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Strength and Toughness of a Cold Rolled

l3Ni-l5Co-lOMo Maraging Steel*

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Synopsis
A study was conducted to determine the effect of cold rolling prior to
aging on the strength and toughness of an ultrahigh strength 13Ni-l5Co-
l OMo maraging steel. The smooth tensile strength of cold rolled and
aged maraging steel increased continuously with increasing amount of cold
reduction. The cold rolled maraging steel exhibited anisotropy in prop-erties; the tensile strength in the transverse direction was higher than in the longitudinal direction, whereas the reduction of area and elongation showed lower values in the transverse direction. The notch tensile strength and plane strain fracture toughness KIC also increased with increasing amount of cold reduction, taking maximum value at the 60N70% reduc-tion. For example, longitudinal KIC value increased from 34 MPa.m112 for 0% reduction to 63 MPa. m112 for 70% reduction. The large amount of KIC increase was attributable to the formation of delaminations running parallel to the rolling plane. In the presence of delaminations, it is con-sidered that the KIC test specimen behaved as the sum of a number of thin plates and each thin plate fractured under the plane stress condition. Based on these results, it was concluded that the good combination of the strength and toughness could be obtained at the 60% cold reduction.

I. Introduction

Maraging steels represent one class of ultrahigh strength steels which attain their strength by precipi-tation hardening. They can be used for a variety of aerospace and other applications which require both good toughness and a high strength-to-weight ratio. So far, the development of maraging steels has been mainly concerned with the 18%Ni maraging grades and various steels with tensile strength up to 245 kgff mm2 (2 400 MN/m2) have been commercialized. The new grade 13%Ni maraging steel has higher strength level than the 18%Ni ones and has been the subject of much investigations in recent years.l-5> As is the case for the 18%Ni grades, the main alloying elements used in this new grade are nickel, cobalt and molyb-denum. However, the nickel content is distinctly lower, whereas the cobalt and molybdenum contents are remarkably higher. For this reason, the applica-tion of the solution treatment conventionally em-ployed in the 18%Ni grades results in a decrease in toughness due to the formation of large, undissolved

precipitates containing molybdenum.s-9) Solution treatment at higher temperatures leads to an improve-ment in toughness associated with the dissolution of large precipitates, but causes an accompanying reduc-

tion of ductility due to the coarsening of austenite

grains.3~ Grain refinement without any harmful pre-cipitates is therefore required. The present authors have attempted to refine the prior austeni.te grain size of this steel by applying the thermomechanical treat-ment and a ± Y cyclic heat treatment. It was found that the combinations of strength, toughness and duc-tility can be greatly improved by such treatments. The details of these investigations have been pub-lished in a series of papers.3-5,10,11)
Maraging steels are commonly used in the form of sheets. Therefore, it is necessary to investigate the strength and toughness of these steels which are subjected to various types of cold rolling.12-22) The

previous investigations have shown that the strength increase due to cold rolling is relatively small as com-

pared with those observed in conventional carbon and alloy steels. This poor strength increase is attributed to the fact that the maraging steel is essentially carbon free and thus the work hardening is very small.12'15,22,23) However, the cold rolling has proved to be attractive in providing substantial toughness improvements.
Because almost no data is available on the effect of

cold rolling on the strength and toughness of the thermomechanically treated 13 %Ni maraging steel, this investigation was aimed to determine these prop-erties.

II. Experimental Procedures

I. Materials and TThermomechanical Treatments

The 13 i Ni maraging steel used was 17.5 kg vac-uum induction melted heat, whose chemical com-

position is given in Table 1. The alloy was homo-genized at 1200°C for 24 h in an atmosphere of hydrogen, hot forged into plates and air cooled. After solution treatment at 1250°C for 1 h, these forged plates were then subjected to thermomechanical treatments to produce the plates of ultrafine austenite grain sizes. Four types of thermomechanical treat-ments were employed, as shown in Table 2, to ex-amine the effect of the prior austenite grain size on
mechanical properties. These had been already

Table 1. Chemical composition of alloy used. (wt%)

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proved to be adequate in providing the good com-bination of the strength and toughness.3-5)

2. Specimens and Testing Methods

Each thermomechanically treated plate was me-chanically ground to the selected thickness and then cold rolled to 1 mm thickness with the exception of the plate # 3 which was cold rolled to 5 mm thick-ness. Smooth tensile sheet specimens 5 mm width, notch tensile sheet specimens 7 mm width with V-notch 1 mm deep (K1= 3.5) were prepared from 1 mm-thick cold rolled sheet, whereas smooth tensile bar specimens 3.3 mm diameter with 16 mm gage length and subsize V-notch Charpy type specimens for fracture toughness measurements were taken from 5 mm-thick cold rolled sheet. These specimens were aged at 500°C for 4 h to produce peak strength. To eliminate any harmful effect of hydrogen on prop-erties, all the tensile test specimens were previously baked at 200°C for 24 h and were tested in an evac-

uated stainless chamber using a cross head speed of 2 mm/ mm. Fracture toughness measurements were conducted in accordance with ASTM specifications. Two specimens were used for each data point reported. Deformation texture was determined from the {l10} and {200} X-ray pole figures obtained by the Schultz technique using Fe-filtered Co radiation. Pole figure specimen 25 mm diameter was taken from the center of each cold rolled sheet with its surface parallel to the rolling plane.

