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Report

on

# EFFECT OF PREVIOUS DEFORMATION ON THE CREEP CHARACTERISTICS OF GRADE B CARBON STEEL AT 600, 850 AND 1000°F.


by

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EFFECT OF PREVIOUS DEFORMATION
on
THE CREEP CHARACTERISTICS OF GRADE B CARBON STEEL
at
600, 850 AND 1000°F.

As a result of the large number of creep tests which have already been conducted by the authors on various types of materials over a rather large temperature range, and from purely theoretical considerations, they feel that the factors which may influence the actual or the observed creep characteristics of metallic materials may be listed as follows:

Chemical Composition

Heat-Treatment

Recrystallization Temperature

Grain Size

Method of Manufacture { Melting Practice, Casting Practice, Fabrication }

Testing Procedure

Previous Deformation

Many of these factors are overlapping and it is difficult to consider one without one or more of the others. Especially is this true of recrystallization temperature and chemical composition, and to a somewhat lesser extent, of grain size and heat-treatment, or of method of manufacture, heat-treatment, and previous deformation.

In previous reports, the authors have considered in detail the effect of recrystallization temperature and grain size on the resulting creep characteristics of a series of non-ferrous alloys, and a paper on this subject is being presented before the June 1932 meeting of the American Society for Testing Materials.

Very little is available in the literature as to the effect of the various other factors, with the possible exception of chemical composition, and it is for this purpose that a series of investigations are being undertaken to throw additional light on these various factors.

The work herein reported concerns the effects of previous deformation on the resulting creep characteristics and, insofar as the authors are aware, it is the first information which is available on this question. In addition to the creep tests, the hardness, the metallographic structure and the x-ray patterns of the materials have been determined both before and after the creep tests. The results obtained are presented in the following sections.

## SUMMARY OF CONCLUSIONS

The results obtained from creep tests conducted at 600, 850 and 1000°F. on specimens of Grade B steel in the "as received" condition and after having been deformed 6 and 12 per cent, show the material in the "as received" condition to possess the maximum creep resistance at each of the temperatures considered.

Hardness tests and a metallographic and x-ray examination was conducted on each of the specimens, both before and after the creep tests in an attempt to determine an explanation for the observed results. The results of these tests, as well as of the creep tests, are summarized in Table I.

The differences in the creep characteristics at 600°F. are observed to be very slight, but the magnitude of the differences increases as the temperature is increased. No differences could be observed in the metallographic structures even though the examinations were made at 1000 diameters.

Neither did the hardness values show any decided differences other than a slight increase at 600°F. followed by a gradual softening as the temperature was increased. A marked difference was obtained, however, by the x-ray study.

Table I

Effect of Previous Deformations of 6 and 12 Per Cent
on
The Creep Resistance, the Hardness, and the Metallographic and X-ray Structures
of
Grade B Steel at 600, 850 and 1000°F.

| Treatment | Temp. of Test Deg. Fahr. | Stress, 1000 Lb./Sq.In. | Creep Characteristics: Total Deformation | Creep Characteristics: Rate, % per 1000 Hrs. | Rockwell B Hardness: Shoulder | Rockwell B Hardness: Center | Rockwell B Hardness: Shoulder | Structure: Metallographic | Structure: X-ray |
|---|---|---|---|---|---|---|---|---|---|
| As Received | | | | | | 84.0 | | Unstrained | 0* |
| 6% Deformed | | | | | | 86.1 | | No visible strain | 1 |
| 12% Deformed | | | | | | 87.3 | | No visible strain | 1 |
| As Received | 600 | 24,200 | .001538 | 0.013 | 82.5 | 87.0 | 80.0 | Unstrained | 0 |
| 6% Deformed | 600 | 24,200 | .001476 | 0.018 | 86.5 | 91.2 | 82.0 | No visible strain | 1- |
| 12 Deformed | 600 | 24,200 | .001550 | 0.020 | 86.7 | 94.1 | 85.0 | No visible strain | 1- |
| As Received | 850 | 19,055 | .002450 | 0.100 | 79.0 | 80.3 | 78.0 | Unstrained | 0 |
| 6% Deformed | 850 | 19,055 | .004130 | 0.198 | 81.3 | 87.3 | 78.0 | No visible strain | 0= |
| 12% Deformed | 850 | 19,055 | .005040 | 0.295 | 86.3 | 90.7 | 80.3 | No visible strain | 0= |
| As Received | 1000 | 5,000 | .000980 | 0.152 | 78.3 | 75.5 | 72.3 | Unstrained | 0 |
| 6 Deformed | 1000 | 5,000 | .002600 | 0.374 | 79.3 | 82.5 | 74.6 | No visible strain | 0 |
| 12% Deformed | 1000 | 5,000 | .005530 | 0.323 | 79.3 | [illegible] | 76.3 | No visible strain | 0 |

