Designation: A1033 – 10 (Reapproved 2015)

Standard Practice for Quantitative Measurement and Reporting of Hypoeutectoid Carbon and Low-Alloy Steel Phase Transformations[1]

This standard is issued under the fixed designation A1033; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This practice covers the determination of hypoeutectoid steel phase transformation behavior by using high-speed dilatometry techniques for measuring linear dimensional change as a function of time and temperature, and reporting the results as linear strain in either a numerical or graphical format.

1.2 The practice is applicable to high-speed dilatometry equipment capable of programmable thermal profiles and with digital data storage and output capability.

1.3 This practice is applicable to the determination of steel phase transformation behavior under both isothermal and continuous cooling conditions.

1.4 This practice includes requirements for obtaining metallographic information to be used as a supplement to the dilatometry measurements.

1.5 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.6 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E3 Guide for Preparation of Metallographic Specimens

E112 Test Methods for Determining Average Grain Size

E407 Practice for Microetching Metals and Alloys

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *diametrical linear engineering strain*—the strain, either thermal or resulting from phase transformation, that is determined from a change in diameter as a result of a change in temperature, or over a period of time, and which is expressed as follows:

$$e_D = \Delta d/d_0 = (d_1 - d_0)/d_0$$

3.1.2 *hypoeutectoid steel*—a term used to describe a group of carbon steels with a carbon content less than the eutectoid composition (0.8 % by weight).

3.1.3 *longitudinal linear engineering strain*—the strain, either thermal or resulting from phase transformation, that is determined from a change in length as a result of a change in temperature, or over a period of time, and which is expressed as follows:

$$e_L = \Delta l/L_0 = (l_1 - l_0)/l_0$$

3.1.4 *steel phase transformation*—during heating, the crystallographic transformation from ferrite, pearlite, bainite, martensite or combinations of these constituents to austenite. During cooling, the crystallographic transformation from austenite to ferrite, pearlite, bainite, or martensite or a combination thereof.

3.1.5 *volumetric engineering strain*—the strain, either thermal or resulting from phase transformation, that is determined from a change in volume as a result of a change in temperature, or over a period of time, and which is expressed as follows:

$$e_V = \Delta v/v_0 = (v_1 - v_0)/v_0$$
$$e_V \approx 3e_L \approx 3e_D$$

3.2 *Symbols:*

e_L = longitudinal linear engineering strain

e_D = diametrical linear engineering strain

e_V = volumetric engineering strain

Δl = change in test specimen length

l_1 = test specimen length at specific temperature or time, or both

l_0 = initial test specimen length

Δd = change in test specimen diameter

d_1 = test specimen diameter at specific temperature or time, or both

[1] This practice is under the jurisdiction of ASTM Committee A01 on Steel, Stainless Steel and Related Alloys and is the direct responsibility of Subcommittee A01.13 on Mechanical and Chemical Testing and Processing Methods of Steel Products and Processes.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

***A Summary of Changes section appears at the end of this standard**

d_0 = initial test specimen diameter
Δv = change in test specimen volume
v_1 = test specimen volume at a specific temperature or time, or both
v_0 = initial test specimen volume
Ac_1 = the temperature at which austenite begins to form on heating
Ac_3 = the temperature at which the transformation of ferrite to austenite is complete on heating
M_s = the temperature at which the transformation of austenite to martensite starts during cooling

4. Summary of Practice

4.1 This practice is based upon the principle that, during heating and cooling of steels, dimensional changes occur as a result of both thermal expansion associated with temperature change and phase transformation. In this practice, sensitive high-speed dilatometer equipment is used to detect and measure the changes in dimension that occur as functions of both time and temperature during defined thermal cycles. The resulting data are converted to discrete values of strain for specific values of time and temperature during the thermal cycle. Strain as a function of time or temperature, or both, can then be used to determine the beginning and completion of one or more phase transformations.

5. Significance and Use

5.1 This practice is used to provide steel phase transformation data required for use in numerical models for the prediction of microstructures, properties, and distortion during steel manufacturing, forging, casting, heat treatment, and welding. Alternatively, the practice provides end users of steel and fabricated steel products the phase transformation data required for selecting steel grades for a given application by determining the microstructure resulting from a prescribed thermal cycle.

5.1.1 There are available several computer models designed to predict the microstructures, mechanical properties, and distortion of steels as a function of thermal processing cycle. Their use is predicated on the availability of accurate and consistent thermal and transformation strain data. Strain, both thermal and transformation, developed during thermal cycling is the parameter used in predicting both microstructure and properties, and for estimating distortion. It should be noted that these models are undergoing continued development. This process is aimed, among other things, at establishing a direct link between discrete values of strain and specific microstructure constituents in steels. This practice describes a standardized method for measuring strain during a defined thermal cycle.

5.1.2 This practice is suitable for providing data for computer models used in the control of steel manufacturing, forging, casting, heat-treating, and welding processes. It is also useful in providing data for the prediction of microstructures and properties to assist in steel alloy selection for end-use applications.

5.1.3 This practice is suitable for providing the data needed for the construction of transformation diagrams that depict the microstructures developed during the thermal processing of steels as functions of time and temperature. Such diagrams provide a qualitative assessment of the effects of changes in thermal cycle on steel microstructure. Appendix X2 describes construction of these diagrams.

5.2 It should be recognized that thermal and transformation strains, which develop in steels during thermal cycling, are sensitive to chemical composition. Thus, anisotropy in chemical composition can result in variability in strain, and can affect the results of strain determinations, especially determination of volumetric strain. Strains determined during cooling are sensitive to the grain size of austenite, which is determined by the heating cycle. The most consistent results are obtained when austenite grain size is maintained between ASTM grain sizes of 5 to 8. Finally, the eutectoid carbon content is defined as 0.8 % for carbon steels. Additions of alloying elements can change this value, along with Ac_1 and Ac_3 temperatures. Heating cycles need to be employed, as described below, to ensure complete formation of austenite preceding strain measurements during cooling.

6. Ordering Information

6.1 When this practice is to be applied to an inquiry, contract, or order, the purchaser shall so state and should furnish the following information:
6.1.1 The steel grades to be evaluated,
6.1.2 The test apparatus to be used,
6.1.3 The specimen configuration and dimensions to be used,
6.1.4 The thermal cycles to be used, and
6.1.5 The supplementary requirements desired.

7. Apparatus

7.1 This practice is applicable to several types of commercially available high-speed dilatometer apparatus, which have certain common features. These include the capabilities for: heating and cooling a steel specimen in vacuum or other controlled atmosphere; programmable thermal cycles; inert gas or liquid injection for rapid cooling; continuous measurement of specimen dimension and temperature; and digital data storage and output. The apparatus differ in terms of method of specimen heating and test specimen design.

7.1.1 *Dilatometer Apparatus Using Induction Heating*—The test specimen is heated by suspending it inside an induction-heating coil between two platens as shown schematically in Fig. 1. Cooling is accomplished by a combination of controlled reduction in heating current along with injection of inert gas onto the test specimen. Dimensional change is measured by a mechanical apparatus along the longitudinal axis of the test specimen, and temperature is measured by a thermocouple welded to the surface of the specimen at the center of the specimen length. For this apparatus, only Type R or S thermocouples should be used.

