Methods of Determining Hardenability of Steels — SAE J406c

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METHODS OF DETERMINING HARDENABILITY OF STEELS—SAE J406c

Report of Iron and Steel Division approved January 1942 and completely revised by Iron and Steel Technical Committee December 1977.

Scope This SAE Standard prescribes the procedure for making hardenability tests and recording results on shallow and medium hardening steels, but not deep hardening steels that will normally air harden.

Included are procedures using the 1 in (25 mm) standard hardenability end quench specimen for both medium and shallow hardening steels, Surface-Area-Center (SAC) method for shallow hardening steels, subsize method for bars less than 1 1/4 in (32 mm) in diameter, and methods for determining carburized hardenability.

Any hardenability tests made under other conditions than those given in this SAE Standard will not be deemed standard and will be subject to agreement between supplier and user. Whenever check tests are made, all laboratories concerned must arrange to use the same alternate procedure with reference to test specimen and method of grinding for hardness testing.

For routine testing of the hardenability of successive heats of steel required to have hardenability within certain limits, it is sufficient to designate hardenability simply in terms of distance from the quenched end to the point at which a certain hardness is obtained. This designation is also adequate for comparing steels of different compositions to see whether they have similar hardenability.

Hardenability limits for specifying steel in this manner are obtained by measuring the hardenability of a steel which has proved satisfactory for the use intended. The hardenability test may be used in this way as an empirical test.

Hardenability data may be used to estimate hardnesses obtainable with any steel in new machine parts not yet in production and not similar to any parts on which production experience is available. Various hardenability application methods are described in the selected references in the Bibliography. It appears none of these methods are precise, but these are often useful for estimation purposes. Final correlation on actual parts is necessary.

HARDENABILITY TEST FOR MEDIUM HARDENING STEELS

Introduction—This method covers the procedure for determining the hardenability of steel by the end quench test for both the 1 in (25 mm) standard specimen and the sub-size test specimen. Also included are charts for plotting hardenability test results and for predicting hardness U curves in various sizes of rounds.

Test Specimen—The test specimen is a 1 in (25 mm) diameter cylinder 4 in (102 mm) long with means for hanging it in a vertical position for end quenching. Fig. 1 shows a test specimen in the fixture ready for quenching illustrating the preferred form of specimen. Fig. 2 gives the details of the preferred test specimen. Fig. 3 is an example of an optional specimen which provides the same diameter and approximately the same length and will provide satisfactory heat transfer characteristics.

The bar from which the specimen is machined shall be a forged or rolled 1 1/4 in (32 mm) round representing the full cross-section of the product. A cast specimen may be used in lieu of a rolled or forged specimen, except in the case of boron-treated steels: experience has shown that cast specimens of boron-treated steels give erratic results. The option of using as-cast specimens for non-boron steels, deletion of normalizing prior to heating for end-quenching or modification of other testing details shall be negotiated between supplier and user. It is of primary importance that the specimen represent the full cross section of the ingot since test specimens from a portion of the bloom, billet, or bar may introduce factors tending to affect the reproducibility of results. The condition of this hot formed bar shall be such that there is no decarburization on the 1 in (25 mm) specimen machined from it. If any test specimen shows obvious defects or flaws, the specimen should be discarded and a new specimen obtained.

Optional Specimen Preparation—The following method is satisfactory for most purposes, but for check testing against specifications, the method in the preceding paragraph is mandatory.

The test specimen shall be machined from the center of the bar in the case of sections from 1 1/4 to 2 in (32–51 mm) round or square. In sections over 2 in (51 mm), the test specimen shall be machined from one-half of

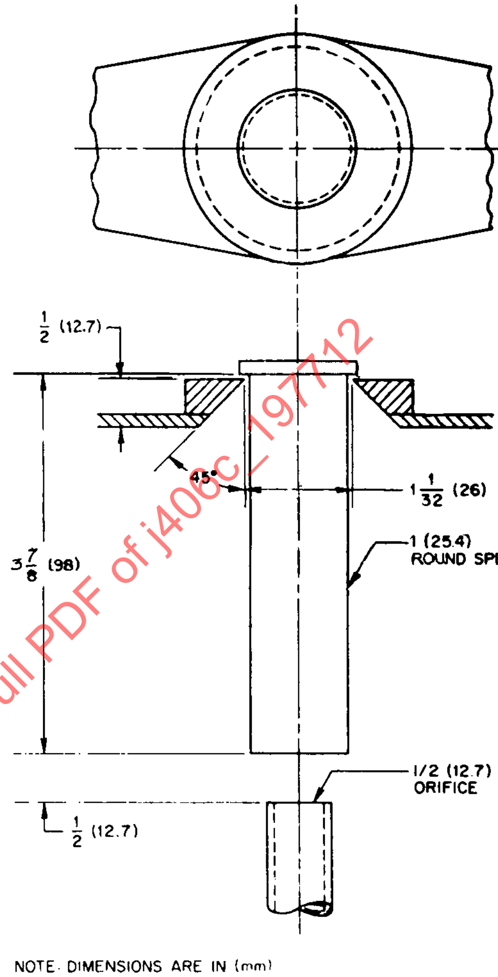


FIG. 1—HARDENABILITY TEST SPECIMENS IN FIXTURE FOR WATER QUENCHING

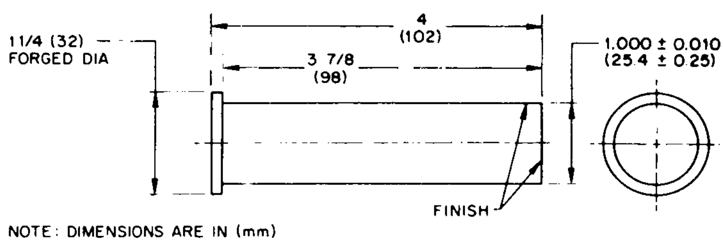


FIG. 2—PREFERRED TEST SPECIMEN

the section with the axis of the specimen located at a point halfway between the center and surface of the bar and marked to identify the position of the test bar with reference to the original bar. The hardness readings shall be made on the two sides of the test specimen corresponding to a position in the bar approximately halfway between the center and the surface.