* 0 Unstrained
1 Strained
1- Slightly strained
1= Very slightly strained

The x-ray pattern of the material in the "as received" condition showed the structure to be free from strain, and also that no marked changes were produced in the structure by the creep tests. The deformed specimens, on the other hand, were observed to possess a strained structure in the "as deformed" condition and this structure was found to be unstable at all of the temperatures used in the creep tests.

On the basis of these findings, it is, therefore, believed that the observed differences in creep characteristics are due to the "as received" material having a more stable structure at the temperatures employed in the creep tests than has the deformed specimens. An unstable structure implies that the crystals are in a greater state of mobility and will, therefore, deform more readily under an applied stress than if they were less mobile.

## PROCEDURE

The material chosen for this investigation was the ordinary commercial grade of Grade B steel. It was obtained by The Detroit Edison Company from the National Tube Company in the form of a seamless tube with a wall thickness of 3/4 inches.

The chemical composition of this material is given in Table II.

Table II

Chemical Composition of Grade B Seamless Steel Pipe

| Designation | Chemical Composition, Per Cent | | | | |
|---|---|---|---|---|---|
| | Carbon | Manganese | Silicon | Sulphur | Phosphorus |
| Grade B | 0.408 | 0.917 | 0.21 | 0.031 | 0.014 |

The tensile properties at room temperature were as follows:

Table III

Tensile Properties at 80°F. of Grade B Seamless Steel Pipe

| Designation | Tensile Strength Lb/Sq.In. | Yield Point Lb/Sq.In. | Prop. Limit Lb/Sq.In. | Elongation % in 2 In. | Reduction of Area--% |
|---|---|---|---|---|---|
| Specified | 62,000 | 35,000 | | 25.0 | |
| As Received | 90,300 | 43,000 | 30,000 | 28.0 | 46.4 |

The material was subjected to creep tests at 600, 850 and 1000°F. in the "as received" condition and after having been plastically deformed 6 and 12 per cent at room temperature previous to the actual creep test. The deformation was accomplished on machined, standard 0.505 inch diameter test specimens and the deformation referred to, that is, 6 and 12 per cent, was that which was obtained over the two-inch gage section of the test piece. In other words, the deformation refers to the increase in length of the test piece rather than to its reduction in area.

All the specimens were subjected to metallographic and x-ray examination, both before and after the creep tests at the various temperatures. The x-ray method of examination was used as this is more sensitive than the metallographic test in detecting the presence of strains within a metallic material. All the examinations were conducted on longitudinal specimens.

Hardness values were also taken in all cases to determine whether or not the creep test produced any change in the hardness of the original specimens.

In the creep tests at the various temperatures, only one load was used in each case and this load was so selected that a definite rate of creep would be obtained. The use of a single load does not make possible the determination of the complete creep characteristics at any given temperature, but it was believed that this method would clearly bring out any differences in creep characteristics which might exist due to the amount of previous deformation which the specimen had undergone.

## RESULTS

The results of the creep tests, the hardness tests, and the metallographic and x-ray examination are given in the following sections.

### Creep Tests.

As stated previously creep tests were conducted at 600, 850 and 1000°F. on Grade B steel in the "as received" condition and after having been previously deformed 6 and 12 per cent at room temperatures.

Tests at 600°F. The creep tests at 600°F. were conducted on each of the three specimens under a stress of 24,200 pounds per square inch and the tests were continued for 570 hours. The results which were obtained are given in Figure 1.

