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ISOTHERMAL TRANSFORMATION OF AUSTENITE
UNDER EXTERNALLY APPLIED TENSILE STRESS

Technical Report to Office of Naval Research
Contract No. Nonr 266 (18), Task No. NR 031-456
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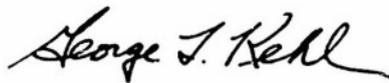
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Approved:



George L. Kehl, Project Director

ISOTHERMAL TRANSFORMATION OF AUSTENITE UNDER
EXTERNALLY APPLIED TENSILE STRESS *

By Subrata Bhattacharyya^{*} and George L. Kehl^{**}

Abstract

The effect of externally applied tensile stress and consequent plastic deformation on the isothermal transformation of austenite to bainite in AISI 1085, 4340, and 1045 steels at 535 and 700 F (280 and 370 C), 650 and 845 F (345 and 450 C) and 700 F (370 C), respectively, has been investigated. The applied stress was varied, in general, between no stress and a stress of 60,000 psi, and, in a few cases, stress up to 100,000 psi was applied.

It has been observed that applied stress has a marked effect on both the beginning and the ending times of transformation; they are shortened by factors ranging from 2 to 100,000, depending on the steel and temperature of transformation. For certain times of isothermal transformation, the amount of austenite transformed increases greatly at a certain stress range, and this stress is observed to be well correlated with the yield stress of unstable austenite. It is also possible to correlate, in a similar manner, the increase in the amount of austenite transformed with plastic strain and applied strain energy.

The mechanical strength of an aggregate of austenite and bainite is a logarithmic function of the amount of bainite present in the structure.

It has been observed further that the effect of stress on the transformation of austenite persists even when the applied stress has been removed. The applied stress is most effective in accelerating transformation when it is applied to austenite after an elapsed time equivalent to the beginning time of transformation under no stress.

Applied stress exceeding the yield stress of austenite is observed to produce a marked orientation effect on the resulting bainite needles. Under high stress, twinning is observed to occur in the austenite.

*This paper is based upon part of the dissertation submitted in partial fulfillment of the requirements for the D. Eng. Sc. degree, Columbia University, New York, N. Y.

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INTRODUCTION

When austenite is isothermally transformed at a temperature level between the pearlite knee of the C-curve and the M_s temperature, it transforms to an aggregate of acicular ferrite and carbide particles, known as bainite. Since the experiments of Davenport and Bain (1)¹, extensive work has been carried out to determine the structure and mechanism of its formation. The structure of bainite has been accurately determined and the difference between the structures of the high temperature and the low temperature types has been clearly established. On the other hand, the exact mechanism of bainite formation still remains controversial.

Several authors (1-8) suggest that bainite is formed from austenite by a martensite-type mechanism through an intermediate stage of martensite, or in general, supersaturated ferrite. Thermodynamic calculations have been made in support of this suggestion, indicating strong possibilities of this type of transformation mechanism.

On the other hand, investigations by others (9-12) indicated that the austenite-bainite transformation is a nucleation and growth process. Gradual thickening and lengthening of bainite needles with time were shown to occur and thus lend support to this type of transformation mechanism.

As early as 1924, Thompson and Millington (13) expressed the view that the formation of martensite is the result of mechanical stress sufficient to exceed the elastic limit of the parent austenite. They proposed that under the stress to which the crystals of austenite are subjected during quenching, the easy glide movement shear on the {111} plane of the austenite is initiated. Normally, this produces twinned material in a close-packed cubic metal. In the present case, however, austenite being an unstable cubic phase at the temperature of transformation, the easy glide movement causes the atoms to reorient themselves into a stable crystallographic form to become alpha iron, with the carbon in supersaturated solid solution. The presence of a stress factor was also suggested by Bain (14) in commenting on work by Mathews (15) who observed that in a considerable variety of steels, oil hardening retained more austenite than water hardening. Bain suggested that water hardening induces a large stress factor, and these stresses are responsible for the larger amount of transformation in water-hardened steel.

Several investigators have studied the effect of stress on the transformation of austenite (16-35).

1. The figures appearing in parentheses pertain to the references appended to this paper.

Cottrell (24) conducted a series of experiments on unstable austenite and concluded that plastic strain causes a breakdown to ferritic structures. He also observed that at temperatures where austenite transforms readily, complete transformation may be induced by straining, but at temperatures where the reaction is sluggish, partial transformation may be obtained. In conclusion, he remarked that the generation of transformed material is linearly proportional to the plastic strain at 645 F (340 C).

Guarnieri and Kanter (26) conducted a series of experiments using standard 0.505 inch tensile test specimens of 5% Cr + 1/2% Mo steel mounted in a modified creep testing machine. Their data indicated that stresses capable of plastically deforming the austenite at the transformation temperature of 800 to 1200 F (425 to 650 C) definitely accelerated both the nucleation and the growth processes of the reaction. This effect was observed at temperatures below the knee of the C-curve. At temperatures above the knee, they noticed little effect of stress in accelerating transformation. They observed that in the latter case the temperatures were sufficiently high so as to render the more rapid diffusion rates relatively insensitive to the strain factor.

Using 0.16 inch diameter eutectoid carbon steel specimens, under both tensile and compressive stresses, Jepson and Thompson (30) observed that the imposition of stress during transformation increases the rate of austenite decomposition. They also observed that transformation under stress to low temperature bainite is marked by certain distributional effects, transformation taking place preferably within slip or twin bands present in the parent austenite. To explain these observations, they suggested that the formation of low temperature bainite was due to combined action of shear and nucleation. The transformation was initiated by shear and continued by nucleation. The importance of the two effects varied with temperature, nucleation being of greater importance at higher temperatures and shear of greater importance at lower temperature. As regards transformation in the pearlite range and high temperature bainite, they suggested that deformation produced nuclei of alpha iron in greater abundance than under no deformation.

It is of interest to note that Savage (27), investigating the geometrical aspects of the mechanism of gamma to alpha transformation in iron, concluded that if the {110} planes of a face-centered cubic lattice of iron were sheared at $19^{\circ}28'$, a structure that was nearly body-centered cubic would be obtained. Through this shearing process the original {110} planes of gamma iron were transformed into {211} planes of alpha iron. This mechanism, he observed, involved no distortion of {110} planes of the face-centered lattice, but consisted of a pure translation in the

direction of the closest atomic packing. Such movements of rows of atoms are very characteristic of slip processes during plastic deformation. He also demonstrated that during the shearing of parallel sets of these {110} planes, all intermediate stages between the shear angles of 0° and $19^\circ 28'$ had a structure that was nearly body-centered tetragonal.

No systematic investigations have been carried out to determine the effect of varying amounts of plastic deformation on the rate of transformation of austenite and the distribution and orientation of the resulting phases. So far, no conclusive experiments have been carried out to establish a quantitative relationship between applied stress producing acceleration in austenite transformation and some mechanical property of the unstable austenite at the transformation temperature level. In the work to be described experiments were conducted in the bainite transformation range with three commercial steels. The experimental results indicate the effect of applied stress to be similar for the three steels and thus data for only one of the steels (0.89% C), isothermally transformed at 535 F (280 C) is presented in detail in the paper. Wherever it was believed desirable, however, data of the other steels were included for comparative purposes.

EXPERIMENTAL PROCEDURE

The chemical composition of the three steels is given in Table I.

