Mechanical Properties of 7075 Aluminum Alloy at 6–130 K

By Shigeoki Saji*, Katushi Yasuhara** and Shigenori Hori*

Temperature dependence of tensile strength, ductility, toughness, work-hardenability and the parameter of serrated deformation was investigated in the temperature range from 6 to 130 K for as-solutionized and peak-aged aluminum alloy A7075. The tendency for the tensile strength, elongation, toughness and work-hardening exponent to increase with decreasing temperature changes to the decreasing tendency in the temperature range from 30 to 20 K. The change in the temperature dependence of the mechanical properties corresponds to that of the amount and total number of load drop in the serrated deformation. The load drop is due to thermally assisted discontinuous glide of dislocations. Disturbance of the uniform deformation which is due to the discontinuous glide of dislocations may be the main cause for the degradation of the mechanical properties.

(Received January 19, 1987)

Keywords: 7075 aluminum alloy, mechanical properties, low temperature, serrated deformation, laminated cracking

I. Introduction

Recently, various instruments and facilities have been developed in cryogenic service, and aluminum alloys have been proposed for structural applications at low temperatures because of their low density, non ferromagnetism, high thermal conductivity, low emissivity, superior out-gas property in vacuum service, shorter waiting time to reduce induced radioactivity and so on. However, the high strength aluminum alloy A7075 (Al–Zn–Mg–Cu system) has not been used for cryogenic service because of doubts about low temperature brittleness(1)–(4). There is no detailed data on the temperature dependence of the mechanical properties in the range from 4.2 to 77.4 K. Thus information on the mechanical properties and deformation behavior below 77.4 K is essential for the application of the aluminum alloy to cryogenic service.

In the present work, tensile tests were carried out on the aluminum alloy A7075 at various temperatures from 6 to 293 K. The temperature dependence of strength, ductility, toughness, work-hardenability and the parameter of serrated deformation were investigated in detail, and relations between these mechanical properties and the serration were discussed.

II. Experimental

The 7075 alloy was obtained from a manufacture, and the chemical composition of the alloy is shown in Table 1. Tensile specimens with the shape and size shown in Fig. 1(a) were cut from the hot- and cold-rolled plates 9.7 mm in thickness as shown in Fig. 1(b). The specimens were solution-treated at 723 K for 7.2 ks and then quenched into iced water. Some specimens were aged at 393 K for 172.6 ks before tensile tests, and this aging treatment put the specimens in the peak-aged (T6) condition. Hereafter the aged specimens are referred to as T6 specimens. The solution-treated specimen was a supersaturated solid solution of the main alloying elements Zn, Mg and Cu and they formed MgZn2(η’ or η) and Al2CuMg (S’ or S) precipitates in the peak-aged (T6) specimens. Mechanical properties of this alloy on the two typical condition were compared at low temperatures. Tensile tests in

| Table 1 Chemical composition of the alloy used (mass%). |
|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Cu  | Si  | Fe  | Mn  | Mg  | Zn  | Cr  | Ti  | Al  |
| A7075 | 1.34 | 0.084 | 0.202 | 0.058 | 2.17 | 5.68 | 0.184 | 0.033 bal. |

* Faculty of Engineering, Osaka University, Suita 565, Japan.
** Undergraduate Student, Osaka University, Suita, Now: TDK Co., Ltd., Narita 286, Japan.
temperature range from 6 to 130 K were carried out in He gas environment at the initial strain rate of $4.2 \times 10^{-4} \text{s}^{-1}$ by an INSTRON machine. Temperature was measured by a chromel: Au–0.03%Fe alloy thermocouple cemented to the surface of specimens and kept constant within the accuracy of ±1 K. Cracking and fractured surfaces were observed by means of optical and scanning electron microscopy.

III. Results

1. Strength and Ductility

Figure 2 shows the temperature dependence of proof stress and ultimate tensile strength for T6 and solution-treated specimens. Though both of the strengths increase with decreasing temperature, the increasing tendency in ultimate tensile strength is more remarkable than that in proof stress. The increase in strength is arrested or retarded below about 20 K in both cases.

Temperature dependences of the uniform elongation, $\varepsilon_U$, that is, the true strain up to the maximum tensile strength and of the localized elongation, $\varepsilon_F - \varepsilon_U$ are shown in Figs. 3 and 4, respectively, where $\varepsilon_F$ is the true strain up to fracture. For both specimens $\varepsilon_U$ increases with decreasing temperature to about 30 K and then decreases in the temperature range between 30
and 20 K. The increasing trend of $\varepsilon_U$ with decreasing temperature starts at a higher temperature in the solution-treated specimen than in the T6 specimen. Temperature dependence of the localized elongation is quite different from that of the uniform elongation (Fig. 3). The localized elongation nearly 1/10 smaller than the uniform elongation at temperatures below about 30 K. Thus, the total elongation to fracture is largely attributed to the uniform elongation.