From the figure it is evident that all three specimens underwent the same elastic deformation upon the application of the load, but thereafter the amount of deformation obtained varied. The specimen in the "as received" condition suffered the least amount of total deformation, while that deformed 12 per cent possessed the greatest. The differences were not great, for that of the "as received" specimen was 0.001338 inches per inch, that of the specimen deformed 6 per cent was 0.001476 and that of the specimen deformed 12 per cent was 0.001550.

As for the average rate of creep obtained for the different specimens during the latter part of the test, it will be observed from the figure that while the "as received" specimen was creeping at a rate of 0.013 per cent per 1000 hours, the corresponding values for the specimens deformed 6 and 12 per cent, were 0.018 and 0.020 per cent respectively. Again, the differences between the three specimens is not very great, but the "as received" specimen does possess the maximum creep resistance, and the specimen with the greater amount of previous deformation, the lowest.

On the basis of the results at this temperature, it may be said that previous deformation decreases to a slight extent the ability of this steel to resist creep, at least when stressed to a load of 24,200 pounds per square inch.

Tests at 850°F. The creep tests at 850°F. were conducted on each of the three specimens under a stress of 19,055 pounds per square inch and the tests were continued for periods from 583 hours to 683 hours. The results which were obtained are given in Figure 2.

As was the case at 600°F., all three specimens underwent practically the same elastic deformation upon the application of the load, but thereafter the "as received" specimen suffered the least, and the more severely deformed specimen the greatest, elastic plus plastic deformation. The differences between the three specimens is much more marked at this temperature than was true at the temperature previously considered. For example, the total elastic plus plastic deformations suffered by the "as received" and the specimens deformed 6 and 12 per cent were, at the end of 550 hours, 0.002450, 0.004130 and 0.005040 inches per inch respectively.

Also, if the average rate of creep occurring during the latter portion of the test be considered, it will be found that while, in the case of the "as received" specimen, the rate of creep was 0.10 per cent per 1000 hours, the corresponding values for the 6 and 12 per cent deformed specimens were 0.198 and 0.295 per cent per 1000 hours.

On the basis of the results at this temperature, it may, therefore, again be said that previous deformation decreases to a rather marked extent the ability of this steel to resist creep, at least when the stress considered is 19,055 pounds per square inch.

Tests at 1000°F. The creep tests at 1000°F. were conducted on each of the three specimens under a stress of 5,000 pounds per square inch and the tests were continued for periods varying from 525 hours to 670 hours. The results which were obtained are given in Figure 3.

As was true at the two temperatures previously considered, the "as received" material undergoes the least amount of elastic plus plastic deformation, while the more severely deformed specimen suffers the greatest amount. For example, the respective amounts of elastic plus plastic deformation obtained during 525 hours with the "as received" and the 6 and 12 per cent deformed specimens were respectively 0.000980, 0.002600 and 0.003330 inches per inch respectively.

If the average rate of creep occurring during the latter portions of these tests be considered, a somewhat different condition will be found to exist than was true at the previously considered temperatures. In the other cases, the rate of creep increased with increasing amounts of previous deformation. At this temperature, however, 1000°F., it is found that while the "as received" material still possesses the lowest rate of creep, the maximum is possessed not by the specimen deformed 12 per cent, but by that deformed 6 per cent. The three rates of creep obtained are 0.132, 0.374, and 0.323 per cent per 1000 hours.

The curve representing the results obtained on the specimen deformed 12 per cent, however, is rather irregular and there are certain portions which show a much higher creep rate than the average which is reported. The irregularities in the curve are not felt to be due to experimental defects, but rather to marked recrystallization which is without doubt occurring within the specimen. This point will be considered later in the report.

Hardness Tests.

The hardness of each specimen was determined both before and after the creep tests at the various temperatures. The Rockwell machine was used, and in the case of the completed creep test specimens, readings were taken both on the shoulders and over the gage section. The results obtained are given in Table IV.

It will be observed that, in the case of specimens before being subjected to the creep tests, the deformations employed results in only a very slight increase in the hardness. For example, the material in the "as received" condition possessed a Rockwell "B" hardness of 84, while the hardness values of the specimens deformed 6 and 12 per cent were only 86.1 and 87.3 respectively.

