EFFECT OF TEMPERATURE AND FORMING RATE ON FORMABILITY OF ALUMINIUM ALLOY 5083 SHEET

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ABSTRACT Uniaxial tension tests were performed on a fine-grain Al-Mg alloy (5083-O) sheet at a wide range of 5.6×10^{-5} to 5.3×10 s^{-1} at various temperatures of 173 to 623 K. Strong temperature dependence of flow stress was found at low strain rates. This Al-Mg alloy exhibits the superplasticity at high temperatures and low strain rates. In certain conditions of temperature and strain rate, the stretcher-strain (st-st) marks appear on the surface of the sheet caused by the dynamic strain ageing. The test conditions of strain rate and temperature when the st-st mark appears were determined. In order to show how the forming speed and temperature affects the forming limit in actual press-forming, cylindrical deep drawing tests were performed on a aluminium-magnesium alloy sheet at various forming speed of 0.2 to 500 mm · min^{-1} and tested temperatures were 298, 353, 423 and 453 K. The limiting drawing ratio (LDR) became higher with decreasing forming speed at any temperatures of 298 to 453 K. The LDR became minimum at 353 K because at this specific temperature the flow stress reaches maximum value due to dynamic strain aging.

Keywords: *Al-Mg alloy, Deep drawing, Forming temperature, Forming speed, Limiting drawing ratio*

1. INTRODUCTION

Nowadays, there is a great concern about the weight reduction of vehicles, consequently the production of high-strength aluminium alloy is continuing to increase. In particular, the aluminium-magnesium (Al-Mg) alloy sheets are widely used in the car and shipbuilding industries, as the substitute of steel sheets and fiber reinforced plastic (FRP) panels, due to their excellent properties such as high strength, corrosion resistance and weldability [1, 2].

Since the press-formability of aluminium alloy is strongly influenced by deformation temperature and the forming speed, it is of great importance to determine the appropriate conditions of temperature and deformation speed in metal-forming operations. Although the Al-Mg alloy sheets have many advantages over conventional materials, their formability is lower than that of steel sheets. Moreover, on the surface of sheets the stretcher-strain (st-st) marks frequently appear during the metal-forming processes [3,4]. Obviously, such st-st marks are not required, since they decrease the quality of final products such as outer panels of cars, and also they may sometimes lead to strain localization and fracture. Therefore, it is very important to know about the conditions (strain rate and temperature) under which the st-st marks would appear.

The mechanical behavior of Al-Mg alloys have already been investigated for three decades. The study included st-st mark characterizations [5], the effect of Mg-content on the surface quality [6], and the influence of strain rate and temperature on the mechanical properties of the Al-Mg alloys [3, 5, 7, 8]. Such informations will enable us to determine the optimum forming condition of temperature and forming speed.

In the present work, Mg-rich aluminium-alloy sheet was examined, in order to determine the effect of strain rate and temperature on the flow stress and ductility, by performing uniaxial tension tests at wide range of strain rates of 5.6×10^{-5} to 5.3×10 s^{-1} at various temperatures of 173 to 623 K. The test conditions of strain rate and temperature when the st-st marks appear on the surface of the sheet were also experimentally determined. As an example showing how the forming speed and temperature affects the forming limit in actual press-forming, cylindrical deep drawing test were performed at various forming speeds of 0.2 to 500 mm · min^{-1} and different temperatures at 298, 353, 423 and 453 K.

2. EXPERIMENTAL PROCEDURES

We examined the 1-mm thick aluminium-magnesium alloy sheet (JIS-A5083P-O in Japanese standard). The chemical compositions of the sheet was such as given in Table 1.

2.1 Uniaxial tension test

Uniaxial tension tests were performed using type JIS-13B specimens at wide range of strain rate from static to dynamic strain rate conditions (5.56×10^{-5}, 5.56×10^{-4}, 5.56×10^{-3} and 5.56×10^{-2} s^{-1} in an Instron-type screw-driven machine; 5.28×10^{-1} s^{-1} in a flywheel-driven machine; and 52.9 s^{-1} in a drop-hammer-type testing machine. The testing temperatures were 173, 223, 258, 303, 353, 373, 423, 473, 523 and 623 K.

2.2 Cylindrical deep drawing test

The diameters of the blanks we used (see Fig. 1) ranged from 74.5 (DR-2.07) to 85.5 mm (DR-2.38), and the schematic of experimental equipment for cylindrical deep drawing test is illustrated in Fig. 1. The diameters of the flat punch and the die are 36 and 40 mm, respectively, while the corner radius equaled 4 mm (see Fig. 1).

