Effect of Heat Treatment on Strain Rate Sensitivity in Tensile Properties of 13Ni-15Co-10Mo-0.2Ti Maraging Steel*

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Synopsis

Tensile properties and resistivity changes during isothermal aging have been investigated mainly on a 13Ni-15Co-10Mo-0.2Ti maraging steel aged in the range from 400° to 575°C. A crosshead speed has been varied from 1 mm/min to 0.005 mm/min, in order to investigate the effect of strain rate on the tensile properties.

The embrittlement caused by the decrease in strain rate is found in the tensile properties of the maraging steel containing fine and coherent precipitates. The ductility of the overaged 13Ni-15Co-10Mo-0.2Ti maraging steel is also decreased at a lower strain rate. When this steel is overaged after cold rolling to 40%, the ductility parallel to the rolling direction is not decreased by the decrease in strain rate. Tensile properties insensitive to strain rate are obtainable after aging for about 10~100 min in the range from 525° to 575°C.

Investigation carried out on 14Ni-10Co-10Mo and 14Ni-15Co-7Mo maraging steels is included in order to consider the effect of chemical composition on the strain rate sensitivity. The maraging steels containing fine and coherent precipitates are also embrittled by the decrease in strain rate. The 14Ni-15Co-7Mo maraging steel continues to precipitate coherent precipitates for longer times at a certain aging temperature than does the 14Ni-10Co-10Mo one.

I. Introduction

Effect of heat treatment on strain rate sensitivity in the tensile properties of commercial 210 kg/mm² grade and 245 kg/mm² grade maraging steels was recently reported by Soeno *et al.*¹⁾ It was found that the tensile properties of the maraging steels containing fine and coherent precipitates were very sensitive to strain rate.¹⁾ As a strain rate decreased, the drop in ductility was notable. We considered that relatively intense stress concentrations tended to be produced during plastic deformation of the maraging steels containing fine and coherent precipitates. Accordingly, the embrittled behavior at a lower strain rate was interpreted by assuming that hydrogen diffused to the regions having intense stress concentrations leads to the initiation of cracking.¹⁾ It was also shown that the strain rate sensitivity in the tensile properties was decreased when the partially coherent precipitates were increased by lengthening aging time or by raising aging temperature.¹⁾

The present paper is concerned mainly with the

strain rate sensitivity in the tensile properties of a 13Ni-15Co-10Mo-0.2Ti (280 kg/mm² grade) maraging steel subjected to isothermal agings in the range from 450° to 575°C. For considering the effect of chemical composition on the strain rate sensitivity in the tensile properties, the present paper also includes an investigation carried out on 14Ni-10Co-10Mo and 14Ni-15Co-7Mo maraging steels aged isothermally in the range from 425° to 475°C.

II. Experimental Procedure

The chemical compositions of the maraging steels used are shown in Table 1. The 13Ni-15Co-10Mo-0.2Ti maraging steel was remelted in a vacuum arc furnace by using a consumable electrode melted in an induction (vacuum) furnace, homogenized for 20 hr at about 1 200°C, and hot forged. Two sheets of 1 mm and 1.5 mm thickness are made by cold rolling a 50 mm wide, 10 mm thick and 100 mm long plate machined from a slab. After solution for 1 hr at 1 100°C in a vacuum furnace, the 1 mm thick sheet and the 1.5 mm thick one were cold rolled to 0.5 mm and to 0.84 mm respectively.

A tension specimen used is shown in Fig. 1. Tension specimens parallel to the rolling direction were made by using the 0.5 mm thick sheet, solution-treated for 1 hr at 1 075°C in an electric furnace filled with argon, and quenched in water. Austenitic grain size number was in the range of ASTM No. 3.5 to No. 4.5. The 0.84 mm thick sheet was also solution-treated for 1 hr at 1 075°C, and cold rolled 40% to

T = 0.5mm for 13Ni-15Co-10Mo-0.2Ti
T = 0.25mm for 14Ni-10Co-10Mo &
14Ni-15Co-7Mo.

Fig. 1. Tensile test specimen.

Table 1. Chemical compositions of maraging steels investigated. (wt%)

No.	Ni	Co	Mo	Ti	Al	C	N	Si	Mn	P	S
1	12.96	15.15	10.26	0.16	0.01	0.003	0.003	0.01		0.006	0.005
2*	14	10	10						0.15		
3*	14	15	7						0.15		

* Nominal composition

* Partly published in *Tetsu-to-Hagane*, **65** (1979), 665, in Japanese. English version received March 14, 1980.

