Effect of Strain-Temperature History on the Flow and Fracture of Ingot Iron at Low Temperatures

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The effect of the strain-temperature history of ingot iron on the true stress-strain relationship for tensile specimens extended at temperatures ranging from $-196^\circ$ to $+100^\circ$C is reported. Specimens of ingot iron in various initial conditions were extended to a specified strain at a selected temperature and subsequently extended to fracture at a different temperature. The deviation of the true stress-strain values for the second stage of these tests from corresponding values for a single-stage test generally increase at a decreasing rate as the prestrain of the specimen increases.

The "rheotropic embrittlement" and work hardening (strain hardening plus strain aging) vary with the heat treatment and prestrain history of the ingot iron. The brittleness at or below $-78^\circ$C of normalized or hot-rolled ingot iron is partially curable by prestraining in tension at room temperature. However, prestraining in tension of annealed ingot iron at room temperature decreases the ductility retained at $-15^\circ$ and $-196^\circ$C. The predominance of strain aging at the higher temperatures and strain hardening at the lower temperatures causes the total work hardening of the specimen during deformation to maximum load to increase as the test temperature is either increased or decreased from about $-120^\circ$C.

1. Introduction

In recent years several investigations [1 to 11] on the mechanical properties of metals at low temperatures have shown conclusively that the true stress-strain relationship of metals and alloys extended in tension depends on the strain-temperature history, as well as on the instantaneous values of strain, strain rate, and test temperature. In most of these investigations very little information was reported on the part played by strain aging during the prior history of the specimen, as strain aging was not pronounced in most of the metals studied. A previous investigation [10] at the Bureau showed that strain aging affected the true stress-strain relationship of ingot iron specimens extended in tension at slightly elevated temperatures and even at some sub-zero temperatures ($-120^\circ$ to $+100^\circ$C). Within the temperature range, $-196^\circ$ to $+100^\circ$C, of that investigation the strain hardening of ingot iron increased with a decrease in temperature, whereas the strain aging decreased with a decrease in temperature. Therefore, work hardening of ingot iron may either increase or decrease with increase in testing temperature, depending upon the relative magnitude of the changes in strain hardening and strain aging with variation in temperature.

The rate of strain hardening of ingot iron is influenced by the mechanism of deformation. The spacing of the slip zones within the crystals and also the number of slip bands in a zone vary with the temperature of deformation of the metal. These factors are believed to be directly associated with the increase in the rate of strain hardening of the metal with decreas in testing temperature. Moreover, as previously reported [10], considerable deformation by twinning was observed in specimens of ingot iron slowly extended in tension at temperatures below about $-120^\circ$C. The extent of the twinning during the tension test increased greatly as the temperature was lowered from about $-120^\circ$ to $-196^\circ$C. The influence of this factor on the rate of strain hardening of the iron may be considerable.

The purpose of the present investigation was to obtain additional information on the influence of the strain-temperature history, and especially the effect of strain aging, on some of the tensile properties and the true stress-strain relationship for specimens of ingot iron subsequently tested in tension.

2. Material

The material used in this investigation was ingot iron in the conditions as annealed, hot-rolled, quenched and tempered, normalized, and cold-drawn. A detailed description of this material was reported in a previous paper [10]. The principal chemical constituents (in percent by weight) other than iron are as follows: Carbon, 0.02; manganese, 0.02; phosphorus, 0.005; sulfur, 0.018; silicon, 0.002; copper, 0.10; oxygen, 0.058; nitrogen, 0.002; and hydrogen, 0.0005. This iron was prepared from a single melt and was furnished by the manufacturer in the conditions as hot-rolled and as cold-drawn to 14- and 24-percent reductions of area. The heat treatments applied to the ingot iron in this laboratory are summarized in table 1.