Table 1. The chemical composition of the specimen. (wt.%)

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
0.04	0.04	Tr	0.64	4.58	0.11	Tr	0.01

Cylindrical deep drawing tests were performed with various punch speeds (0.2~500 mm · min^{-1}) in an Instron-type (screw-driven) machine, at temperature equal 298, 353, 423 and 453 K. The punch was water-cooled during the hot working tests. The blanks surface and the punch head were cleaned before each test. They were carefully wiped off the oil by using acetone, while the contact surfaces of the blanks of die and blank holder were coated by the wax type lubricant. The initial blank holder force was determined as a minimum force which can prevent the wrinkle of blanks. The blank holder force varied during the experiment because this device was of the type which enabled us to keep the clearance between the die and the blank constant.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

3.1 Flow stress and ductility

The flow stress decreases with temperature, except for certain test conditions (temperatures and strain rates) at which the serration (repeated yielding) is found in the stress-strain curve. Figure 2 shows the effect of strain rate on the flow stress (at strain of 0.1) at various temperatures. The strain-rate-dependence of flow stress ($\partial\sigma / \partial\dot{\varepsilon}$) is more considerable at higher temperatures, because the dynamic recovery and the grain-boundary sliding, which cases the superplasticity, likely occur at higher temperatures. The superplasticity is found in this material at high temperatures (573 to 623 K) and low strain rates ($5 \cdot 10^{-3}$ to $5 \cdot 10^{-5}$ s^{-1}) since the grain-boundary sliding becomes active at high temperatures and low strain rates. At low strain rates the fracture elongation becomes considerably larger with temperature. In contrast, at high strain rates does not change so much with temperature. The temperature and strain-rate-dependence of the ductility can be explained by the fact that the strain-rate-sensitivity exponent (*m*-value in the constitutive equation of $\sigma = C\varepsilon^n\dot{\varepsilon}^m$) becomes larger with temperature rise and with decreasing strain rate. For example, at 623 K, m=0.34 at strain rates

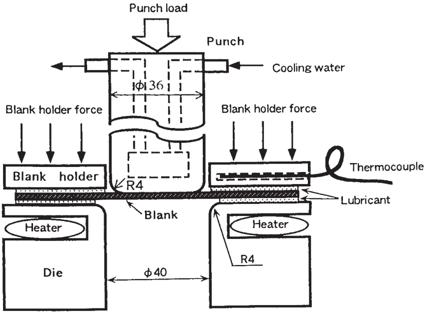

Fig. 1. Schematic of the apparatus for deep drawing test.

of $\dot{\varepsilon} = 10^{-5}$ to 10^{-4} s^{-1}, but m=0.06 at $\dot{\varepsilon} = 10^{-1}$ to 10 s^{-1}. The temperature- and strain-rate-dependence of the tensile ductility exactly corresponds to that of m-value. High tensile ductility appears in the conditions of high m-value, because localized necking unlikely occurs in materials of high strain-rate sensitivity [9]. Low tensile ductility of this material at high strain rates is partly due to the strain localization accelerated by material softening due to plastic deformation-induced temperature rise.

3.2 Stretcher-strain mark

Stretcher-strain marks were found on the surface of the specimens tested under certain conditions of strain rates and temperatures. St-st marks are generated as a result of non-uniform plastic deformation induced by the dynamic strain ageing (the Portevin-Le Chatelier effect) which is characterized by a serrated stress-strain curve. In Fig. 3, the conditions of strain rates and temperatures at which st-st marks appeared are shown by shadowed area in a temperature vs. strain-rate diagram. At sufficiently high temperatures and low strain rates, Mg-solutes can repeatedly lock dislocations during dislocation motion, and as a result, the dynamic strain ageing likely occurs. On the other hand, at higher strain rates, dislocations move so rapidly that the solutes cannot lock them. That is why st-st marks appear only in a certain range of temperatures and strain rates.

3.3 Deep drawability

The variation of LDR with forming speed determined at different temperatures are shown in Fig. 4. The LDR decreases with increasing forming speed, contrary to the case of the steel sheets. [10,11] The LDR increases remarkably with die temperature except for the case of 353 K at which the LDR is the lowest in all the experiments.

In deep drawing, a blank fractures when the punch load caused by the deformation resistance in flange shrinkage reaches the fracture strength of blank in the vicinity of the punch corner. Therefore, in order to discuss the effect of temperature and forming speed on the LDR, it is necessary to know the deformation characteristics of the aluminium alloy at various conditions of temperature and strain

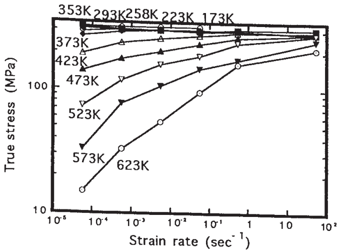

Fig. 2. The effects of strain rate on the flow stress (at strain of 0.1) at various temperatures.

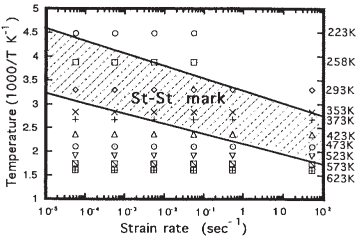

Fig. 3. Condition of temperature and strain rate for the appearance of st-st mark.

rate, as well as the variation of the punch load with the die temperature and forming speed.