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0.5 mm in thickness. In case of this marformed sheet, tensile properties parallel to both the rolling and the transverse direction were measured after aging.

The 14Ni-10Co-10Mo and the 14Ni-15Co-7Mo maraging steel were melted in a tungsten-electrode copper-crucible arc furnace by using vacuum-melted electrolytic iron containing about 0.1%Al and other additional elements having purities of 99% and over. Each heat weighed about 100 gr. Before alloy preparation, the vacuum-melted electrolytic iron ingot was cold rolled to 1 mm in thickness, and annealed in wet hydrogen gas flow for 30 hr at 650°C in order to eliminate carbon and nitrogen. The arc-melted ingots were hot forged after homogenizing in vacuum for 8 hr at 1 000°C, annealed in vacuum for 4 hr at 1 100°C, and cold rolled to 0.25 mm in thickness. Tension specimens parallel to the rolling direction were prepared from the 0.25 mm thick sheets, solution-treated for 30 min at 1 025°C, and quenched in water. Austenitic grain size number was in the range of ASTM No. 7.5 to No. 8.5. The investigation carried out on the 14Ni-10Co-10Mo and the 14Ni-15Co-7Mo maraging steel is included in order to discuss the effect of chemical composition on the strain rate sensitivity in the tensile properties.

Wires of 0.6 mm in diameter were also made for the measurement of electrical resistivity. In order to investigate precipitation behaviors in the maraging steels, resistivity change with aging time was measured at liquid nitrogen temperature by the four-probe potentiometric technique.

Aging for 1 000 min or less was done by using a salt bath. For aging over 1 000 min, specimens aged for 1 000 min in the salt bath were transferred into an electric furnace filled with argon, and aging was continued. Crosshead travel speeds adopted in the present investigation are 0.005 (strain rate, $\dot{\epsilon} \doteq 7.5 \times 10^{-6} \text{ sec}^{-1}$), 0.01 ($\dot{\epsilon} \doteq 15.2 \times 10^{-6} \text{ sec}^{-1}$) and 1 mm/min ($\dot{\epsilon} \doteq 15.2 \times 10^{-4} \text{ sec}^{-1}$). Tensile strengths and elongations were determined from load-elongation curves recorded.

III. Results and Discussion

1. Resistivity Changes and Tensile Properties of 13Ni-15Co-10Mo-0.2Ti Maraging Steel

Figures 2 and 3 show resistivity change measured at liquid nitrogen temperature during isothermal aging and the log (time) derivatives of the resistivity changes respectively. Two peaks, P_L and P_H appear in Fig. 3. The peak, P_L which is apparent in the derivative curves in the range from 400° to 450°C moves toward shorter aging times as aging temperature is raised. The peak, P_H becomes evident in the derivative curves in the range from 475° to 575°C. Although the appearance of P_L is ambiguous in the derivative curves at 475° and 500°C, two stage precipitation is evident from the isothermal aging curves at both temperatures. After long times of aging in the range from 500° to 575°C, the gradual increase in resistivity becomes evident because of the formation

Fig. 2. Resistivity changes measured at liquid nitrogen temperature during isothermal aging of the 13Ni-15Co-10Mo-0.2Ti maraging steel.

Fig. 3. Curves for the log (time) derivatives of the isothermal resistivity curves shown in Fig. 2.

of the gamma-phase.^{2,3)}

The precipitation process in the maraging steel is considered to be similar to that in an Fe-Ni-Co-Mo quaternary maraging steel, as titanium contained is about 0.2%. According to our previous investigations⁴⁻⁷⁾ of the precipitation process in Fe-Ni-Co-Mo quaternary maraging steels, a precipitate formed in the first stage and that in the second stage are referred to phase-L and phase-H, respectively. We have revealed that the phase-H were directly precipitated from the quaternary solutions when aging temperature was raised.⁴⁻⁶⁾ In case of a 14Ni-15Co-5Mo quaternary maraging steel, two types of precipitates were found in isothermal agings at and below 500°C, and the direct precipitation of the phase-H from the solution was found in isothermal agings at 525°C and above. We have also revealed that the critical temperature beyond which the direct precipitation of the phase-H from solution took place was raised when nickel, cobalt or molybdenum content was increased.^{4,6)} Although the critical temperature of the present maraging steel has not yet been investigated thoroughly, it is estimated to be higher than 500°C from our previous investigations^{4,7)} and the present isothermal aging curve at 500°C, shown in Fig. 2.