Cylindrical tensile specimens with a 2-in. gage length were used. The reduced section was gradually tapered from each end; the diameter (0.438 in.) at the midsection of the gage length was about 0.003 in. less than at each end. The specimens were finished to the final dimensions by grinding and polishing in the axial direction. The ends of the specimen were machined with $1/4$ in. X 10 threads, and
the shoulder fillets were machined to a radius of 0.75 in.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Diameter of rod</th>
<th>Temp. of specimen</th>
<th>Time</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annealed</td>
<td>in</td>
<td>°F</td>
<td>hr</td>
<td></td>
</tr>
<tr>
<td>Normalized</td>
<td>0.875</td>
<td>1,750</td>
<td>1</td>
<td>Furnace-cooled to 800°F in 20 hr, then air-cooled.</td>
</tr>
<tr>
<td>Quenched and tempered</td>
<td>1.700</td>
<td>1</td>
<td>Quenched in iced brine.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.350</td>
<td>1</td>
<td>1/4</td>
<td>Furnace cooled to 100°F in 45 hr.</td>
</tr>
</tbody>
</table>

1 All specimens were prepared from hot-rolled rods.

2 Specimens machined to approximate 1/2 in. in diameter in reduced section and 3/4 in. in diameter in shoulders prior to heat treatment.

### 3. Method of Investigation

The specimens were extended in tension in a pendulum hydraulic testing machine of 50,000-lb capacity. The specimens, except those tested at room temperature, were fully immersed in an appropriate liquid maintained at the desired temperature. The loading was so controlled that the rate of reduction of area of the specimen, beyond the region of initial yielding, was maintained at approximately 1 percent/minute. Measurements of the diameter of the specimen throughout the course of each test were made by means of a specially designed reduction of area gage [12]. Changes in diameter of a specimen were measured by this instrument with an accuracy of ±0.0001 in. A detailed description of the testing equipment and the method of maintaining the desired temperature is given in previous papers [10, 12].

#### 4. Results and Discussion

True stress-strain data obtained in two-stage tension tests on ingot-iron specimens at selected temperatures ranging from −196 °C to +100 °C are summarized in figures 1 and 2, and 4 to 9. True stress-strain curves obtained in the single-stage tension tests, reported in a previous paper [10], are included in these graphs as broken-line curves, and the upper end of these curves represents initial fracture. The true stress-strain values representing the completion of the first stage and the data obtained in the second stage of the two-stage tension tests are shown. The data obtained in the first stage of the test conforms to the curve representing the corresponding deformation in a single-stage test and these values are, in most cases, not plotted in these graphs. The true stress-strain values during the unloading and the initial part of the reloading also are not shown in some of the figures. The true-stress and true-strain values attained at the fracture area of the specimen at the initiation of fracture are designated in this paper as the fracture stresses and fracture strains, respectively, and, except for certain specifically designated cases, they are represented by the final true stress-strain values plotted in figures 1 and 2, and 4 to 9.

#### 4.1. Annealed Ingot Iron

In order to determine the direct effect of a reduction of load in a tension test for a short time on the subsequent true stress-strain values, a special tension test was made at a single temperature (room temperature) on a specimen of annealed ingot iron. The deformation of this specimen was carried out in four stages and included an initial loading to a selected extension, an unloading to 200 lb for a period of 5 minutes, followed by a reloading to a second selected extension, then repeating the procedure until a total of four stages had been completed. As shown in figure 1, the true stress-strain values for this four-stage test generally coincided with those of a single-stage test made on a specimen of annealed ingot iron at room temperature, except for the true stresses at the initial strains of the second, third, and fourth stages; these true stresses were slightly higher than the corresponding stresses in a single-stage test. Apparently, the combined effect of the strain aging at room temperature during the 5-minute periods between stages and the unloading and reloading was sufficient to increase the true-stress values at the initial yielding in the last three stages but was not sufficient to affect appreciably the subsequent true-stress values. It is believed that, in general, short
interruptions of this type in a tension test with ingot iron at room or lower temperatures, in which the temperature of the specimen is held constant during the test, have very little effect on the true stress-strain values, except those during the initial yielding in the next stage of the test.