The creep test at 600°F. under a stress of 24,200 pounds per square inch resulted in a slight increase in hardness in the gage section of each of the specimens. This condition is commonly observed when cold worked materials are slightly heated and is believed to be due to an age-hardening effect. Again, at this temperature, the previously deformed specimens are slightly harder than the "as received" one.

Table IV

Effect of Previous Deformation and Creep Tests
at Indicated Temperatures
on
The Hardness of Grade B Steel

| Condition | Temp. of Creep Test Deg.Fahr. | Time of Creep Test Hours | Rockwell "B" Hardness* 1/16" Ball, 100 Kg.Load Shoulder | Gage | Shoulder |
|---|---|---|---|---|---|
| As Received | | | | 84.0 | |
| 6% Deformed | | | | 86.1 | |
| 12% Deformed | | | | 87.3 | |
| As Received | 600 | 570 | 82.5 | 87.0 | 80.0 |
| 6% Deformed | 600 | 570 | 86.3 | 91.2 | 82.0 |
| 12% Deformed | 600 | 570 | 86.7 | 94.1 | 85.0 |
| As Received | 850 | 673 | 79.0 | 80.3 | 79.0 |
| 6% Deformed | 850 | 583 | 81.3 | 87.3 | 78.0 |
| 12% Deformed | 850 | 683 | 86.3 | 90.7 | 80.3 |
| As Received | 1000 | 575 | 78.3 | 75.5 | 72.3 |
| 6% Deformed | 1000 | 525 | 78.3 | 82.5 | 74.6 |
| 12% Deformed | 1000 | 670 | 78.3 | 82.3 | 76.3 |

*Values are the average of at least five readings.

The creep test at 850°F. resulted in a slight softening of the specimens, as compared to the values obtained at 600°F., but the hardness values of the previously deformed specimen are still somewhat higher than what they were before being subjected to the creep test. In no case, however, is the observed change very marked.

The creep test at 1000°F. has resulted in a further influencing of each of the specimens and all of the values are now lower than what they were before the creep test. Even though these tests were conducted for 525 hours or more, the hardness values of the previously deformed specimens are still higher than that of the material in the "as received" condition. Both of the deformed specimens, however, possess the same hardness.

## Metallographic Examination.

The metallographic structures of each of the three specimens were examined both before and after the creep tests at the various temperatures. The results obtained are shown in Photomicrographs 1 through 12. In order to be better able to detect any structural changes, the examinations were made at a magnification of 1000 diameters.

Photomicrographs 1 to 3 inclusive show the structure of the steel in the "as received" condition and after having been deformed 6 and 12 per cent. Even at the magnification used no appreciable strain hardening is detectable even in the specimen deformed the greatest amount. It does appear, however, that the pearlite in the deformed specimens is somewhat more distinctly laminated than what it is in the "as received" condition.

Photomicrographs 4 to 6 show the corresponding structures after the specimens had been subjected to creep tests at 600°F. for 570 hours. No visible structural changes have occurred during the creep tests at this temperature.

Photomicrographs 7 to 9 show the structures after the specimens had been subjected to creep tests at 850°F. for periods ranging from 583 to 683 hours. Again, no visible structure change has occurred.

Photomicrographs 10 to 12 show the structures after the specimen had been subjected to creep tests at 1000°F. for periods ranging from 525 to 670 hours. After this test, the pearlite of the steel in the "as received" condition seems to be somewhat less distinctly laminated than was true after the previous tests, but the deformed specimens still possess a distinctly laminated structure.

Considering these photomicrographs as a whole it may be said that no marked structural changes were produced, either by the deformations of 6 and 12 per cent at room temperature, or by the creep tests to which they were afterwards subjected.

It is felt that this should not be taken to mean, however, that no changes are actually occurring, for certain may be taking place which are of such a type, or of such order of magnitude, that the metallographic examination is not able to detect them.

X-ray Examination.