III. Results and Discussion

1. Smooth and Notch Tensile Strength of Sheet Specimens

The results of the tensile tests of longitudinal (ten-sile axis parallel to the rolling direction) sheet speci-mens are shown in Figs. 1 and 2. Figure 1 shows the change of smooth tensile strength for reductions up to 86%. It is seen that the cold rolling of the thermo-mechanically treated steel prior to aging causes a significant improvement in its tensile strength, al-though the magnitude of strength increase is not large as compared with those observed in carbon-containing alloy steels. The aging treatment (500°C, 4 h) after rolling increases the tensile strength to about 1 350 MPa above the prior cold rolled strength, irrespective of the amount of cold reduction. It is also seen that

the tensile strength at an equivalent amount of cold reduction tends to exhibit higher value for the speci-

men which has smaller prior austenite grain size. Figure 2 shows the notch tensile strength in the cold rolled and aged condition. The notch tensile ratio (the ratio of notch tensile strength to smooth tensile strength) is also included in this figure. As can be seen, both notch tensile strength and notch tensile ratio are greatly increased, indicating that the cold rolling is effective in providing notch toughness im-

provement. However, these values take maximum at about 60% cold reduction and decrease rapidly with further increase in cold reduction. Similar re-

sults have been also reported by Kunitake and Okada for a cold rolled 18%Ni 400 grade maraging steel.24) Photograph 1 shows the fracture surface of notch tensile test specimen. Note that the fracture of each specimen was initiated from the lower mechanical notch of this photograph. For reductions up to 60%, shear-lips are observed at both sides and just beneath the notch root. The percentage of shear-lips as com-

pared with the total fracture surface, which is a qualitative indication of notch toughness, increases with increasing amount of cold reduction. These ob-servations agree well with the fact that the notch

Table 2. Rolling

ment.

conditions for thermomechanical treat-

Fig. 1. Effect of cold reduction on smooth tensile strength
of the 13Ni-15Co-IOMo maraging steel having dif-
ferent prior austenite grain size. Longitudinal sheet
tensile test specimens were used.

Fig. 2. Effect of cold reduction on notch tensile strength and notch tensile ratio of the 13Ni-l5Co-IOMo
maraging steel having different prior austenite grain
size. Longitudinal sheet notch tensile test speci-
mens were used.

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tensile strength can be improved in the reduction range up to 60%. On the contrary, the fracture sur-face of the 80% cold rolled specimen exhibits a quite different appearance. Delaminations which run par-allel to the rolling plane are observed over the whole area of the fracture surface. It is to be noted that delaminations are also seen on the fracture surface of

60% cold rolled specimen, although they are not re-markable. These delaminations were produced as a result of the splittings of the weakly bonded interfaces due to the presence of the triaxial stress ahead of the stressed notch or crack.25> It is not certain at this

time whether these delaminations were formed during loading or during fracturing. In either case, the fracture initiation load will not be changed by the formation of delaminations, because delaminations do not exist just beneath the mechanical notch but are formed in some distance away from it, as is typically shown in 60% cold rolled specimen. The area of the shear-lip beneath the notch for 80% cold rolled speci-men is obviously smaller as compared with that for the 60% cold rolled specimen. From this observa-tion, it can be considered that the intrinsic toughness was greatly degraded by cold reduction greater than 60% and this toughness degradation caused a sig-nificant decrease in notch tensile strength.

2. Smooth Tensile Strength of Bar Specimens

In order to investigate the mechanical anisotropy, tests were conducted on both longitudinal and trans-verse (tensile axis perpendicular to the rolling direc-

tion) specimens. Figure 3 shows the changes in smooth tensile strength, reduction of area, and elonga-tion for reductions up to 70%. Open and closed marks refer to the longitudinal and transverse values, respectively. It is seen that, as expected, there are appreciable differences in properties between longi-tudinal and transverse specimens; the tensile strength in the transverse direction is higher than in the longi-

Photo. 1.
Fracture surfaces for
tensile test specimens
of cold reduction.

longitudinal notch
of different amount

Fig. 3. Effect of cold reduction on tensile strength, reduc-tion of area and elongation of the 13Ni-15Co-IOMo
maraging steel. Longitudinal and transverse round
bar tensile test specimens were used.

