Concurrent Improvement of strength, formability and SCC resistance of Al-Zn-Mg-Cu alloy by hot stamping after rapid heating and re-aging on paint baking treatment

HIROSAWA Shoichi[1,a *], KIM Junmo[1,b], MAENO Tomoyoshi[1,c], SUZUKI Yasushi[2,d] and YABUKI Yuuji[2,e]

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

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

[a]hirosawa@ynu.ac.jp, [b]kim-tunmo-dr@ynu.jp, [c]maeno-tomoyoshi-yf@ynu.ac.jp, [d]yasushi_suzuki.nv@g-tekt.jp, [e]yuuji_yabuki@g-tekt.jp

Keywords: Extra Super Duralumin, T6 Temper, High Strength, Formability, Corrosion Resistance, Medium Temperature

Abstract. In this study, the combined application of rapid heating for hot stamping and the subsequent re-aging during a paint baking treatment was newly developed for T6-tempered A7075 Al-Zn-Mg-Cu alloy sheets. From a systematic investigation, rapid heating to 255-260 °C and short-time holding for ~120 s was found to give the best combination of formability, hardness and stress corrosion cracking (SCC) resistance of the final products. In particular, re-aging treatment at 170 °C for 1.2 ks was well exploited not only for further improvement of SCC resistance but also for rebound of the decreased hardness by rapid heating. Therefore, the developed three-step heat treatment is regarded as a promising approach to producing high-strength, easily formable and corrosion-resistant Al-Zn-Mg-Cu alloy parts for automobiles.

Introduction

Recently, a replacement of steel-made parts by aluminum alloys is progressing in automobile industries, but most of those are 6xxx aluminum alloys with good formability, stress corrosion cracking (SCC) resistance, but medium strength. The application of high-strength 7xxx aluminum alloy parts to automobiles is partly attempted for further reduction of the weight and fuel consumption rate of the vehicles, but at present only limited number of automobile parts has been made from 7xxx aluminum alloys. This is because 7xxx aluminum alloys have problems concerning lower ductility at room temperature (RT) and less resistance to SCC. Therefore, a production of high-strength, easily formable and corrosion-resistant 7xxx aluminum alloy parts for automobiles is highly expected.

In aeronautics industries, O-tempered 7xxx aluminum alloy sheets are cold-stamped, solution-treated and then artificially aged, but this procedure is not good for automobile industries because of the prolonged aging treatment. Heat form quenching (HFQ) consisting of rapid heating for solution treatment, hot stamping and die quenching [1] still needs a prolonged aging treatment, although some parts for specialty cars have been made through this procedure. Therefore, three-step heat treatment developed by the authors [2] becomes useful because productivity can be improved by omitting both the solution and aging treatments in parts manufacturers. Fig. 1 shows a schematic illustration of three-step heat treatment utilized in this study. This heat treatment contains rapid heating of T6-tempered sheets to a medium temperature, holding at the temperature for 150 s maximum before hot stamping and die quenching, and re-aging by exploiting paint baking treatment in automobile companies. The rapid heating was intended to improve the formability of the T6-temperted high-strength sheets while minimizing the decrease in strength, whereas the final re-aging treatment not only further improves the SCC resistance but also rebounds the decreased strength by rapid heating.

Therefore, the objective of this study is to elucidate the effectiveness of combined application of rapid heating for hot stamping and the subsequent re-aging during paint baking treatment for producing high-strength, easily formable and corrosion-resistant Al-Zn-Mg-Cu alloy parts for automobiles.

Experiment

In this study, 2 mm-thick sheets of T6-tempered A7075 Al-Zn-Mg-Cu alloy were utilized as a starting material. As 1st step of three-step heat treatment in Fig. 1, the sheets were rapidly heated to 150-280°C at a heating rate of ~10°Cs^{-1} by a contact heating equipment, and then held at the temperature for 150 s maximum before hot stamping and die quenching (2nd step). The formability of the rapidly heated sheets was evaluated by high-temperature tensile test, deep drawing and 90° V-bending test. Some pieces of sheets were just heated and held for 150 s maximum in oil baths, followed by water-quenching without hot stamping. The heating and cooling rates of the two experiments were assured to be almost comparable by monitoring their temperature changes with thermocouples.

After stored at 20°C for 86.4 ks, re-aging treatment at 170°C for 1.2 ks was applied to the sheets with/without hot stamping, as the 3rd step of three-step heat treatment in Fig. 1. The resultant Vickers hardness and electrical conductivity were measured as indexes of mechanical strength and SCC resistance and utilized for establishing a process window with optimized heating conditions at 1st and 2nd step heat treatment for the best combination of formability, hardness and SCC resistance of the final products.