Temperature dependence of total reduction of area, $R_T$ is shown in Fig. 5 along with that of reduction of area during uniform elongation, $R_U$ which was estimated from the value of $\varepsilon_U$ on the assumption of constant volume. The reduction of area from the initiation of necking to fracture, $R_T-R_U$, shows a large decrease in both specimens over the temperature range between about 100 and 30 K.

2. Toughness

Area enclosed by a load-displacement curve and displacement axis corresponds to the total work to be done for fracture, providing an index of toughness. As shown in Fig. 6, the work done and hence toughness of solution-treated specimen increases monotonously with decreasing temperature above about 30 K, but it changes to the decreasing tendency below 30 K. On the other hand, the work done of the T6 specimen remains nearly constant between 293 K and 70 K and then it increases with decreasing temperature to about 30 K, and changes to the decreasing tendency between 30 and 20 K. There are few reports on toughness of this alloy in the temperature range below 70 K. Wigley\(^4\) showed that the fracture toughness, $K_{IC}$, of an A7075-T6 specimen in the temperature range below 77 K was only one-half that at room temperature, and Yoshida et al.\(^5\) reported that energy for fracture of Al-4.7%Zn-1.2%Mg alloy by Instrumented Charpy tests at 4.2 K was about 80 percent of that at room temperature. It is noteworthy that work done for fracture below 20 K is 2.1 and 1.5 times as high as that at 293 K for the solution-treated and T6 specimens, respectively.

3. Work-hardening exponent

The stress-strain curve can often be described by the following relation:

$$\sigma = K\varepsilon^n$$

(1)

where $\sigma$ is the true stress, $\varepsilon$ is the true strain, and $K$ and $n$ are work-hardening parameters. Figure 7 shows some examples of the $\ln \sigma - \ln \varepsilon$ plot for solution-treated and T6 specimens. The data on the T6 specimens show straight lines at all temperatures. In the case of the solution-treated specimens, however, the same plots provide a set of lines containing two straight parts and a transient part between them as seen in Fig. 7. Temperature dependence of the $n$ value for the T6 and the
average value, \((n_1+n_2)/2\) for the solution-treated specimen is shown in Fig. 8. The \(n\) value is approximately constant in the temperature range from 293 to 70 K and increases with decreasing temperature to about 30 K, but it changes into the decreasing tendency between 30 and 20 K. On the other hand, the \((n_1+n_2)/2\) value increases monotonously with decreasing temperature to about 30 K and changes to the decreasing tendency below about 20 K.

4. Serrated deformation

At temperatures below about 30 K, both solution-treated and T6 specimens exhibited such serrated deformation as seen in Fig. 9 (No serrated flow was observed in the temperature range between 40 and 130 K). Another type of serrated flows observed at 293 K may be due to the Portevin-LeChatelier effect, which has previously been reported for various aluminum alloys\(^{(5)-(7)}\). The amount of stress drops, \(\Delta \sigma\) larger than 0.08 MPa are plotted against strain in Figs. 10 and 11 for solution-treated and T6 specimens, respectively. Total number
of stress drops, $N$ is also indicated. There are two groups of stress drops, one consists of increasing with the increase in strain and hence in the stress level, and another consists of $\Delta \sigma$ showing nearly constant small values, regardless of the strain. The 1st group is entirely absent at 30 K. The total number, $N$ decreases with rise in temperature. It can also be seen that the stress drops more frequently in the solution-treated specimen than in the T6 specimen although the amount of stress drop is nearly the same for both specimens.

5. Correspondence between the serrated flow and heat generation

Figure 12 shows a part of the load-displacement curve of a solution-treated specimen strained at 16 K, along with the temperature which was measured by the thermocouple at
attached to the central surface of the specimen. The average temperature was kept constant within the accuracy of ±1 K. Good correspondence is confirmed between the large serrated flow and the local heat generation for both solution-treated and T6 specimens.