In order to determine whether or not changes were actually taking place that could not be detected by metallographic means, specimens of the steel in the "as received" condition and after having been deformed 6 and 12 per cent were subjected to x-ray examination, both before and after the creep tests, at the various temperatures. The x-ray method of examination is much more sensitive than the metallographic one, and if any changes do occur, they should be able to be detected by x-ray examination even though they are very slight. The results obtained are shown in Figures 4 and 5.

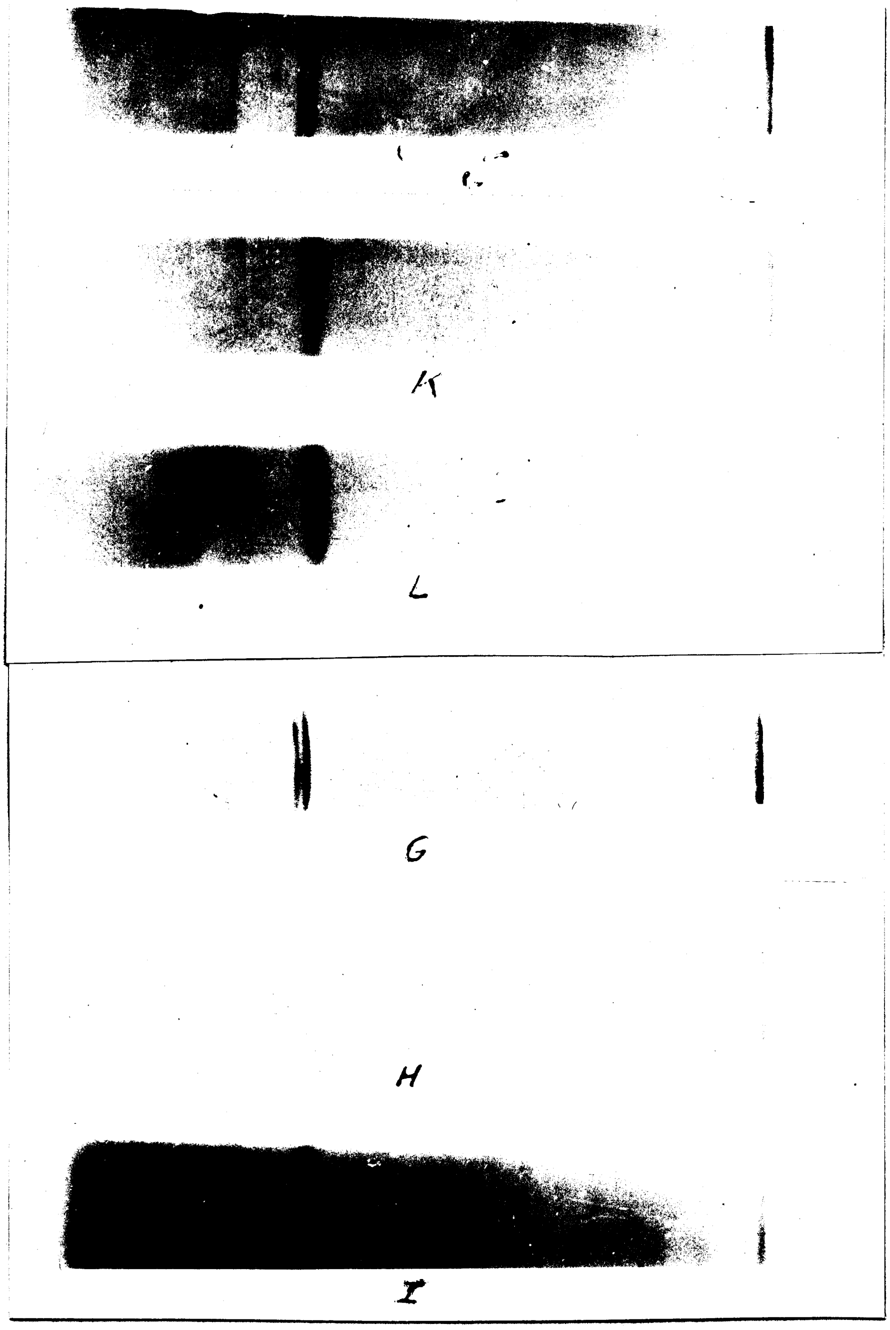


Figure 4

X-Ray Patterns of Grade B Steel
Before and After Creep Tests at 600°F.

