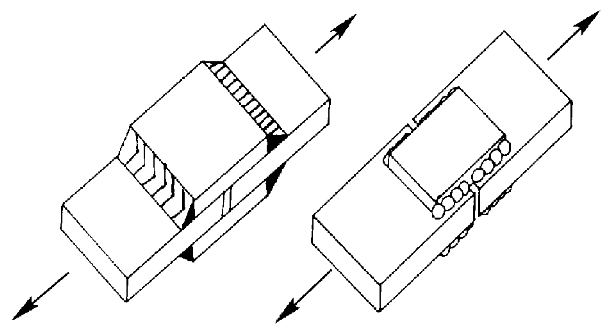
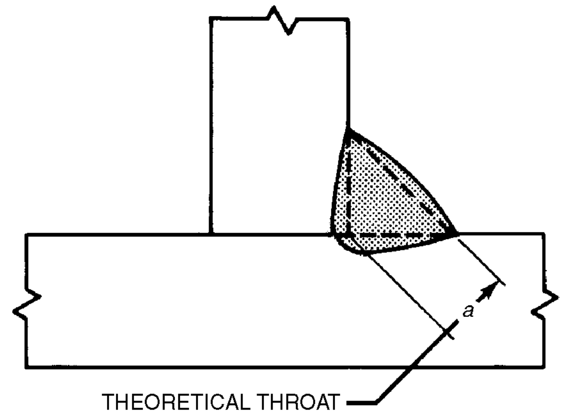


Figure 6.6—Longitudinal and Transverse Fillet Weld Specimens for Shear Stress Testing



$$\tau = \frac{P}{L \times a}$$

Key:
τ = Shear strength of the weld, psi (N/mm^2)
P = Load, lb (N)
L = Total length of the fillet weld sheared, in. (mm)
a = Theoretical throat dimension, in. (mm)

Figure 6.7—Method Used to Determine the Shear Strength of Fillet Welds

are to be obtained. For example, the stress concentration at the root of the transverse fillet weld increases with increasing root opening, and variations in root opening can cause inconsistent test results. Test specimens are also sensitive to heat-affected-zone cracking, undercut, and bead surface contour. For this reason, the longitudinal edges of transverse specimens should be machined to provide smooth surfaces, eliminating crater effects. Corners should also be rounded slightly.

The results normally reported for transverse and longitudinal shear tests are the shear strength of the weld metal and the location of the fracture. The shear strength is calculated by dividing the load by the shear area (effective weld length multiplied by the theoretical throat), as shown in Figure 6.7. Transverse shear specimens are tested as double lap joints to avoid rotation and bending stresses during testing.

The longitudinal shear test measures the shear strength of fillet welds when specimens are loaded parallel to the axis of the welds. To avoid bending during testing, two identical welded specimens are machined and then tack welded together, as indicated in Figure 6.8. Alternatively, the lap plates can be welded to a single set of base plates. Test results are calculated and reported as shown in the figure.

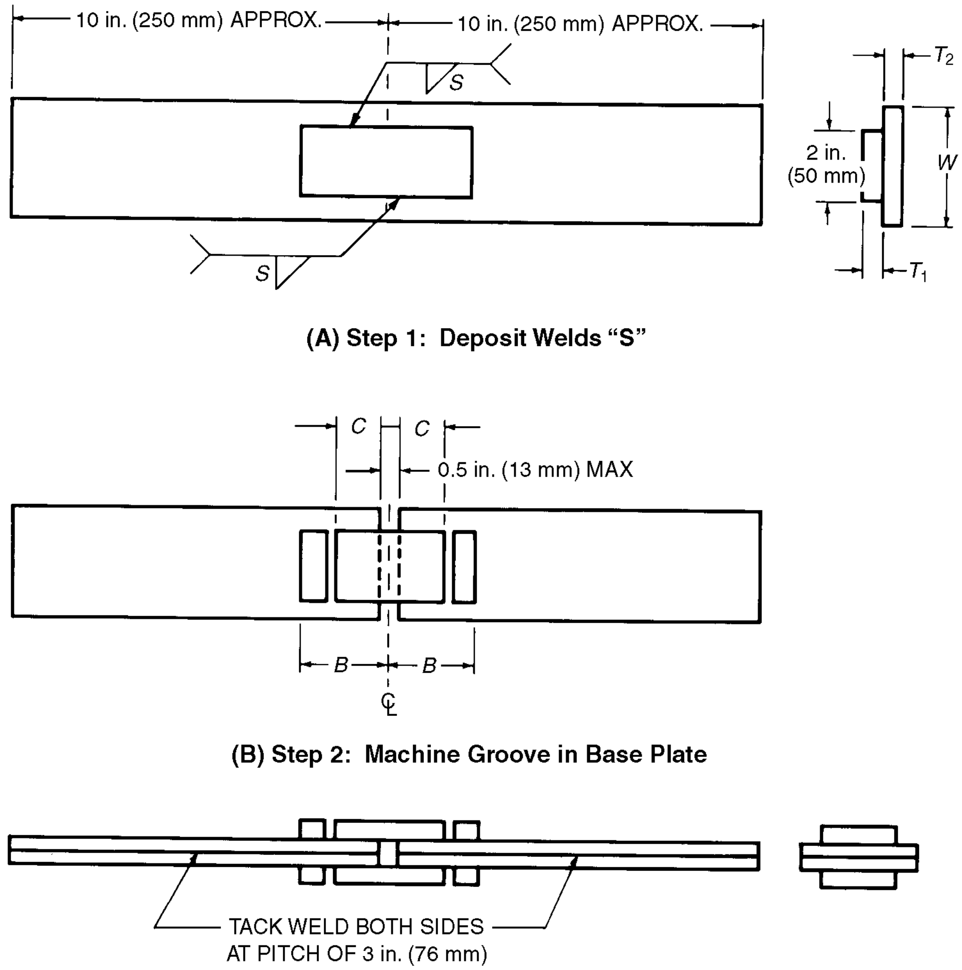
Tension-Shear Test for Brazed Joints. The tension-shear test is used on brazed joints to determine the strength of the filler metal. Figure 6.9 illustrates the specimen configuration and joint designs used for this test. Two single ferrous or nonferrous sheets 1/8 in. (3 mm) thick are joined by brazing with a filler metal. The shear strength of the filler metal is calculated by dividing the tensile load at failure by the brazed area. Such test specimens require suitable fixturing during brazing to maintain accurate specimen alignment.