Furthermore, to directly prove the improved SCC resistance, corrosion test by immersing into a solution of NaCl was conducted for three-step heat-treated specimen (255°C120 s+170°C1.2 ks) together with T6-tempered and T73-tempered specimens. As illustrated in Fig. 2, four-point bending along ST direction under a constant stress of 330MPa was applied to the three specimens, and then imemersed into a solution of 3.5±0.1% NaCl (PH=6.4-7.2) at 25±3°C under a humidity of 40-75%. After repeating immersion (0.6 ks) and drying (3.0 ks) for 90 days, cracks and pitting on their RD-ND planes were observed by dark-field optical microscopy. Transgranular and intergranular precipitates in the three specimens were also observed by transmission electron microscopy.

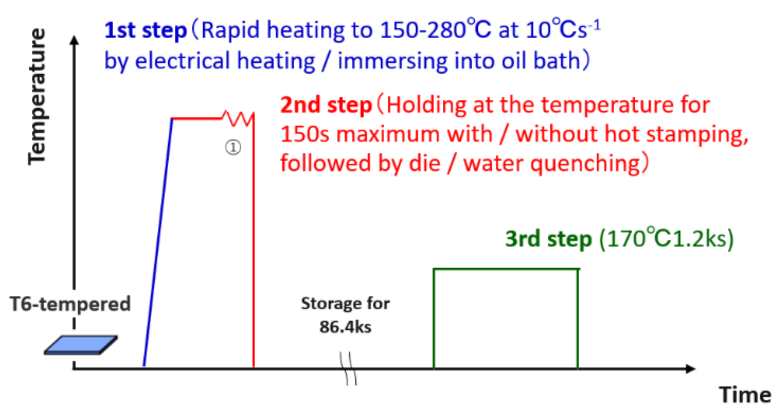

Fig. 1. Three-step heat treatment utilized in this study [2].

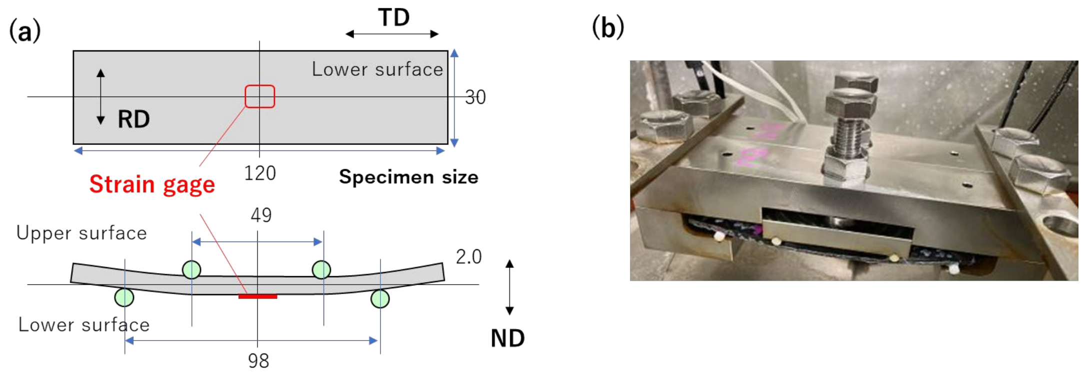

Fig. 2. The dimensions of corrosion test specimen under four-point bending along ND direction (a). The utilized V-bending equipment (b) was repeatedly immersed into a solution of NaCl and dried for 90 days.

Results and discussion

Fig. 3 shows stress-strain curves of T6-tempered sheets obtained from high-temperature tensile test at 150, 200 and 250 °C. As a result of rapid heating by 10℃s^{-1} and holding for 10s, lower deformation resistance and larger elongation to fracture was obtained than those at RT; i.e. 540MPa of ultimate tensile stress (UTS) and 7% of elongation to fracture. Such improved formability at higher temperatures was also confirmed from the result of deep drawing in Fig. 4, in which rapid heating to 200 °C improved deep drawability from <1.46 (RT) to 1.88 in limiting drawing ratio (LDR). Fig. 5 compares springback and residual stress of V-bent sheets at RT to 250 °C. By rapid heating to 200 or 250℃, springback and residual stress after bending was reduced, resulting in the increase in bending radius / thickness ratio from <0.2 (RT) to >0.6 (200 ℃). It should be noted that those are all positive evidence for the improved formability by rapid heating.