Tensile properties of the maraging steel aged isothermally are shown in Figs. 4 to 9 as a function of aging time. Data shown in the figures are averages taken from three to seven tensile test results. Maximum aging time in each isothermal aging is determined so as not to exceed the time period for the resistivity increase due to the formation of the gamma-phase to begin.

As seen in Fig. 4, it is found that premature brittle failure takes place at a crosshead speed of 0.01 mm/min. As aging for 50~500 min at 450°C is within the first stage of the resistivity decrease, the phase-L is considered to be mainly precipitated. Specimens aged for 500~10 000 min fracture in a brittle manner at a crosshead speed of 1 mm/min; hence tensile strengths indicated appear not to be true but incidental because of premature brittle failure. As seen in the derivative curve at 450°C, the resistivity decrease with the progress of the second precipitation stage becomes evident after aging over about 2 000 min. Accordingly, the phase-H increases after aging over 2 000 min with the gradual decrease of the phase-L formed in the first stage.

As seen in Fig. 5, effect of crosshead speed on elongation is evident in specimens aged for 25~250 min. Specimens aged for 500~5 000 min fracture at small elongation, and the dependence of elongation on strain rate is ambiguous. However, premature brittle failure in the specimens aged for 1 000~5 000 min is more evident at 0.005 mm/min than at 1 mm/min. As seen in the resistivity curve for aging at 475°C, the resistivity decrease with the progress of the second precipitation stage becomes evident after aging for about 500 min or longer; therefore the phase-H is considerably increased after aging for 5 000 min.

Tensile properties of specimens aged at 500°C are shown in Fig. 6. Regarding the specimens aged for 10~1 000 min, no significant difference in elongation is observed between the crosshead speeds at 1 mm/min and 0.01 mm/min. However, the decrease in elonga-

tion is found when a crosshead speed is decreased to 0.005 mm/min. Overaging is observed after aging for 2 500 min. The strain rate sensitivity is also increased after aging for 2 500 min. In case of aging at 500°C, the resistivity decrease with the progress of the second precipitation stage becomes evident after aging for about 70 min or longer, and the resistivity increase due to the formation of the gamma-phase is observed after aging over 6 000 min. Accordingly, the phase-L is mainly precipitated after aging for 10~50 min and the formation of the phase-H progresses in aging for 100~2 500 min with the decrease of the phase-L. Peak strength appears in the progress of the second precipitation stage, and overaging is observed after aging for 2 500 min, where the resistivity decrease due to the second precipitation stage approaches ceasing.

Tensile properties after relatively short times of aging in the temperature range from 525° to 575°C are insensitive to strain rate, as seen in Figs. 7 to 9. However, the tensile properties of the specimens aged for periods of 250 min or longer are sensitive to strain rate. Since considerable amounts of molybdenum and cobalt are contained in the maraging steel, the phase-L is rapidly precipitated at 500°C, as seen in Figs. 2 and 3. As stated before, the critical temperature beyond which the phase-H is directly precipitated from the solution is estimated to be higher than

Fig. 4. Tensile properties of the 13Ni-15Co-10Mo-0.2Ti maraging steel aged at 450°C after solution-treatment for 1 hr at 1 075°C.

Fig. 5. Tensile properties of the 13Ni-15Co-10Mo-0.2Ti maraging steel aged at 475°C after solution-treatment for 1 hr at 1 075°C.

Fig. 6. Tensile properties of the 13Ni-15Co-10Mo-0.2Ti maraging steel aged at 500°C after solution-treatment for 1 hr at 1 075°C.

Fig. 7.
Tensile properties of the 13Ni-15Co-10Mo-0.2Ti maraging steel aged at 525°C after solution-treatment for 1 hr at 1 075°C.

Fig. 8.
Tensile properties of the 13Ni-15Co-10Mo-0.2Ti maraging steel aged at 550°C after solution-treatment for 1 hr at 1 075°C.

Fig. 9.
Tensile properties of the 13Ni-15Co-10Mo-0.2Ti maraging steel aged at 575°C after solution-treatment for 1 hr at 1 075°C.

500°C. Because the precipitation of the phase-L progresses until the specimens are heated to an aging temperature, both the phase-L and the phase-H are considered to be contained in the specimens after relatively short times of aging in the range from 525° to 575°C. Precipitates of the phase-L are considered to be decreased with the progress of the second precipitation stage.