The relationship between the maximum punch load (drawing force) and the forming speed at various temperatures is shown in Fig. 5. The flow stress of the aluminium alloy sheet under uniaxial tension is shown as a function of temperature in Fig. 2. Here, the deformation characteristics of the aluminium alloy found in Fig. 2 is summarized as follows:

- at 423 and 453 K the flow stress increases with increasing strain rates, on the contrary, it slightly decreases with strain rate at 298 and 353 K because of dynamic strain ageing.
- the flow stress decreases considerably with increasing temperature, except for a temperature range of 293-353 K in which the flow stress is almost unchanged at a strain rate higher than 0.01 sec^{-1}.

The fore-mentioned effects of temperature and strain rate on the LDR can be explained by the above deformation characteristics as follows:

- the LDR increases remarkably with die temperature (except for the case of 353 K) , because the deformation resistance at a flange decreases rapidly with temperature,
- the LDR attains the lowest value at a temperature of 353 K due to most prominent dynamic strain ageing (the apparent serration was found in the stress-strain curve [3]), and as a result, the large shrinkage stress of the blank at a flange,
- the LDR becomes lower with increasing forming speed. One of the reasons for the phenomenon is that the flow stress of the blank around the punch corner decreases with increasing forming speed due to dynamic strain ageing. Moreover, above 423 K, it occurs mainly due to the increase in the shrinkage stress of the blank at a flange with forming speed.

It is found in Fig. 4 that for a punch speed higher than 100 mm · min^{-1}, all the punch loads are almost equal to each other at any die temperatures. This fact suggests that the blanks around the punch corner were completely cooled during the tests. In contrast, at a punch speed below 100 mm · min^{-1}, the punch load slightly decreases with die temperature. For such a case of low punch speed, it seems that the blanks around the punch corner were being heated up, and as a result, were being softened during the tests. If the cooling of the blanks had been sufficient, even for a case of high die temperature of 453 K, the LDR would have been higher than the present experimental results.

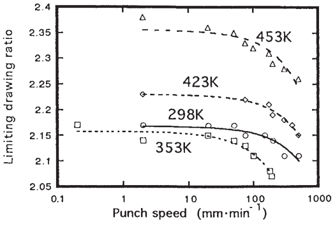

Fig. 4. The effect of forming speed on limiting drawing ratio at various temperatures.

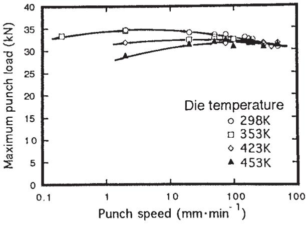

Fig. 5. The relationship between the maximum drawing force and the forming speed at various die temperatures.

4. CONCLUDING REMARKS

The effects of temperature and strain rate on the flow stress and ductility of Al-Mg alloy (5083-O) sheet have been experimentally investigated at a wide range of strain rates at various temperatures.

The present findings are summarized as follows.

- The temperature-dependence of flow stress is strongly expressed at low strain rates. Especially, at high deformation temperatures of over 523 K, the flow stress drastically decreases with decreasing strain rate, because this material exhibits superplasticity at high temperatures and low strain rates.
- At low strain rates the fracture elongation becomes considerably larger with temperature rise, but in contrast, at high strain rates does not change considerably. The temperature-and strain-rate-dependence of the ductility can be explained by the fact that the strain-rate sensitivity exponent (m-value) becomes larger with temperature rise and with decreasing strain rate.
- The temperature- and strain-rate-conditions in which the stretcher-strain marks appear on the surface of the sheet have been experimentally determined.
- The effects of temperature and forming speed on deep drawability of Al-Mg alloy (5083-O) sheet have been experimentally investigated for a various speeds ($0.2\sim500$ mm · min^{-1}) and temperatures (298, 353, 423 and 453 K). In the present paper, we have clarified that the variation of the LDR with temperature and forming speed is associated with the deformation characteristics of the aluminium alloy, such as dynamic strain ageing, temperature- and strain rate-dependence of flow stress.

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REFERENCES

[1] K. Takeuchi, *J. Japan Inst. Light Metal*, **41-11** (1991), 787. (in Japanese)

[2] O. Takezoe, *Kobe Steel Eng. Reports*, **42-1** (1992), 49. (in Japanese)

[3] T. Naka and F. Yoshida, *Proc. AEPA'96* (1996), 413.

[4] T. Amaike, Y. Abe and Y. Suzuki, *Proc. Plasticity'95* (1995), 241.

[5] A. T. Thomas, *Acta.Metll.*, **14**(1966), 1363 .

[6] R. A. Ayres, *Met. Trans.*, **10A**(1979), 849 .

[7] M. Otsuka and R. Horiuchi, *J.Japan Inst. Metals*, **48** (1984), 688. (in Japanese)

[8] M. Otsuka and R. Horiuchi, *J.Japan Inst. Metals*, **48** (1984), 1143. (in Japanese)

[9] E. W. Hart, *Acta Met.*, **15** (1967), 351.

[10] T. Nakagawa,K. Abe and Y. Hayashi, in *Press Working of the Sheet Metal*(1991), 119, Jikyou Shuppan Ltd.,Tokyo . (in Japanese)

[11] M. Murata, in *Data Book for Press Working*, (eds., T. Nakagawa et al.,)(1993), 198, The Nikkann Kougyou Shinbun Ltd.,Tokyo. (in Japanese)