Normalizing Prior to Heating for End Quenching—The forged or rolled round shall be normalized prior to machining the test specimen. This is of importance since the structure of material before the final austenitizing treatment may materially affect the hardening characteristics. In order that variations in prior structure may be controlled as much as possible, the normalizing temperature listed in Table 1 should be used. The steel shall be held at such temperature for 1 h and cooled in still air. If the normalized specimen is too hard, it may be given a short time temper at about 100°F (55°C) below the Ac_1 to improve machinability. Cast specimens usually are not normalized before quenching. The record of hardenability test results must always state the prior thermal history of the specimen tested.

Heating for End Quenching—The specimen shall be heated to the austenitizing temperature shown in Table 1. The specimen shall be placed in a furnace which is at the specified temperature and shall be held at this temperature for 30 min.[1] It is necessary to determine by means of a thermocouple the time required for a test specimen to come to temperature to be sure that the above heating time and temperature requirements are met.

[1] In production testing, slightly longer times up to 35 min may be used without appreciably affecting results.

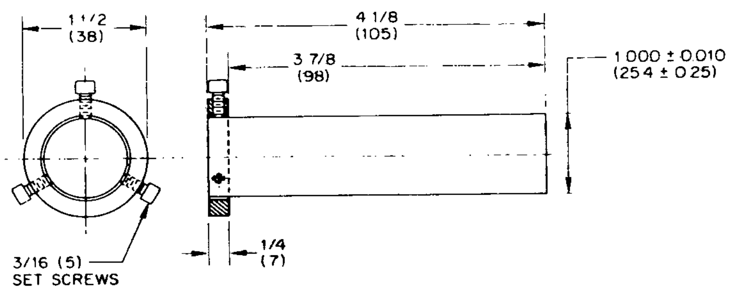


FIG. 3—OPTIONAL TEST SPECIMEN

TABLE 1—NORMALIZING AND QUENCHING TEMPERATURES[a,b] APPLICABLE TO STEEL ORDERED TO END-QUENCH HARDENABILITY REQUIREMENTS

Max Ordered Carbon Content, %	Normalizing Temperature °F	Normalizing Temperature °C	Austenitizing Temperature °F	Austenitizing Temperature °C
Steel Series 1000, 1300, 1500, 4000, 4100, 4300, 4600, 5000, 5100, 6100[c], 8600, 8700, 9400				
Up to 0.25 incl	1700	925	1700	925
0.26 to 0.36 incl	1650	900	1600	870
0.37 and over	1600	870	1550	845
Steel Series 4800, 9200				
Up to 0.25 incl	1700	925	1550	845
0.26 to 0.36 incl	1650	900	1500	815
0.37 and over	1600	870	1475	800
0.50 and over (9200)	1650	900	1600	870

[a] A variation of ±10°F (±5°C) from the above temperature is permissible.

[b] When testing H steels, the normalizing and austenitizing temperatures should be the same as for the equivalent standard steels. EXAMPLES: For 8622 H, the normalizing and austenitizing temperature should be the same as for SAE 8622; for 4032 H (carbon 0.30/0.37), the temperature should be the same as for SAE 4032 (carbon 0.30/0.35).

[c] Normalizing and austenitizing temperatures shall be 50°F (30°C) higher for the 6100 series.

It is important that while heating the test specimen care be taken that its environment is such that practically no scaling or decarburization takes place on the end to be quenched. An adequately protective atmosphere in the furnace is suitable for meeting the above requirements. In the absence of such atmospheres, the specimen shall be inserted in a suitable container which maintains a nonoxidizing atmosphere. Placing fine graphite powder or cast iron chips in the base of the container are two methods of preventing oxidation of the quenched end.

Fig. 4 illustrates a type of container which has been used with success. However, any similar type will be satisfactory.

Quenching—The test piece shall be placed on a fixture so that a column of water at a temperature of 40–85°F (5–30°C) may be directed against the bottom face of the piece. The column of water passing through an opening 1/2 in (13 mm) in diameter shall rise to a free height of 2 1/2 in (63 mm) above the opening. The fixture shall be dry at the beginning of each test.

In performing the test, the water supply shall be shut off with a quick-opening valve and the hot specimen placed over the water pipe so that the bottom of the specimen is 1/2 in (13 mm) from the opening of the water pipe and the water shall then be turned on. The time between removal of the specimen from the furnace and the beginning of the quench shall be not more than 5 s. The sample shall remain on the fixture for at least 10 min. A condition of still air shall be maintained around the piece during cooling.

Hardness Measurement—Two flats 180 deg apart shall be ground to a minimum depth of 0.015 in (0.38 mm) along the entire length of the bar and Rockwell C hardness measurements made along the length of the bar. Deviation from the standard depth can affect reproducibility of results; and correlation with cooling rates in quenched bars.

