Tensile Properties of Internally Hydrided and T6-Treated Mg–10%Y–2%Nd Alloys at Elevated Temperatures

Shotaro Morozumi¹ and Hiroshi Saikawa²

¹Magnesium Research Center, Chiba Institute of Technology, Narashino 275-0016, Japan

²Department of Metallurgical Engineering, Chiba Institute of Technology, Narashino 275-0016, Japan

Chill-cast Mg–10%Y–2%Nd alloy was internally hydrided and examined for tensile properties up to 773 K by short-time tensile and creep tests at strain-rates of 1.4×10^{-9} to $2.78 \times 10^{-4} \text{ s}^{-1}$, in comparison with those of the T6-treated alloy. The results obtained were analyzed for the relationship of stress, σ (0.2% yield stress or applied creep stress), vs. strain rate, $\dot{\epsilon}$ (initial strain rate or minimum creep rate). Generally, the stress exponent, n ($= d \log \dot{\epsilon} / d \log \sigma$)-value of the hydrided alloy is larger than that of the T6-treated alloy at the same test temperature. Consequently, the strength of the hydrided alloy becomes higher than that of the T6-treated alloy at strain rates lower than 10^{-5} s^{-1} at and above 723 K. This fact can be attributed to the stable hydride precipitates in the internally hydrided alloy.

(Received January 23, 2001; Accepted May 28, 2001)

Keywords: *magnesium-yttrium-neodymium alloy, internally hydrided magnesium alloy, tensile test, creep, hydrogenation, mechanical property*

1. Introduction

It is well known that an age-hardenable Mg–Y–Nd alloy, such as WE54, containing a high percentage of Y and a low percentage of Nd has good mechanical properties at elevated temperatures. This kind of alloy can also be hardened with dispersed particles of III_a transition metal hydrides precipitated throughout the alloy by hydrogenation at about 773 K. It has been shown that the internally hydrided Mg–10%Y–2%Nd alloy is superior in the term of tensile properties to the as-cast alloy at 673 K, though the tensile properties of the former are somewhat inferior to those of the latter at room temperature.¹⁾

Although some fundamental research studies on the creep behavior of magnesium alloys containing yttrium have been performed so far,^{2–6)} only a few studies on the internally hydrided Mg–Y alloy have been carried out. In the present paper, the tensile properties of internally hydrided cast Mg–10%Y–2%Nd alloy are examined at elevated temperatures and compared with those of the T6-treated alloy.

2. Experimental

2.1 Preparation of specimens

The alloy used in the present experiment was prepared by an ordinary flux process for melting of magnesium alloys. Chill-cast alloy ingots of size 12 mm × 35 mm × 100 mm, prepared from the same charge, were machined in the shape of a round bar test piece of 6 mm in diameter and 30 mm gauge length. The chemical composition of the alloy is listed in Table 1.

2.2 Pretreatment of specimens

2.2.1 Hydrogenation

Mechanically finished specimens were held for 2 h (7.2 ks) at 773 K under a pressure of $1 \times 10^5 \text{ Pa}$ of hydrogen and then furnace-cooled.

Table 1 Chemical composition of Mg–10%Y–2%Nd alloy.

Chemical composition (mass%)		
Y	Nd	Mg
10.12	2.06	Bal.

2.2.2 T6-treatment

Mechanically finished specimens were solution-treated for 24 h (86.4 ks) at 800 K in an Ar atmosphere and then water-quenched; this was followed by aging for 100 h (360 ks) at 473 K in ambient atmosphere and then air-cooling.

2.3 Tensile tests

2.3.1 Short-time tensile test

A short-time tensile-test was performed at strain rates of 2.78×10^{-5} to $5.56 \times 10^{-4} \text{ s}^{-1}$ at 573 to 723 K in ambient atmosphere.

2.3.2 Creep test

Tensile creep test was carried out under stresses of 5 to 10 MPa at 573 to 723 K in ambient atmosphere. The minimum creep rate was measured as 1.40×10^{-9} to $3.76 \times 10^{-6} \text{ s}^{-1}$.

2.4 Microscopic observation

Optical microscopy (OM) and scanning electron microscopy (SEM) observations were performed for each specimen before and after the tensile or creep test.