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tudinal direction, whereas the reduction of area, and elongation exhibit lower values in the transverse direc-tion. As is the case for smooth sheet specimens, the tensile strength increases almost linearly with in-creasing amount of cold reduction in both as-rolled, and cold rolled and aged conditions. The reduction of area, and elongation tend to exhibit the overall decrease. However, note that the longitudinal reduc-tion of area increases slightly in the reduction range between 0 and 40%. Therefore, it can be said that the longitudinal ductility expressed in terms of reduc-tion of area is somewhat improved in the lower reduc-tion range.

3. Plane Strain Fracture Toughness Kic
The plane strain fracture toughness KIC in the cold rolled and aged condition was evaluated using three-point bending method. Schematic illustration of the specimen orientations with respect to rolling plane and rolling direction is inserted in Fig. 5. Testing conditions were all in accord with ASTM specifica-tions.26~ Therefore, the results obtained here can be regarded as valid KIC values.
Figure 4 shows the load-displacement curves for longitudinal KIC test specimens. Overall trend of load-displacement curves for transverse specimens was quite the same as Fig. 4. It is seen that the load at which unstable crack extension occurs increases as the

amount of cold reduction becomes large. For reduc-tions greater than 30%, load-displacement relation-ship deviates from linearity during loading and this deviation becomes more pronounced with increasing amount of cold reduction.
The KIC values calculated based on the results

shown in Fig. 4 are plotted by symbol in Fig. 5. As can be seen, both longitudinal and transverse Kic values increase rapidly with increasing amount of cold reduction. This increase is particularly larger in the longitudinal specimens. For example, longi-tudinal KIC value increases from 34 MPa2 m1"2 for 0% reduction to 63 MPa. m112 for 70% reduction (about two-fold increase).
As described previously, the notch toughness of cold rolled materials was greatly degraded in the higher reduction range. This observation strongly suggests that the KIC value may be decreased beyond the cold reduction of 70%. To verify this, KIC meas-urements were performed on the newly prepared heavily cold rolled specimens. The poor ability of the laboratory cold rolling mill made it impossible to prepare the 5 mm-thick specimens, so that the measurements were conducted on the 3 mm-thick

specimens. In addition, it was also difficult to pre-pare the fatigue-precrack in the aged condition. The specimen which was fatigue-precracked in the as-rolled, or in the solution-treated condition takes higher fracture toughness value than that where the fatigue-precrack was prepared in the aged condition.5~ How-ever, the testing conditions employed here were con-sidered to be sufficient to understand the general tendency of the changes in fracture toughness values. The results obtained in this manner are included in

Fig. 5 by symbol b. It is obvious that the KIC value actually decreases in the higher reduction range. The fracture surfaces of the KIC test specimens were examined by a scanning electron microscope to deter-mine whether cold rolling causes a change in the frac-ture mode. These results are shown in Photo. 2. The fracture mode for 0% reduction is characterized

by a mixture of dimple and cleavage fracture, whereas the dimple fracture is dominant for reductions greater than 50%. Note that delaminations can be clearly seen on the fracture surfaces of the 70% cold rolled

specimens.
These delaminations come to be seen as the amount of cold reduction is exceeded 30%. In the lower

reduction range, they appear as numerous tiny cracks whose orientations are randomly distributed. They become sharper with further increase in cold reduc-tion and are observed in the form of distinct straight lines for reductions greater than 60%. At an equiva-lent amount of cold reduction, delaminations in the longitudinal specimen appeared as more distinct straight lines than in the transverse specimen. As is clearly seen from the bottom two photographs of Photo. 2, delaminations are formed not only on the fracture surface but also on the fatigue-precrack sur-face. In addition, each delamination is continuously

Fig. 4. Schematic load-displacement curves for longitudinal
KIC test specimens of different amount of cold
reduction.

Fig. 5. Effect of cold reduction on KIC of the
IOMo maraging steel.

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connected in both surfaces.

Photograph 3 is the fracture appearance of the 70% cold rolled specimen at a lower magnification, and was taken to examine whether or not the delamination

spacing is constant over the whole area of the fracture surface. As can be seen, the delamination spacing in a region just ahead of the fatigue-precrack (about 0.1 mm wide) is considerably smaller as compared with the remaining portion of the fracture surface. In order to clarify when these narrowly distributed delaminations were formed, the following additional experiments were made. First, the K1 test specimens were unloaded at various stages in the load-displace-ment curve. These specimens were then fractured at a liquid nitrogen temperature; at this temperature delaminations disappeared and fracture surfaces show-ed flat appearance. From these experiments, it was found that the narrowly distributed delaminations were formed during loading where the load-displace-ment relationship exhibited the non-linear behavior of up to maximum load.
Figure 6 shows the relationship between the de-lamination spacing and the amount of cold reduc-

tion. Each data point in this figure was taken from a region just ahead of the fatigue-precrack. The delamination spacing decreases linearly with increas-ing amount of cold reduction for reductions greater than 50%. It is to be mentioned that there was no

Photo. 2.
Fracture surfaces for longitudinal (L) and trans-
verse (T) K1 test specimens of different amount
of cold reduction.