However, the higher the temperature or more prolonged the holding time, more decreased strength of the T6-temperted sheets was obtained due to overaging of the precipitation-hardened alloy. Fig. 6 shows changes in Vickers hardness and electrical conductivity after rapid heating to

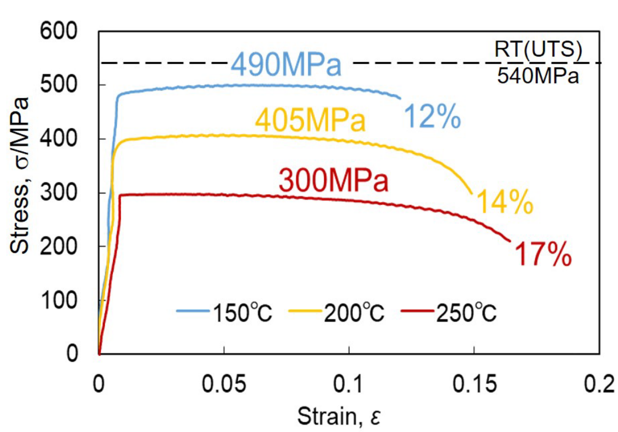

Fig. 3. Stress-strain curves of T6-tempered A7075 alloy sheets after rapid heating to 150, 200 and 250℃ (Heating rate: 10℃s^{-1}, holding time: 10 s, initial strain rate: 1s^{-1}).

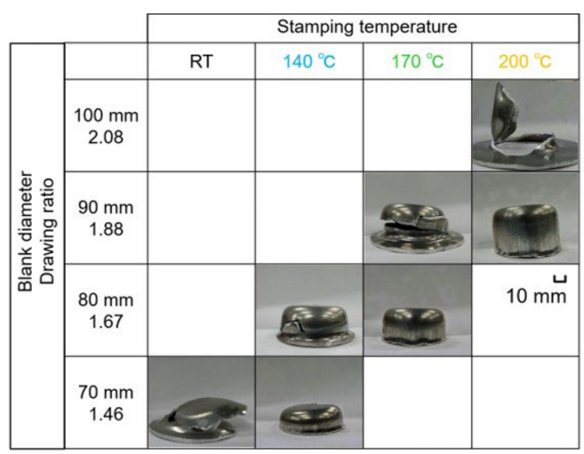

Fig. 4. Deep drawability of T6-tempered A7075 alloy sheets after rapid heating to 140, 170 and 200℃ (Heating rate: 10℃s^{-1}, holding time: 10 s).

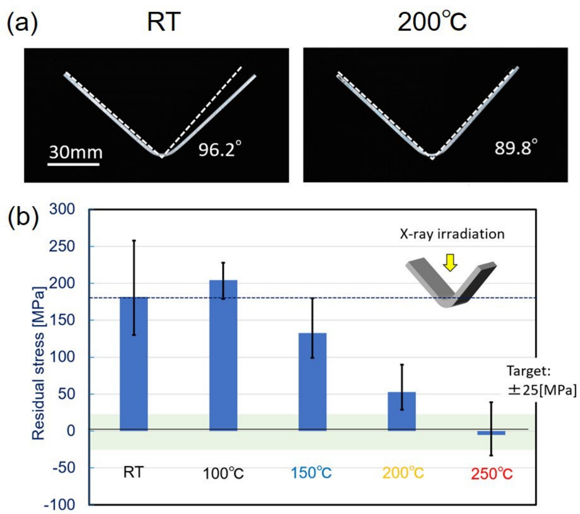

Fig. 5. Results of 90˚ V-bending test of T6-tempered A7075 alloy sheets at RT to 250℃ (Punch radius: 9 mm). Residual stress after bending was also mesured by a X-ray analyzer.

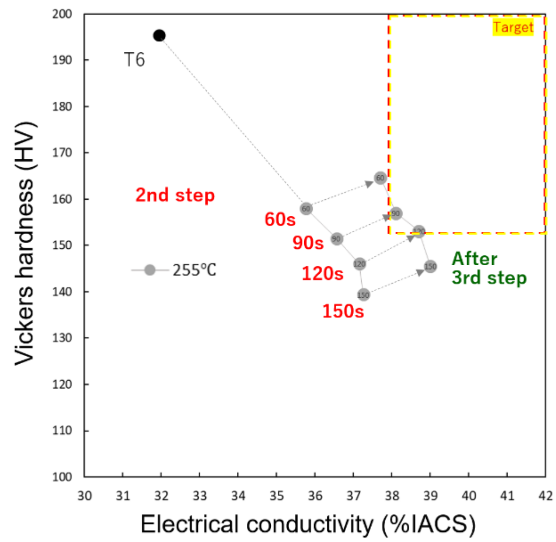

Fig. 6. Changes in Vickers hardness and electrical conductivity of T6-tempered A7075 alloy sheets after rapid heating to 255℃ for 60-150 s and re-aging at 170 ℃ for 1.2 ks without hot stamping.