Although the tension-shear test has been standardized for the control testing of samples from production brazing cycles, it is used primarily as a research tool for the development of filler metals and brazing procedures. It is also used to compare filler metals produced by various manufacturers.[15]

STRENGTH TESTS FOR RESISTANCE WELDS

Tension and tension-shear tests determine the strength of welds from specimens that can be pulled in a tension testing machine. These tests are used to determine the effect of weld parameter changes on resistance and seam welds. Test specimen dimensions, test fixtures, and statistical methods for evaluating resistance weld test results are specified in *Recommended Practices for Resistance Welding,* AWS C1.1M/C1.1.[16]

15. For additional information, consult American Welding Society (AWS) Committee on Brazing and Soldering, *Standard Methods for Evaluating the Strength of Brazed Joints in Shear,* ANSI/AWS C3.2, Miami: American Welding Society.
16. American Welding Society (AWS) Committee on Resistance Welding, *Recommended Practices for Resistance Welding,* AWS C1.1M/C1.1, Miami: American Welding Society.



(A) Step 1: Deposit Welds "S"

(B) Step 2: Machine Groove in Base Plate

(C) Step 3: Tack Two Pieces As Indicated

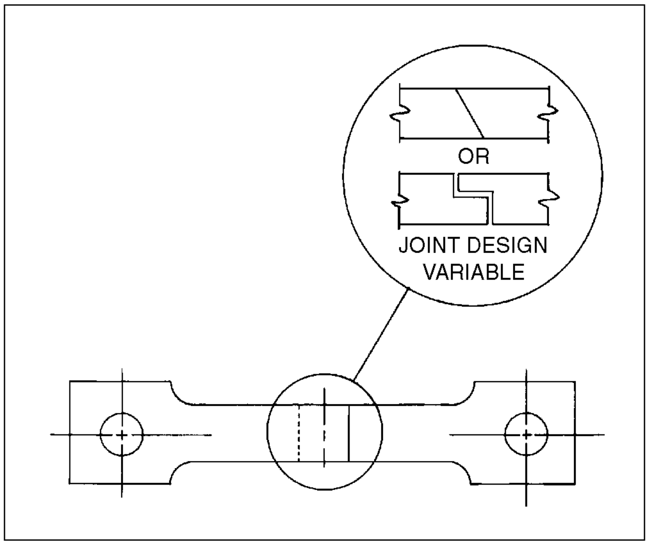
Key:
- $2B$ = Length of the lap piece, in. (mm)
- C = Length of weld tested, in. (mm)
- S = Specified size of the weld, in. (mm)
- T_1 = Thickness of the lap piece, in. (mm)
- T_2 = Thickness of the base plate, in. (mm)
- W = Width of the lap piece, in. (mm)

S	T_1	T_2	W	B	C
1/8	1/4	1/4	3		1-1/2
1/4	1/2	3/8	3		1-1/2
3/8	3/4	1/2	3		1-1/2
1/2	1	5/8	3-1/2*		1
ALL				2-1/4	

*For 7 in. (178.0 mm) on each end of the base plates, the 3-1/2 in. (89.0 mm) width may have to be reduced to 3 in. (76.0 mm) to accommodate the jaws of the test machine.

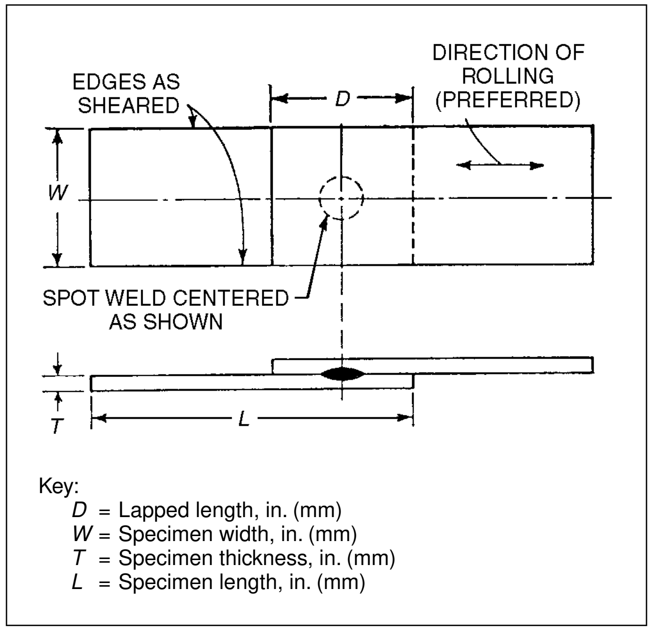
in.	mm	in.	mm
1/8	3.0	1-1/2	38.0
1/4	6.5	2	51.0
3/8	9.5	3	76.0
1/2	12.5	3-1/2	89.0
5/8	16.0	7	178.0
3/4	19.0	10	254.0
1	25.5		

Figure 6.8—Procedure for the Preparation of a Longitudinal Fillet Weld Specimen for a Shear Test



Source: American Welding Society (AWS) Committee on Brazing and Soldering, 1982, *Standard Methods for Evaluating the Strength of Brazed Joints in Shear,* ANSI/AWS C3.2-82R, Miami: American Welding Society, Figure 12.7.