3. Experimental Results

3.1 Short-time tensile test

3.1.1 Temperature dependence of strength

As reported in a previous paper,¹⁾ 0.2% offset yield strength (or stress) (YS), ultimate tensile strength (or stress) (UTS) and elongation to failure (E) of internally hydrided Mg–10%Y–2%Nd alloy tensile-tested at a strain rate of $2.78 \times 10^{-4} \text{ s}^{-1}$ at room temperature (296 K) are 140 MPa, 192 MPa and 4.5%, respectively. Both the YS and the UTS of the T6-treated specimen are higher than those of the hydrided

Table 2 Strain-rate dependence of 0.2%YS of hydrided and T6-treated Mg-10%Y-2%Nd alloys at 573–723 K.

Temper	Strain-rate, $\dot{\epsilon}/s^{-1}$	0.2%YS, $\sigma_{0.2}/MPa$			
		Testing temperature, T/K			
		573	623	673	723
Hydrided	2.78×10^{-4}	59.0	76.0	34.0	21.5
	2.78×10^{-5}	60.0	58.1	26.7	16.0
T6-treated	2.78×10^{-4}	195.0	135.0	85.0	28.6
	2.78×10^{-5}	138.0	107.5	32.8	13.3

specimen, respectively and this is maintained up to 673 K, as seen in Table 2. The decrease in the strength of the T6-treated specimen with an increase in testing temperature up to 673 K is significant. Above 673 K, however, the decrease in the strengths of all of the specimens, particularly of the hydrided alloy, becomes smaller with an increase in testing temperature.

3.1.2 Strain-rate dependence of strength

Generally, the strain-rate dependence of strength in magnesium alloys is not high at room temperature and it is above 673 K where the strength of the hydrided specimen can compete with that of the T6-treated specimen, as shown in Table 2. The comparison of the strain-rate dependence of the YS between the internally hydrided alloy and the T6-treated alloy was performed by tensile testing at the two strain rates of 2.78×10^{-4} and $2.78 \times 10^{-5} s^{-1}$ at 573 to 723 K.

At 573 K, the YS and its strain-rate dependence for the T6-treated specimen are relatively high, in comparison with the hydrided specimen.

At 623 K, the strength level of the T6-treated specimen and the strain-rate dependence are still higher than those of the hydrided specimen.

At 673 K, the T6-treated specimen is still superior to the hydrided specimen in terms of strength at both strain rates.

At 723 K, the strength of the hydrided specimen becomes larger than that of the T6-treated specimen at a low strain-rate, but the strength of the T6-treated specimen becomes higher than that of the hydrided specimen at a high strain-rate.

3.1.3 Stress-strain curves at different strain-rates

Typical stress-strain curves of the hydrided and T6-treated specimens tensile tested at strain rates of 2.78×10^{-4} and $2.78 \times 10^{-5} s^{-1}$ at 673 K, are illustrated in Fig. 1, where the strain-rate dependence is emphasized in the T6-specimen, and shows a sharp and high YS peak at $2.78 \times 10^{-4} s^{-1}$, while a relatively low YS at the smoothly curved portion of the curve is seen in the hydrided specimen tested at the same strain-rate.

At 723 K, the strain-rate effect becomes less than that at 673 K, and the YS of the hydrided specimen is a little larger than that of the T6-treated specimen at the strain-rate of $2.78 \times 10^{-5} s^{-1}$ as shown in Fig. 2.

3.2 Creep test

Strain-time curves for both the hydrided and T6-treated specimens creep-tested under initial stresses of 10 MPa at 673 K, and 5 and 10 MPa at 723 K, are shown in Figs. 3 and 4, respectively. It is noted that the hydrided specimen is considerably superior to the T6-treated specimen under the present creep conditions. Minimum measured strain rates of the specimens are plotted against the initial stress on the log-log

Fig. 1 Stress-strain curves for hydrided and T6-treated cast Mg-10%Y-2%Nd alloys tensile-tested at initial strain-rates of (a) 2.78×10^{-4} and (b) $2.78 \times 10^{-5} s^{-1}$ at 673 K.

Fig. 2 Stress-strain curves for hydrided and T6-treated cast Mg-10%Y-2%Nd alloys tensile-tested at initial strain-rates of (a) 2.78×10^{-4} and (b) $2.78 \times 10^{-5} s^{-1}$ at 723 K.

Fig. 3 Strain-time curves for hydrided and T6-treated cast Mg-10%Y-2%Nd alloys creep-tested under stress of 10 MPa at 673 K.

scale in Fig. 5, where the results of the short-time tensile test are also plotted. It can be seen that the data obtained from both short-time tensile and creep tests are consistent, except for two data points for the T6-treated specimen at the strain-rate of $2.78 \times 10^{-4} s^{-1}$ at 673 and 723 K.