J = "As Received"
K = Deformed 6%
L = Deformed 12%
G = "As Received" Creep Test at 600°F.
H = 6% Deformed, Creep Test at 600°F.
I = 12% Deformed, Creep Test at 600°F.

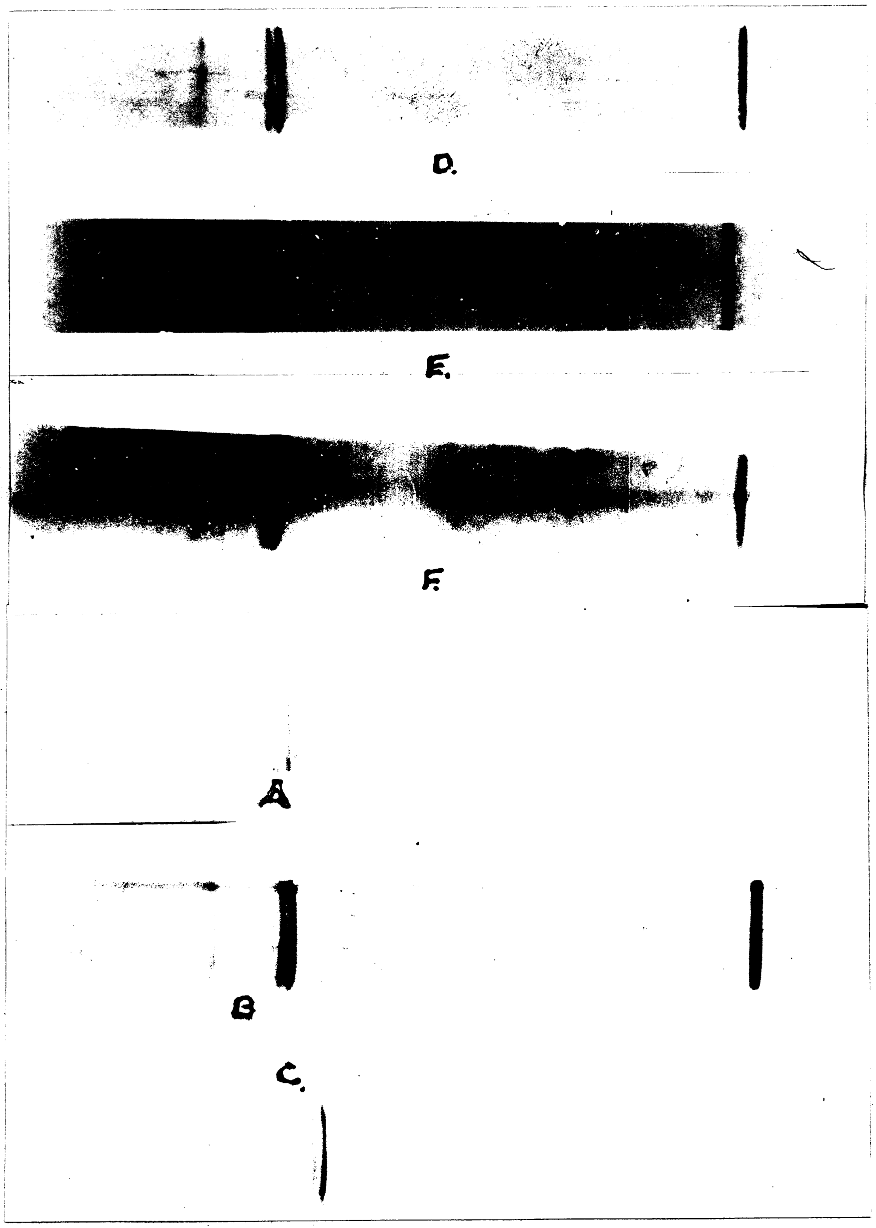


Figure 5

X-Ray Patterns of Grade B Steel
After Creep Tests at 850 and 1000°F.