Figure 6.9—AWS Standard Tension-Shear Test Specimen Used in the Testing of Brazed Joints



Source: Adapted from American Welding Society (AWS) Committee on Resistance Welding, 2000, *Recommended Practices for Resistance Welding*, AWS C1.1M/C1.1:2000, Miami: American Welding Society, Figure 8.

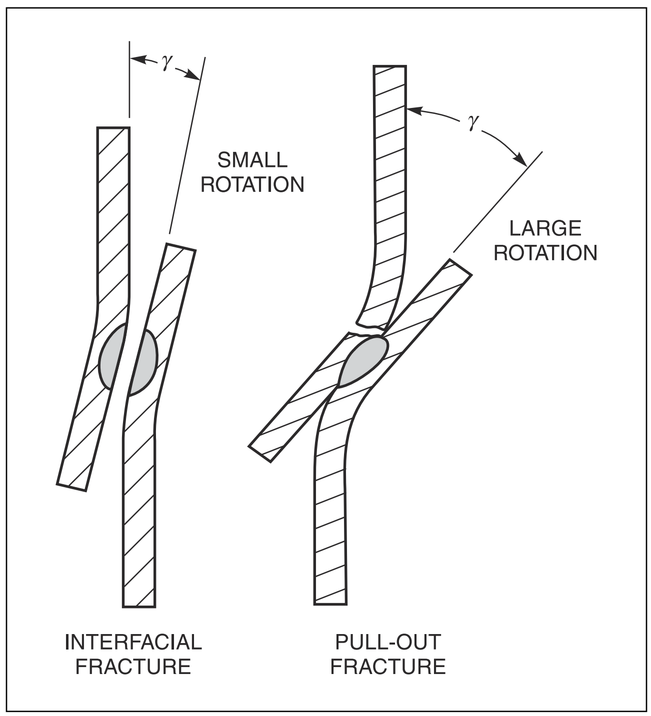
Figure 6.10—Tension-Shear Test Specimen

Tension-Shear Test

The tension-shear test for resistance welds is similar to the test used to evaluate the strength of arc welds. The spot weld test specimen depicted in Figure 6.10 is prepared by overlapping suitable-sized coupons and making a spot weld in the center of the overlapped area. A similar specimen can be prepared to test resistance seam welds. In this case, a transverse specimen is used; that is, the weld is placed across the width of the coupon. The specimen is then tested in a standard tension test machine.

As the sheet metal coupons are lapped, the tensile specimen generally bends and rotates, as illustrated in Figure 6.11. Failure generally occurs in the form of either an interfacial fracture or a pull-out fracture. Interfacial fractures, which occur because the bond between the two members is weaker than the base material, are generally undesirable. Pull-out fractures occur either because (1) the weld is stronger than the base metal, which results in significant rotation if the weldment is ductile, as shown in Figure 6.11, or (2) the base metal or the heat-affected zone is brittle.

The rotation within the sample may cause the spot weld to fail through or around the nugget. When the specimen thickness is 0.10 in. (2.6 mm) or greater, the wedge grips of the test machine should be offset to reduce the eccentric loading on the weld. Alternatively,



Source: American Welding Society (AWS) Committee on Resistance Welding, 2000, *Recommended Practices for Resistance Welding*, AWS C1.1M/C1.1:2000, Miami: American Welding Society, Figure 9.

Figure 6.11—Twisting Angle, γ, at Fracture in the Tension-Shear Test

metal pads can be applied to the ends of the specimens to eliminate the bending forces.

Easy and inexpensive, tension-shear tests are commonly used in the quality assurance testing of production welds. The ultimate strength of the specimen and the mode of failure, such as the shearing of the weld metal (interfacial fracture) or tearing of the base metal (pull-out fracture), and the type of fracture (ductile or brittle) are determined and reported. It may also be desirable to measure the bend angle between the weld interface and the tensile axis at fracture, as shown in Figure 6.11. The ductility of the weld is frequently reported by taking the ratio of the direct-tension load to the tension-shear load. Typical results are listed in Table 6.1.

Direct-Tension Test

The direct-tension spot weld test is used to measure the strength of welds for loads applied in a direction normal to the interface of the spot weld. Applicable to ferrous and nonferrous metals of all thicknesses, this test is employed to determine the relative notch sensitivity of spot welds. It is also used in the development of welding schedules and in researching the weldability of new alloys. It is important to note, however, that direct-tension testing is not normally used for the quality control of production welds.

Two types of specimens, the cross-tension and the U-specimen, are used in the performance of direct-tension testing. Cross-tension specimens, shown in Figure 6.12, can be used for all alloys and thicknesses. The specimen shown in Figure 6.12(A) is used when the thickness of the metal is under 0.19 in. (4.8 mm) because the specimen must be reinforced to prevent excessive bending. For thicker specimens like those shown in Figure 6.12(B), the holes may be eliminated.