6. Laminated cracking

It is well known that intergranular fracture in Al-Zn-Mg alloys\(^{(8-9)}\) becomes more remarkable in the specimens consisting of larger and equiaxed grains. In the present work, however, specimens have elongated grains parallel to the rolling direction, as shown in Fig. 13. There are many intermetallic particles smaller than an about 4 \(\mu\)m\(^2\) in area and a few particles denoted by arrows larger than about 20 \(\mu\)m\(^2\) within grains and at grain boundaries. They are insoluble at the solution-treated temperature. Figure 14 shows fractographs of the T6 specimens strained at 6.5, 30, 70 and 293 K. Cracks are observed along lamellar boundaries at all temperatures. They become more remarkable with decreasing temperature down to about 30 K, but are blurred at 6.5 K. Similar temperature dependence of the laminated cracking was observed in the solution-treated specimen, though the cracks were less and blurred compared with the T6 specimen.

IV. Discussion

It deserves particular attention in the present work that the change in the mechanical properties with decreasing temperature becomes anomalous at temperatures below about 30 K. So we discuss here the relations between the anomaly in the temperature dependence of the mechanical properties and the serrated deformation. Increasing difficulty in cross slips of dislocations causes an increase in flow stress and work-hardenability with decreasing temperature. The increase in the work-hardenability and hence in the work-hardening exponent brings about an increase in the uniform elongation comprising above 90 percent of the total elongation in the present work. The higher value and more remarkable temperature dependence of toughness in the solution-treated specimen are due to those of uniform elongation (Fig. 3). The higher value and more remarkable temperature dependence of the uniform elongation may be attributed to the lower stacking fault energy and the more homogeneous microstructure in the solution treated specimens. In general, the stacking fault energy decreases with increasing amount of solute atoms in solid solutions.\(^{(10)}\) Saji et al.\(^{(11)}\) reported previously that the higher value and more remarkable temperature dependence of uniform elongation was observed in the solution-treated specimen than in the aged specimens of a Cu-4\%Ti alloy.

On the other hand, possible sources of serrated flow at a very low temperature are as follows; (1) thermally assisted discontinuous glide of dislocations\(^{(12-14)}\) (2) stress-induced
martensitic transformation\(^{(15)}\), and (3) deformation twinning\(^{(16)(17)}\). Stress-induced martensitic transformation may not be considered in aluminum alloys and no deformation twin was observed in this alloy because of the comparatively high stacking fault energy. The one-to-one correspondence between a larger load drop and a local heat generation (Fig. 12), supports the 1st term. Because of the polycrystalline specimens consisting of elongated fine grains with various particles (Fig. 13), attempts to confirm coarse slip bands corresponding to a large load-drop were unsuccessful in the present work. However, Fukushima et al.\(^{(18)}\) observed five coarse slips corresponding to a load-drop during deformation of coarse grained aluminum (AE1100) at 4.2 K.

More numerous serrated flows, larger load drops and the anomalies in the mechanical properties occurred in the same temperature range. This suggests that thermally assisted discontinuous glide of dislocations causes a decrease in work-hardenability resulting in the decreasing tendency in the uniform elongation, ultimate tensile strength and toughness at temperatures below about 20 K. The laminated cracks were most remarkable on the fracture
surfaces at 30 K, at which uniform elongation and toughness showed a largest value. Thus, they have a negligible influence on the low temperature mechanical properties at least in the rolling direction.

V. Conclusions

The dependence of strength, ductility, toughness, work-hardenability and serrated deformation on temperature between 6 and 293 K, was investigated for the solution-treated and T6 specimens of the commercial aluminum alloy A7075. Results and conclusions are summarized as follows:

(1) A characteristic serrated deformation occurs during straining at temperatures below about 30 K. The load drop in this type of serration is due to the thermally assisted discontinuous glide of dislocations.

(2) The uniform and total elongations increase monotonously with decreasing temperature down to about 30 K and change to the decreasing tendency at temperatures below about 30 K. The change in the temperature dependence of the uniform elongation corresponds to that of the work-hardening exponent.

(3) The tendency for the tensile strength and toughness to increase with decreasing temperature arrests and changes to the decreasing tendency at temperatures below about 30 K, respectively. However, the work done for fracture below 20 K is 2.1 and 1.6 times as high as that at 293 K for the solution-treated and T6 specimens, respectively.

(4) These changes in temperature dependence of the mechanical properties may be attributed to the degradation of work-hardenability which is due to the thermally assisted discontinuous glide of dislocations.

(5) Laminated cracking along grain boundaries has a negligible influence on the anomalous mechanical properties at very low temperatures.

Acknowledgments

The low temperature tensile tests has been performed using the mechanical testing facilities of the Low Temperature Center, Osaka University.

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