The preparation of the two flats must be carried out with considerable care. They should be mutually parallel and the grinding done in such a manner that no change of the quenched structure takes place. Very light cuts (less than 0.0005 in (0.013 mm) with water cooling and a coarse, soft grinding wheel are recommended to avoid heating the specimen. In order to detect tempering due to grinding, the flat shall be etched as follows.

Two etchant solutions are used:

No. 1—5% nitric acid (concentrated) and 95% water by volume.

No. 2—50% hydrochloric acid (concentrated) and 50% water by volume.

Wash the sample in hot water. Etch in solution No. 1 until black. Wash in hot water. Immerse in solution No. 2 for 3 s and wash in hot water. Dry in air blast.

The presence of lighter or darker areas indicates that hardness and structure have been altered in grinding. All structural changes caused by grinding shall be removed before hardness tests are made. This may be accomplished by resurfacing and again etching, or new flats may be prepared.

When hardness readings are made, the test specimen rests on one of its flats on an anvil firmly attached to the hardness machine. It is important

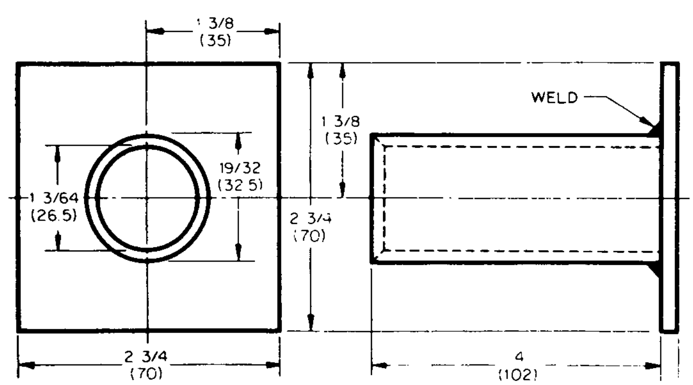


FIG. 4—HARDENING BAR PROTECTING FIXTURE TO BE CONSTRUCTED OF HEAT RESISTING ALLOY

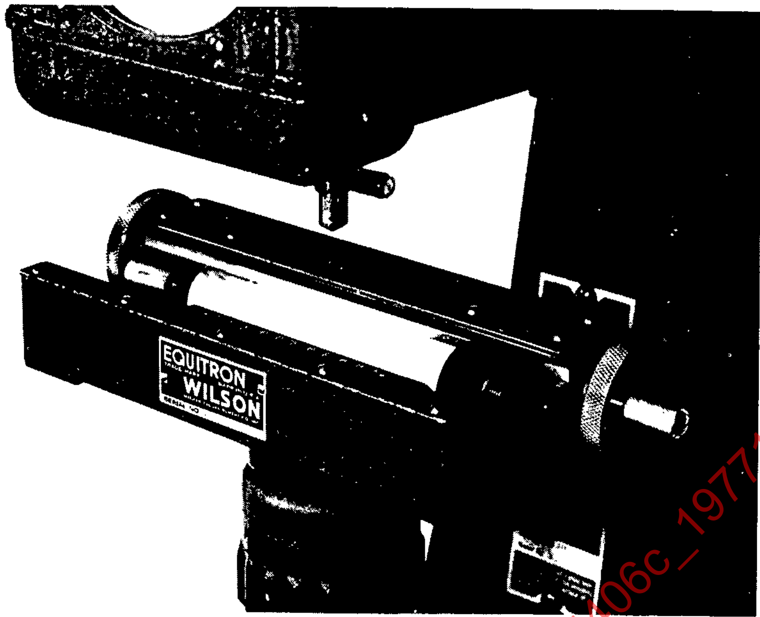


FIG. 5—COMMERCIALLY AVAILABLE FIXTURE FOR POSITIONING SPECIMEN FOR HARDNESS INDENTATIONS

that no vertical movement be allowed when the major load is applied. The anvil must be constructed to move the test specimen past the penetrator in accurate steps of 1/16 in (1.6 mm). Fig 5 is an example of a fixture commercially available which provides for the controlled movement of the specimens.

The Rockwell tester should be checked against standard test blocks before testing the hardenability bar. It is recommended that the test block be interposed between the specimen and the indenter to check the seating of the indenter and the specimen simultaneously.

Care must be exercised in registering the point of the indenter with the hardened end of the specimen, as well as providing for accurate spacing between indentations. A low power measuring microscope is suitable for use in determining the distance from the quenched end to the center of the first impression and in checking the distance from center to center of the succeeding impressions. It has been found that with reasonable operating care and a well-built fixture, it is practical to locate the center of the first impression 0.0625 ±0.003 in (1.6 ±0.075 mm) from the quenched end. The variations between spacings should be even smaller. Obviously, it is more important to position the indenter accurately when testing low hardenability steels than when testing high hardenability steels. The positioning of the indenter should be checked with sufficient frequency to provide assurance that accuracy requirements are being met. In cases of lack of reproducibility or of differences between laboratories, indenter spacing should be measured immediately.

Readings shall be taken in steps of 1/16 in (1.6 mm) for the first 1 in (25 mm). Distance between readings for the last 2 in (51 mm) may be at the discretion of the tester. When a flat on which readings have been made is used as a base, the burrs around the indentation shall be removed by grinding unless a fixture is used which has been relieved to accommodate the irregularities due to the indentations.