Table 6.1
Ratio of Direct-Tension to Tension-Shear Specimen Loads

Material	Typical Ratio Range
Low-carbon steel	0.60 to 0.99
Medium-carbon steel (0.2 C)	0.18 to 0.21
Low-alloy, high-strength steel	0.21 to 0.28
Austenitic stainless steel	0.55 to 0.82
Ferritic stainless steel	0.25 to 0.33
Aluminum base	0.37 to 0.43
Nickel base	0.71 to 0.81
Titanium base	0.27 to 0.52

The test fixture depicted schematically in Figure 6.13 is used to provide additional support for specimens up to 0.19 in. (4.8 mm) thick. This fixture is utilized with a standard tensile testing machine. The fixture illustrated in Figure 6.14 is used for specimens 0.19 in. thick and greater. Depending on the orientation of the specimen, either compression [Figure 6.14(A)] or tension [Figure 6.14(B)] may be used to apply tension to the spot weld.

The U-specimen, shown in Figure 6.15, is the other type of specimen used in direct-tension testing. To form a test specimen, two U-channels are spot welded back to back. The specimens are then pinned to filler blocks with pull-tabs. A tensile load is applied to the spot weld through the pin connections. Finally, the maximum load that causes the weld to fail is measured and recorded. The weld fails by either pulling a plug (tearing around the edge of the spot weld) or by pulling apart across the weld metal (tensile failure).

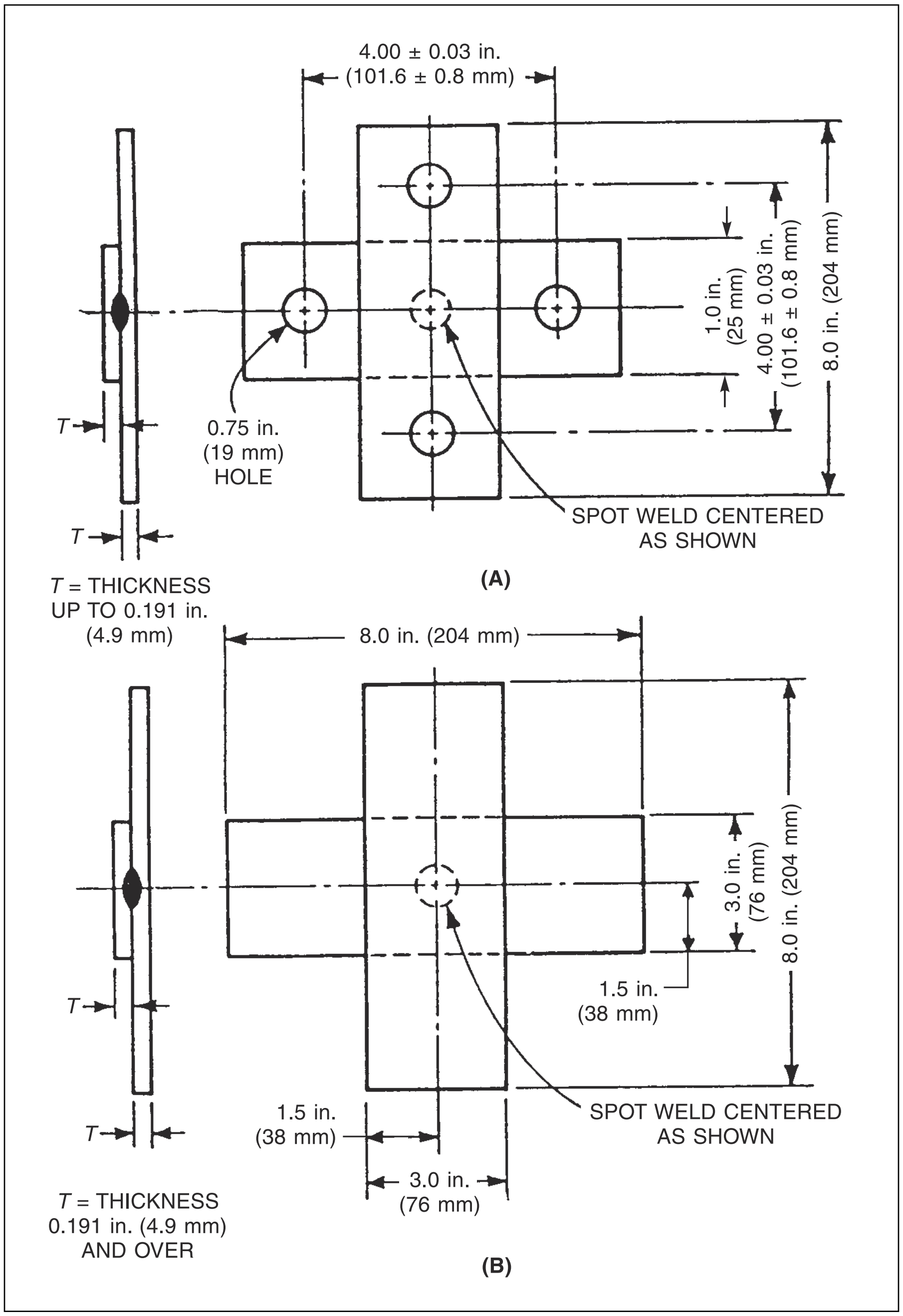
The direct-tension load is normally lower than the tension-shear load for the same weld size and base alloy. The ratio of the direct-tension load to the tension-shear load is frequently referred to as the *ductility* of the weld, which is a measure of the notch sensitivity of the weld. A ratio greater than 0.5 is considered ductile. Table 6.1, presented above, lists typical ratio ranges for spot welds in several base metals. Ratios less than 0.30 indicate notch-sensitive welds.

