Hot forming-quenching integrated process with cold-hot dies for 2A12 aluminum alloy sheet

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Abstract

A novel process called hot forming-quenching integrated process with cold-hot dies was proposed to improve the formability and avoid thermal distortion in solution heat treatment. In this process, the heated lower dies were used to improve the forming temperature and the cooled upper dies were utilized to accomplish quenching and reduce thermal distortion. The effects of temperatures of the hot dies ranging from 100 to 450 °C on strengthening were systematically investigated. The strengths were measured by Vickers hardness test and uniaxial tensile test. It was found that the temperature of heated lower dies could be improved to 450 °C to slow the temperature decrease of heated sheet besides obtaining excellent strength. The temperature of both hot dies could only be improved to 250 °C. The strengthening phase was the dispersed lath-shaped S precipitate with an average cross-section of approximately 50×100 nm.

Keywords: Heat treatable aluminum alloy sheet; Hot forming-quenching integrated process; Die quenching; Cold-hot dies; Strengthening

1. Introduction

Aluminum alloys are widely used to meet the need for lightweight structural metals in automotive and aerospace industries because of their benefits such as good corrosion resistance, high strength-to-weight ratio and advantageous structural performance (Yuan et al., 2012). In order to improve the formability and avoid thermal distortion in solution heat treatment, a novel process called hot forming-quenching integrated process was proposed in this study. The heated lower dies were used to improve the forming temperature and the cooled upper dies were utilized to accomplish quenching and reduce thermal distortion. The effects of temperatures of the hot dies ranging from 100 to 450 °C on strengthening were systematically investigated. It was found that the temperature of heated lower dies could be improved to 450 °C to slow the temperature decrease of heated sheet besides obtaining excellent strength. The temperature of both hot dies could only be improved to 250 °C. The strengthening phase was the dispersed lath-shaped S precipitate with an average cross-section of approximately 50×100 nm.

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distortion of formed part during heat treatment, hot forming-quenching integrated process (so-called hot stamping of aluminum) has been developed recently for heat-treatable aluminum alloy forming, which was proposed firstly by Lin et al. (2008). The technology combines hot forming and quenching together in one operation. Heated sheet after solution heat treatment is formed immediately and then cooled rapidly within forming dies. The advantages are as follows: one is to improve formability with the forming temperature close to solution temperature, the second is to achieve rapid quenching to avoid the formation of coarse precipitates and the third is to restrict the thermal distortion during quenching. Wang et al. (2012) has focused on the investigations including formability, fracture and viscoplastic model in this process. The increased formability can indeed be achieved. Water cooled forming dies are used in the integrated process.

In the process with cold dies, it is extremely critical to control the forming temperature of heated sheet at temperature close to solution temperature because of heat loss to air and cold dies during transferring and forming. Otherwise, great decrease in temperature of heated sheet will result in the decrease of formability, and the part cannot be formed successfully. In order to slow the temperature decrease of heated sheet, elevating the temperature of forming dies is one reasonable method. However, the temperature of forming dies should be carefully controlled and it is unpractical to elevate the temperature to a too high level. Otherwise, it cannot ensure enough cooling ability to realize rapid quenching of the formed sheets, resulting the formation of coarse precipitates at the sensitive temperature range and the resultant weak strengthening.

Considering the critical requirement on short time for both material transferring and hot forming in the integrated process, a novel process called hot forming-quenching integrated process with cold-hot dies is proposed. Heated sheet after solution heat treatment is transferred to the heated lower dies, hereafter formed into the required shape with cooled upper dies pressing, then separated from the heated lower dies and held within cooled upper dies for several seconds to rapidly decrease the temperature, finally aged at room or elevated temperature to obtain enough strength. In this process, heated lower dies with possible temperature close to solution temperature can decrease heat loss of heated sheet to improve the forming temperature. The cooled upper dies can accomplish rapid quenching and reduce thermal distortion. However, the strengthening effect in the integrated process with cold-hot dies has not been investigated.

In this paper, the effect of temperatures of heated lower dies ranging from 250 to 450 °C on strengthening will be investigated. The strengths will be measured by Vickers hardness test and uniaxial tensile test. Microstructure evolution will be examined to clarify the strengthening mechanism with TEM and SEM methods. For comparison, the process with both hot dies at temperatures ranging from 100 to 350 °C will also be conducted.

2. Experimental methods and material

2.1. Hot forming-quenching integrated process

Fig. 1 shows the schematic diagram of different hot forming-quenching integrated processes. In the processes with both cold dies and hot dies, the parts were cooled within the closing dies. In the process with cold-hot dies, the parts were separated from the heated lower dies and held within upper cold dies to cool. The main differences in the integrated process with different cold or hot dies were the forming temperature of heated sheet, completion temperature of hot forming and cooling rate of final formed part, as shown in Fig. 2.

2.2. Experimental procedure

The experiments were carried out at different hot dies temperatures ranging from 100 to 450 °C to investigate the strengthening behavior of 2A12 sheet, as shown in Table 1. Solution heat treatment was carried out at 498 °C for 30 min and aging was conducted at room temperature. The specimen was heated by a resistance furnace. The hot dies were heated via resistance heating controlled by a PID controller. The cold dies were cooled by flowing water at temperature of 10 °C. The formed part was designed almost without plastic deformation to avoid the effect of deformation degree on strengthening. Down displacement of punch was 40 mm. The specimen was cut with 360 mm in length and 80mm in width.
Fig. 1. Schematic diagram of hot forming-quenching integrated process with: (a) both cold dies, (b) both hot dies and (c) cold-hot dies.