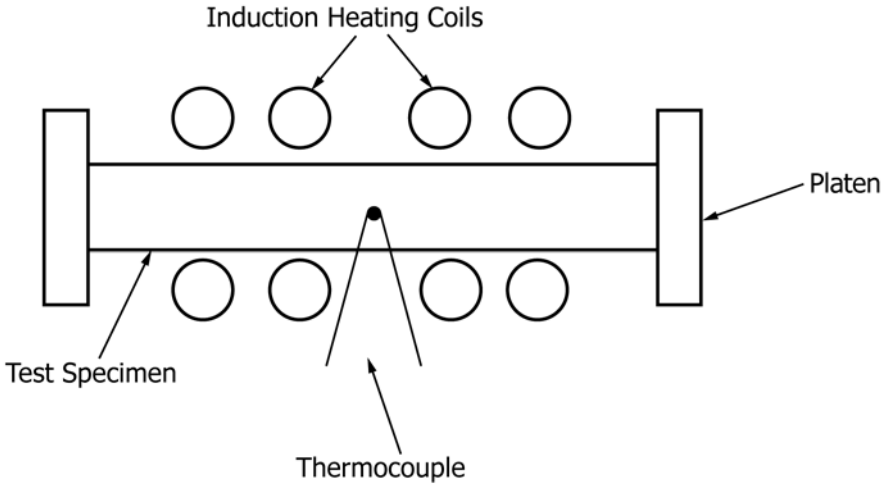


FIG. 1 Schematic of Transformation Testing Using Induction Heating

7.1.2 *Dilatometer Apparatus Using Resistance Heating*[3]—The test specimen is supported between two grips as shown schematically in Fig. 2, and heated by direct resistance heating. Cooling is accomplished by a combination of controlled reduction in heating current along with injection of inert gas onto the test specimen or internal liquid quenching. Dimensional change is measured along a diameter at the center of the test specimen length, and temperature is measured by a thermocouple welded to the surface of the specimen at the center of the specimen length. Dimensional change can be measured by either mechanical or non-contact (laser) dimension measuring apparatus. Temperature measurement can be made using Type K, Type R, or Type S thermocouples.

8. Test Specimens and Sampling of Test Specimens

8.1 *Test Specimens*—The test specimens to be used with each type of test equipment shall be selected from those shown in Figs. 3-5.

8.1.1 *Dilatometers Apparatus Using Induction Heating*—The specimens to be used with this type of apparatus are shown in Fig. 3. The solid specimens may be used for all thermal cycling conditions. The hollow specimens may also be used for all thermal cycling conditions. The hollow specimens will achieve the highest cooling rates when gas quenching is employed.

8.1.2 *Dilatometer Apparatus Using Resistance Heating*[3]—The specimens for use with this type of apparatus are shown in Figs. 4 and 5. The specimen with the reduced center section (Fig. 4) allows for internal cooling of the specimen ends by either liquid or gas. The solid specimen shown in Fig. 5 may be used for all thermal cycling conditions. The hollow specimen shown in Fig. 5 may also be used for all thermal cycling conditions. The hollow specimens will achieve the highest cooling rates when quenching is employed.

8.2 *Sampling*—Test specimens may be obtained from any steel product form, including steel bar, plate, and sheet and strip products. Care should be exercised to avoid the effects of metallurgical variables, such as chemical segregation, in determining where test specimens are obtained from a product form. Procedures have been designed that offer the advantage of equivalency of strain determination using specimens from both

[3] The sole source of supply of the apparatus known to the committee at this time is Dynamic Systems Incorporated, Postenkill, NY. If you are aware of alternative suppliers, please provide this information to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee [1], which you may attend.

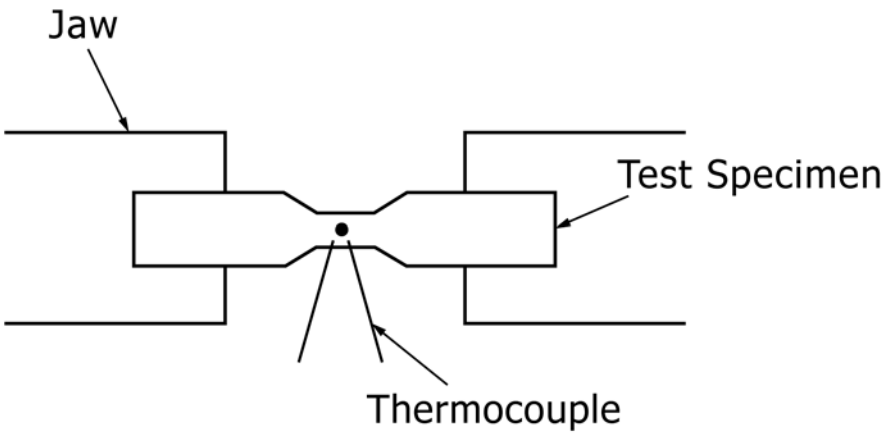
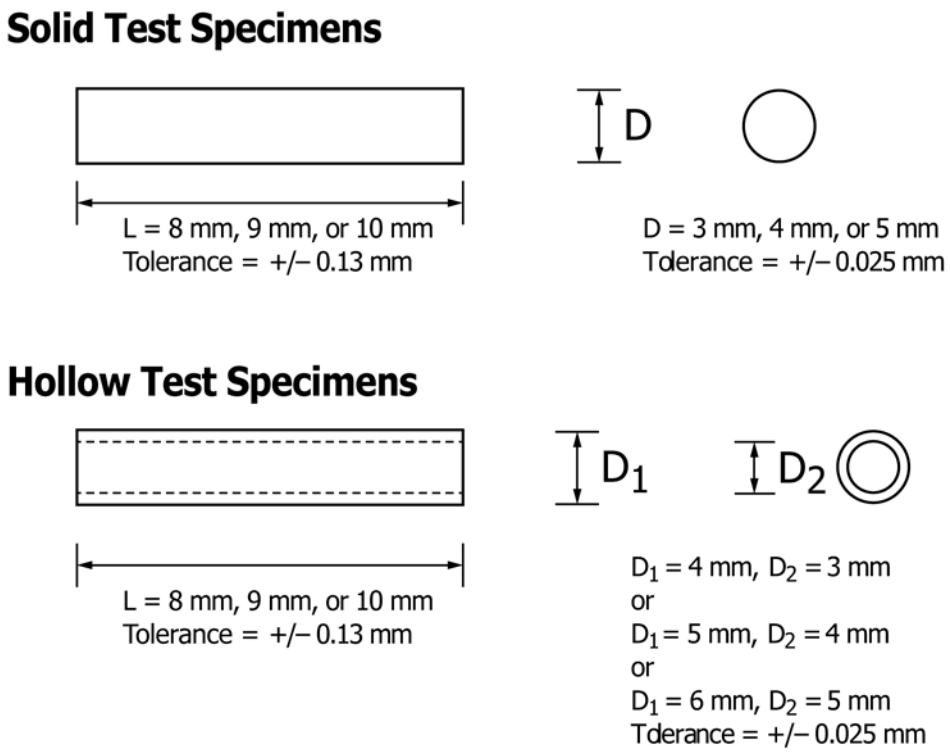
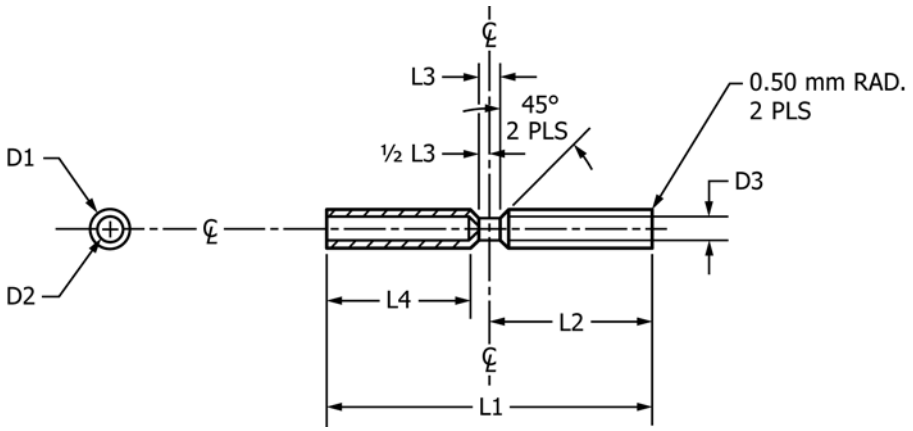