Peel Test

The peel test, depicted in Figure 6.16, is a simple variation of the direct-tension test. It is commonly used as a production control test. In this test, the size of the weld button is measured, and the weld fracture mode is determined. The production welds are acceptable if the measured weld button size is equal to or greater than the standard weld size as determined by tension-shear and direct-tension tests.

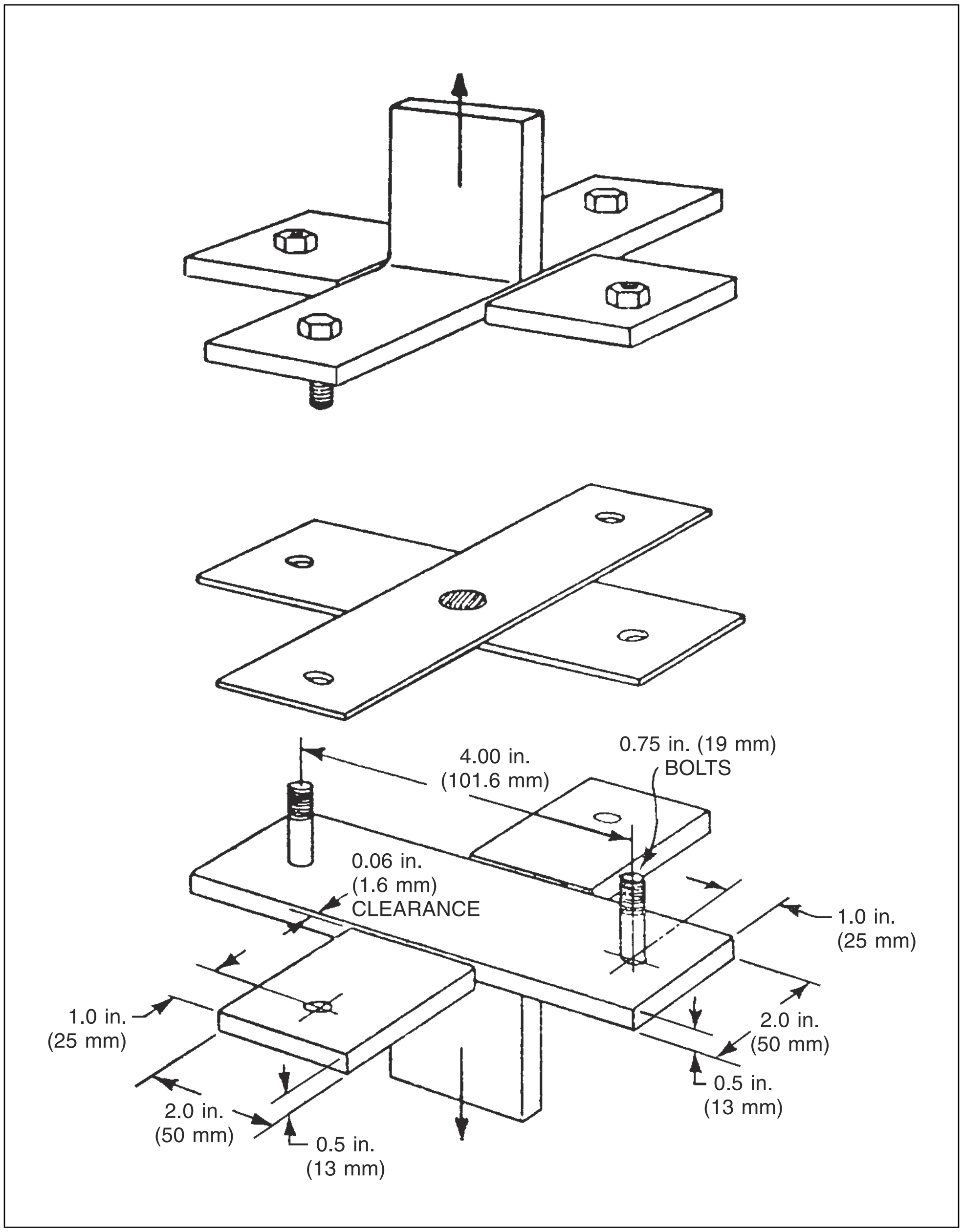
Although this test is rapid and inexpensive, it may not be suitable for high-strength base metals or thicker sheets. If this is the most important production test, it is advisable to consider that the results may be influenced significantly by the speed and direction of the pulling force. The successful pulling of a weld button may not be a significant indicator of ductility or notch sensitivity. It is possible that a button may be pulled with a slow tearing motion, whereas a quick tug would result in interfacial fracture. The publication *Recommended Practices for Resistance Welding*, AWS C1.1M/C1.1,[17] should be consulted for specimen dimensions.