Four specimens of annealed ingot iron were extended in tension at room temperature to specified strains (indicated as short vertical bars on the 27°C curve in fig. 2), and subsequently extended to fracture at -196°C. As shown in figure 2, these specimens exhibited very little ductility in the second-stage test, although a specimen of annealed ingot iron that was extended in a single-stage test at -196°C deformed to a strain of about 0.05 before initial fracture. In the two tests, in which the deformation of the specimen in the first stage of the test at room temperature was greater than the maximum load strain, the specimens fractured in the second-stage test without any appreciable plastic deformation, and the fractures occurred at the shoulder of the necked section (fig. 3). The final true stress-strain values as determined by the final load and minimum cross-sectional-area measurements for these specimens are designated as points A and B in figure 2. As the fractures did not occur at the minimum cross section of the specimens, the stress values represented by points A and B are not fracture stresses; these data indicate only that the fracture stresses at -196°C for the position of the minimum section of the specimens of annealed ingot iron that were extended in tension at room temperature to these designated strain values were greater than the indicated stress values. The fracture stresses and fracture strains at -196°C of these specimens under the multiaxial stress conditions existing at the position of the actual fracture in the shoulder of the necked section are shown by the corresponding points A' and B' in figure 2. It may be noted that the fracture stresses at -196°C in the shoulder portion of the neck of the specimens are lowered to values below that of the tension specimen fractured at -196°C in uniaxial tension after extension at room temperature to maximum load. This may be attributed to the influence of biaxial compressive stresses at these positions.

As the ductility of specimens of annealed ingot iron in single stage tests at -196°C was small (strain of approximately 0.05), very little information could be obtained on the effect of prior strain at -196°C of specimens of annealed ingot iron on their tensile properties at room temperature. The data obtained on a specimen extended in the first stage of the test at -196°C to a strain of about 0.02 and then extended to fracture in the second-stage test at room temperature indicated that the total work hardening during the deformation at -196°C was approximately equivalent to the total work hardening of a specimen deformed the same amount at room temperature; the true stress-strain values obtained in the second stage of the test approximately coincided with the corresponding values ob-

**Figure 1.** True stress-strain values obtained with an annealed ingot-iron specimen that was extended in a four-stage tension test at room temperature.

**Figure 2.** True stress-strain values obtained with annealed ingot-iron specimens that were extended in two-stage tension tests at room temperature and -196°C.

**Figure 3.** Portions of two specimens of annealed ingot iron that were extended in tension at room temperature to strains beyond maximum load and subsequently fractured in tension at -196°C.

A. True strain of 0.62 at room temperature; B, true strain of 0.94 at room temperature.
tained in the single-stage test at room temperature (fig. 2). Thus the increase in the strain hardening at $-196^\circ$ C above that at room temperature was approximately equal to the strain aging at room temperature.

A specimen of annealed ingot iron was prestrained in tension at room temperature to maximum load and then extended to fracture at $-154^\circ$ C. This specimen retained considerably less ductility and hence had a lower fracture stress than a specimen extended to fracture in a single-stage test at $-154^\circ$ C, as shown in figure 4. The strain during the second stage of this test was very small in comparison with the strain beyond maximum load in the single-stage test at $-154^\circ$ C. The strain aging of the specimen during the deformation at room temperature apparently made the specimen quite brittle at the lower temperature.