FIG. 2 Schematic of Transformation Testing Using Resistance Heating



NOTE 1—All machining surface finishes being 0.8 μm RMS

FIG. 3 Test Specimens for Induction Heating Apparatus



NOTE 1—All machining surface finishes being 0.8 μm RMS

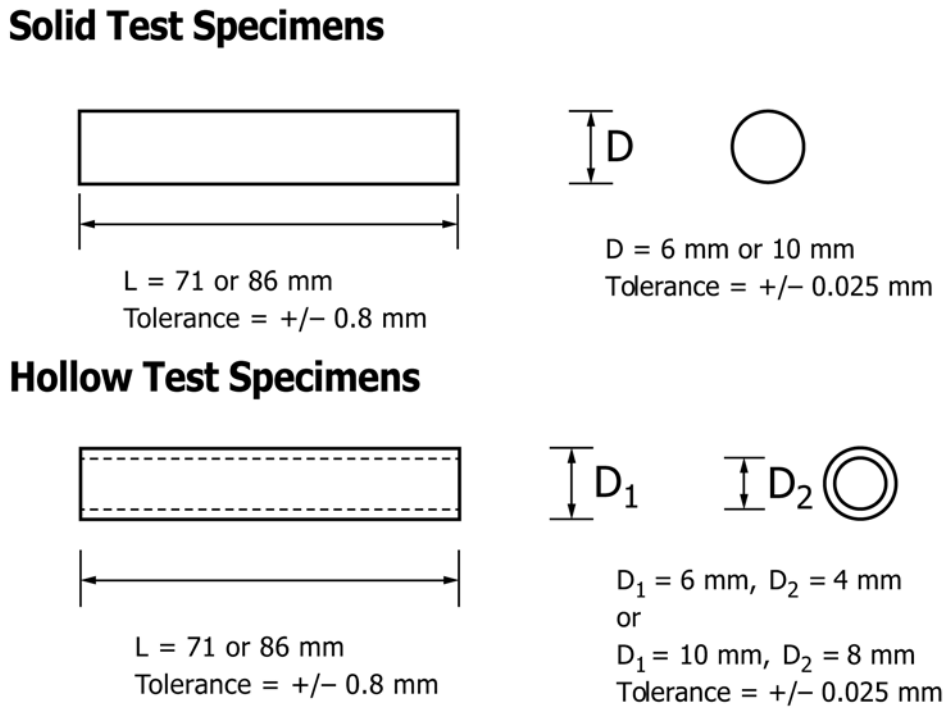
Test Specimen Dimension Guide Table

Specimen Length, L1 ± 0.10 (mm)	Specimen Half Length, L2 ± 0.05 (mm)	Reduced Section Length, L3 ± 0.025 (mm)	Reduced Section Diameter, D3 ± 0.025 (mm)	OD at Grip End, D1 ± 0.025 (mm)	ID at Grip End, D2 ± 0.025 (mm)	Grip End Drill Depth, L4 ± 0.05 (mm)
90	45	6	6	10	6.3	40
84	42	6	6	10	6.3	37
84	42	5	5	10	6.3	37

FIG. 4 Test Specimens with Reduced Center Section for Resistance Heating Apparatus

types of apparatus described in 7.1.1 and 7.1.2. For equivalency of strain, the orientation of the longitudinal axis of test specimens for induction heating apparatus should be at 90 degrees to the longitudinal axis of specimens for resistance heating.

8.2.1 *Example Sampling for Steel Bar Product Forms*—Where material thickness permits, a selected test specimen should be machined from the mid-radius position. Where material thickness is insufficient to permit machining a selected test specimen from the mid-radius position but sufficient to



NOTE 1—All machining surface finishes being 0.8 µm RMS.

Test Specimen Dimension Guide Table

Specimen Length, L1 ± 0.10 (mm)	Specimen Half Length, L2 ± 0.05 (mm)	Reduced Section Length, L3 ± 0.025 (mm)	Reduced Section Diameter, D3 ± 0.025 (mm)	OD at Grip End, D1 ± 0.025 (mm)	ID at Grip End, D2 ± 0.025 (mm)	Grip End Drill Depth, L4 ± 0.05 (mm)
90	45	6	6	10	6.3	40
84	42	6	6	10	6.3	37
84	42	5	5	10	6.3	37

FIG. 5 Test Specimens for Resistance Heating Apparatus

permit machining the test specimen from the mid-diameter position, the test specimen may be obtained from the mid-diameter position. In all cases, material thickness must be sufficient to permit machining a fully dimensioned test specimen.

8.2.1.1 *Dilatometer Apparatus Using Induction Heating*—The test specimens are to be machined with the longitudinal axis of the test specimen perpendicular to the rolling direction of the bar. Fig. 6 shows example orientations.

8.2.1.2 *Dilatometer Apparatus Using Resistance Heating*—The test specimens are to be machined with the longitudinal axis of the test specimen parallel to the rolling direction of the bar. Fig. 6 shows example orientations.

9. Calibration

9.1 *Apparatus and Components*—Individually calibrate the temperature, time (sampling rate), and length change signals according to appropriate manufacturer's recommendations.

9.2 *Use of Standard Reference Material*—To ensure accurate test results, a calibration procedure must be followed which involves using the apparatus to measure strain as a function of temperature for a standard reference material. A test specimen should be prepared from a standard reference material for which thermal expansion data has been documented. The test specimen should be heated to 1000°C ± 5°C, at a nominal rate of 1°C/s, held at temperature for 60 s and then cooled at a nominal rate of 1°C/s to room temperature. This is to be followed by a second thermal cycle whereby the test specimen is heated to 1000°C ± 5°C, at a nominal rate of 10°C/s and then cooled at a nominal rate of 10°C/s to room temperature. The appropriate specimen dimension is to be continuously measured during each thermal cycle.

9.3 *Standard Reference Material*—The standard reference material recommended for calibration is high purity nickel (99.995 %).

9.4 *Calibration Curves*—Curves of strain versus temperature are to be prepared from the dimension measurements for both thermal cycles. Such curves must compare favorably with an accepted strain-temperature curve for the selected reference material. A recommended strain-temperature curve for high purity nickel is shown in Fig. 7. The band describes an error band of ±3 % strain calculated at 800°C. The curves determined by the user of this practice must fall within this band.

10. Procedure

10.1 *Test Environment*—All thermal cycles employed shall be carried out under a vacuum of 1.33×10^{-3} PA maximum.

10.2 *Test Specimen Preparation*—Test specimens are to be machined from steel product stock to the dimensions and