Hardness readings should be made on one flat, or preferably, two flats 180 deg apart. Testing on two flats will assist in the detection of errors in specimen preparation and hardness measurement. If the two probes on opposite sides differ by more than 4 HRC points at any one position, the test should be repeated on new flats, 90 deg from first two flats. If the retest also has greater than 4 HRC points spread, a new specimen should be tested.

For reporting purposes, hardness readings should be recorded to the nearest integer, with 0.5 HRC values rounded to the next higher integer.

Plotting of Tests—Tests should be plotted on a standard chart prepared for this purpose (Fig. 6) in which the ordinates represent hardness and the

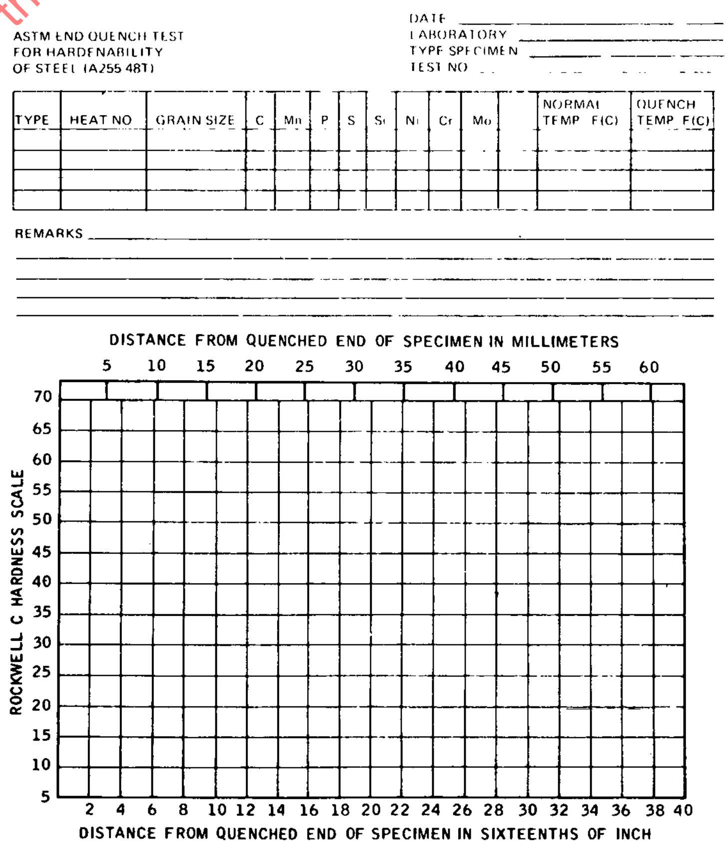


FIG. 6—STANDARD FORM FOR PLOTTING HARDENABILITY CURVES

abscissas represent distance from the quenched end. Readings at identical distances should be averaged and the resultant values used for plotting.

Fig. 6 shows the Standard Form for Plotting Hardenability Curves.

Construction of Hardness U Curves—A chart is also provided for using the hardenability curve to predict hardness U curves in various sized rounds when oil or water quenched. Fig. 7 shows this chart. The curves show the locations in various sizes of rounds where the cooling rates are the same as at various positions along the end-quenched hardenability test bar. It should be noted that these curves assume good heat treatment practice: separation of pieces in the quench and good control of temperature and cleanliness of the quench medium. The ranges given reflect variations found under experimental conditions; under production conditions even wider variations may be found.

Index of Hardenability—The hardenability of steel is usually reported as a series of values of hardness versus distance from the quenched end of the test bar, either in graphical or tabular form. Hardenability may also be designated by the use of either one or the other of the two following codes, the first of which is preferred.

(a) That code which designates a minimum hardness value at a distance specified as J 36 min = 8/16 in (13 mm) or in case of both minimum and maximum limitations may also be specified in terms of Rockwell C hardness at the required distance from the quenched end.

As an example of this method, a hardenability requirement could be specified as J 36 min = 8/16 in (13 mm) or in case of both minimum and maximum restrictions, could be specified as J 36–50 = 8/16 in (13 mm). This means that at the specified distance of 8/16 in (13 mm) from the quenched end the Rockwell C hardness should be a minimum of 36 and a maximum of 50.