The following features will be summarized from Figs. 4 to 9:

(1) Tensile properties after relatively short times of aging in the range from 450° to 500°C are sensitive to strain rate. For example, the tensile properties highly sensitive to strain rate are observed after aging for 50~500 min at 450°C, or 25~100 min at 475°C. As reported in the previous paper,¹⁾ the tensile properties of the 210 kg/mm² grade and the 245 kg/mm² grade maraging steel were also strain rate sensitive after relatively short times of aging at lower temperatures.

(2) Tensile properties of the overaged specimens are also sensitive to strain rate. This fact was impossible to be revealed in the previous investigation,¹⁾ as conspicuous overaging was not observed in aging conditions previously investigated. Typical examples are found in the tensile properties after aging for 2 500 min at 500°C, 250~1 000 min at 525°C, 250~500 min at 550°C, or 250 min at 575°C. As tensile properties are investigated on the specimens before the beginning of the resistivity increase due to the formation of the gamma-phase, overaging can be interpreted in terms of the growth of precipitates.

Uniform elongation at a crosshead speed of 1 mm/min can be measured except for the case of fracture without local elongation. Figure 10 shows uniform elongations of the specimens before overaging. Results for the specimens overaged in the range from 475° to 575°C are shown in Fig. 11.

As seen in Fig. 10, a uniform elongation at a given tensile strength level tends to increase with the decrease in aging temperature. It is well known that in most precipitation-hardening alloys, precipitates produced at lower temperatures and shorter time of aging are coherent with the matrix and small in size.⁸⁾ Further, cross-slipping in the maraging steel of a certain strength level becomes relatively difficult as

Fig. 10. Uniform elongation vs. tensile strength of the 13Ni-15Co-10Mo-0.2Ti maraging steel before overaging.

Fig. 11. Uniform elongation vs. tensile strength of the overaged 13Ni-15Co-10Mo-0.2Ti maraging steel.

coherent precipitates are increased by decreasing aging temperature.⁹⁻¹²⁾ The difficulty to cross-slip causes the increase in the uniform elongation, *i.e.*, the strain hardening exponent *n* in the form

$$\sigma_{tr} = K \epsilon_{tr}^n$$

where σ_{tr} and ϵ_{tr} are true stress and true strain, respectively. Many investigations⁸⁾ carried out on the plastic deformation of precipitation-hardening aluminium or copper alloys have also revealed that dislocations are possible to pass through small coherent precipitates and intense slip bands tend to be formed. Thus, it is concluded that intense and straight-like slip bands tend to be formed across grains during plastic deformation of the maraging steel containing coherent precipitates. Intense stress concentrations may also be produced in the regions where the intense and straight-like slip bands cross prior austenitic grain

boundaries or pass through a tension specimen. For example, investigations carried out on Fe-18Ni-2Al¹³⁾ and Fe-18Ni-5Si¹⁴⁾ maraging steels revealed metallographic evidences for intense stress concentrations produced at prior austenitic grain boundaries crossing the intense and straight-like slip bands.

As discussed in the previous paper,¹⁾ the ductility loss at a decreased strain rate may be explained in terms of the hydrogen embrittlement,¹⁵⁾ which is caused by the diffusion of hydrogen to the regions having relatively intense stress concentrations. However, it is also considered that intense stress concentrations produced during the course of straining the specimens strengthened to high strength level by coherent precipitates cause cleavage fracture without influence of the hydrogen embrittlement. Examples for the cleavage fracture are observed in the tensile properties of the specimens aged for 500~10 000 min at 450°C or 500~1 000 min at 475°C. Considering the dependence of cleavage strength upon grain size,¹⁶⁾ it is considered that the maraging steel of coarse austenitic grains is more prone to cleavage fracture than that of fine austenitic grains.

As seen in Fig. 11, the uniform elongation, *i.e.*, the strain hardening exponent, is increased with the progress of overaging. The increment of strain hardening must be attributed to the fact that dislocations moving in the matrix form very many loops around hard precipitates formed in overaging, and, in addition, the operation of a large number of slip systems leads to many dislocation intersections.⁸⁾ Photograph 1 shows examples of thin foil electron micrographs after aging for various times at 550°C. As the maraging steel contains considerable amounts of molybdenum and cobalt, the growth of precipitates

is more rapid in the maraging steel than in a 210 kg/mm² grade or a 245 kg/mm² grade maraging steel. Further, precipitates tend to be coarsened at prior austenitic grain boundaries. In the present investigation, we can not discuss in detail the sites where relatively intense stress concentrations are mainly formed during the course of straining the overaged specimens. However, it appears probable that stress concentrations tend to be formed at prior austenitic grain boundaries, and are relatively intense in case of the overaged specimens of a higher strength level. Thus, the ductility loss at a decreased strain rate may also be attributed to the hydrogen embrittlement, which is caused by the diffusion of hydrogen to the regions having intense stress concentrations. Crack propagation along the prior austenitic grain boundaries is considered to be relatively easy in the overaged specimens because of the presence of coarsened precipitates.