In order to determine the specific influence of the degree of the pretraining of annealed ingot-iron specimens at one temperature on their deformation characteristics at another temperature, two series of two-stage tests were made. One series of specimens was pretrained in tension at room temperature to different strains and subsequently extended to fracture at $-78^\circ$ C. The true stress-strain data for these tests are summarized in figure 5. The true stress-strain curves for the second stage of these tests are above the corresponding portion of the curve for a single-stage test at $-78^\circ$ C. Another series of specimens was pretrained in tension at $-78^\circ$ C to different strains and subsequently extended to fracture at room temperature. The true stress-strain curves (fig. 5) for the second stage of each test, except for the specimen pretrained only to the lower yield, are below the corresponding portion of the curve for a single-stage test at room temperature. The curve for the second-stage test of the specimen pretrained to the lower yield coincided with the curve for the single-stage test at room temperature. The combined effect of the strain hardening and strain aging during the pretraining at $-78^\circ$ C in this test was equivalent to the combined effect of the strain hardening and strain aging during the deformation to the same strain at room temperature. In general, the deviation of the true stress-strain curve for the second stage of a two-stage test from the curve for a single-stage test at the same temperature (fig. 5) increases at a decreasing rate as the amount of pretraining in the first stage increases. The above data indicate that...
the strain aging of a specimen of annealed ingot iron at any strain during deformation in tension at a constant temperature varies with the strain; the strain aging at any strain depends greatly upon the amount of the prior strain aging of the specimen.

In order to determine the effect of maintaining a relatively high stress on the specimen between test stages, two special tests were made in which the load attained at the end of the first stage was maintained on the specimen until the beginning of the second stage. The true stress-strain values obtained in these tests (fig. 5) show no significant deviation from the true stress-strain curves of corresponding two-stage tests in which the load was reduced to about 200 lb between stages. The retained ductility at 

\[ -78^\circ C \]

of the specimen prestrained at room temperature to a strain of about 0.26 with no reduction of the load between stages was slightly greater than that of the specimen prestrained at room temperature to approximately the same amount, with the load reduced to 200 lb between stages. This small difference in ductility, however, is not believed to be significant. In general, the strains to fracture of the specimens in the two-stage tests summarized in figure 5 were approximately the same at both temperatures and also were about the same as those for the single-stage tests at these temperatures.

Ripling and Baldwin in reporting on the phenomenon they called the “rheotropic embrittlement” of steel [11] concluded that a large part of the deficiency in ductility of annealed steels at low temperatures is rheotropic and can be removed by prestraining under more ductile conditions at a higher temperature. The data obtained in the present investigation on annealed ingot iron, however, indicate that the low-temperature embrittlement of this material is not rheotropic in the manner proposed by Ripling and Baldwin; prestraining of the annealed ingot iron at room temperature reduced, rather than increased, the ductility retained either at 

\[ -154^\circ C \] or \[ -196^\circ C \]. The embrittlement due to strain aging during the prestraining of the specimens at room temperature, is believed to be the main cause for the loss in the retained ductility at 

\[ -154^\circ C \] or \[ -196^\circ C \]. Another factor that probably has considerable influence on the retained ductility is a decrease in the degree of deformation twinning occurring at the low temperature following a prestraining at room temperature. This latter factor is being studied in some detail and will be discussed in a separate report.

4.2. Normalized Ingot Iron

The true stress-strain data for two normalized ingot-iron specimens that were extended in tension in two-stage tests at room temperature and \[ -78^\circ C \] are presented in figure 6. The effect of the prestraining in the first stage of the tension test on the total work hardening of these specimens was similar to that already described for two-stage tests with annealed ingot iron at these temperatures. The ductility, however, was affected quite differently. As illustrated in figures 25 and 26 of the previous paper [10], the ductility of normalized ingot iron, and to a lesser degree that of hot-rolled ingot iron, extended to fracture in single-stage tests was much lower at 