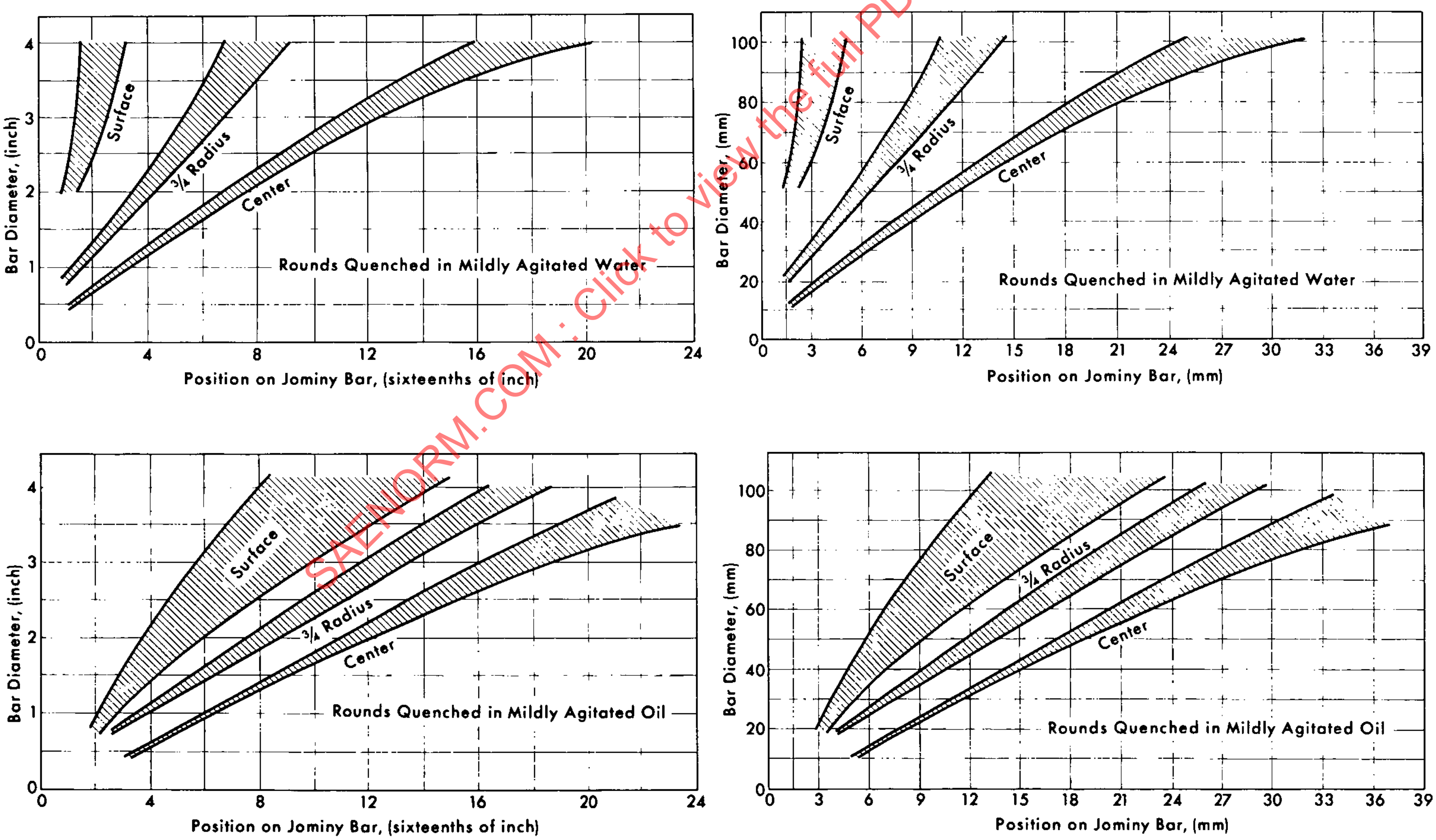
(b) The alternate method would be a code which indicates the distance from the quenched end where the following hardness reference numbers occur. The requirement may be specified as a minimum distance only or as a minimum and a maximum distance at the hardness reference number which applies. Table 2 indicates the hardness reference numbers in terms of Rockwell C values for various carbon contents.

As an example, an alloy steel of 0.34 mean carbon content could be specified to have a hardenability index of J 45 = 4/16 in (6.3 mm) min which means that the minimum requirements of this steel would be 45 HRC at a distance of 4/16 in (6.3 mm) from the quenched end.

If this steel were one having both minimum and maximum curves or limits, the index of hardenability might be specified as J 45 = 4/16–11/16 in (6.3–17 mm).

In addition to the specification in accordance with either of the above two codes, the minimum and maximum hardness at the 1/16 in (1.6 mm) position may be specified. These hardness values should be in agreement with the maximum and minimum carbon content specified.

Subsize Test Specimen—For determining hardenability of steel received in bars less than 1 1/4 in (32 mm) in diameter, the test bar may be made 3/4, 1/2, or 1/4 in (19, 13, or 6.3 mm) diameter, as desired, and end quenched as prescribed for the 1 in (25 mm) round. Modifications in the water orifice are required for quenching cylinders of less than 1 in (25 mm) diameter.



These charts have been revised by a Division 8 task force, to reflect probable variations in actual cooling rates of round bars.

FIG. 7—CORRELATION OF COOLING RATES IN JOMINY BAR AND QUENCHED ROUND BARS

The details of orifices for quenching specimens less than 1 in (25 mm) diameter are given in Table 3.

Because of the greater aircooling effect on test bars less than 1 in (25 mm) diameter and especially in bars smaller than 3/4 in (19 mm) diameter, the cooling rates at various distances from the quenched end will not be the same as in the standard test bar.

Hardness curves from these smaller bars are not comparable with curves from the 1 in (25 mm) diameter specimen. If the standard hardness curve from subsize specimens is needed, it becomes necessary to make actual cooling rate determination on the subsize specimen in question.

HARDENABILITY TESTS FOR SHALLOW HARDENING STEELS

Introduction—This method covers two different tests: the 1 in (25 mm) standard hardenability specimen method, and the SAC hardenability test method. These methods are applicable to carbon and low alloy steels, other than carbon tool steels, and are suitable only for shallow hardening steels which will not harden completely through in 1 in (25 mm) and larger diameters with a water quench.

The 1 in (25 mm) Standard Hardenability Specimen Method

Procedure—The 1 in (25 mm) standard hardenability specimen may be used to determine the hardenability of shallow hardening steels other than the carbon tool steels by a modification in the hardness survey. The procedure in preparing the specimen prior to hardness measurements is that given in the section on Test Procedure for 1 in (25 mm) Standard Hardenability Specimen. An anvil providing a means of very accurately measuring the distance from the quenched end is essential.