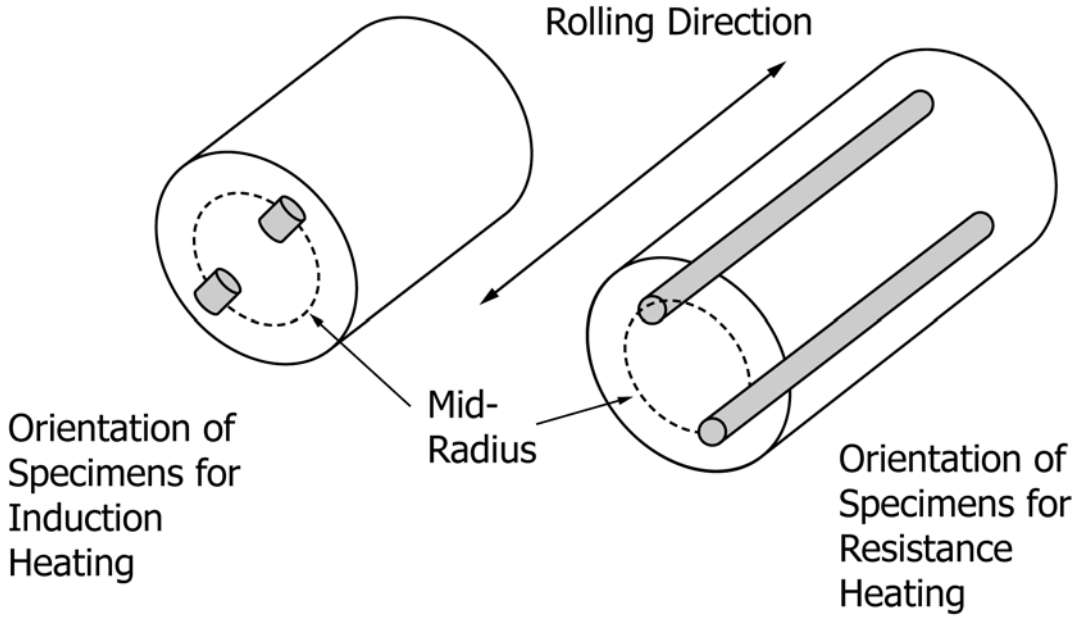


FIG. 6 Machining Orientations for Bar Steel Product Forms

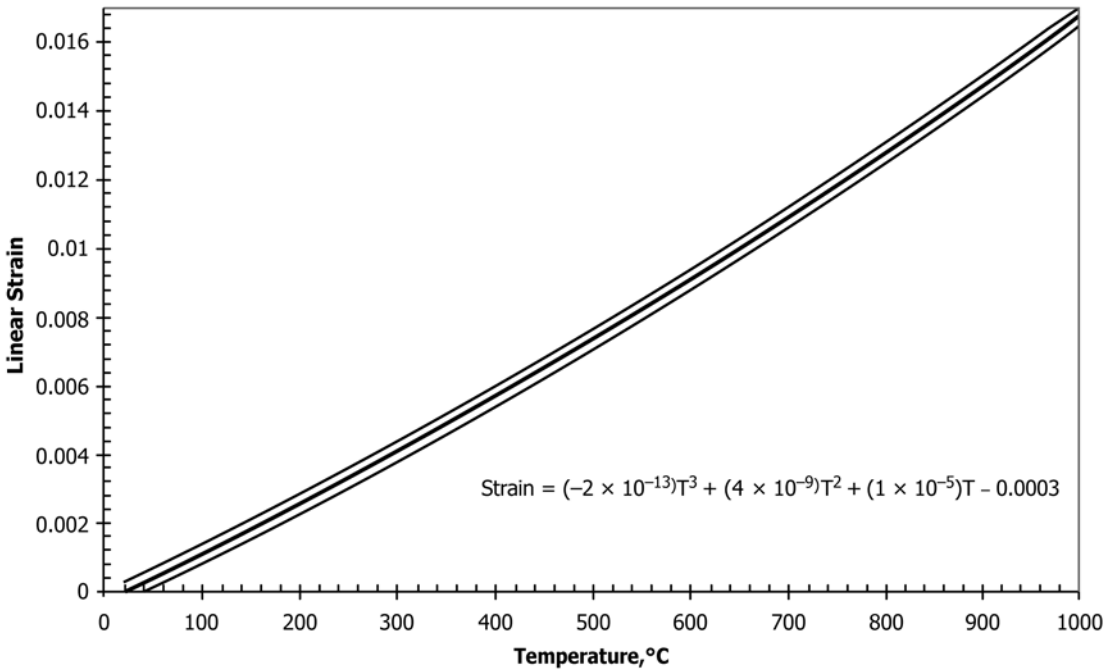


FIG. 7 Strain versus Temperature for High Purity Nickel

tolerances shown in Figs. 3-5. Test specimens must be properly prepared and thermocouples must be properly attached to the specimens to ensure reliable and repeatable results. Care must also be taken to properly install specimens in the dilatometer apparatus. Procedures for specimen preparation and installation are described below.

10.2.1 *Dilatometer Apparatus Using Induction Heating*—The test specimen must be degreased using a solvent such as acetone or methyl alcohol. To achieve a proper connection of the thermocouple to the test specimen, the surface of the test specimen, at the point of thermocouple attachment, must be lightly sanded using a 600 grit paper to remove any surface oxide. Significant removal of metal must be avoided. The length and diameter of the test specimen must then be measured with a micrometer. The diameter must be measured at a point away from the sanded region to avoid any error in measuring actual diameter. These measurements will aid in verifying dimensional changes that occur during thermal cycling. The thermocouple must then be welded to the surface of the test specimen. Sheathed thermocouple wires with a nominal diameter of 0.13 mm must be used. The thermocouple wires must be individually welded to the specimen surface at

the point of attachment, and separated from each other by two wire diameters. The welding procedure must result in a secure attachment of each wire, but must avoid excessive melting of either wire. This will weaken the interface between unwelded and welded sections of each wire, and could also cause metal flow between the wires, which will result in an erroneous voltage output from the thermocouple. The specimen must be then placed between the holding platens in the dilatometer apparatus giving attention to achieving the best possible alignment. For maximum accuracy, the length change measuring device, for example, the linear variable differential transformer (LVDT), must be adjusted so that it will not pass through its natural zero point during thermal cycling. Once the specimen is in place, the insulating sheaths on the thermocouple wires must be moved along the thermocouple wires until they contact the specimen surface. This will prevent undesirable heat loss, and will avoid contact between the two thermocouple wires. Once the specimen has been subjected to thermal cycling as described below, and has been removed from the apparatus, the thermocouple sheaths may be moved away from the test specimen surface, and the thermocouple leads cut away. The specimen diameter and length must then be re-measured as described above.

10.2.2 *Dilatometer Apparatus Using Resistance Heating*—The test specimen must be degreased using a solvent such as acetone or methyl alcohol. To achieve a proper connection of the thermocouple to the test specimen, the surface of the test specimen, at the point of thermocouple attachment, must be lightly sanded using a 600 grit paper to remove any surface oxide. Significant removal of metal is to be avoided. The diameter of the test specimen must then be measured with a micrometer. The diameter must be measured at a point away from the sanded region to avoid any error in measuring actual diameter. These measurements will aid in verifying dimensional changes that occur during thermal cycling. The thermocouple must then be welded to the surface of the test specimen. Thermocouple wires with a nominal diameter of 0.2 mm must be used. The thermocouple wires must be individually welded to the specimen surface at the mid-span of the specimen and perpendicular to the longitudinal axis of the specimen. The wires must be separated from each other by five wire diameters. A ceramic tube is used to cover each wire at the junction to minimize heat loss to the environment. The welding procedure must result in a secure attachment of each wire, but must avoid excessive melting of either wire. This will weaken the interface between unwelded and welded sections of each wire, and could also cause metal flow between the wires, which will result in an erroneous voltage output from the thermocouple. The specimen must then be inserted into the jaws or grips of the apparatus, with the thermocouple located at the mid-span, and aligned such that the thermocouple will not interfere with the dimension measuring apparatus. The specimen must then be tightened in the jaws or grips while maintaining alignment of the thermocouple and positioning of the specimen. The jaws or grips must be tightened evenly to avoid mechanical stresses on the test specimen. The jaws or grips must allow for free expansion and contraction of the test specimen during heating and cooling. Once the specimen has been subjected to thermal cycling as described below, and has been removed from the apparatus, the thermocouple leads may be cut away. The specimen diameter must then be re-measured as described above.

10.3 *Test Specimen Stabilization*—Remove residual stresses and stabilize the position of the test specimen within the apparatus. Carry out a preliminary thermal treatment of each test specimen prior to measuring dimensional change during thermal cycling. This treatment consists of heating the test specimen to 650°C ± 5°C, at a nominal rate of 10°C/s, holding the test specimen at 650°C for 10 min and then cooling to room temperature at a cooling rate not exceeding 20°C/s. The test specimen must not be removed from the apparatus prior to conducting dimensional measurements.

10.4 *Determination of Critical Temperatures*—The critical temperatures, Ac_1 and Ac_3, shall be determined from a test specimen separate from those used for other transformation measurements. The thermal cycle to be used is to heat the test specimen to 700°C ± 5°C, at a nominal rate of 10°C/s. Heating must then be continued at a nominal rate of 28°C/h while strain is continuously measured until the Ac_1 and Ac_3 temperatures are identified. Strain increases with temperature until Ac_1 is reached. Ac_1 is the temperature at which austenite begins to form on heating, and strain will begin to decrease with increasing temperature. Ac_3 is the temperature at which the transformation from ferrite to austenite is completed and strain will again begin to increase with increasing temperature. Both critical temperatures can be determined from changes in the slope of a strain versus temperature plot as shown in Fig. 8.