TABLE I
Check Analysis of Steels Investigated

Steel	Percent							
	<u>C</u>	<u>Mn</u>	<u>P</u>	<u>S</u>	<u>Si</u>	<u>Ni</u>	<u>Cr</u>	<u>Mo</u>
1065	0.89	0.29	0.013	0.013	0.19	----	0.08	----
4340	0.42	0.78	0.018	0.027	0.24	1.79	0.80	0.33
1045	0.44	0.86	0.027	0.035	0.20	0.02	0.04	----

The steels were obtained in the form of round bars, 1-1/8 inch in diameter, and initially heat-treated to form a spheroidite structure. They were then machined to 3/8 inch diameter, subsequently wire drawn, and centerless ground to a finished diameter of 0.051 ± 0.0002 inch. The specimen wire was then cut into 5-1/2 inch lengths. To provide a means for attaching the specimen to the grips of the apparatus, spherically shaped beads were formed on each end of the specimen by melting the ends within a graphite mold. The specimens were copper plated to prevent

decarburation during subsequent austenitizing, and finally normalized in argon atmosphere to ensure a uniform initial structure.

A line diagram of the apparatus is shown in Fig. 1. It consists of an automatically operated transport system that moves

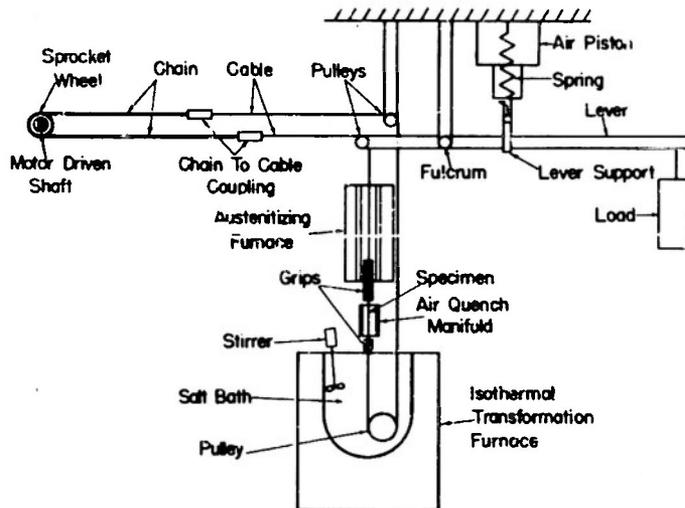


Fig. 1—Schematic Diagram of the Transformation Apparatus.

the wire specimen from a vertically mounted austenitizing furnace to an isothermal transformation salt bath, and thence to an air quenching fixture to interrupt the transformation; an air-operated piston to release the lever arm and dead weights at an appropriate time; and a timing system that could be preset to allow the specimen to remain for a given time in the austenitizing furnace; the transformation bath, and the air-quenching manifold, and to apply the stress to the specimen at any time during the cycle of specimen movement.

A split-type vertical electric tube furnace was used to austenitize the specimens. A constant flow of argon was maintained within the furnace as an added precaution in avoiding decarburation of the specimen. The control of the furnace temperature was within ± 5 F (3 C) of the desired austenitizing temperature.

The isothermal salt bath was continuously agitated by means of an electric stirrer. The variation in salt bath temperature was within ± 1 F (0.5 C) in the temperature range of investigation, 535 to 845 F (280 to 450 C).

At an appropriate time, stress was applied to the specimen by means of dead weights. An air-piston was employed to release

the lever arm and its suspended weights. By means of a leak valve in the air-piston line, the rate of load application could be varied, and for the experiments to be described, a low rate of load application was employed to avoid dynamic loading of the specimen.

Calibration of the loading system is shown in Fig. 2. A theoretically calculated curve is also shown, the difference between

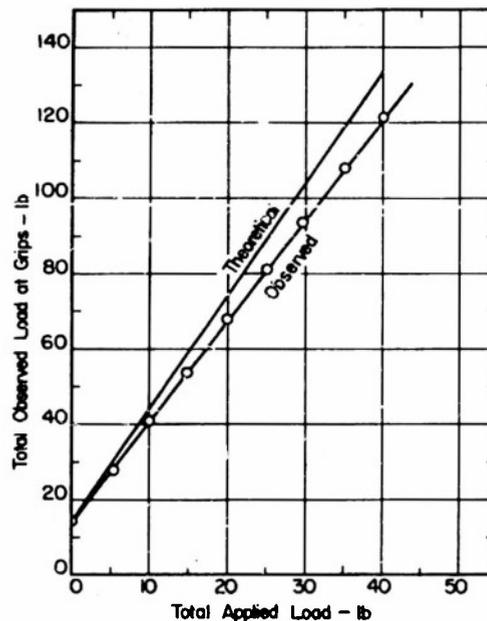


Fig. 2—Calibration Curve of the Dead Weight Loading System.

the two curves at any applied load being attributable to reproducible friction and other losses in the cable-transport system. The origin of the curves at 14.5 lb. (ordinate) corresponds to the load applied at the grips owing to the weight of the lever arm and the weight counterpoise located at the end of the lever.

The actual cycle of operations consisted of austenitizing the specimen at a desired temperature for a pre-set length of time, isothermally transforming at the salt-bath temperature for varying lengths of time under different applied stresses, and finally quenching the untransformed austenite to martensite in an air blast. The range of these variable factors is given in Table II.

The transport of the specimen from the austenitizing furnace to the salt bath, and from the salt bath to the air-quench manifold, took about 1 second and 1/2 second, respectively. Two seconds were allowed to the salt bath for the specimen to attain the temperature of the transformation bath.

Percentage of transformation was determined metallographically using both chart-comparison and lineal analysis methods.

TABLE II
Range of Transformation Times and Applied Stresses

Steel AISI	Austenitizing Temperature, F	Treatment Time, min	Isothermal Transformation Temperature, F	Range of Isothermal Transformation Time, sec	Range of Applied Stress, psi	Austenitic Grain Size, A.S.T.M.
1065	1620	7	{ 535 700	15-1800 5-150	0-60,000	Large number of 5, some 6, few 4
4340	1550	7	{ 650 845	10-1200 5-100,000	0-80,000	Predominantly 10, some 9
1045	1580	7	760	0.5-80	0-60,000	Predominately 8, some 7

EXPERIMENTAL RESULTS AND DISCUSSION

Effect of Stress on the Beginning and Ending Times of Transformation

The amount of bainite formed isothermally under different average stress conditions (ranging from 0 to 60,000 psi) is plotted vs. log-time, and is shown in Figs. 3 and 4, 5 and 6, and 7 for

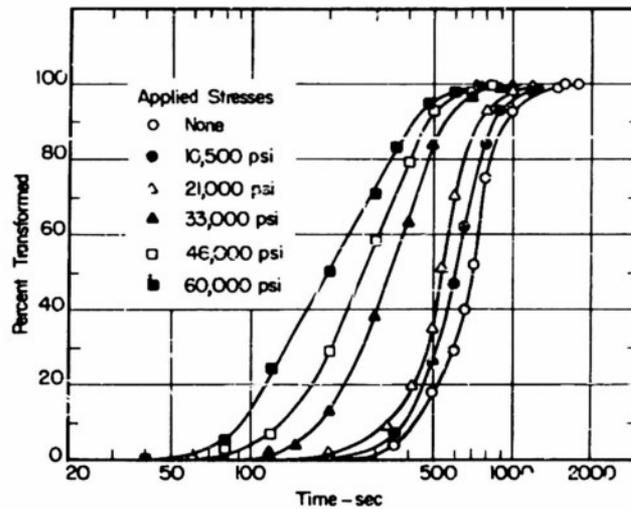


Fig. 3—AISI 1085 Steel Isothermally Transformed at 535 F.

