al-12%Si alloy because relieved stress concentration between Si particles and Al matrix delays the propagation of cracks.

References

[1] J. Cui, H.J. Roven, Recycling of automotive aluminum, Trans. Nonferrous Met. Soc. China, 20 (2010) 2057−2063. https://doi.org/10.1016/S1003-6326(09)60417-9

[2] S. Kumai, Role and potential of aluminium and its alloys for a zero-carbon society, Mater. Trans. 64 (2023) 319-333. https://doi.org/10.2320/matertrans.MT-LA2022009

[3] S. Hirosawa, T. Maeno, J. Kim, K. Nariya, Y. Suzuki, International patent, WO2023/053845 A1.