10.5 *Continuous Cooling Transformation Data Sets*—Each continuous cooling transformation thermal cycle shall consist of heating a test specimen to an austenitizing temperature of Ac_3 + 50°C ± 5°C at a nominal rate of 10°C/s. The test specimen shall be held at the austenitizing temperature for 5 min and then cooled to room temperature at nominal rates of 0.05 to 250°C/s. Data must be sampled and recorded at the rate of one dimension measurement per degree Celsius. Linear cooling rates are to be utilized to the maximum cooling rate possible. At cooling rates where linear control is not possible, the rate at 700°C is to be reported along with the cooling time between 800°C and 500°C. A separate test specimen shall be used for each thermal cycle. At least twelve specimens must be evaluated to completely characterize each steel composition over the range of cooling rates cited above. The specific cooling rates used may be selected at the discretion of the user of this practice. Replicate tests may be desirable if uncertainty in one or more test results is encountered.

10.6 *Isothermal Transformation Data Sets*—Each isothermal transformation thermal cycle shall consist of heating a test specimen to an austenitizing temperature of Ac_3 + 50°C ± 5°C, at a nominal rate of 10°C/s. The test specimen shall be held at the austenitizing temperature for 5 min and then quenched to the isothermal hold temperature. A cooling rate of at least 175°C/s shall be employed. During the quench, the temperature of the test specimen must not undershoot the isothermal hold temperature by more than 20°C, and must be stabilized at the isothermal hold temperature within 2 s. The temperature of

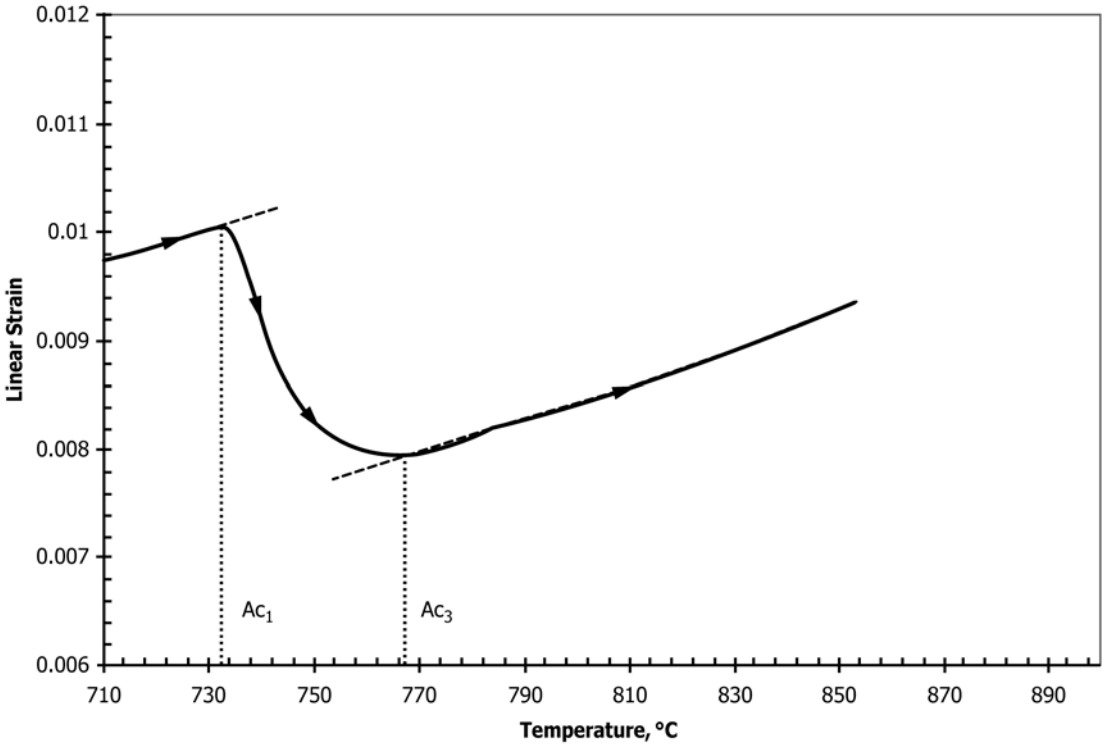


FIG. 8 Strain versus Temperature Showing Determination of Ac_1 and Ac_3 Temperatures

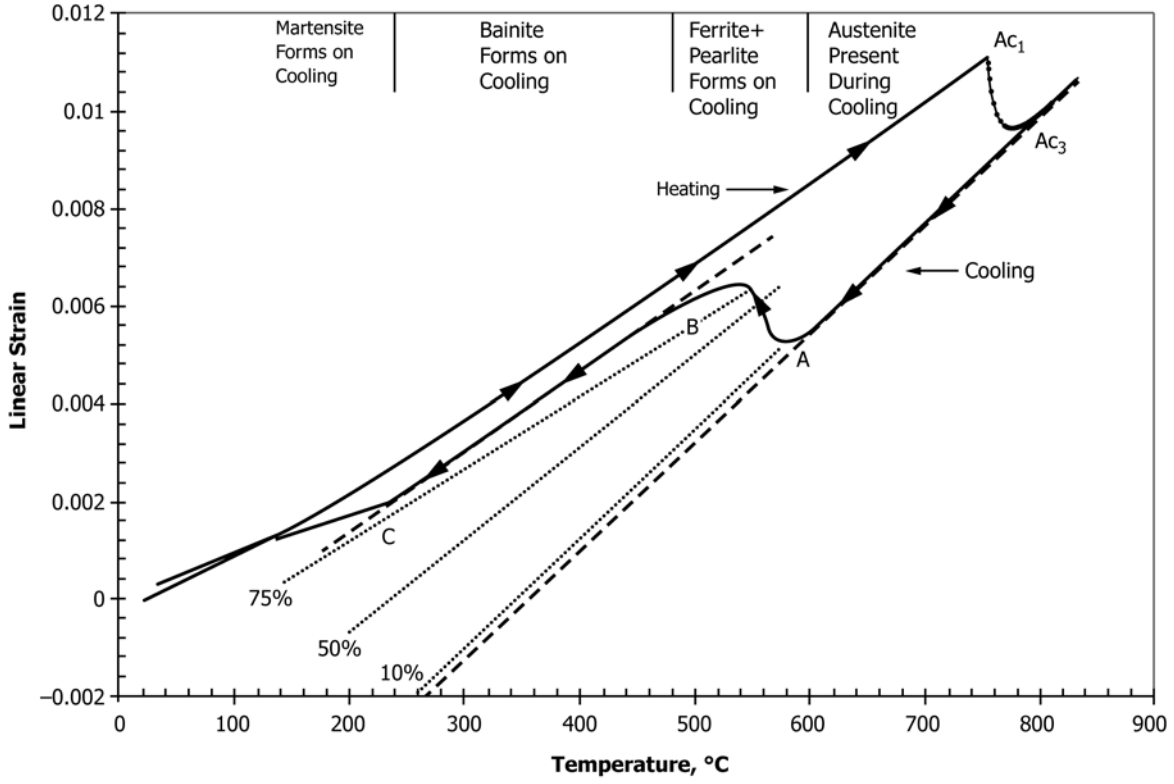


FIG. 9 Strain versus Temperature for Continuous Cooling

the specimen must be maintained within ±5°C of the isothermal hold temperature during dimension measurement. The test specimen is to be held at the isothermal hold temperature, and dimension continuously measured until transformation is 100 % complete. The specimen must then be quenched to room temperature. Data must be sampled and recorded at a rate of at least five dimension measurements per second. Complete transformation is defined as the time at which maximum