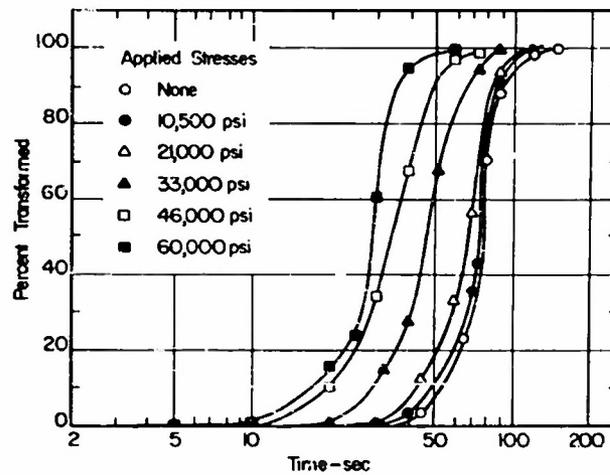


Fig. 4—AISI 1085 Steel Isothermally Transformed at 700 F.

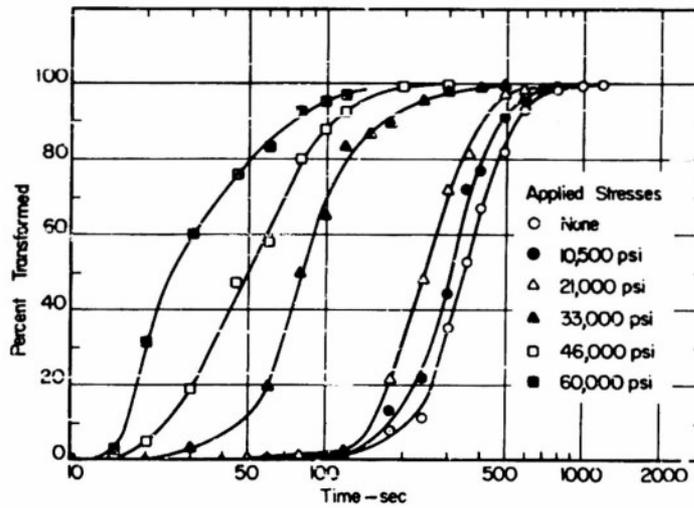


Fig. 5—AISI 4340 Steel Isothermally Transformed at 650 F.

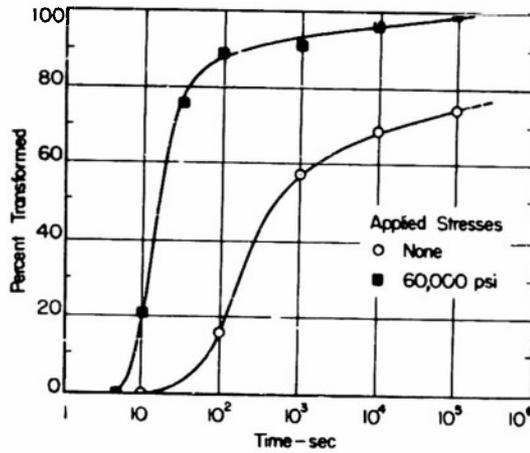


Fig. 6—AISI 4340 Steel Isothermally Transformed at 845 F.

1085, 4340, and 1045 steels, respectively. It is evident from these data that under increasing amounts of stress the beginning and ending times² of transformation are shortened and the rates of transformation are increased as evident by the slopes of the curves. It is to be noted that the effect of applied stress in shortening the beginning and ending times of transformation is not so

2. The criteria of the beginning and end of transformation are taken at 1% and 99% bainite formation, respectively.

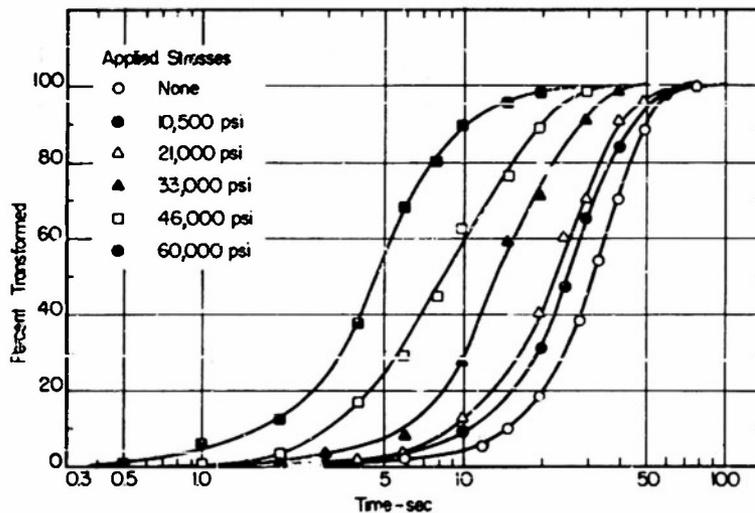


Fig. 7—AISI 1045 Steel Isothermally Transformed at 700 F.

pronounced in the applied stress range of 0 to 21,000 psi as compared to that in the range of 33,000 to 60,000 psi. It may be further observed in Table III that the beginning time of transformation is shortened by a stress of 60,000 psi to a greater extent

TABLE III
Effect of A Stress of 60,000 psi on the Beginning and Ending Time of Bainite Formation.

Steel	Isothermal Transformation Temperature, F	Ratio of	Ratio of
		Time to Form 1% Bainite Without Stress	Time to Form 99% Bainite Without Stress
AISI		Time to Form 1% Bainite With 60,000 psi Stress	Time to Form 99% Bainite With 60,000 psi Stress
1085	535	6	2.5
	700	4	2.5
4340	650	7	5
	845	4	10,000-100,000*
1045	700	8	3

*Owing to uncertainties in extrapolation of the no stress curve (Fig. 6) to the time for completion of transformation, these data are shown as a range of time factors.

than is the ending time, with one exception. In the case of 4340 steel transformed at 845 F (450 C), the data indicate that a stress of 60,000 psi shortens the ending time of transformation by a factor of 10,000 to 100,000.

Relation Between Applied Stress and Percent Transformation;
Determination of a Critical Stress Range

From Figs. 3, 4, 5, and 6, there can be obtained a relationship between the applied stress and percentage of bainite formed for any selected time of transformation at the given transformation temperature. The derived data thus obtained from Fig. 3 is plotted in Fig. 8.

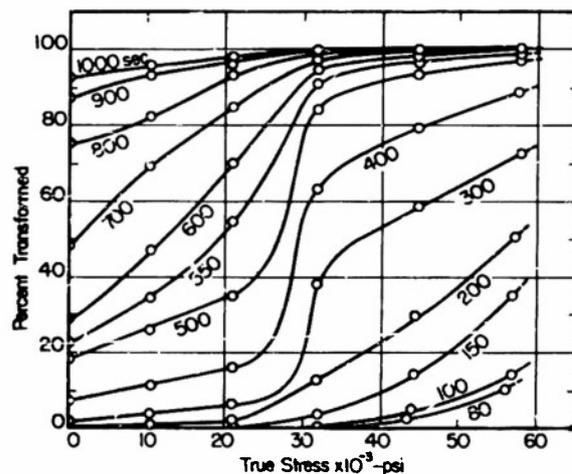


Fig. 8—Variation in the Amount of Bainite as a Function of True Stress in AISI 1085 Steel Isothermally Transformed at 535 F.