Photo. 3. Fracture surface for 70%
test specimen.

cold rolle d longitudinal Kic

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great difference in delamination spacing between longitudinal and transverse specimens at an equivalent amount of cold reduction.

Photograph 4 shows the cross sections perpendic-ular to the fracture surfaces of the KIC test specimens. It can be seen that the depth of a delamination in-creases with increasing amount of cold reduction. From the results shown in Fig. 6 and Photo. 4, it is obvious that the formation of delaminations has the

effect of dividing KIc test specimens into thin plates; the degree of this dividing effect and also the number of thin plates increase with increasing amount of cold reduction. Therefore, it may be said that the KIc value of a delaminated specimen correspond to that of a laminate made of a number of thin plates.
It is well known that the fracture toughness value is higher for a thinner specimen compared with a thicker one.27,28~ This is based on the fact that the fracture mode changes from plane strain to plane stress as the thickness of the plate is decreased. As is typically shown in Photo. 3, the fracture appearance of each thin plate exhibits the plane stress behavior, i.e., the tear-type fracture is observed in the middle and the shear-lips at the both sides. Therefore, it seems that the fracture mode of the delaminated speci-men corresponds to the plane stress condition and that the resultant fracture toughness value is much higher as compared with that in the plane strain condition.

As described previously, the notch toughness in-creases in the reduction range up to 60% and de-creases with further increase in cold reduction. This

intrinsic change in toughness and also the apparent fracture toughness improvement associated with plane stress behavior may be responsible for the observed

large increase in the K10 value.

4. Texture

Texture analysis for each of cold rolled specimens has revealed that there is a marked transition in the

shape of pole figures at about 60% cold reduction. Figure 7 shows, as typical examples, the {110} and {200}

pole figures taken from 40% and 80% cold rolled specimens. The 40% cold rolled specimen exhibits

Fig. 7. { 110} and {200} pole figures of the cold rolled 13Ni-15Co-IOMo maraging steel.

Fig. 6.
Relation between delamination spac-
ing and amount of cold reduction.

Photo. 4.
Profiles of cross sections perpendicular
to fracture surfaces (hatched area in
the figure below) for longitudinal KIc
test specimens of different amount of
cold reduction.

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the strong {1 11 } <1 12> textural component with minor components of {l 12} <1 10> and { 100} 011 >, whereas 80% cold reduction sharpens the { 100} (011 > and {l12}<110> components at the expense of the {l1l} < 112> component. Similar correlation has been also reported for the cold rolled 18%Ni maraging steel.21,29~ These observations clearly show that the crystallo-graphic texture is well related to the intrinsic tough-ness changes of the cold rolled materials. The in-trinsic toughness improvement for reductions up to 60% may be attributed to the development of the { 111} <112> component and the toughness degradation for reductions greater than 60% may be caused by the development of the { 100} X011 > and { 112} <1 10> com-ponents.
A marked anisotropy in mechanical properties that were observed in the present study may also be ac-counted for by the formation of the crystallographic texture.30-32) However, at this time, it is not pos-sible to discuss quantitatively the relationship between texture and anisotropy in properties. In order to clarify this, further texture analysis must be performed.

Iv. Conclusions

(1) The smooth tensile strength of cold rolled and aged 13Ni-15Co-IOMo maraging steel increases continuously with increasing amount of cold reduc-tion. The cold rolled maraging steel exhibits an-isotropy in properties; the tensile strength in the trans-verse direction is higher than in the longitudinal direc-tion, whereas the reduction of area and elongation shows lower values in the transverse direction. The

notch tensile strength and the plane strain fracture toughness K10 also increase with increasing amount of cold reduction, taking maximum values at the 6O' 70% cold reduction.

(2) Delaminations which are formed parallel to the rolling plane are observed on the fracture surfaces of both notch tensile test specimens and K10 test speci-
mens. I t is considered that the formation of de-

laminations might not have any direct effect on notch tensile strength, whereas these are mainly responsible for the observed large K10 increase. In the presence of delaminations, the K10 test specimen behaves as the sum of a number of thin plates and the fracture appearance of each thin plate exhibits plane stress behavior.

(3) There is a marked transition in the mode of the deformation texture at about 60% cold reduc-

tion. The { 111 } <112> textural component is domi-nant in the lower reduction range, whereas the { 112} <110> and { 100} <011> components are dominant in the higher reduction range.

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