Hardness values are obtained from 1/16–1/2 in (1.6–13 mm) from the quenched end in intervals of 1/32 in (0.8 mm). Beyond 1/2 in (13 mm) from the quenched end, the intervals are the same as for the 1 in (25 mm) standard hardenability specimen. For readings to 1/2 in (13 mm) from the quenched end, two hardness traverses are made, both with readings 1/16 in (1.6 mm) apart; one starting at 1/16 in (1.6 mm) and being completed at 1/2 in (13 mm) from the quenched end, and the other starting at 3/32 in (2.4 mm) and being completed at 15/32 in (12 mm) from the quenched end.

Only two flats 180 deg apart need be ground if the mechanical fixture has a grooved bed which will accommodate the indentations on the flat surveyed first. The second hardness traverse is made after turning the bar over. If the fixture does not have such a grooved bed, two pairs of flats should be ground, the flats of each pair being 180 deg apart. The two hardness surveys are made on adjacent flats.

For plotting test results, the Standard Form for Plotting Hardenability Curves (Fig. 6) should be used. Distances for the odd number 1/32 in (0.8 mm) should be estimated with care.

TABLE 2—HARDNESS REFERENCE NUMBERS FOR STEELS OF VARIOUS CARBON CONTENTS

Mean of Ordered Carbon Range	Hardness Reference No., HRC	
	Alloy Steels	Carbon Steels
0.08–0.17	25	–
0.18–0.22	30	25
0.23–0.27	35	30
0.28–0.32	40	35
0.33–0.42	45	40
0.43–0.52	50	45
0.53–0.62	55	50

SAC Hardenability Test Method

Introduction—This method is referred to as the SAC test. The designation SAC means Surface-Area-Center, the area being determined and calculated from a cross section hardness survey of a suitably quenched 1 in (25 mm) diameter cylindrical test specimen.

Sampling—The bar from which the specimen is machined shall be a forged or rolled 1 1/4 in (32 mm) diameter round representing the full cross section of the product. Specimen locations representing other than the full cross section may introduce factors tending to offset reproducibility of results and shall be subject to agreement between steel producer and user.

In all cases, specimens shall be machined from bars of sufficient diameter to ensure freedom from decarburization.

Normalizing Prior to Heating for Quench—The material from which the test specimen is to be machined shall be normalized, holding for 1 h at the appropriate temperature designated in Table 1 followed by cooling in air. The record of hardenability test results must always state the prior thermal history of the specimen tested.

Test Specimens—The test specimen is a 1 in (25 mm) diameter cylinder 4 in (102 mm) long, as shown in Fig. 8. Specimen A is for use with quenching fixture A, Fig. 9, and specimen B is for use with quenching fixture B, Fig. 9.

Heating for Quenching—The specimen shall be heated to the austenitizing temperature shown in Table 1. The specimen shall be held at the specified temperature for 30 min. The furnace chamber shall be muffle type, and the amount of scaling controlled only by standardizing the time of exposure.

Quenching—Frequently SAC test specimens are hand quenched by laboratories that do not have the special quenching fixture shown in Fig. 9. In most cases, hand quenching yields satisfactory results provided the specimen is well agitated during quenching. However, it is recommended that one of the quenching fixtures shown in Fig. 9 be used. The apparatus shall be adjusted so the water flows upward through the top opening to a free height of 2 1/2 in (63 mm) without specimen, guide tube, or basket in place. The water temperature shall be 65–85°F (18–30°C).

The specimen shall be removed from the furnace by gripping near one end with tongs, and it shall then be dropped into the basket or guide tube. Time to remove the specimen from the furnace and drop it into the quenching fixture shall be 5 s max. The specimen shall remain in the quench for 60 s and shall then be removed by lifting out the basket or guide tube and inverting.

Preparation for Hardness Testing—The quenched specimen shall be cut transversely so that the top portion is 2 in (50 mm) long as illustrated in Fig. 10. The test slug can be 1/2–1 in (13–25 mm) long. A suitable soft cutoff wheel shall be used with precaution against heating of the specimen.

The faces of the test slug shall be ground flat and parallel and finished with a grit sufficiently fine to permit satisfactory hardness determination. Four flats shall be ground 0.005–.008 in (0.12–0.20 mm) deep at 90 deg spacing on the cylindrical surface of the test slug.

The test surfaces shall be checked for freedom from tempering by etching as recommended in the section on Hardness Measurement on medium

TABLE 3—ORIFICES FOR QUENCHING SMALL SPECIMENS

Test Bar Dia		Orifice Size		Distance from Orifice to Quenched End of Specimen		Free Height of Water Column	
in	mm	in	mm	in	mm	in	mm
3/4	19	1/2	13	1/2	13	2-1/2	63
1/2	13	1/4	6.3	3/8	9.5	4	102
1/4	6.3	1/8	3.2	1/4	6.3	8	203