D = As Received, Creep Test at 850°F.
E = 6% Deformed, Creep Test at 850°F.
F = 12% Deformed, Creep Test at 850°F.
A = As Received, Creep Test at 1000°F.
B = 6% Deformed, Creep Test at 1000°F.
C = 12% Deformed, Creep Test at 1000°F.

From these two figures it is evident that certain changes have occurred within the specimen due both to the deformation at room temperature and to the creep tests to which the specimens were afterwards subjected. It will be observed that with the material in the "as received" condition, x-ray doublets are distinct and sharply defined, thus denoting the absence of any appreciable strain within the material. In the case of the specimens which have been deformed, however, the doublets are not distinctly defined, thus denoting the presence of strain.

With the specimens subjected to the creep tests at 600°F., the doublets are again clearly defined in the case of the "as received" material and indistinct in the case of those which were originally deformed. The doublets of the deformed specimens, however, are not quite as indefinite as they were in the "as deformed" condition. This shows two facts: first, that the stress employed, that is, 24,200 pounds, was not sufficient at this temperature to produce appreciable strain hardening within the "as received" specimen and second, that the temperature and stress conditions were not suitable to produce very much recrystallization in the previously deformed specimens.

With the specimens subjected to the creep tests at 850°F., the doublets obtained with the "as received" material are again clear and distinct. Those from the previously deformed specimens are much clearer and more distinct than what they were after the 600°F. test, but are not as definite as those obtained from the material in the "as received" condition. This indicates that some recrystallization has occurred at this temperature, but that the recrystallization has not been complete.

After the creep tests at 1000°F., the x-ray doublets obtained from all three specimens are exactly similar, and are very sharp and distinct. This indicates that sufficient recrystallization has occurred to remove all the strains which were originally produced by the deformations of 6 and 12 per cent at room temperature.

## EXPLANATION OF RESULTS

Since it is a recognized fact that cold-working increases the strength characteristics of steel at room temperature, some metallurgists have accepted the belief that such will also be the case at elevated temperatures. In fact, one metallurgist has questioned whether or not the socalled first stage of creep could not be eliminated through previous working and thus the amount of deformation occurring during the creep test could be considerably reduced.

The results herein presented indicate that cold-working decreases a steel's ability to withstand creep, at least at temperatures of 600, 850 and 1000°F., and with the loads in question, and it is believed that these findings are consistent with what should be expected from theoretical considerations.

As a general rule it may be said that the material which possesses the most stable structure at any given temperature will also possess the greatest creep resistance at that same temperature. If a metal's structure is unstable it is implied that the molecules or crystals are in a more mobile condition and possess a tendency to change into a form which will make them more stable. Because of this greater mobility, any applied stress should cause the crystals to deform to a greater extent than would be the case if they were already in a stable condition. In other words, if a metal's structure is in a strained condition, the crystals possess a greater tendency to move, and so can be more easily displaced by an applied stress.

If now the x-ray patterns of the materials are referred to, it will be seen that while the structure of the "as received" material is the same both before and after the creep tests, those of the deformed specimens are changed by the creep tests, even by the ones conducted at 600°F. The relationship between the structure and the creep results is, therefore, in agreement with the explanation outlined above.

The time-elongation curves obtained during the creep tests, and shown in Figures 1 through 3, also indicate the "as received" material to possess the more stable structure. It will be observed that especially at 600 and 850°F., the curve for the "as received" material is considerably more regular and uniform than are those obtained for the previously deformed specimens. It is felt that this difference is due to the fact that in the case of the "as received" material, the deformation is entirely due to the applied stress, while in the case of the previously deformed specimens, the observed changes are due to the applied stress plus structural changes which are occurring at more or less irregular time intervals.

The question now arises as to whether or not the observed structural changes at 600°F. are due to actual recrystallization within the metal, or to other changes. This question is one which is receiving considerable attention at the present time and on which there is as yet no agreement. It is felt by many that because of the great sensitivity of the x-ray, the observed changes are due to slight rearrangements which may occur at temperatures considerably below the recrystallization temperatures. Others feel that this first observed change, no matter how slight it is, should be considered as the lowest recrystallization temperature.