All of the stress data shown in plotted form are in terms of "true" stress. These data, as well as "true" strain measurements to be described, were calculated on the basis of final cross sectional area of the specimen, and in consequence, the values so derived are not true stresses by conventional definition. The final cross-sectional area was used, rather than the original area, because after an initial elongation of the specimen when the load was applied, the specimen no longer elongated to any significant extent. The error involved in the true stress calculations is estimated to be about $\pm 5\%$, and comprise mainly variation in the diameter of the specimens, and volume changes accompanying the

formation of bainite during transformation and formation of martensite during subsequent quenching of the untransformed austenite.

The data shown in Fig. 8 indicates that the amount of bainite formed isothermally increases rapidly over a certain stress range, henceforth to be called the critical stress range. The increase in the amount of bainite formation in the critical stress range, however, is most significant only for certain periods of isothermal transformation times. For a selected time of transformation, a series of photomicrographs is shown in Fig. 9 for 1085 steel. These photomicrographs indicate clearly the effect of a stress just exceeding the critical stress range in promoting the formation of large amounts of bainite. The critical stress ranges determined for the steels used in this investigation are shown in Table IV.

TABLE IV
Determined Critical Stress Range Within Which Bainite
Formation May Be Significantly Accelerated

Steel	Isothermal Transformation Temperature, F	Critical Stress Range psi
1085	535	25,000-28,000
	700	25,000-28,000
4340	650	23,000-26,000
1045	700	26,000-29,000

As will be shown later, the large increase in the amount of transformation occurring within the critical stress range is related to deformation of the austenite. In order to determine the significant relationship between true strain and amount of austenite transformed for different isothermal transformation times, it is necessary to consider the fact that deformation of the austenite varies with transformation time and attendant increasing amounts of transformation product. The approach is best made through first determining the relationship between true strain and time of transformation.

True Strain vs. Time; the Creep Behavior

True strain is defined as $\log_e \left(\frac{d_0}{d} \right)^2$, where d_0 is the original diameter and d the instantaneous diameter of the specimen, with the assumption of volume constancy. As described heretofore,

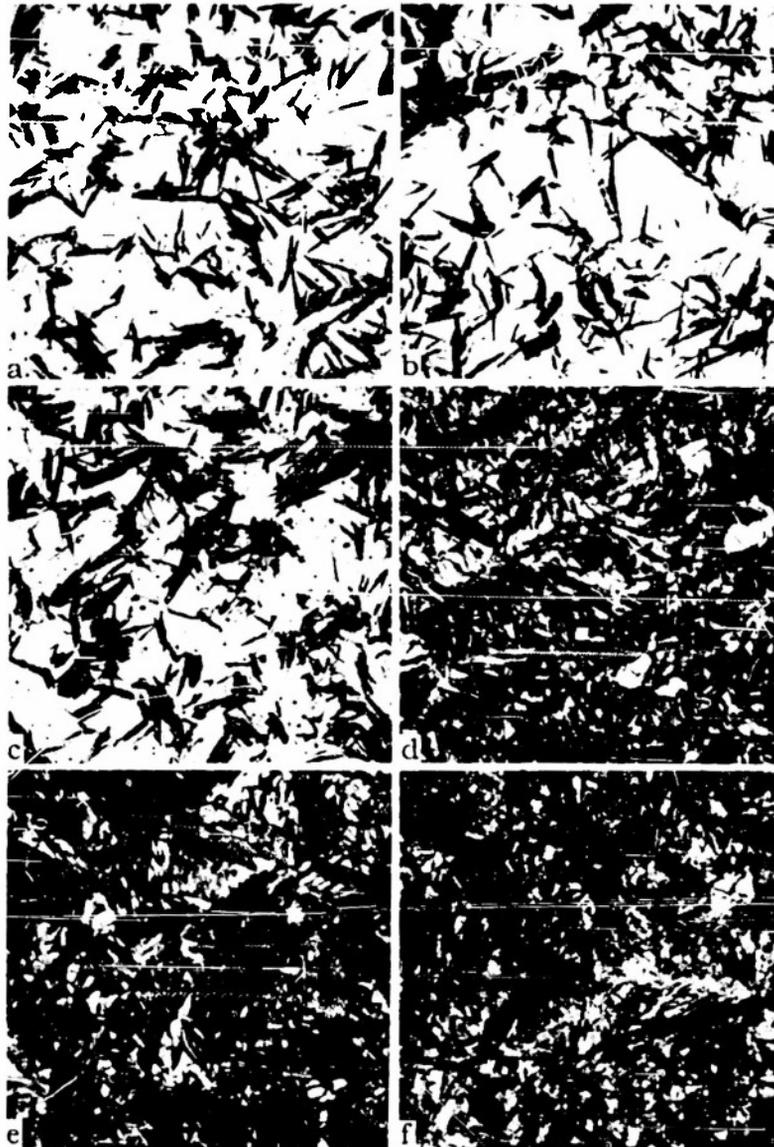


Fig. 9—Photomicrographs of Bainite Illustrating the Effect of Stress on the Amount of Bainite Isothermally Formed in 500 seconds at 535 F in AISI 1085 Steel. (a) No Stress, (b) 10,500 psi, (c) 21,000 psi, (d) 33,000 psi, (e) 46,000 psi, (f) 60,000 psi X 500. Etchant - Saturated Picral.

however, the final diameter was used in true strain calculations rather than the instantaneous diameter.

After an experimental run, the copper plating of the specimen is carefully dissolved in nitric acid. After dissolution of the plating, the diameter is measured by micrometric methods at ten or more different places close to the central parts of the 5-1/2 inch long specimen and the average diameter determined. The variation of ± 0.0002 inch in diameter of the specimen, and the estimated volume strains and those associated with recovery of elastic strains, produce an estimated error of ± 0.010 inch per inch in the final true strain measurements.

The variation of true strain with transformation time under different average applied stresses is illustrated in Fig. 10 for

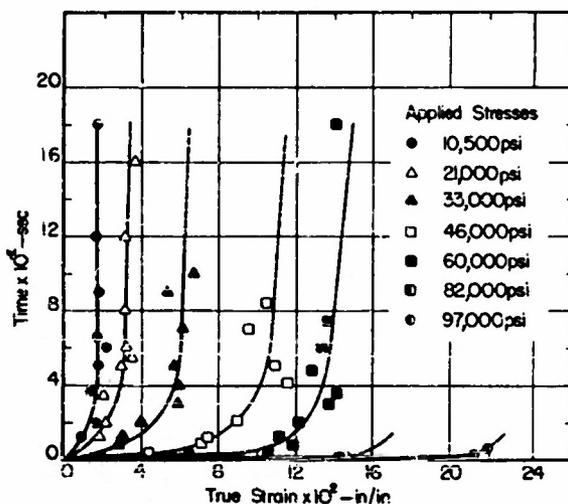


Fig. 10—Variation of True Strain Under Different Average Stress With Transformation Time in AISI 1085 Steel Isothermally Transformed at 535 F.