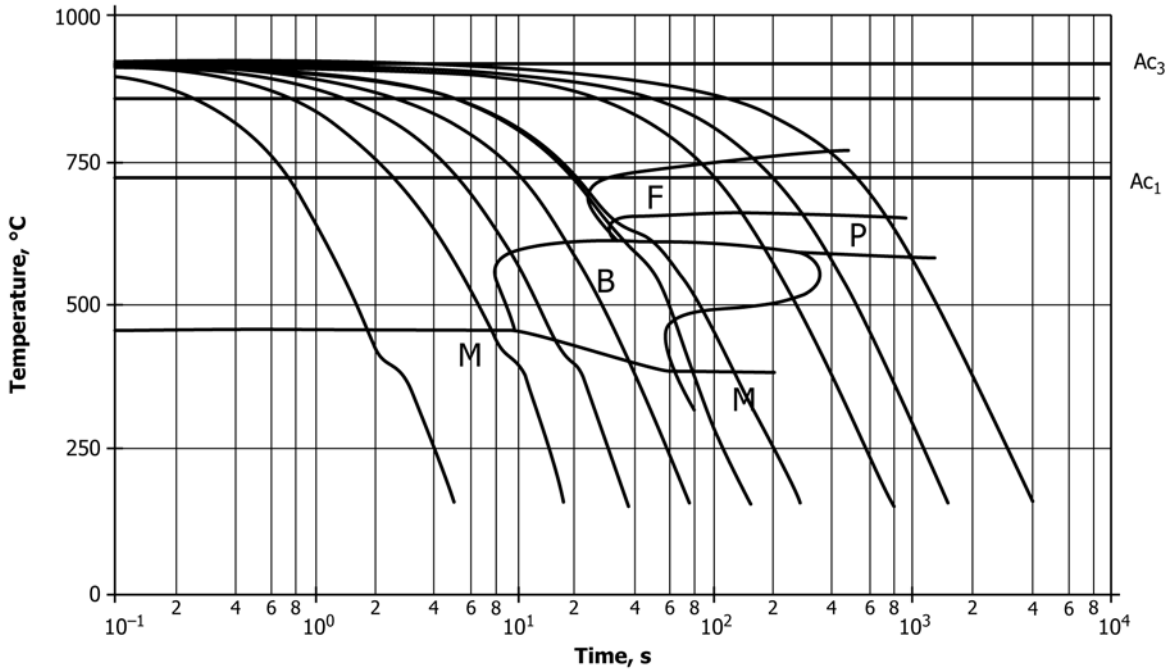


FIG. 10 Example Continuous Cooling Transformation Diagram

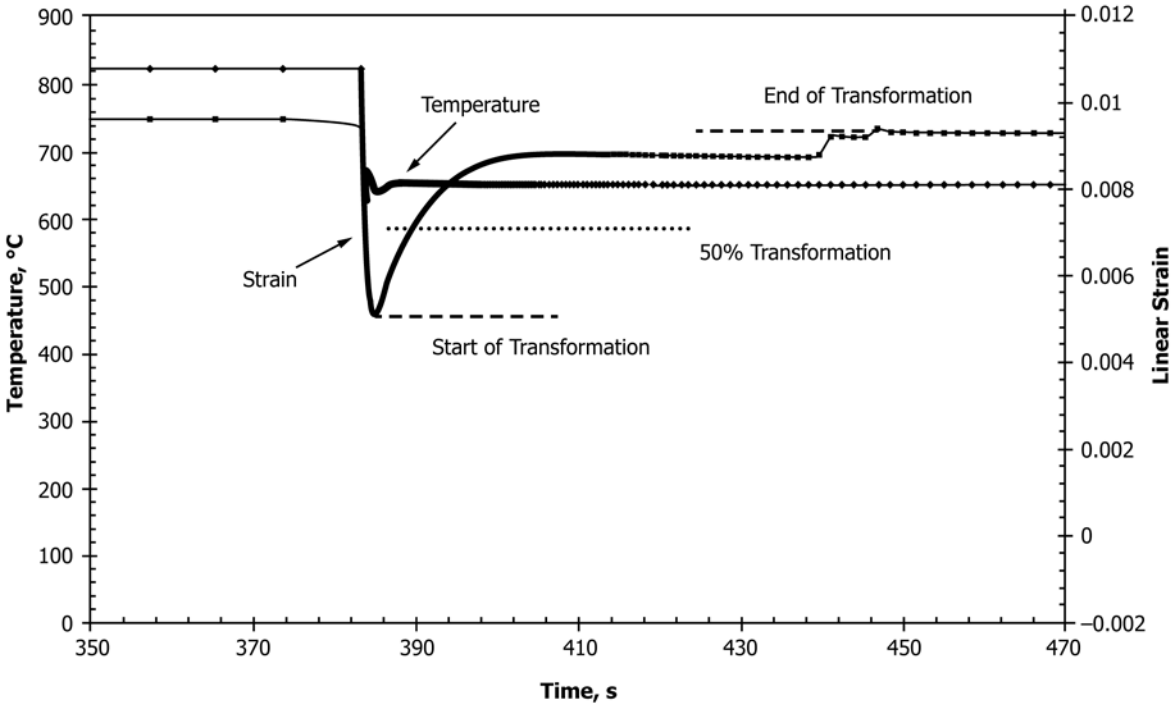


FIG. 11 Strain and Temperature versus Time for Isothermal Transformation

dimensional change has occurred. A separate test specimen shall be employed for each thermal cycle. At least twelve specimens must be evaluated over a temperature range between Ac_1 and room temperature to completely characterize each steel composition. Specific isothermal hold temperatures may be selected at the discretion of the user of this practice. Replicate tests may be desirable if uncertainty in one or more test results is encountered. The purpose of quenching from the austenitizing temperature is to avoid transformation of austenite prior to the isothermal hold temperature, and to permit measurement of the start, progress, and finish of transformation at constant temperature. It should be recognized that some steel grades might exhibit very rapid transformation kinetics at certain temperatures, and partial transformation of austenite

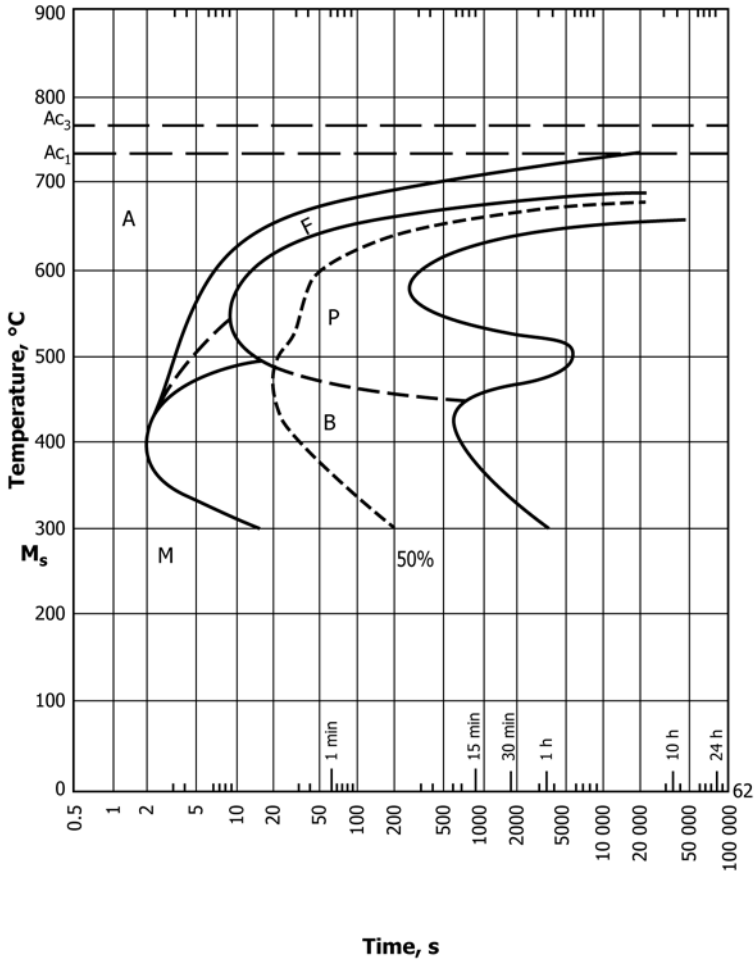


FIG. 12 Example Isothermal Transformation Diagram

may occur during the quench. Under these circumstances uncertainty in determining the start of transformation may be encountered.