17. See Reference 16.



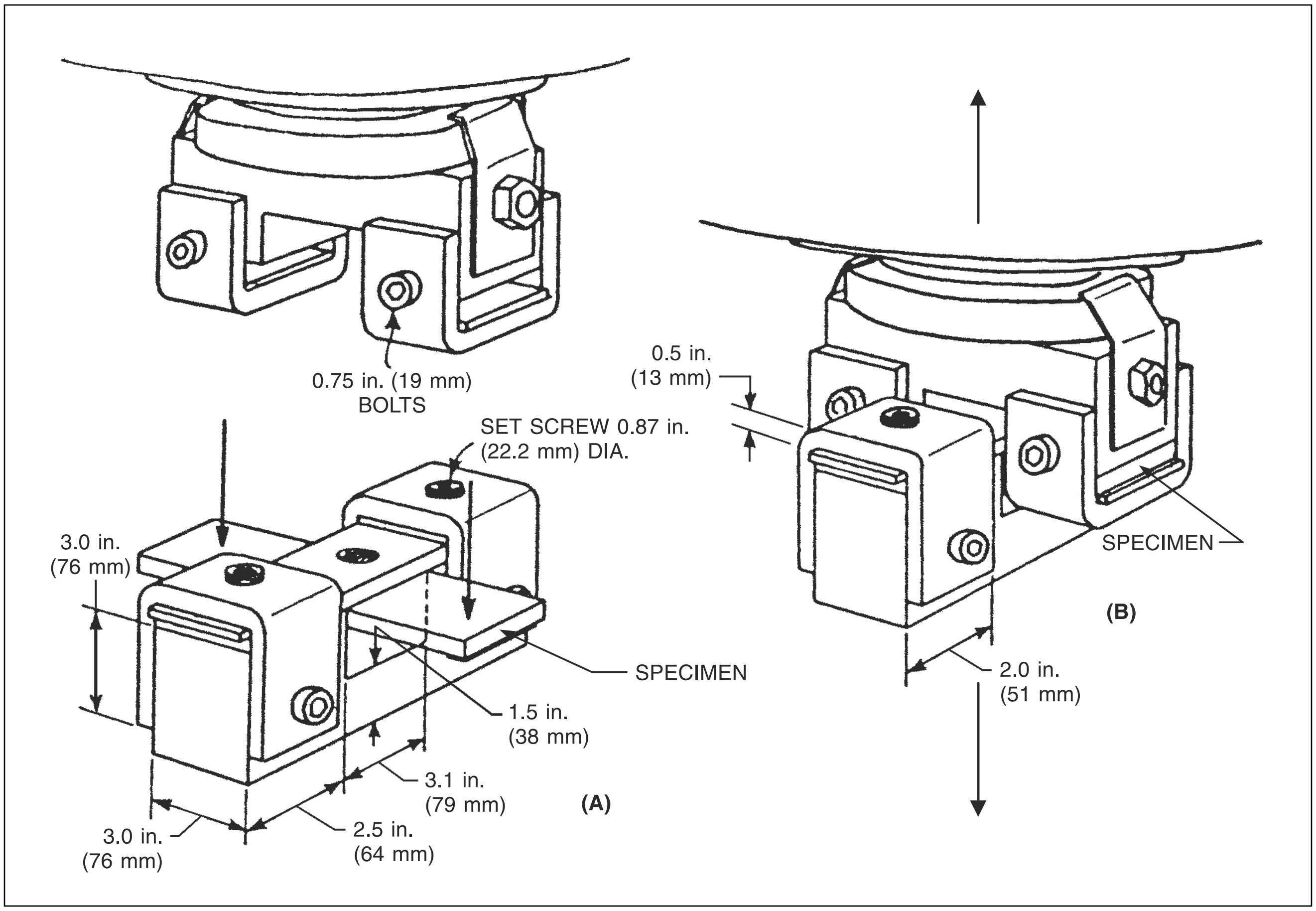
Source: Adapted from American Welding Society (AWS) Committee on Resistance Welding, 2000, *Recommended Practices for Resistance Welding*, AWS C1.1M/C1.1:2000, Miami: American Welding Society, Figure 10.

Figure 6.12—Cross-Tension Test Specimens: (A) Thin and (B) Thick



Source: Adapted from American Welding Society (AWS) Committee on Resistance Welding, 2000, *Recommended Practices for Resistance Welding*, AWS C1.1M/C1.1:2000, Miami: American Welding Society, Figure 11.

Figure 6.13—Fixture Employed in Cross-Tension Testing for Thicknesses up to 0.19 in. (4.8 mm)



Source: Adapted from American Welding Society (AWS) Committee on Resistance Welding, 2000, *Recommended Practices for Resistance Welding*, AWS C1.1M/C1.1:2000, Miami: American Welding Society, Figure 12.

Figure 6.14—Fixture Employed in Cross-Tension Testing for Thicknesses of 0.19 in. (4.8 mm) and Over: (A) Compression Loading and (B) Tension Loading