1085 steel. These curves are similar to conventional creep curves, except that those in Fig. 10 represent a situation where decomposition of one phase into others is continuously occurring during extension. The new constituent, bainite, being harder than the decomposing phase austenite, thus modifies the creep behavior of the unstable austenite. At all of the temperature levels studied, the applied stresses for the time of transformation involved was chosen so as not to cause any necking down of the specimen.

True Strain vs. Amount of Bainite Formed; Determination of a Critical True Strain

The amount of bainite formed during different constant periods of transformation time vs. true strain is plotted in Fig. 11 for

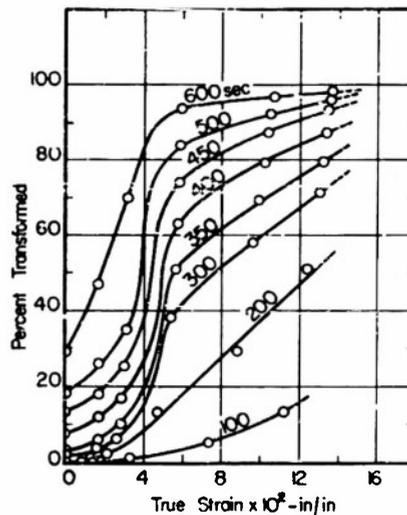


Fig. 11—Variation in the Amount of Bainite Formed With Strain in AISI 1085 Steel Isothermally Transformed at 535 F.

1085 steel. The true strain values for different isothermal transformation times were derived from Fig. 10. The data shown in Fig. 11 indicate that the amount of bainite formed isothermally increases to a great extent in a certain strain range, henceforth to be called the critical strain range. In almost all respects the shape of the curves in Fig. 11 is similar to that in Fig. 8.

True Stress - True Strain Relationship of Unstable Austenite Prior to Bainite Formation.

If a true stress - true strain relationship of the unstable austenite could be established without the presence of any decomposition product, then the true significance of the critical stress range could be evaluated. As derived from Fig. 10, Fig. 12 illustrates the true stress - true strain relationship of unstable austenite in 1085 steel. The isothermal transformation time of 20 sec., for which the curve is drawn, is sufficiently short that even under the highest stress no transformation of austenite to bainite occurs.

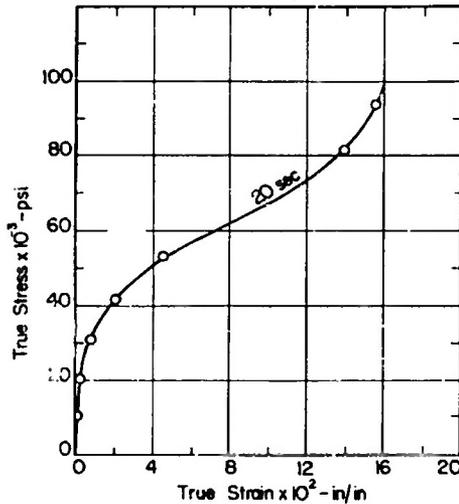


Fig. 12—Stress - Strain Relationship of Unstable Austenite Prior to Isothermal Transformation at 535 F in AISI 1085 Steel.

It is clearly indicated in Fig. 12 that the stress - strain relationship deviates from linearity in a certain stress range, which is designated as the yield stress range of the unstable austenite. The yield stress range of the unstable austenite in the three steels at their respective transformation temperatures are given in Table V.

TABLE V
Relationship between Critical Stress and Yield Stress Ranges of Unstable Austenite

Steel AISI	Isothermal Transformation Temperature, F	Critical Stress Range psi	Yield Stress Range of Unstable Austenite psi
1085	535	25,000-28,000	25,000-29,000
	700	25,000-28,000	25,000-27,000
4340	650	25,000-26,000	22,000-26,000
1045	700	26,000-29,000	24,000-28,000

The data of Table V indicate that the critical stress range and the yield stress range of the unstable austenite are identical within the experimental error. Thus the large increase in the amount of austenite transformation within the critical stress range that was first observed, and shown in Fig. 8, is in reality due to the application of stresses within the yield stress range of the unstable austenite.

True Stress - True Strain Relationship of Unstable Austenite with Simultaneous Transformation to Bainite

It has been mentioned heretofore that under applied stress the deformation suffered by the specimen is modified owing to increasing amounts of bainite being formed with time. For certain constant periods of transformation time, data shown in Fig. 13,

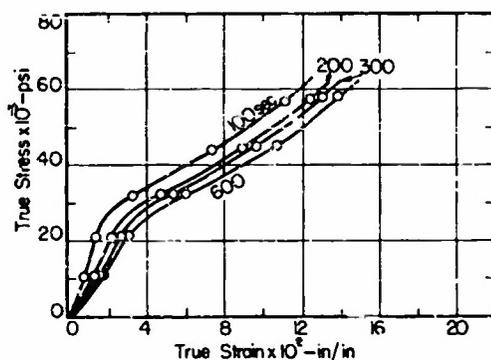


Fig. 13—Stress - Strain Relationship of Unstable Austenite Prior to and Including Isothermal Transformation at 535 F in AISI 1085 Steel for Different Isothermal Holding Times.

therefore, illustrates the characteristic deformation of the austenite as modified by the presence of increasing amounts of bainite. The similarity in shape of these curves to that in Fig. 12 is to be noted.

From the curves of Fig. 13, the energy required to deform the specimens with any given stress and for any definite period of transformation time can be determined graphically. From such determinations, the strain energy in units of psi may be readily converted into more familiar units of cal per mole. The

relationship between strain energy and the amount of bainite formed at different transformation times for 1085 steel is shown in Fig. 14.

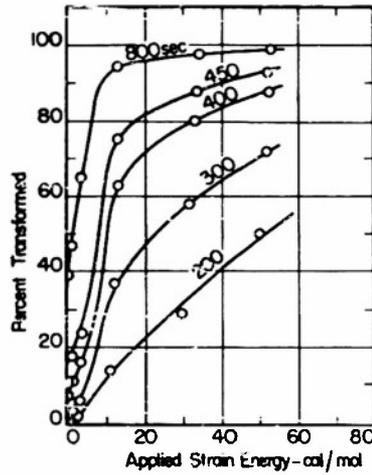


Fig. 14—Variation in the Amount of Bainite Formed With Applied Strain Energy in AISI 1085 Steel Isothermally Transformed at 535 F.

The Effect of Applied Stress on the Rate of Decomposition of Austenite

From the data in Figs. 3, 4, 5, 6, and 7, the true rate of austenite decomposition can not be determined readily since the amount of austenite remaining untransformed continuously decreases as transformation proceeds. Inasmuch as the true rate of austenite decomposition must be related to a unit volume of untransformed austenite, it becomes necessary to determine the true rate by plotting $\log_e (1-x)$ vs. transformation time under different average stresses, where x is the fractional amount of austenite transformed isothermally in a given time. Such a determination is illustrated in Fig. 15 for 1085 steel. The slopes of the curves represent the rate of decomposition of residual austenite per unit volume of untransformed austenite, and may be expressed,

$$\frac{d}{dt} \left\{ \log_e (1-x) \right\} = \frac{d}{d(1-x)} \left\{ \log_e (1-x) \right\} \cdot \frac{d(1-x)}{dx} \cdot \frac{dx}{dt} = \frac{1}{1-x} \cdot \frac{dx}{dt}$$

where $\frac{dx}{dt}$ is the rate of decomposition and $(1-x)$ is the fractional amount of austenite remaining after a transformation time t .