11. Calculation

11.1 The dimensional changes measured for each value of time and temperature recorded during thermal cycling are to be converted to values of average engineering strain as described below.

11.2 *Dilatometer Apparatus Using Induction Heating*—Linear longitudinal engineering strain is calculated by the following equation:

$$e_L = \Delta l/l_0 = (l_1 - l_0)/l_0 \quad (1)$$

where:

l_0 = initial test specimen length, and
l_1 = length of the test specimen at corresponding values of time and temperature.

11.3 *Dilatometer Apparatus Using Resistance Heating*—Linear diametrical engineering strain is calculated by the following equation:

$$e_D = \Delta d/d_0 = (d_1 - d_0)/d_0 \quad (2)$$

where:

d_0 = initial test specimen diameter, and
d_1 = final diameter of the test specimen at corresponding values of time and temperature.

11.4 *Determination of Thermal versus Transformation Strain*—Thermal strain is the strain developed only as a result of temperature change. Transformation strain results from crystallographic phase changes. Each type of strain can be established as follows:

11.4.1 *Isothermal Transformation Measurements*—Thermal strain occurs during the quench from the austenitizing temperature to the isothermal hold temperature. Thermal strain is determined from the change in test specimen length or diameter, which occurs between the austenitizing temperature and the isothermal hold temperature. At the isothermal hold temperature, the transformation strain is determined from the change in test specimen length or diameter between the time at which transformation begins and the time at which transformation ends.

11.4.2 *Continuous Cooling Transformation Measurements*—Thermal strain occurs during the cooling from the austenitizing temperature to room temperature. The thermal

strain between any two temperatures is determined from the change in test specimen length or diameter between the two temperatures. The transformation strain occurs over the temperature range during which transformation takes place. The transformation strain is determined from the change in test specimen length or diameter between the temperature at which transformation begins and the temperature at which transformation ends.

11.5 *Volumetric Strain*—Under certain circumstances it may be desirable to estimate volumetric strain from linear strain. Volumetric strain may be estimated as follows:

$$e_V = \Delta v/v_0 = (v_1 - v_0)/v_0 \quad (3)$$

$$e_V \approx 3e_L \approx 3e_D$$

12. Report

12.1 The report for each thermal cycle shall include the following information (an appendix is attached to this practice which provides a suggested format for reporting the information):

12.1.1 Identification of the steel grade.

12.1.2 The chemical composition of the steel.

12.1.3 Additional information regarding the condition of the steel at the time of testing if applicable. Such information should include prior austenite grain size, initial microstructure, and processing information.

12.1.4 Type of thermal cycle used in measuring transformations, for example, continuous cooling or isothermal.

12.1.5 Brief description of the apparatus used in the test.

12.1.6 Description of the test specimen used in the test and orientation relative to the steel product form.

12.1.7 Numerical time-temperature-strain data. A row and column format is suggested to permit ease of entry into predictive computer models and to permit construction of transformation diagrams. An example format is included with this practice as an appendix item. The format used, however, may be left to agreement between the person or organization conducting the test and the person or organization which contracts for the test.

12.1.8 Photomicrographs obtained from metallographic examination.

13. Reproducibility of Results

13.1 Reproducibility of results obtained from the use of this practice will depend upon both test material variations and variations in equipment capability. This practice relates to the measurement of phase transformations in steel, which is not an isotropic material. It is subject to variations in chemical composition within a given section of a product form, and these variations will affect measured results. The types of high-speed dilatometer apparatus used in the testing described in this practice have evolved over several years. As a result, reproducibility of results will depend upon the response of temperature, time (sampling rate), and length change signals of given apparatus to changes in specimen test temperature and dimension during thermal cycling.

14. Keywords

14.1 dilatometry; phase transformations; steel; strain

SUPPLEMENTARY REQUIREMENTS

This requirement only applies when specified by the person or organization contracting for this practice.

S1. Metallography

S1.1 *Test Specimens*—The microstructure of test specimens shall be documented. Practices E3 and E407 shall be followed. The details of the metallographic examination, including the number, type (longitudinal, transverse, and so forth), and locations (mid-thickness, quarter-thickness, and so forth) of the specimens shall be as agreed between the purchaser and the testing organization.

NOTE 1—In addition to documenting all of the products of transformation of austenite and the amount of retained austenite in the microstructure, it may be desirable to determine the prior austenite grain size of one or more specimens. Procedures for this determination are described in Test Methods E112 as well as in other documents referenced at the end of this practice. It may also be desirable to check the specimens for decarburization. If decarburization is detected in a specimen, a new specimen should be tested. It may be desirable to document the initial microstructure prior to performing transformation measurement procedures using a separate specimen that has not been subjected to transformation measurement procedures.

APPENDIXES

(Nonmandatory Information)

X1. SUGGESTED FORMAT FOR REPORTING DATA

X1.1 The following is a suggested format for reporting transformation strain data as a function of time and temperature. It may be used as a guide or a template.

1] FILE NAMING. Tab delimited text with file names having the following structure:

<steel grade> _ <prior austenite grain size> _ <LABORATORY NAME> _ <cooling rate in °C/s or isothermal hold temperature in °C> _ <completion date in MMDDYY> _ <run number>.DAT

An example file name is as follows:

1050_9_ABC_600_091102_3.DAT

In this example, Laboratory ABC performed an isothermal test on September 11, 2002, and the file is for the third 600°C run performed on that day. The material has a prior austenite grain size of ASTM 9. Caps are used for the laboratory name and the file extension, DAT.

2] PEDIGREE. The pedigree must be in a fixed format with the same number of lines in each file. The format below is to have two entries on every line. The first entry is the data specific to the test, while the second entry explains what the first entry is. The second entry should be typed in exactly the same way in the data files. There should be no blanks. Put NA for "Not Applicable" if there is no information to provide.

Rows 1–2: File Name And Material Provider
- row 1: repeat of file name FILE NAME
- row 2: material supplier SOURCE

Rows 3–18: Material Chemical Composition In Weight Percent.

Each line should have two entries separated by a space. The first entry should be the number value of the weight percent of the element. The second entry should be the letter designation (for example, C, Mn) for the element. If a given element is not present, type in a "0.0" for this element. There should be no blanks.
- row 3: number C
- row 4: number Mn
- row 5: number Si
- row 6: number Ni
- row 7: number Cr
- row 8: number Mo
- row 9: number S
- row 10: number Co
- row 11: number Cu
- row 12: number P
- row 13: number V
- row 14: number Ti
- row 15: number Nb
- row 16: number B
- row 17: number N
- row 18: number Al
- row 19: number O

Rows 20–21: Additional Material Information.
- row 20: number STEEL HEAT IDENTIFICATION NUMBER
- row 21: number ASTM PRIOR AUSTENITE GRAIN SIZE NUMBER

Use "NA" for "Not Applicable" if there is no entry.

Rows 22–26: Specimen Preparation Information.
- row 22: remarks on material PREPARATION REMARKS
- row 23: transverse or longitudinal specimen geometry TRANS or LONG
- row 24: machining location QUARTER/MID THICKNESS/ RADIUS
- row 25: machining source MACHINING SOURCE
- row 26: specimen type SOLID/HOLLOW

Use "NA" for "Not Applicable" if there is no entry.

Rows 27–29: Apparatus Information.
- row 27: apparatus used for test INDUCTION/ RESISTANCE
- row 28: test laboratory LABORATORY NAME
- row 29: remarks on platform REMARKS

Use "NA" for "Not Applicable" if there is no entry.

Rows 30–33: Post-Test and Author Information.
- row 30: metallography YES/NO
- row 31: metallography archive identification IDENTIFICATION
- row 32: remarks on test performed TEST REMARKS
- row 33: author of this file AUTHOR

Use "NA" for "Not Applicable" if there is no entry.