Fig. 4 Strain-time curves for hydrided and T6-treated cast Mg-10%Y-2%Nd alloys creep-tested under stresses of 5 and 10 MPa at 723 K.

Fig. 5 Stress vs. strain-rate plots for hydrided and T6-treated cast Mg-10%Y-2%Nd alloys tensile-tested or creep-tested at various temperatures: Stress is 0.2%YS or applied creep stress, and strain rate is initial tensile strain rate or minimum creep rate.

3.3 Microscopic observation

3.3.1 Internally hydrided specimen

As reported in the previous paper,¹⁾ magnesium alloys which contain III_a transition metals can be reinforced with dispersed hydride precipitates of the metals by an appropriate

Fig. 6 Scanning electron micrograph (SEM) image of internally hydrided cast Mg-10%Y-2%Nd alloy.

hydrogenation process and the precipitates in the matrix are formed on the specific crystallographic planes. The III_a transition metal hydrides precipitate in the matrix and at grain boundaries. The SEM structure of the internally hydrided alloy is illustrated in Fig. 6. Hydrides formed in the alloy are identified as YH₂ by X-ray diffraction analysis, as reported in the previous work on the Mg-Y binary system.¹⁾

3.3.2 T6-treated specimen

OM observation does not clearly reveal any of the precipitates in the matrix of the as-T6-treated specimen as seen in Fig. 7(a). After tensile testing at elevated temperatures, however, the microstructure changes as shown in Figs. 7(b)–(e): At 573 K, a fine striation of precipitates almost parallel in one direction is seen in the matrix; at 623 K, a cross striation structure of precipitates is also seen in the matrix, together with a thin precipitate network along the grain boundaries; at 673 K, the striation diminishes and the amount of platelet-like hydrides increases in the matrix and massive hydrides are seen at grain boundaries; finally at 723 K, needle-like and platelet-like precipitates coarsely disperse in the matrix and a continuous thicker hydride-network is formed along the grain boundaries. The precipitate in the T6-treated alloy was not identified, but it may be a β phase (Mg-Y-Nd).

4. Discussion

4.1 Structural dependence of strength in the internally hydrided specimen

As already reported,¹⁾ the structure of the internally hydrided Mg-Y-Nd alloy varies with the hydrogenation condition, to which the alloy is subjected. That is, depending on the hydrogenating temperature and time, the interlamellar distance of hydride precipitates varies. A finer structure produced at a lower hydrogenation temperature and/or a shorter hydrogenation duration results in a higher strength of the alloy. From this point of view, the hydrogenation condition in the present experiment is not necessarily the most appropriate condition, but is rather a stabilizing condition. Therefore, the structure of the hydrided specimens does not change significantly after testing at elevated temperatures.

Fig. 7 Optical micrographs of Mg–10%Y–2%Nd alloy cast and (a) T6-treated, and then tensile-tested at (b) 573, (c) 623, (d) 673 and (e) 723 K.

4.2 Stress-strain rate relationship

Generally, the relationship of stress and strain rate can be represented by equation (1):

$$\dot{\varepsilon} = k\sigma^n, \quad (1)$$

where $\dot{\varepsilon}$ is the strain rate, σ is the stress, and k and n are constants. According to this equation, $\log \dot{\varepsilon}$ (ordinate) can be linearly plotted against $\log \sigma$ (abscissa) and the gradient of the plot gives the n -value. Therefore, the data obtained are listed in Table 3.

The data for the hydrided and T6-treated alloys obtained by the short-time tensile and creep tests at 573 to 723 K are plotted in Fig. 5.

At and below 673 K, the YS of the T6-treated alloy is higher than that of the hydrided alloy under the present experimental conditions, and the n -value of the former is 5–7; this excludes the YS at the strain rate of $2.78 \times 10^{-4} \text{ s}^{-1}$ at 673 K, of which the strain rate dependence is extremely high as shown in Fig. 1, while the n -value of the T6-treated alloy is 6–8 except for the case of 573 K, where the n -value of the specimen is as large as 13. At 673 K, under the stress of 10 MPa, the strain-rate of the hydrided specimen is lower than that of the T6-treated specimen, while above 10 MPa, the strain rate of the hydrided alloy is higher than that of the T6-treated alloy.

At 723 K, the plotted lines of the hydrided and the

Table 3 n -values for hydrided and T6-treated Mg–10%Y–2%Nd alloys.