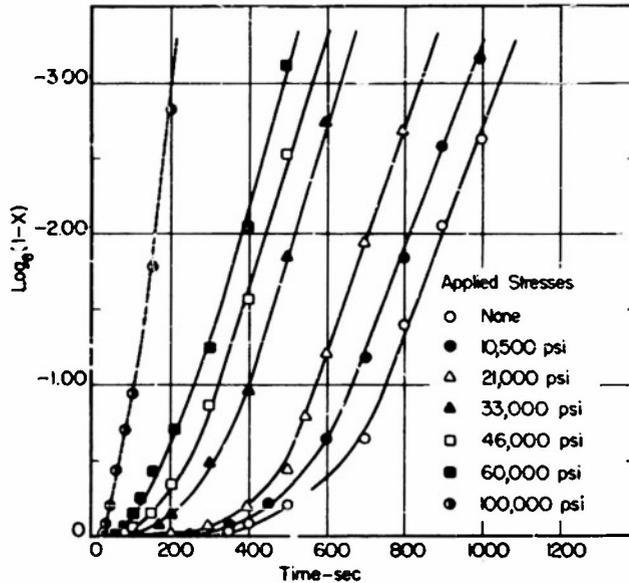


Fig. 15—Relationship Between the Amount of Untransformed Austenite and Transformation Time at 535 F in AISI 1085 Steel for Different Applied Stresses.

It can be observed in Fig. 15 that the rate of decomposition per unit volume of untransformed austenite under imposed stress increases with increase in transformation time up to some limiting value and then becomes constant. The onset of a constant decomposition rate is shown to occur at shorter times of transformation the higher the applied stress, and the constant rate increases with increasing stress. These data are summarized in Tables VI and VII.

The Character of Bainite Formed Under Applied Stress

As illustrated in Fig. 16 for 1085 steel, which is representative of all the steels investigated, there is a definite preference in orientation of low-temperature bainite with increasing amounts of applied stress. As related to prior deformation of the austenite, the orientation effect becomes more pronounced at stress greater than the yield stress of the austenite. Although not illustrated, a more random orientation of the high-temperature bainite occurred in 1085 steel at comparable stress applications, and a completely random orientation in 4340 steel. There is indicated

TABLE VI
Variation in the Amount of Decomposed Austenite
After Which a Constant Rate of Decomposition of
Residual Austenite Is Obtained Under Different
Applied Stresses:

Steel	Isothermal Transformation Temperature, F	Amount of Austenite Decomposed After Which a Constant Rate of Decomposition of Residual Austenite Is Obtained Under Different Applied Stresses									
		No Stress	10,500 psi	21,000 psi	33,000 psi	46,000 psi	60,000 psi	80,000 psi	100,000 psi		
1085	525	55	55	55	55	50	35	--	20		
	700	53	53	53	53	46	41	--	31		
4340	650	50	50	50	35	30	5	3	--		
1045	700	65	65	65	45	35	30	--	--		

Note: Average critical stresses for 1085, 4340, and 1045 steels are 26,500, 24,500, and 27,500 psi, respectively.

TABLE VII
Variation of the Constant Rate of Decomposition
of Residual Austenite with Applied Stress

Steel AISI	Isothermal Transformation Temperature, F	Ratio of									
		The Constant Rate of Decomposition of Residual Austenite Under Applied Stress					The Constant Rate of Decomposition of Residual Austenite Under No Applied Stress				
		10,500 psi	21,000 psi	33,000 psi	46,000 psi	60,000 psi	86,000 psi	100,000 psi			
1085	535	1.0	1.1	1.3	1.3	1.4	---	---	3.0		
	700	1.0	1.0	1.0	1.3	2.0	---	---	3.0		
4340	650	1.1	1.4	2.2	3.3	4.6	10.0	---	---		
1045	700	1.0	1.0	1.1	1.4	2.7	---	---	---		

Note: Average critical stresses for 1085, 4340, and 1045 steels are 26,500, 24,500, and 27,500 psi, respectively.

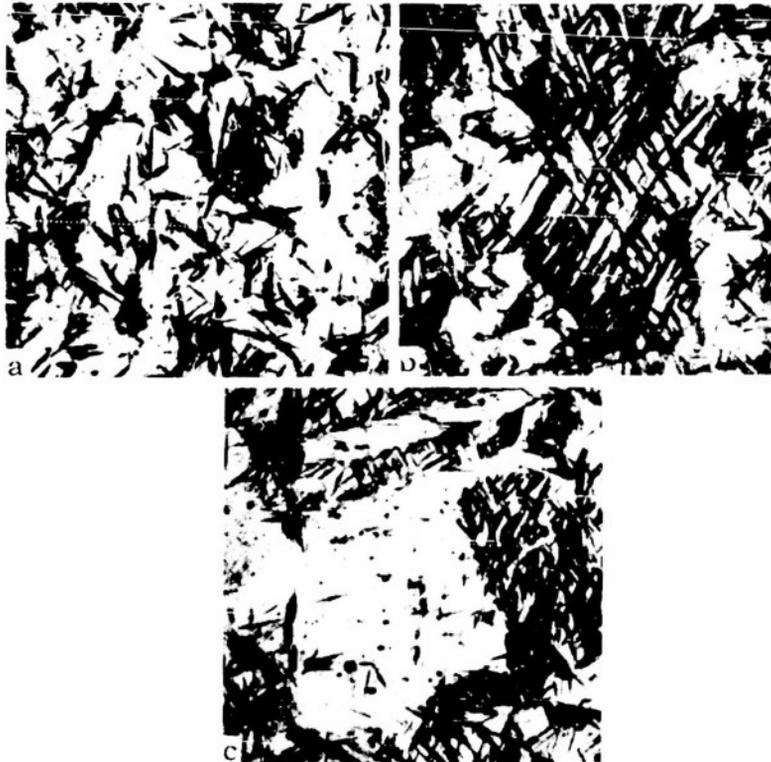


Fig. 16—Illustrating the Preferential Orientation of the Bainite Needles as a Function of Stress in AISI 1085 Steel Isothermally Transformed at 535 F. X 500. (a) 21,000 psi; 450 seconds, (b) 33,000 psi; 300 seconds, (c) 60,000 psi; 120 seconds. Etched in Saturated Picral.

in Fig. 16, and particularly in Fig. 16C, that the fineness of the bainite needles increase with increase in applied stress, although this was not observed in the case of high-temperature bainite.

Figs. 16c and 17 illustrate the twinning that occurs in the austenite at stresses greater than about 45,000 psi. It is of interest to note in Fig. 17 no transformation has occurred in the twin band, although the parent grain surrounding it has undergone considerable transformation.

At comparatively high values of applied stress, where significant differences exist in the degree to which the variously-oriented austenite grains have been strained, preferential transformation occurs. As illustrated in Fig. 18, some of the austenite grains have suffered complete transformation whereas others have only partially transformed and some not at all.



Fig. 17—Illustrating Twinning in a Prior Austenite Grain in AISI 1085 Steel Transformed at 535 F Under a Stress of 60,000 psi. X 1500. Etched in Saturated Picral.