\[ -78^\circ C \] than at room temperature. The strain to fracture of ingot iron in the annealed, quenched, and tempered, or cold-drawn conditions, however, was nearly the same at room temperature and at \[ -78^\circ C \]. The decrease in the ductility at \[ -78^\circ C \] of the ingot iron in the normalized or hot-rolled condition may be associated with a greater amount of carbon and nitrogen initially retained in solid solution in these conditions than in the other conditions. The data for the two-stage tests of the normalized ingot iron (fig. 6) show that the iron in this condition apparently is subject to rheotropic embrittlement in the manner proposed by Ripling and Baldwin; prestraining the specimen at room temperature to just beyond the maximum load increased greatly the ductility retained at \[ -78^\circ C \], as indicated by the fracture strain of approximately 1.1 for this two-stage test and the fracture strain of approximately 0.5 for the single-stage test at \[ -78^\circ C \]. Prestraining a specimen at 

\[ -78^\circ C \] to the maximum load decreased the ductility retained at room temperature. Apparently, the rheotropic embrittlement of the specimen during the prestraining at \[ -78^\circ C \] was not completely removed by the subsequent deformation at room temperature.

4.3. Quenched and Tempered Ingot Iron

The data obtained in two-stage tension tests with specimens of quenched and tempered ingot iron are summarized in figure 7. These results indicate that the effect of prestraining specimens at room temperature and \[ -78^\circ C \] is approximately the same as that described previously for specimens of the annealed ingot iron; the difference in magnitude of strain aging at \[ -78^\circ C \] and room temperature was greater than the difference in strain hardening at these tempera-
The points
INITIAL
FRAC TURE
-END

I
L

stage of the tests was not affected
ged in the second stage of the tests.
In aging resulted in a difference in
ductility retained in the specimens in the second
stage of the tests was not affected appreciably by the
difference in the prior strain histories.

4.4. Hot-Rolled Ingot Iron

As the ductility of the hot-rolled ingot iron was
considerable, even at low temperatures (fracture
strain of approximately 0.3 at −196°C), specimens
were pretrained in tension at temperatures ranging
from −196°C to +100°C and then extended to frac
ture at different temperatures. The true stress-
strain data for these tests and the curves obtained in
single-stage tests at these temperatures are summa-
rized in figure 8. Pretraining specimens approxi-
mately to maximum load at −196, −120, or
−78°C had little specific effect on the ductility
retained in the second stage of the tests at room
temperature. The deformation under ductile condi-
tions at room temperature apparently removed any
rheotropic embrittlement that may have occurred
during the pretraining at low temperature. As the
work hardening of a specimen of ingot iron during
def ormation at −196°C is mainly strain hardening,
and as strain hardening increases with decrease in
temperature from −78°C to −196°C, the data showing
equal work hardening of the hot-rolled ingot-iron
specimens during the pretraining at −78°C and
−196°C (fig. 8) indicate that strain aging occurred
to a considerable extent during the prestrain of the
specimen at −78°C. The work hardening during
the prestraining in tension at −120°C of a specimen
approximately to maximum load was the least for
this series of tests and resulted in the greatest lowering
of the points representing the true stress-strain
values for the second stage of the tests from the curve
for the single-stage test at room temperature. The
strain aging of hot-rolled ingot iron during deforma-
tion was very much less at −120°C than at −78°C.
However, as shown in figure 12 of a previous inves-
tigation [10], strain aging occurs to an appreciable
extent in specimens of hot-rolled ingot iron deformed
in tension at −120°C and at −138°C.

Although the total work hardening (mainly strain
hardening) of a specimen during prestraining ap-
proximately to maximum load at −196°C was about
equal to the total work hardening (strain hardening
plus strain aging) of a specimen deformed to the same
strain at −78°C, the resulting rheotropic properties
of these two specimens were different. The points
representing the true stress-strain values for the
second-stage test at −78°C of the specimen pre-
strained at −196°C gradually rise above the corre-
sponding portion of the curve for the specimen ex-
tended in the single-stage test at −78°C (fig. 8).
These data indicate that the strain aging during the
deformation from maximum load to fracture of the
former specimen was much greater than that of the
latter specimen. As the fracture strains of the above
specimens were about equal, the deformation during
the second-stage test at −78°C apparently removed
most of the low-temperature embrittlement that had
occurred during the prestraining at −196°C.