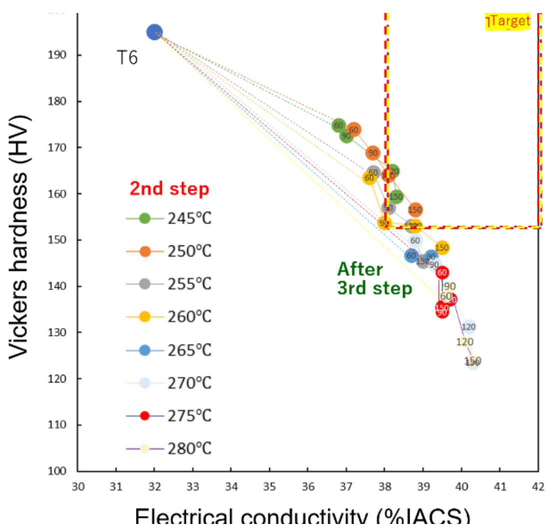

Fig. 7. Vickers hardness and electrical conductivity of T6-tempered A7075 alloy sheets after rapid heating to various temperatures and re-aging at 170℃ for 1.2 ks without hot stamping. The numbers within plots indicate holding times in second at a given rapid heating temperature.

Table 1. Constructed process window of optimized heating conditions at 1st and 2nd step heat treatment for fulfilling target properties of the final products (>HV153 and >38.0 %IACS).

	60s	90s	120s	150s
245˚C	-	-	○	○
250˚C	-	-	○	○
255˚C	-	○	○	-
260˚C	-	△	○	-
265˚C	-	-	-	-
270˚C	-	-	-	-
275˚C	-	-	-	-
280˚C	-	-	-	-

255℃ for 60-150 s (1st and 2nd step), and re-aging at 170℃ for 1.2 ks (3rd step) without hot stamping. Monotonous decrease in hardness was observed with increasing holding time at 2nd step; i.e. from HV196 (T6-tempered) to HV138 (after 150 s holding), but the subsequent 3rd step heat treatment could successfully rebound the decreased hardness with further increase in electrical conductivity (See arrows in Fig. 6). Therefore, from the plots of all the resultant Vickers hardness and electrical conductivity after 3rd step heat treatment in Fig. 7, optimum heating conditions at 1st and 2nd step can be found. Table 1 is a constructed process window of optimized heating conditions at 1st and 2nd step heat treatment for fulfilling target properties of the final products (i.e. >HV153 and >38.0%IACS). It should be noted that these values were preset as compatible ones of A7075-T76 and -T73 alloys, where SCC resistance is regulated by their electrical conductivity [3].

Fig. 8 shows dark-field optical micrographs on RD-ND planes of T6-tempered and three-step heat treated (255℃120 s+170℃1.2 ks) specimens after four-point bending SCC test. Cracks were generated in the lower surface in the former, but only pitting corrosion with 0.1 mm depth was observed in the latter, suggesting that SCC resistance is significantly improved by the authors' developed three-step heat treatment [2].

In this study, to clarify the mechanism of such improved SCC resistance, TEM microstructures of transgranular and intergranular precipitates were observed. Fig. 9 shows TEM images of transgranular and intergranular precipitates in T6-tempered, two-step heat treated (255℃120 s)

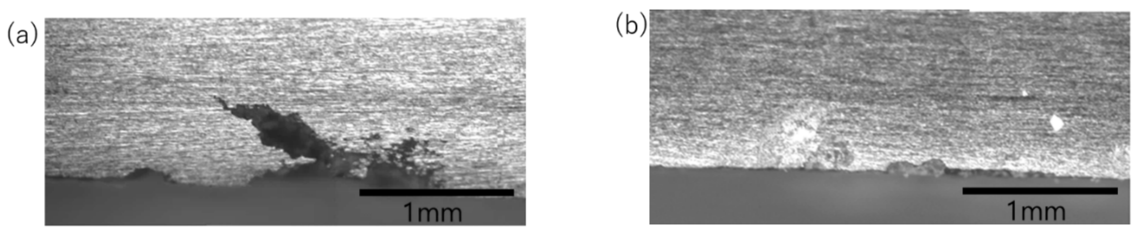

Fig. 8. Dark-field optical micrographs on RD-ND planes of (a) T6-tempered and (b) three-step heat treated (255℃120 s+170℃1.2 ks) specimens after four-point bending SCC test.