Transformation Under Applied Stress for Only a Portion of the Total Transformation Time

The curve in Fig. 19 illustrates the reaction curve of austenite transformation in 1085 steel under an applied stress of 60,000 psi. The lettered plotted points correspond to the respective transformation schedule described in Table VIII. From the proximity of the plotted data with respect to the reaction curve, it is evident that the amount of austenite transformed in a given time under a stress of 60,000 psi continuously applied is equivalent to that transformed when the stress is removed and the austenite is allowed to transform further under no stress for the same total time. Fig. 19, along with other data not given, indicates that the total time of transformation is the significant consideration, and regardless of the times of transformation under stress and with the stress removed, the plotted points would conform to the

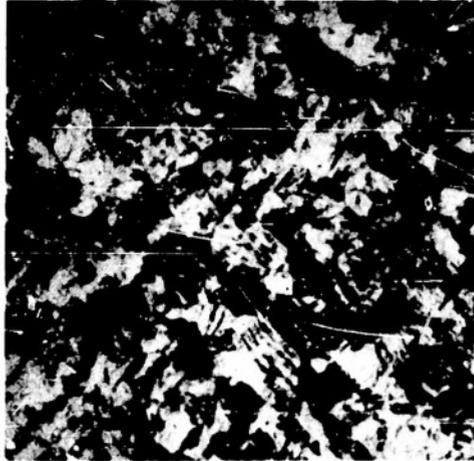


Fig. 18—Illustrating the Preferred Transformation of Some Prior Austenitic Grains with Respect to Others. AISI 4340 Steel Isothermally Transformed at 650 F for 30 seconds. Under stress of 60,000 psi. X 500. Etched in Saturated Picral.

TABLE VIII

The Amount of Bainite Formed at 535 F (1085 Steel) as Influenced by Stress Application for Different Times Prior to Transformation Under No Stress

Transformation Schedule		Amount of Bainite Initially Formed Under 60,000 psi %	Total Transformation %	Letter Symbols In Fig. 19
Time Under 60,000 psi sec	Subsequent Time Under No Stress sec			
20	60	0	1	N
120	60	24	39	M
300	60	71	86	L
480	60	95	98	K

reaction curve. This will occur, however, only when the stress is allowed to remain for a time sufficient to deform the austenite.

Conversely to the transformation schedule described, data in Table IX (pertaining to Fig. 20) and Fig. 20 show the amount of austenite transformed under a schedule of partial transformation under no stress to form varying amounts of bainite (about 30 to

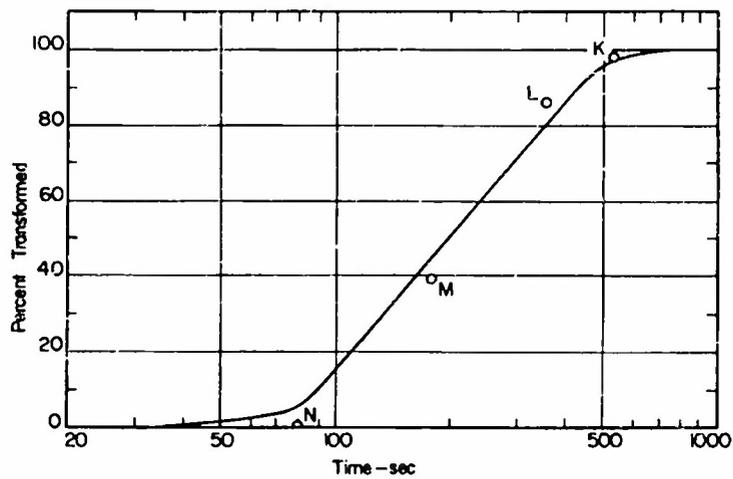


Fig. 19—The Austenite Decomposition Curve for AISI 1085 Steel Isothermally Transformed at 535 F Under 60,000 psi. Lettered Data Pertaining to Transformation Schedule Described in Table VIII.

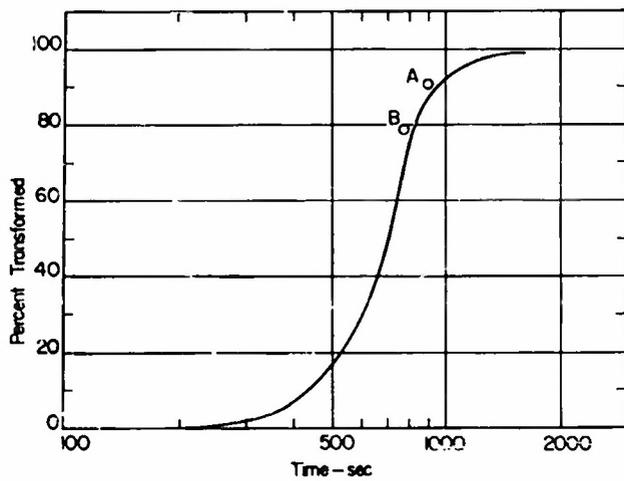


Fig. 20—The Austenite Decomposition Curve for AISI 1085 Steel Isothermally Transformed at 535 F Under No Stress. Lettered Data Pertaining to Transformation Schedule Described in Table IX.

TABLE IX
 The Amount of Bainite Formed at 535 F (1085 Steel)
 as Influenced by Different Isothermal Holding
 Times Under No Stress Prior to Application of
 Stress for Various Times

Transformation Schedule		Amount of Bainite		Total Transformation %	Letter Symbols in Figs. 20 and 21	True Strain $\times 10^2$ in/in
Time Under No Stress sec	Subsequent Time Under 60,000 psi psec	Initially Formed Under No Stress %	Transformation %			
Fig. 20 } 720 600 480	180	52	91	A	1.7	
	180	29	79	B	2.8	
	180	16	60	-	3.2	
360 } 240 210	180	4	45	I	9.8	
	180	1	44	H	10.9	
	180	<1	47	G	11.0	
Fig. 21 } 180 150 120	180	0	42	F	11.0	
	180	0	41	E	11.1	
	180	0	40	D	11.2	
30	180	0	39	C	11.9	

50%), and then a stress of 60,000 psi subsequently applied and transformation allowed to proceed for a given time. The data indicate that an applied stress of 60,000 psi has little effect in accelerating austenite decomposition if the stress is applied to an aggregate structure of austenite and bainite containing bainite in excess of about 30%. This circumstance is probably related to the increased strength of the aggregate and the consequential lower influence of stress on the austenitic phase (see Fig. 22).

Fig. 21 and the data in Table IX pertaining to this figure are the results of a transformation schedule similar to that shown

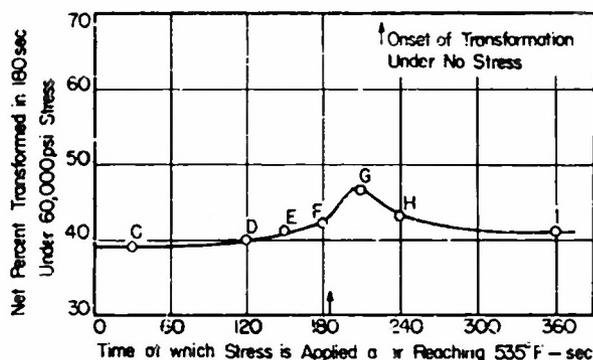


Fig. 21—Influence of the Time of Stress Application on the Net Amount of Austenite Transformed in 180 seconds. Under 60,000 psi. AISI 1085 Steel Isothermally Transformed at 535 F.

in Fig. 20. An exception is that no transformation (or practically none) of the austenite had occurred prior to the application of 60,000 psi stress. It is significant to note that the influence of stress in accelerating the formation of bainite is most pronounced when applied at the end of the no-stress incubation period. This is specifically illustrated by point G, and arises from two simultaneously operative effects; the progressive increase in the total amount of bainite formed with time and the strengthening of the aggregate structure owing to increasing amounts of bainite initially formed under no stress.