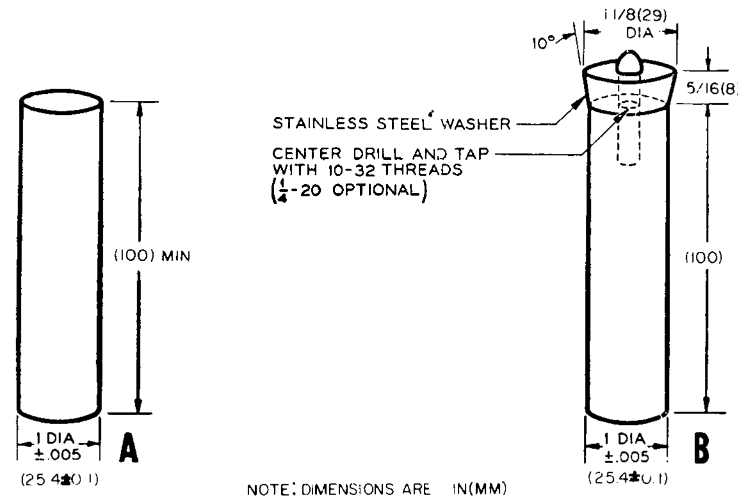


FIG. 8–SAC TEST SPECIMENS

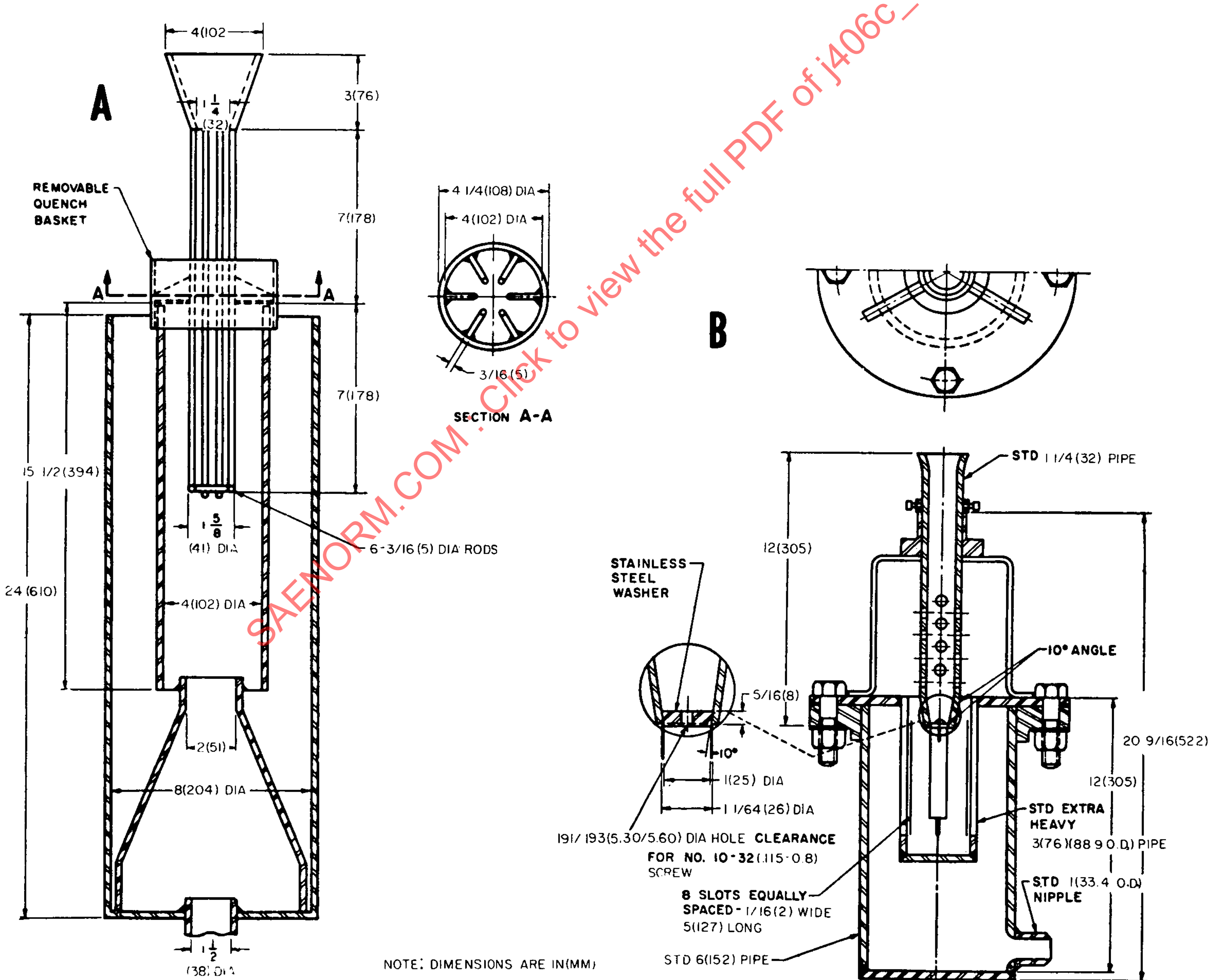


FIG. 9–SAC QUENCHING FIXTURES

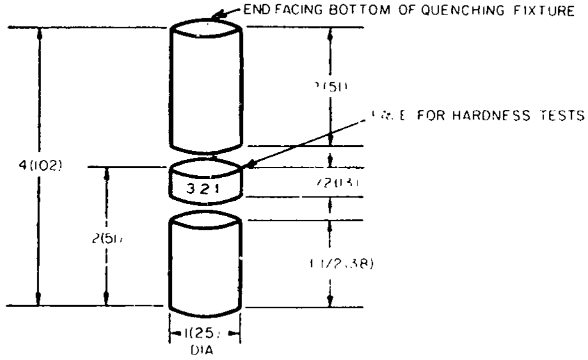


FIG. 10–LOCATION OF TEST SLUG AND OF STAMPED IDENTIFICATION

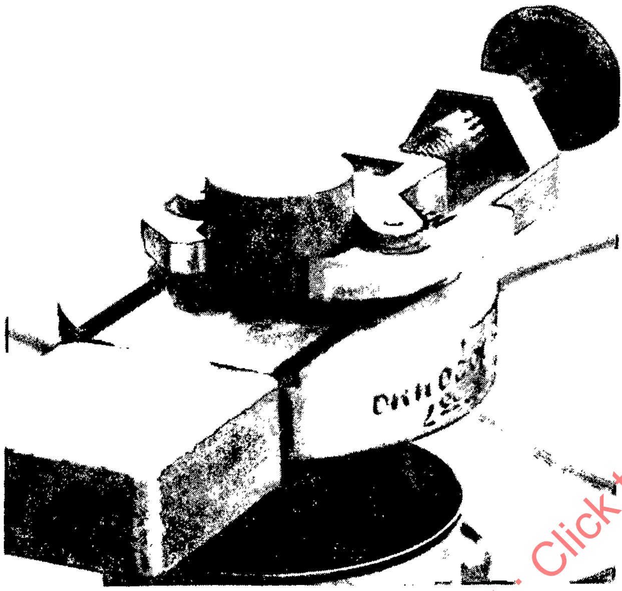
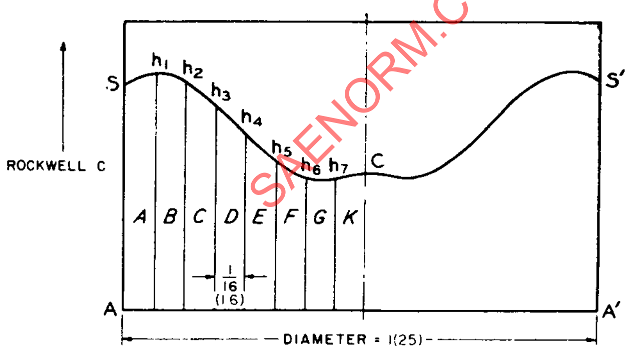


FIG. 11–INDEX FIXTURE



Let S = average surface hardness
h_1, h_2, h_3, and so forth = average hardness at depths indicated
C = average center hardness

Then: area of A $= \frac{S + h_1}{2} \times \frac{1}{16}$ (1.6) area of B $= \frac{h_1 + h_2}{2} \times \frac{1}{16}$ (1.6)

total area = 2 (A + B + C + D + E + F + G + K)

$$= 1/8\,(3.2)\left(\frac{S}{2} + h_1 + h_2 + h_3 + h_4 + h_5 + h_6 + h_7 + \frac{C}{2}\right)$$

NOTE: DIMENSIONS ARE IN (mm)

FIG. 12–SAC ESTIMATION OF AREA

hardening steels. The presence of darkened areas indicates that tempering has taken place and grinding shall be continued until tempering effects are removed.

Hardness Testing–Surface hardness shall be taken on the surfaces of the four ground flats. The average of these readings shall represent the surface hardness.

Face readings shall be obtained by testing at 1/16 in (1.6 mm) increments across two diameters 90 deg removed. A fixture suitable for indexing the specimen is illustrated in Fig. 11. Readings for each comparable distance from the surface shall be averaged. Since only one center reading can be taken, the average center hardness shall be the average of five readings; the center reading and the four readings taken at 1/16 in (1.6 mm) from the center.