It may be concluded that the strain rate sensitivity in the tensile properties is decreased in the specimens having microstructures in which intense stress concentration is difficult to be produced during plastic deformation. As the decrease in the strain rate sensitivity is observed after relatively shorter time of aging in the range from 525° to 575°C, the greater part of precipitates contained in the specimens are considered to be partially coherent and finely dispersed.*

2. Tensile Properties of 13Ni-15Co-10Mo-0.2Ti Maraging Steel Aged after Marforming

Tensile properties after aging of the maraging steel cold rolled to 40% are shown in Figs. 12 to 14 as a function of aging time. For the tensile properties parallel to the rolling direction, elongations of the

Photo. 1. Transmission electron micrographs of the 13Ni-15Co-10Mo-0.2Ti maraging steel aged at 550°C for various times. ($\times 50\,000$) ($\times 4/5$)

* The strain rate sensitivity in tensile properties is essentially caused by the combined effect of intense stress concentrations produced during plastic deformation and the diffusion of hydrogen to the regions having intense stress concentrations. However, it is considered that not only the microstructure after aging but also the prior austenitic grain size influences the formation of stress concentration at the prior austenitic grain boundaries. The effect of prior austenitic grain size on the strain rate sensitivity will be described elsewhere.¹⁷⁾

specimens aged for 50~500 min at 500°C are decreased at a crosshead speed of 0.005 mm/min, as seen in Fig. 12. This fact is in agreement with the case for aging of the solution-treated specimens at 500°C (Fig. 6). However, the strain rate dependence of elongation parallel to the rolling direction is not observed after overaging at 500°C. The elongation is also insensitive to strain rate after aging at 525° or 550°C, as seen in Figs. 14 and 15. It must be noted that overaging of the specimens parallel to the rolling direction does not bring about the strain rate sensitivity in tensile properties, which is observed after overaging of the solution-treated specimens, as described in the preceding section.

In case of the specimens parallel to the transverse direction, tensile properties after aging at 500°C are sensitive to strain rate, as seen in Fig. 12. As the previous investigation¹⁾ done on the tensile properties parallel to the transverse direction was considered to be somewhat insufficient in specimens aged for 10~100 min at 525° or 550°C, the effect of crosshead speed on the elongation parallel to the transverse direction was re-examined. As seen in Figs. 13 and 14, it can be concluded that the decrease in elongation parallel to the transverse direction is not observed in straining the specimens aged for 10~100 min at 525° or 550°C at a crosshead speed of 0.005 mm/min. However, the tensile properties parallel to the transverse direction become very sensitive to strain rate after overaging.

As the present investigation is focused on the tensile properties after aging of the specimens cold rolled to 40%, the effect of the reduction in cold rolling on the tensile properties after aging is impossible to be extensively discussed. However, it is noteworthy that the strain rate sensitivity in tensile properties is not observed in the overaged specimens parallel to the rolling direction. The following will supply a main reason for the above fact. As prior austenitic grains in the specimens cold rolled to 40% are elongated to the rolling direction, crack prop-

agation along the prior austenitic grain boundaries may be relatively difficult in straining parallel to the rolling direction of the overaged specimens in which coarsened precipitates are present at the prior austenitic grain boundaries.

3. Tensile Properties of 14Ni-10Co-10Mo and 14Ni-15Co-7Mo Maraging Steels

Results for the 14Ni-10Co-10Mo maraging steel are shown in Figs. 15 to 17 as a function of aging time. Elongations of the specimens aged for relatively short times at 425° or 450°C are sensitive to strain rate. However, the tensile properties after aging for 100~2 500 min at 475°C are insensitive to strain rate.