The specimen of hot-rolled ingot iron that was pre-
strained in tension at room temperature to a small
strain of approximately 0.03, broke in the threads
during the second-stage test at −196°C without any
appreciable plastic deformation of the specimen.
The final value plotted in figure 8 for this test does not represent the fracture stress and fracture strain at \(-196^\circ\text{C}\) of the prestrained metal. As the yield stress of this specimen at \(-196^\circ\text{C}\) was at least equal to or greater than that represented by the final plotted value, and as this point lies approximately on the true stress-strain curve for the single-stage tension test on hot-rolled ingot iron at \(-196^\circ\text{C}\), the prestraining of the specimen at room temperature, apparently did not decrease the stress necessary for continued deformation of the metal at \(-196^\circ\text{C}\).

Specimens of hot-rolled ingot iron that were prestrained in tension at room temperature approximately to maximum load and then extended to fracture at \(-78^\circ, -120^\circ,\) and \(-196^\circ\text{C}\), exhibited strain-aging effects similar to those described above for the specimens pretrained at low temperatures. However, a difference was observed in the effect of the prestraining at room temperature on the ductility retained at lower temperatures, and this should be pointed out. Prestraining at room temperature approximately to the maximum load improved the ductility retained by the specimen at the lower temperature and the fracture strains of the specimens in the two-stage tests were greater than those of the specimens fractured in the single-stage tests at the same low temperatures (fig. 8). Thus, the rheotropic embrittlement of the hot-rolled ingot iron during the second stage of these tests was reduced by the prestraining under the more ductile conditions at room temperature.

A specimen of hot-rolled ingot iron was pretrained in tension at \(100^\circ\text{C}\) to a strain slightly beyond the maximum load and then extended to fracture at \(-78^\circ\text{C}\). The strain aging of this specimen during the deformation at \(100^\circ\text{C}\) was much greater than that of specimens deformed at room temperature, and is indicated by the position of the true stress-strain values in figure 8 for the second stage of the test; the elevation of these points above the curve for the single-stage test at \(-78^\circ\text{C}\) is much greater than that for the specimen pretrained at room temperature. The fracture strain of the specimen pretrained at \(100^\circ\text{C}\) was about equal to that of the specimen extended to fracture in a single-stage test at \(-78^\circ\text{C}\). However, it was considerably less than that of the specimen pretrained at room temperature and extended to fracture at \(-78^\circ\text{C}\). The embrittlement of the specimen by the great amount of strain aging during the deformation at \(100^\circ\text{C}\) apparently was about equal to the rheotropic embrittlement during the deformation of a specimen to the same strain in the single-stage test at \(-78^\circ\text{C}\).

The true stress-strain data for hot-rolled ingot iron specimens (fig. 8) indicate that the strain hardening is the predominating factor affecting the variation of the total work hardening with temperature at temperatures below \(-120^\circ\text{C}\), whereas the strain aging is the predominating factor affecting the total work hardening at temperatures above \(-120^\circ\text{C}\).

As described earlier, the ductility of specimens of normalized ingot iron was much less at \(-78^\circ\text{C}\) and at lower temperatures than at room temperature, and prestraining of a specimen at room temperature greatly improved the ductility retained at \(-78^\circ\text{C}\). The ductility of the annealed ingot iron specimens was less at \(-154^\circ\text{C}\) and \(-196^\circ\text{C}\) than at room temperature. However, prestraining specimens of annealed ingot iron at room temperature reduced the ductility retained at \(-154^\circ\text{C}\) and \(-196^\circ\text{C}\). Moreover, the ductility of specimens of ingot iron in the condition either as annealed, or as quenched and tempered, was about the same at \(-78^\circ\text{C}\) as at room temperature and prestraining specimens at room temperature had little, if any, effect on the ductility retained at \(-78^\circ\text{C}\). The effect of prestraining of ingot iron at room temperature on the rheotropic embrittlement of the specimens at lower temperatures apparently depends greatly upon the initial condition of the iron.