If an indexing fixture is not available, the surface to be tested may be lightly scribed with two diameters 90 deg removed, and with seven circles 1/16 in (1.6 mm) removed. Test locations shall be on each circle at the intersection of each of the four radii.

Estimation of Area–*Area* shall be computed by Rockwell Inch (Rockwell millimetre) units, as shown in Fig. 12. Ordinates shall be Rockwell C units starting with Rockwell C of zero. Abscissas shall constitute 1 in (25 mm) max. Areas shall be Rockwell Inches (Rockwell millimetres) under the curve S-s', computed by the total of the trapezoids.

Index of Hardenability–The hardenability (and hardness) of a steel shall be designated by a code known as the SAC number. The code shall consist of a set of three numbers, including first, the surface hardness; second, the Rockwell Inch (Rockwell millimetre) area; and last, the center hardness, each of which shall be determined as herein described. Values shall be rounded to the nearest whole number.

SAC TEST REPORT

DATE ______ TEST NO. ______

LABORATORY ______ SOURCE ______

GRADE	HEAT NO.	GRAIN	ANALYSIS								
			C	Mn	S	P	Si	Ni	Cr	Mo	

NORMALIZING TEMP (F) ______ QUENCHING TEMP (F) ______

REMARKS ______

	INDIVIDUAL READINGS				AVERAGE ORDINATES	
S						S/2
1						1
2						2
3						3
4						4
5						5
6						6
7						7
C						C/2
TOTAL ORDINATES						
AREA = TOTAL ORDINATES DIVIDED BY 8						
HARDENABILITY RATING					S	A	C

	INDIVIDUAL READINGS				AVERAGE ORDINATES	
S						S/2
1						1
2						2
3						3
4						4
5						5
6						6
7						7
C						C/2
TOTAL ORDINATES						
AREA = TOTAL ORDINATES DIVIDED BY 8						
HARDENABILITY RATING					S	A	C

FIG. 13–SAC TEST REPORT