3] DATA STRUCTURE. First line after the pedigree should be a single header that describes each of the columns. The labels of each column, in order, should read exactly as follows (do not use quotation marks or commas):

TIME (s) TEMPERATURE (°C) LINEAR STRAIN STRESS (MPa)

There should be four columns in total. Data should be entered in each column. Dimension measurements should be converted to linear engineering strain. To do this, simply divide the dilatometer measurement by the original room temperature specimen length or diameter as required.

X2. GRAPHICAL ESTIMATES OF TRANSFORMATION PROGRESS AND CONSTRUCTION OF TRANSFORMATION DIAGRAMS

X2.1 Estimates of the progress of transformation of austenite can be made through the use of strain-temperature plots for continuous cooling transformation conditions, and through the use of strain-time plots for isothermal transformation conditions. It should be emphasized that graphical estimates of transformation progress are of a qualitative nature only. The discrete temperature-time-strain data are needed for computer modeling. These estimates can be used however to construct transformation diagrams that exhibit the microstructures that can be expected from various thermal cycling conditions.

X2.2 *Progress of Transformation Under Continuous Cooling Conditions*—The progress of austenite transformation under continuous cooling conditions can be estimated from plots of strain versus temperature. Each continuous cooling test carried out as described in 10.5 results in discrete corresponding values of time, temperature, and strain. Strain is plotted versus temperature for each continuous cooling cycle using the strain and temperature data as described in 12.1.7. An example of the resulting graph is shown in Fig. 9. As can be seen in Fig. 9, strain increases with temperature during heating until the Ac_1 temperature is reached. Strain then decreases during austenite formation until the Ac_3 temperature is reached, where upon strain then increases with temperature. During cooling of the austenite, strain decreases approximately linearly until transformation starts. Once begun, the start and finish of the formation of various microstructure constituents can be estimated from inflections in the slope of the cooling portion of the strain-temperature plot. These are shown as points A, B, and C in Fig. 9. In this example, the continuous transformation of austenite to several different constituents is shown, and the constituents are annotated along the top of the figure. The progress of austenite transformation may be estimated in each strain-temperature plot using a method involving the construction of constant percent transformation lines such as the 10 %, 50 %, and 75 % transformation lines shown in Fig. 9. The method makes the assumption that the progress of transformation is linearly dependent on strain. The austenite cooling curve is first extrapolated to low temperatures, as shown by the dashed line extending from Point A in Fig. 9. At each of several temperatures, the difference in strain between the heating curve and the extrapolated austenite cooling curve is calculated. This difference is multiplied by a selected percentage and added to the value of strain shown by the extrapolated austenite cooling curve. This gives a value of strain at each temperature representing the selected percent of austenite transformed. This results in a locus of points representing a constant percent of austenite transformed. This series of calculations can be repeated for any desired percentage of transformation. The progress of transformation can be estimated by tracing the cooling curve across the constant transformation lines. It should be noted that the lines are an estimate of the percent austenite transformed, and do not necessarily indicate the final volume fractions of microstructure constituents. Metallographic analysis is recommended to determine the relative amounts of various microstructure constituents once transformation is complete. This entire process is repeated for each continuous cooling cycle used to characterize a given steel grade in order to evaluate transformation behavior as a function of cooling rate. It should be emphasized that the microstructure constituents formed will vary with cooling rate as well as with steel composition. In some cases, only ferrite plus pearlite may form, and in other cases only martensite may form, and so forth. Also, for some steel grades, transformation may not be continuous, but may halt for a temperature interval. Thus the position and magnitude of the inflection points on the cooling portion of the strain-temperature curve will vary.

X2.3 *Construction of Continuous Cooling Transformation Diagrams*—Continuous cooling transformation diagrams may be constructed from strain-temperature plots, and the associated temperature-time cooling curves. All of the cooling rates used to characterize a given steel grade are plotted as temperature versus time curves on a semi-logarithmic graph as shown in Fig. 10. The cooling curves should commence at the vertical axis from the Ac_3 temperature to eliminate any variability in cooling time due to differences in austenitizing temperature. From the strain-temperature curve for each cooling rate (see X2.1), the start and finish temperatures for the formation of each microstructure constituent are marked on the corresponding temperature-time curve. The locus of points representing the start and finish of the formation of the same microstructure constituent are joined together by a single line. The resulting diagram, shown in Fig. 10 describes the range of cooling rates over which a given microstructure constituent is formed.

X2.4 *Progress of Transformation Under Isothermal Conditions*—The progress of austenite transformation under isothermal conditions can be estimated from plots of strain versus time and temperature versus time. Each isothermal test carried out as described in 10.6 results in discrete corresponding values of time, temperature, and strain. Both strain and temperature are plotted versus time for each isothermal cycle using the strain, temperature, and time data as described in 12.1.7. An example of such a graph is shown in Fig. 11. A stable value of strain and temperature is exhibited during austenitizing. Both temperature and strain rapidly decrease during the quench to the isothermal hold temperature. Both temperature and strain are stabilized at the isothermal hold temperature, and strain then increases while temperature remains constant as transformation proceeds. The start and finish of transformation can be estimated by drawing horizontal lines tangent to the point of minimum and maximum strain respectively. The example shown is for the formation of a two microstructure constituents as indicated by an initial increase in strain, a short period of stable strain, and a second increase in strain. If multiple constituents are formed, additional inflections in the strain time plot will be observed between the start

and finish of transformation. The progress of austenite transformation can be estimated by taking the difference between the strain at the end of transformation and the strain at the beginning of transformation, and multiplying this difference by a selected percentage. The resulting value is then added to the strain at the start of transformation. The strain value obtained represents the percent austenite transformed. Fig. 11 shows the 50 % transformation of austenite as a horizontal line between the start and finish of transformation. The progress of transformation can be estimated by tracing the strain-time curve across the constant transformation lines. It should be noted that the lines are an estimate of the percent austenite transformed, and do not necessarily indicate the final volume fractions of microstructure constituents. Metallographic analysis is recommended to determine the relative amounts of various microstructure constituents once transformation is complete. This entire process is repeated for each isothermal cycle used to characterize a given steel grade in order to evaluate transformation behavior as a function of transformation temperature and time. It should be emphasized that the microstructure constituents formed will vary with steel composition. Thus the position and magnitude of the inflection points on the strain-time curve will vary.

X2.5 *Construction of Isothermal Transformation Diagrams*—Isothermal transformation diagrams can be constructed from plots of strain versus time and temperature versus time taken from all of the isothermal cycles used to characterize a given steel grade. The start and finish times for each microstructure constituent at each isothermal temperature are plotted as points on a semi-logarithmic temperature versus time graph as shown in Fig. 12. The locus of points representing the start and finish of the formation of the same microstructure constituent are joined together by a single line. The resulting diagram, shown in Fig. 12 describes the range of transformation times over which a given microstructure constituent is formed at various temperatures.

REFERENCES

(1) *ASM Handbook*, Eighth Edition, Volume 1, American Society for Metals, 1961.

(2) Determination of the Ferritic or Austenitic Grain Size of Steel and Ferrous Materials, DIN Specification 50801.

(3) Atkins, M., *Atlas of Continuous Cooling Transformation Diagrams for Engineering Steels*, American Society for Metals, 1980 .

(4) Delbart, C., Constant, A., and Clerc, A., *Courbes de Transformation des Aciers de Fabrication Francaise*, L'Institut de Recherches de la Siderurgie, Saint Germain-en-Laye, 1956.

(5) Schmitz, H-P, ThyssenKrupp Stahl, Standarization Efforts in Europe, Private Communication, 2001.

SUMMARY OF CHANGES

Committee A01 has identified the location of selected changes to this standard since the last issue (A1033 – 04) that may impact the use of this standard. (Approved April 1, 2010.)

(1) Added Section 1.5 on units.

(2) Removed "(0.02 in. RAD.)" from Fig. 4.

(3) Revised 10.1