The data shown in Fig. 22 were derived through a transformation schedule similar to that employed to secure the data of Fig. 21. The curves reflect the mechanical strength of the austenite-bainite aggregate at the transformation temperature, and it is evident that the relationship is logarithmic with respect to the amount of bainite present in the structure prior to application of stress. This relationship is undoubtedly associated with the extent of the mean free path in the continuous austenitic phase.

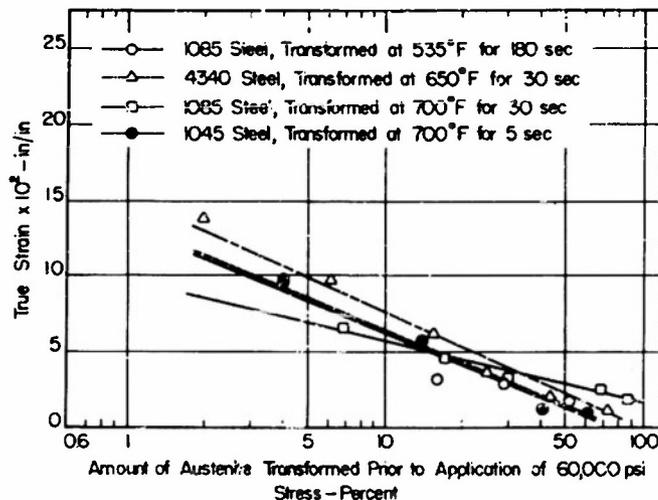


Fig. 22—Variation of True Strain With Amount of Austenite Transformed at the Time a Stress of 60,000 psi is Applied.

Electron Microscope and Diffraction Observations

To determine whether or not the formation of bainite under stress resulted in any significant change in the character of the carbide phase in bainite, not detected by optical microscopy, selected observations were made by means of the electron microscope. As illustrated in Fig. 23, which is typical of the structures examined, there appears to be no significant difference between that formed under no stress and a stress of 60,000 psi.

Using the extraction replica technique, (36) electron diffraction patterns were secured of the carbide particles in bainite of 1085 steel, formed at 535 F (280 C), under no stress and 60,000 psi.³

It is known that hexagonal epsilon carbide structure exists in 1085 bainite formed under no stress at a temperature of 500 F (260 C), but not in bainite formed at 550 F (290 C). Therefore, the purpose of the electron diffraction observations was to determine if the presence of hexagonal epsilon carbide existed in 1085 bainite at the transformation temperature of 535 F (280 C) and if applied stress in any way altered the character of the carbide structure. The diffraction patterns indicated that in both cases only the conventional carbide phase was present.

3. The electron diffraction patterns were secured through the courtesy of Mr. R. M. Fisher, Research Laboratory, U. S. Steel Corp. Kearny, New Jersey.

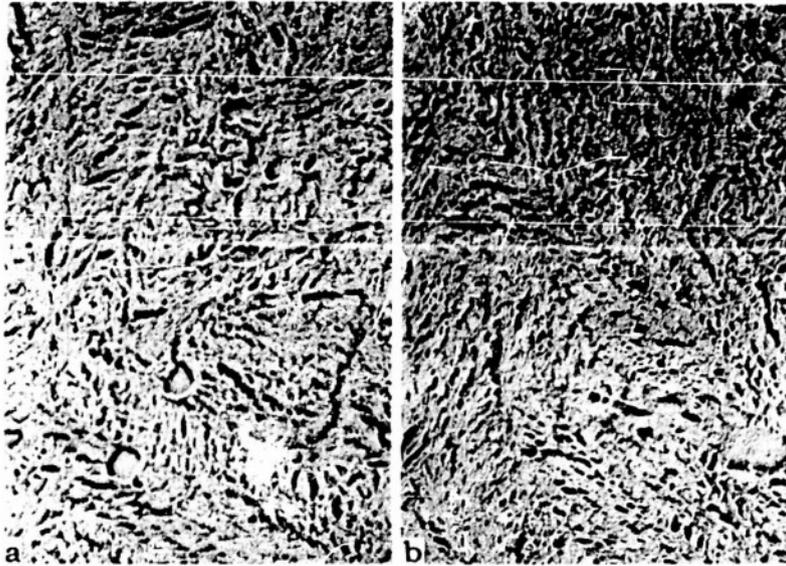


Fig. 23—Electron photomicrographs of Bainite Formed at 535 F in AISI 1085 Steel. X 12,000. a. Without Stress
b. 60,000 psi

CONCLUSIONS

An applied stress exceeding the yield stress of unstable austenite accelerates the isothermal transformation of austenite to bainite in AISI 1085, 4340, and 1045 steels.

Both the beginning and ending times of the austenite to bainite transformation are shortened by applied stress. This is illustrated in Fig. 24 for a stress of 60,000 psi, in terms of the attendant shift in the lower part of the C-curve for 1085 steel.

A pronounced increment in the amount of transformation to bainite occurs within the critical stress range. This critical range is observed to be identical with the yield stress range of unstable austenite.

Relationships of true strain and strain energy with the amount of bainite formed isothermally are observed to be similar to the relationship between true stress and the amount of bainite formed.

Owing to slip and twinning along preferred planes and in preferred directions in the austenite lattice, the formation of bainite is preferred with respect to distribution and orientation.

Under large stress applications, compartmentalization in deformed austenite grains, due to competing slip systems, reduces the coarseness of the bainite needles.

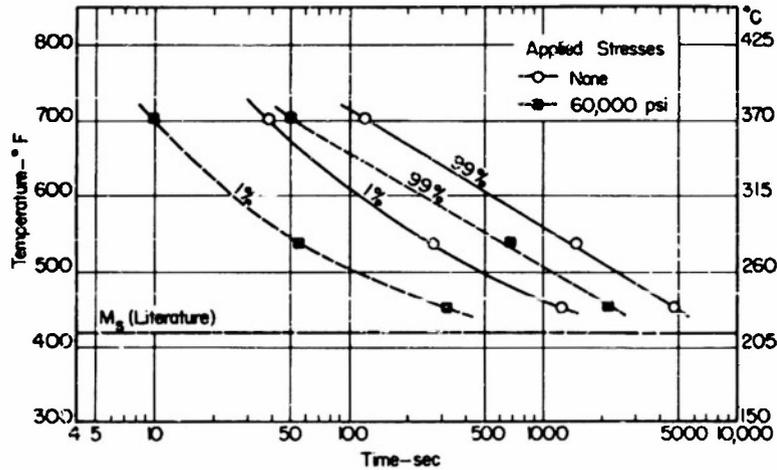


Fig. 24—Illustrating the Displacement of the Beginning and Ending Times of Bainite Formation Due to Stress of 60,000 psi.

The mechanical strength of the austenite-bainite aggregate at the transformation temperature is observed to be a logarithmic function of the amount of bainite present in the aggregate.

Electron microscopical observations indicate close similarity in the size, shape and distribution of the cementite particles in bainite formed with and without applied stress. The structure of the cementite particles in AISI 1085 steel, as revealed by electron diffraction patterns, is observed to be unaffected by applied stress.

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