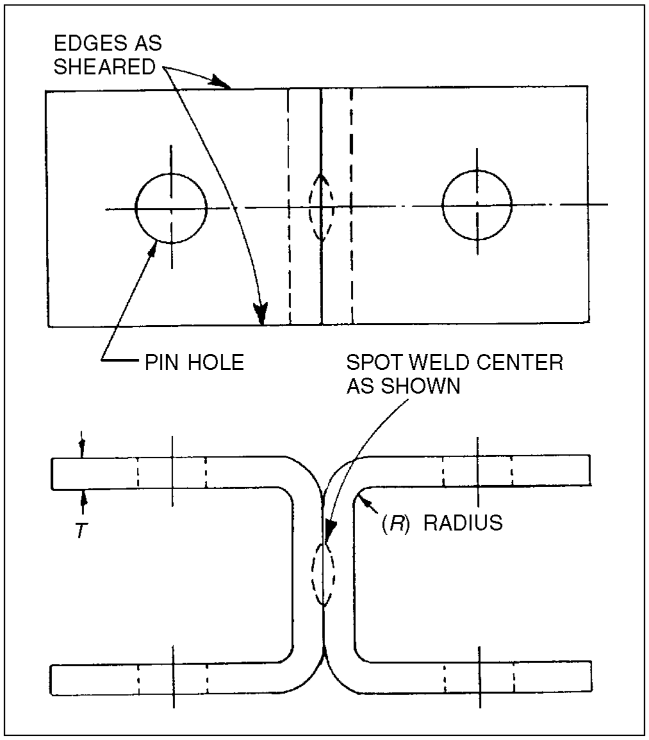
Torsion-Shear Test

A torsion-shear test may be used to evaluate spot welds where a measure of strength and ductility are required. This test can be performed as a simple production test with little or no equipment. It can also be used as a laboratory test. A typical coupon and fixture for this test are shown in Figure 6.17.

In this case, torsional shear is applied on the weld of a square test specimen by placing the specimen between two recessed plates. The upper plate is held rigid by a hinge while the lower plate is fastened to a rotating disk. After the specimen is placed in the square recess of the lower plate, the upper plate is closed over it and locked into position. Torque is applied by means of a rack and pinion attached to the disk. It is important that the two halves of the specimen be engaged separately by the two plates and that the weld be centrally located with respect to the axis of rotation. Values for the ultimate torque can be calculated by multiplying the length of the moment arm by the maximum load required to twist the sample to destruction.

A simplified qualitative variation of this method is presented in *Structural Welding Code—Sheet Steel,* ANSI/AWS D1.3.[18] A spot weld is made between a sheet steel and a base plate, and the sheet is hammered sideways until the welds fails. The acceptance criteria are limited to the presence of full fusion and the absence of weld defects.

18. American Welding Society (AWS) Committee on Structural Welding, *Structural Welding Code—Sheet Steel,* ANSI/AWS D1.3, Miami: American Welding Society.



Source: Adapted from American Welding Society (AWS) Committee on Resistance Welding, 2000, *Recommended Practices for Resistance Welding*, AWS C1.1M/C1.1:2000, Miami: American Welding Society, Figure 13.

Figure 6.15—Direct-Tension U-Test Specimen

Pillow Test for Continuous Resistance Seam Welds

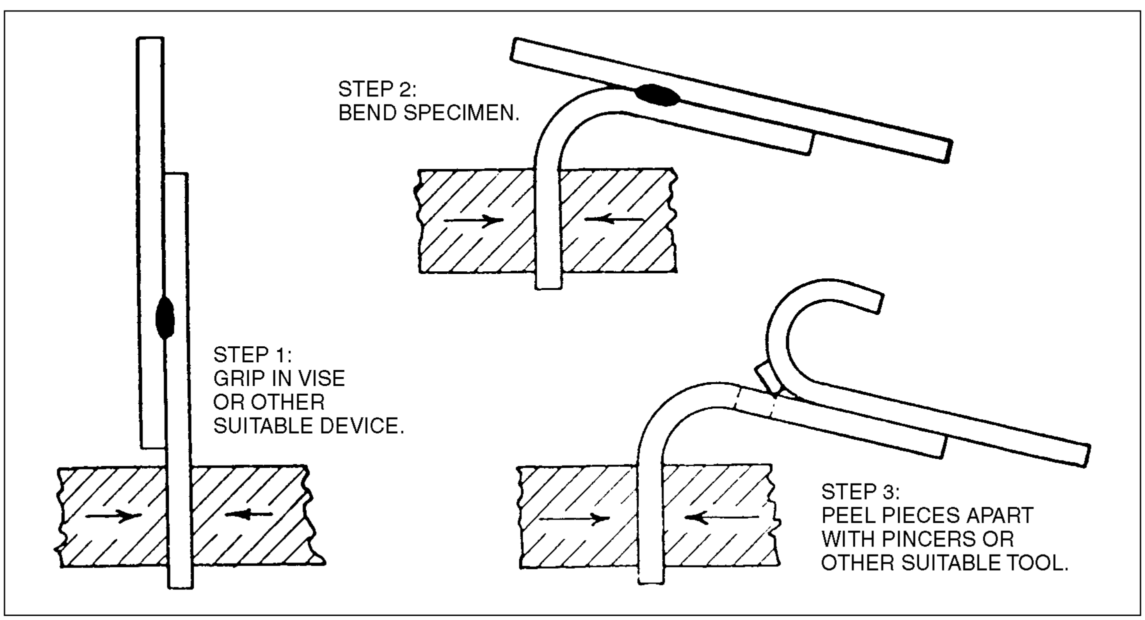
The pillow test is used in seam welding applications to simulate the service conditions of the welded leak-tight joint. The test configuration is shown in Figure 6.18. One of the two flat plates is fitted with a pressure connection. The two plates are then joined with a continuous seam weld around the outside edge. The specimen is then pressurized (e.g., with hydraulic fluid).

Evaluation of the test includes examining the specimen for leakage or base metal failure at the proof pressure. It may be necessary to contain the specimen between two plates during the test to restrict its deformation and balance the stress along the weld seam.