4.5. Cold-Drawn Ingot Iron

The true stress-strain data obtained in two-stage tension tests with specimens of cold-drawn ingot iron are summarized in figure 9. These samples of the originally hot-rolled ingot iron had been cold-drawn by the manufacturer to 14- and 24-percent reduction of area, and were aged at room temperature for several months. The total work hardening during the prestraining in tension at room temperature to a strain of approximately 0.25 of a specimen of ingot iron cold-drawn to 14 percent reduction of area was slightly greater than that of a specimen deformed to the same strain at \(-78^\circ\text{C}\). The total work harden-
ing during the prestraining in tension to a strain of approximately 0.25 at room temperature and at 
−78°C of specimens of ingot iron cold-drawn to 
24-percent reduction of area was approximately the same as indicated by the coincidence of the true 
stress-strain values for the second stage of these 
tests with the true stress-strain curves for the single-
stage tests. The degree of strain aging during the 
deformation in tension of these specimens of the 
cold-drawn iron was much less than that of the hot-
rolled ingot-iron specimens due to the prior strain 
aging that had occurred during the cold-drawing and 
storage of the iron.

5. Summary

A study was made to determine the effect of the 
strain-temperature history of ingot iron on the true 
stress-strain relationship for specimens extended in 
tension at temperatures ranging from −196°C to 
+100°C. Specimens of annealed, normalized, 
quenched and tempered, hot-rolled and cold-drawn 
ingot iron were extended in tension to specified true-
strain values at a selected temperature and subse-
quently extended to fracture at a different temperature. The true stress-strain values obtained in 
these two-stage tests were compared with those 
obtained in single-stage tension tests at the same 
temperatures. The deviation of the true stress-
strain curves for the second stage of these tension 
tests with ingot iron from the true stress-strain curve 
for a single-stage test at the same temperature 
generally increases at a decreasing rate as the prestrain 
of the specimen is increased.

The amount of strain aging and the rheotropic 
brittleness of specimens of ingot iron vary with the 
heat treatment and prestrain history of the speci-
mens. The rheotropic brittleness at −78°C or at 
lower temperatures of normalized or hot-rolled ingot 
iron is sensitive to and in part curable by prestrain 
deter under ductile conditions at higher temperatures; the 
ductility retained by the specimens in subsequent 
extension in tension at low temperature is increased. 
However, prestraining specimens of annealed ingot 
iron in tension under ductile conditions at room 
temperature decreases the ductility retained in sub-
sequent extension in tension at −154° or −196°C.

The work hardening of ingot iron during deforma-
tion in tension at temperatures below −120°C is 
mainly strain hardening, and increases with lowering 
of the testing temperature. As the temperature is 
increased above −120°C, the influence of the strain 
aging during the deformation in increasing the total 
work-hardening rate becomes the predominating 
factor, and the rate of work hardening increases with 
increase in testing temperature. The data obtained 
on the tension specimens of hot-rolled ingot iron 
indicate that the part of the total work hardening 
due solely to the strain aging during the deformation 
to maximum load is considerable at temperatures 
as low as −78°C. Even at −78°C the work harden-
ing due to the strain aging is approximately equal to 
the increase in strain hardening that occurs as the 
testing temperature is lowered from −78°C to −196°C. 
At +100°C, the magnitude of the strain aging is 
least equal to or greater than the strain hardening.

The data presented in this paper, together with 
those reported previously [10], show that the strain 
aging of ingot iron is a very important factor affecting 
the true stress-strain relationship at temperatures 
as low as −120°C. Strain aging apparently occurs 
to some extent at temperatures as low as −154°C. 
These data are contrary to the generally prevailing 
belief that the strain aging of ingot iron is insig-
nificant at sub-zero temperatures.

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