Temperature, T/K	Temper	Stress, σ/MPa^*	Strain rate, $\dot{\epsilon}/\text{s}^{-1}^*$	n
573	Hydrided	30–70	4×10^{-8} – 3×10^{-4}	13
	T6-treated	30–190	4×10^{-8} – 3×10^{-4}	7
623	Hydrided	25–70	7×10^{-8} – 3×10^{-4}	8
	T6-treated	30–130	4×10^{-8} – 3×10^{-4}	6
673	Hydrided	10–35	2×10^{-8} – 3×10^{-4}	7
	T6-treated	9–30	2×10^{-8} – 3×10^{-5}	6
		30–80	3×10^{-5} – 3×10^{-4}	2
	Hydrided	10–22	3×10^{-8} – 3×10^{-4}	7
723	T6-treated	5–14	1×10^{-7} – 3×10^{-5}	5
		14–18	3×10^{-5} – 2×10^{-4}	3

*Figures in this column are approximate numbers.

T6-treated specimens cross each other at a strain-rate of about $5 \times 10^{-5} \text{ s}^{-1}$, below which the former specimen is superior in strength to the latter, having an n -value of 6, while that of the latter is 5.

As mentioned above, different strain-rate dependencies of strength are observed between hydrided and T6-treated specimens. It is noted, however, that the hydrided specimen is superior in strength to the T6-treated specimen at strain rates below about 10^{-5} s^{-1} at and above 723 K, probably because of stable hydride precipitates dispersed in the specimen at such high temperatures.

The n -value of Mg–Y alloys has been estimated and reported to be 2 to 14;^{2,3,5–7} these vary with different strain rate-control mechanisms depending on the applied stress and temperature: For example, dislocation viscous glide mechanism for $n = 2$ –4, dislocation climb mechanism for $n = 5$ –7, and yielding for $n = 12$ are proposed.⁷ The n -values of the T6-treated specimens in the present experiment may be explained by these mechanisms. However, the change of the n -value of the hydrided specimens with temperature cannot be completely analyzed based on the mechanisms. Further studies, concerning elevated temperature properties of particle-

dispersed magnesium-matrix composite materials, the structure of which may be similar to that of the hydrided specimen, are necessary.

5. Summary

Chill-cast Mg–10%Y–2%Nd alloy specimens in the hydrided and T6-treated conditions were tensile tested at strain rates of 1.39×10^{-9} to $5.56 \times 10^{-4} \text{ s}^{-1}$ by short-time tensile and creep tests at 573 to 723 K. Data obtained, for stress and strain-rate, were plotted on a log – log scale. The results obtained are as follows: At and below 673 K, the YS of the T6-treated specimen is higher than that of the hydrided specimen under the present experimental conditions.

At and above 723 K and at a lower strain rate than 10^{-5} s^{-1} , the hydrided alloy becomes superior to the T6-treated alloy in terms of the YS.

Acknowledgments

The authors are grateful to Messes M. Otsuki and K. Oyama for their assistance in the experimental work.

REFERENCES

- 1) S. Morozumi, H. Saikawa, T. Minegishi, M. Matsuyama, K. Watanabe, M. Iijima and M. Ohtsuki: *J. Mater. Sci.* **31** (1996) 4647–4654.
- 2) W. Henning and B. L. Mordike: *Strength of Metals and Alloys*, (ICSMA 7), (Pergamon Press, 1985) pp. 803–805.
- 3) H. Karimzadeh, J. M. Worrall, R. Pilkington and G. W. Lorimer: *Magnesium Technology*, (Proceedings of the Conference, 1986), (The Institute of Metals, 1987) pp. 138–141.
- 4) B. L. Mordike and W. Henning: *Magnesium Technology*, (Proceedings of the Conference, 1986), (The Institute of Metals, 1987) pp. 54–59.
- 5) M. Ahmed, R. Pilkington, P. Lyon and G. W. Lorimer: *Magnesium Alloys and Their Applications*, (Deutsche Gesellschaft für Materialkunde e.V., 1992) pp. 251–257.
- 6) M. Suzuki, H. Sato, M. Maruyama and H. Oikawa: *Mater. Sci. Eng. A* **252** (1998) 248–255.
- 7) M. Suzuki, R. Inoue, M. Sugihara H. Sato, J. Koike M. Maruyama and H. Oikawa: *Mater. Sci. Forum* **350–351** (2000) 151–156.