Results for the 14Ni-15Co-7Mo maraging steel are shown in Figs. 18 and 19. For example, tensile properties after aging at 450°C are very sensitive to strain rate, and those insensitive to strain rate are obtainable after aging for 10 000 min (see Fig. 18). After aging at a given temperature, the 14Ni-15Co-7Mo maraging steel has a somewhat smaller peak strength than does the 14Ni-10Co-10Mo one. However, with regard to aging at a given temperature, the critical aging time beyond which the elongation becomes insensitive to strain rate is longer in the 14Ni-15Co-7Mo maraging steel than in the 14Ni-10Co-10Mo one. The embrittlement caused by decreasing a strain rate is attributable to the formation of the coherent precipitates. Resistivity changes measured at liquid nitrogen temperature during isothermal aging at 450° or 475°C are given in Fig. 20. Two stage precipitation also appears in the resistivity curves. The first precipitation stage of the 14Ni-15Co-7Mo maraging steel continues for long times of aging at a certain temperature in comparison with that of the 14Ni-10Co-10Mo maraging steel. As the coherent precipitates are formed during the progress of the first precipitation stage, it is naturally concluded that the 14Ni-15Co-7Mo maraging steel continues to precipitate the coherent precipitates at a certain aging temperature for longer times than does

Fig. 12.
Tensile properties of the 13Ni-15Co-10Mo-0.2Ti maraging steel aged at 500°C after cold rolling to 40%.

Fig. 13.
Tensile properties of the 13Ni-15Co-10Mo-0.2Ti maraging steel aged at 525°C after cold rolling to 40%.

Fig. 14.
Tensile properties of the 13Ni-15Co-10Mo-0.2Ti maraging steel aged at 550°C after cold rolling to 40%.

Fig. 15.
Tensile properties of the 14Ni-10Co-10Mo maraging steel aged at 425°C after solution-treatment for 30 min at 1 025°C.

Fig. 16.
Tensile properties of the 14Ni-10Co-10Mo maraging steel aged at 450°C after solution-treatment for 30 min at 1 025°C.

Fig. 17.
Tensile properties of the 14Ni-10Co-10Mo maraging steel aged at 475°C after solution-treatment for 30 min at 1 025°C.

Fig. 18.
Tensile properties of the 14Ni-15Co-7Mo maraging steel aged at 450°C after solution-treatment for 30 min at 1 025°C.

Fig. 19.
Tensile properties of the 14Ni-15Co-7Mo maraging steel aged at 475°C after solution-treatment for 30 min at 1 025°C.

Fig. 20.
Resistivity changes measured at liquid nitrogen temperature during isothermal aging of the 14Ni-10Co-10Mo maraging steel and the 14Ni-15Co-7Mo one.

the 14Ni-10Co-10Mo one. This fact suggests that the aging condition which leads to the embrittlement caused by the decrease in strain rate is connected with the precipitation of the phase-L. It has already been shown in our papers^{5,6)} that the aging condition for the precipitation of the phase-L is extended in the graphic form of aging temperature *vs.* time by the increase in nickel, cobalt or molybdenum content.

IV. Summary

(1) The two stage precipitation is found in the curves of resistivity changes, measured at liquid nitrogen temperature during isothermal aging of the 13Ni-15Co-10Mo-0.2Ti maraging steel. That is also found in the quaternary 14Ni-10Co-10Mo and 14Ni-15Co-7Mo maraging steels.

(2) The embrittlement caused by the decrease in strain rate is found in the 13Ni-15Co-10Mo-0.2Ti maraging steel containing fine and coherent precipitates. The ductility of the overaged maraging steel is also decreased at a lower strain rate. It is interpreted that the strain rate sensitivity in tensile properties is caused by the combined effect of intense stress concentrations produced during plastic deformation and hydrogen diffused to the regions having intense stress concentrations. The strain rate sensitivity is found to be decreased after aging for about

10~100 min in the range from 525° to 575°C.

(3) The uniform elongation increases rapidly with the progress of overaging. For the specimens before overaging, a uniform elongation at a certain strength level tends to decrease with the increase in aging temperature.

(4) For the tensile properties after overaging of the 13Ni-15Co-10Mo-0.2Ti maraging steel cold rolled to 40%, the decrease in ductility by the decrease in strain rate is not found in the specimens parallel to the rolling direction.

(5) The embrittlement at a lower strain rate is also found in the quaternary maraging steels containing coherent precipitates formed in the first stage. The 14Ni-15Co-7Mo maraging steel continues the first stage for longer times at a certain aging temperature than does the 14Ni-10Co-10Mo one.

Acknowledgements

The author wishes to express his sincere thanks to Messrs. K. Taguchi and M. Tsuchiya for their help in the experimental work.

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