Fig. 2. Temperature change in hot forming-quenching integrated process.

Table 1. Process parameters in hot forming-quenching integrated process.

| Type of forming dies | Temperature of hot dies (°C) | Quenching | Analysing |
|----------------------|------------------------------|-----------|-----------|
| Both hot dies        | 100, 150, 200, 250, 300, 350 | Hot dies  |           |
| Upper cold dies + lower hot dies | 250, 350, 450 | Upper cold dies | Vickers Hardness, Mechanical properties |
2.3. Strength measurement

Vickers hardness test for HV$_{0.1}$ hardness was performed at the bottom area of formed parts. The tensile specimen was sectioned from the corresponding position perpendicular to the rolling direction. The gauge length and width of the specimen used were 15 and 5 mm, respectively.

2.4. Microstructure examination

Microstructure characterization was performed at the position of strength measurement with TEM and SEM methods. TEM investigations were used to characterize the strengthening precipitates by being performed on a Tecnai G$^2$ F30. SEM investigations were performed on a Quanta 200 FEG operated at 20 KV in the backscattered electrons mode to observe the precipitates distribution.

3. Results and discussion

3.1. Strengthening behavior

Fig. 3 shows the dependence of Vickers hardness on the temperature of hot dies. It is found that no obvious changes in hardness occurred until reaching the temperature of 250 °C in the process with both hot dies. Thereafter the hardness is seen to decrease obviously with further increase in the temperature of hot dies. When the temperature of hot dies was 350 °C, the Vickers hardness decreased to 120HV from the maximum value of 140 HV. It means that the temperature of hot dies cannot exceed 250 °C for slowing the temperature decrease of heated sheet. In the integrated process with cold-hot dies, it is apparent that the hardness decreased little on increasing temperature from 250 to 350 °C. Then the hardness increased to a higher level with the temperature of lower hot dies improving to 450 °C. They were almost the same level at temperatures ranging from 250 to 450 °C. When the temperature of lower hot dies was 450 °C, the Vickers hardness could still arrive at 140.7 HV.

![Fig. 3. Relationship of Vickers hardness on the temperature of hot dies.](image)

Fig. 4 shows the dependence of mechanical properties on the temperature of hot dies. It is obvious that the yield and tensile strengths decreased with increasing temperature in the integrated process with both hot dies, obvious decrease begun to appear since the temperature of hot dies reached to 250 °C. When the temperature rose to 350 °C, the yield and tensile strengths dropped to 213.5 and 358.2 MPa, respectively, being 27.9% and 22.1% lower than the strengths at 100 °C. However, The strengths increased with increasing temperature of lower hot dies from 250 to 450 °C in the integrated process with cold-hot dies. When the temperature of lower hot dies was 450 °C, the yield and tensile strengths could arrive at 295.7 and 469.2 MPa, respectively. Those were higher than the strengths at the temperature of 100 °C in the integrated with both hot dies. The significant agreement with the hardness
measurement could be got comparatively. It illustrates that the temperature of heated lower dies can be improved to a high level to slow the temperature decrease of heated sheet under the premise of obtaining enough strength.

![Fig. 4. Relationship of mechanical properties on temperature of hot dies: (a) yield strength and (b) tensile strength.](image)

### 3.2. Strengthening mechanism

Fig. 5 shows the TEM bright field images in <100> orientation obtained from the part formed at the temperature of 450 °C in the integrated process with cold-hot dies. It can be seen that the lath-shaped metastable precipitates precipitated with an average cross-section of approximately 50×100 nm in the Al matrix. These particles distributed homogeneously throughout the matrix. The corresponding selected area electron diffraction pattern is shown in Fig. 5(c), which is similar to those found for the same kind of precipitates as reported by Zhao et al. (2013). Therefore, the lath-shaped precipitates should be designated as S phase, which was considered to give the effective strengthening contribution (Wang and Starink, 2005).

![Fig. 5. TEM micrographs and corresponding diffraction pattern of the part formed at 450 °C in the integrated process with cold-hot dies.](image)

Fig. 6 shows the SEM images that illustrate the precipitates distribution at different temperatures in the integrated process with both hot dies. It is clear from that the second phase particles (shown in light) were dispersed evenly in Al matrix (shown in dark), which were the lath-shaped S precipitates identified with the TEM observation. The precipitates almost had the similar distribution through the matrix while the temperature was increased from 150 to 250 °C. With further increasing temperature to 350 °C, the precipitates grew in size obviously showing needle-shaped. Among these precipitates, both the particles themselves and stress fields caused by lattice distortion around the particles could impede the progress of dislocation movement, which plays a
dominant role in strengthening effect. However, the further growth in size of S precipitates led to the decrease in
volume fraction of strengthening S precipitates, which resulted in the final strength decreasing.

Fig. 6. Precipitates distribution by SEM in the integrated process with both hot dies at temperature of: (a) 250 °C, (b) 350 °C and (c) 450 °C.

4. Conclusions

(1) In the integrated process with cold-hot dies, the temperature of heated lower dies can be improved to 450 °C to
slow the temperature decrease of heated sheet besides obtaining enough strength. The corresponding yield and
tensile strengths are 295.7 and 469.2 MPa, respectively. In the integrated process with both hot dies, the
temperature can only be improved to 250 °C.
(2) Precipitation strengthening is the main strengthening mechanism, which depends mainly on the cooling rate in
the integrated process. The strengthening phase in Al matrix is the dispersed lath-shaped S precipitate with an
average cross-section of approximately 50×100 nm. The coarse formation of needle-shaped S precipitates leads
to the decrease in strength.

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