If this latter view be accepted, it will be necessary to decidedly lower the temperatures which have formerly been selected as representing the lowest temperature of recrystallization. For example, on the basis of the work herein recorded, it will be necessary to place the lowest temperature of recrystallization of Grade B steel below 600°F.

## CONCLUSIONS

Creep tests were undertaken at 600, 850 and 1000°F. on specimens of Grade B steel in the "as received" condition, and after having been previously deformed 6 and 12 per cent. Attempts were made to explain the above results through a comparison of the hardness values, the metallographic structures, and the x-ray patterns of the specimens both before and after the creep tests. The following conclusions were reached.

Creep Tests.

The creep test results showed the "as received" material to possess the maximum creep resistance at the three temperatures which were considered and the most severely deformed specimens to possess the least. Moreover, the differences between the "as received" and the deformed specimens were more marked at 850 and 1000°F. than what they were at 600°F.

Hardness Tests.

The hardness tests conducted on the specimens before and after the creep tests showed very little difference in hardness to have been produced either by the initial deformation or by the creep tests. The creep tests at 600°F. produced a slight increase in hardness, while those at 850 and 1000°F. caused a softening. In no case, however, were the differences very marked.

Metallographic Examination.

The metallographic examination showed no appreciable structural changes to be caused either by the initial deformations of 6 and 12 per cent or by the creep tests, even though a magnification of 1000 diameters was employed.

X-ray Examination.

The x-ray patterns of the "as received" material showed it to be practically free from initial strains and also to undergo no marked changes during the creep tests. The patterns of the 6 and 12 per cent deformed specimens show the materials to possess a strained structure before the creep tests and that the creep tests at 600°F. produced a slight change in the original structure and a pronounced changed in the 850°F. and 1000°F. tests. In other words, the structures of the strained specimens were tending to return to a stable condition at 600°F. and 850°F. and had returned to such a state at 1000°F.

Explanation of Observed Results.

It is believed that the superior creep resisting ability of the "as received" material at 600, 850 and 1000°F. is due to the fact that its structure at these temperatures is in a more stable condition than are those of the specimens deformed 6 and 12 per cent. Because of this condition, the crystals of the "as received" material are in a less mobile condition and will not, therefore, be as free to move under an applied stress as will be the case with the two deformed specimens.

PHOTOMICROGRAPHS

No. 1 Grade B Steel
As Received Condition
X1000D

No. 2 Grade B Steel
Deformed 6% Cold
X1000D

No. 3 Grade B Steel
Deformed 12% Cold
X1000D

No. 4 Grade B Steel
Creep Specimen at 600°F.
Tested in As Received Condition
Load: 24,200 Lb./Sq.In.
Time: 570 Hours
X100D

No. 5 Grade B Steel
Creep Specimen at 600°F.
Previously Deformed 6%
Load: 24,200 Lb./Sq.In.
Time: 570 Hours
X1000D

No. 6 Grade B Steel
Creep Specimen at 600°F.
Previously Deformed 12%
Load: 24,200 Lb./Sq.In.
Time: 570 Hours
X1000D

No. 7 Grade B Steel
Creep Specimen at 850°F.
Tested in As Received Condition
Load: [illegible] Lb./Sq.In.
Time: 672 Hours
X1000D

No. 8 Grade B Steel
Creep Specimen at 850°F.
Previously Deformed 6%
Load: 19,055 Lb./Sq.In.
Time: 587 Hours
X1000D

No. 9 Grade B Steel
Creep Specimen at 850°F.
Previously Deformed 12%
Load: 19,055 Lb./Sq.In.
Time: 687 Hours
X1000D

No. 10 Grade B Steel
Creep Specimen at 1000°F.
Tested in As Received
Condition
Load: 5,000 Lb./Sq.In.
Time: 575 Hours
X1000D

No. 11 Grade B Steel
Creep Specimen at 1000°F.
Previously Deformed 6%
Load: 5,000 Lb./Sq.In.
Time: 525 Hours
X1000D

No. 12 Grade B Steel
Creep Specimen at 1000°F.
Previously Deformed 12%
Load: 5,000 Lb./Sq.In.
Time: 670 Hours
X1000D