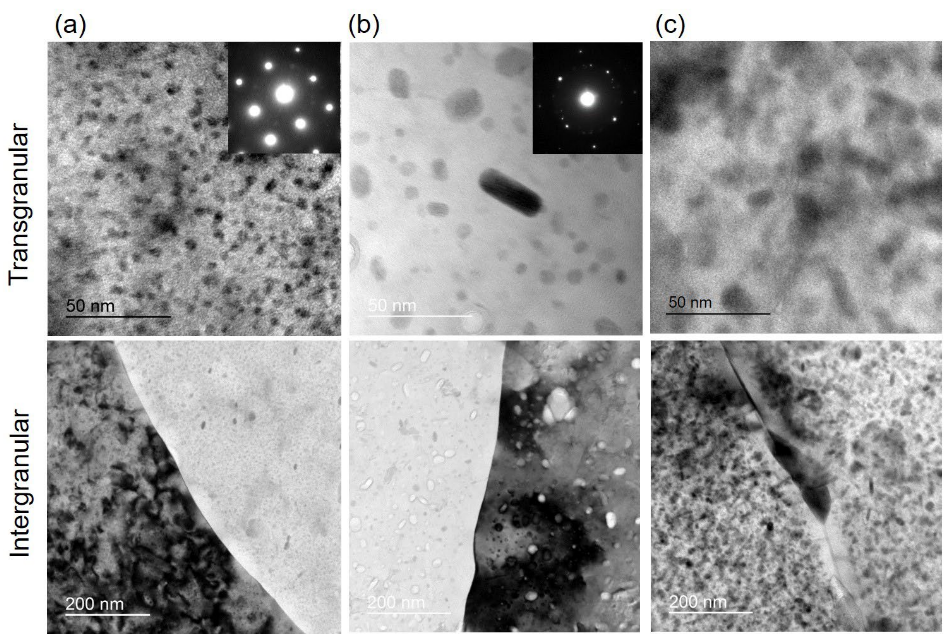

Fig. 9. TEM images of transgranular and intergranular precipitates in (a)T6-tempered, (b)two-step heat treated (255 ℃120 s) and (c)three-step heat treated (255℃120 s+170℃1.2 ks) specimens.

and three-step heat treated (255℃120 s+170℃1.2 ks) specimens. By applying rapid heating and holding (1st and 2nd step), refined GP zones in the α-Al matrix were reverted, but coarser η' phase further grew as indicated in upper images of Fig. 9(a, b). However, 3rd step heat treatment resulted in the reprecipitation of GP zones (upper image of Fig. 9(c)), similar to the microstructural changes of precipitates during retrogression and re-aging (RRA) treatment [4]. As for intergranular precipitates along grain boundaries, on the other hand, sparsely formed η phase was observed only in the specimen after 3rd step heat treatment (lower image of Fig. 9(c)). Therefore, the same mechanism to the RRA treatment could be applicable to the improved SCC resistance accomplished by three-step heat treatment proposed in this study [2].

Summary

1. From a systematic investigation of the effects of 2nd step heat treatment, moderate decrease in hardness after rapid heating to ~250℃ was found to improve not only the formability (i.e. lower deformation resistance and larger elongation to fracture) but also SCC resistance (i.e. increased electrical conductivity).
2. The subsequent re-aging treatment at 170℃ for 1.2 ks (3rd step) could rebound the decreased hardness with further improvement in SCC resistance (i.e. increased electrical conductivity).
3. The optimized conditions of 1st and 2nd step heat treatment include 255℃ for 120 s or 260℃ for 120 s, and thus compatible hardness and electrical conductivity to those of A7075-T76 and T73 could be obtained by the newly developed three-step heat treatment in this study.

Acknowledgement

The authors would like to acknowledge the Light Metal Educational Foundation, Inc. and the Japan Aluminium Association for their generous support to this study.

References

[1] R.P. Garret, J. Lin, T.A. Dean, Solution heat treatment and cold die quenching in forming AA6xxx sheet components: Feasibility study, Adv. Mater. Res. 6-8 (2005) 673-680. https://doi.org/ 0.4028/ ww.scientific.net/AMR.6-8.673

[2] S. Hirosawa, T. Maeno, J. Kim, K. Nariya, Y. Suzuki, International Patent WO2023/053845 A1. Forming method of aluminum alloy sheets, (2023).

[3] Japanese standard association: JIS Handbook, Non-ferrous metals & metallurgy III, (2018), 886.

[4] B.M. Cina, U. S. Patent 3856584. Reducing the susceptibility of alloys, Particularly aluminum alloys, to stress corrosion cracking, (1974).