Additional Resistance Weld Tests

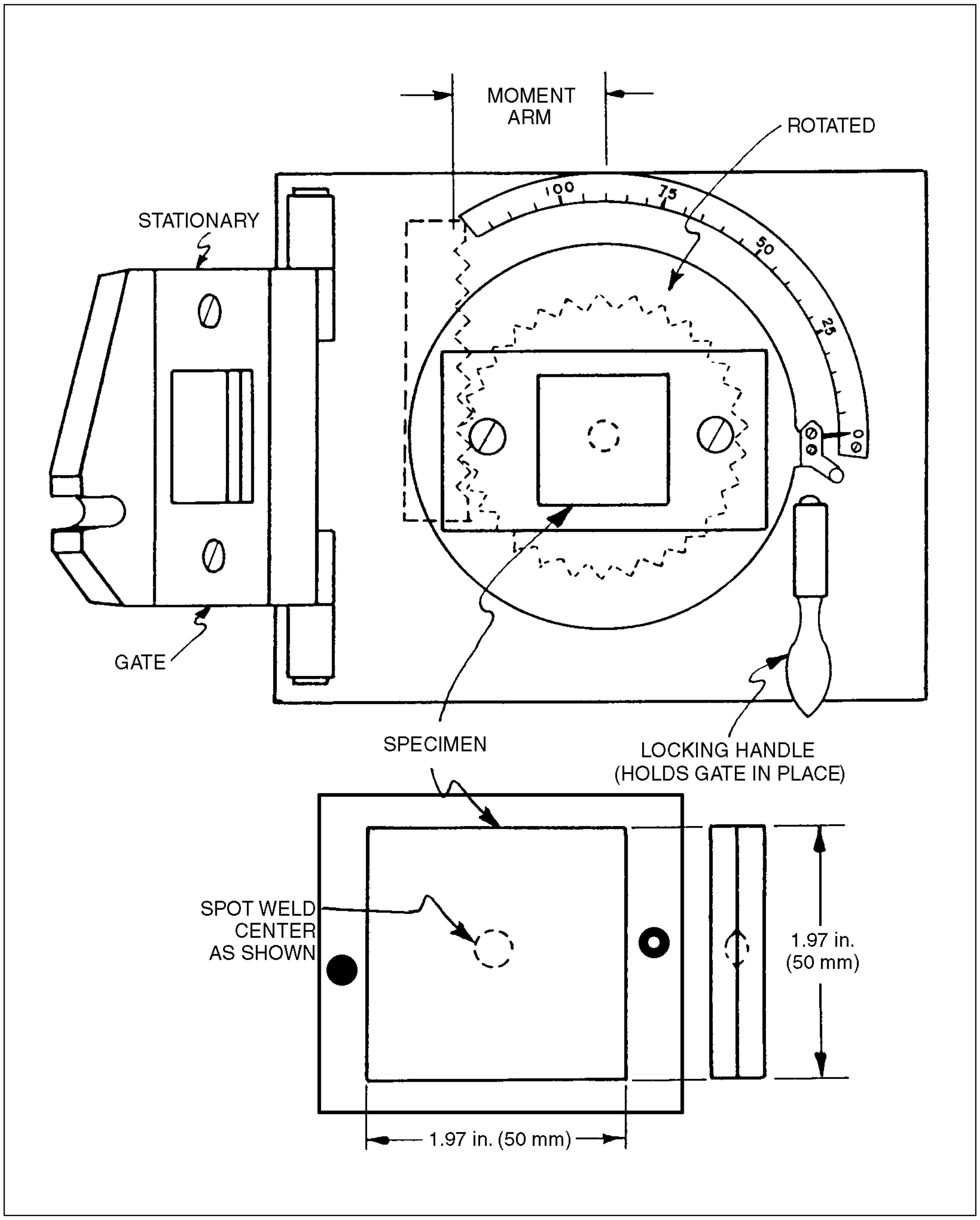
A number of variations of the tests discussed above are described in *Recommended Practices for Resistance Welding*, AWS C1.1M/C.1.[19] This publication provides information on these test variations as well as on the pull test, various impact tests, and fatigue testing.

19. See Reference 16.



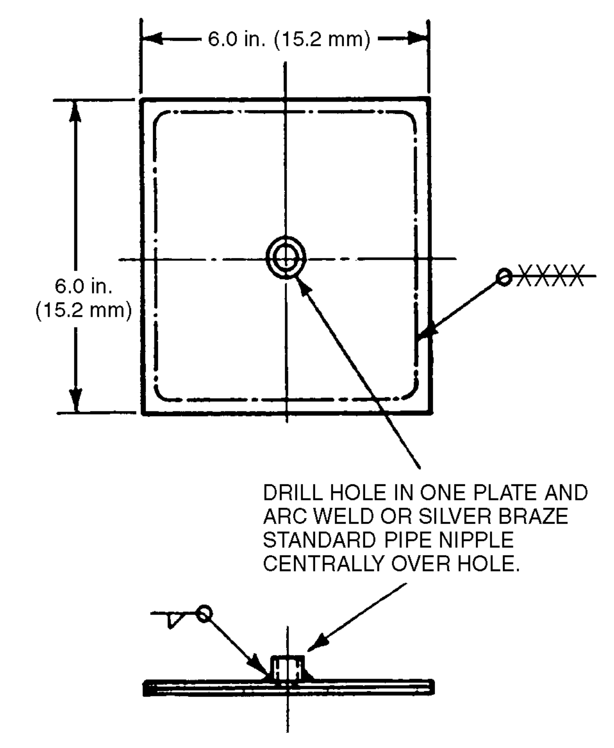
Source: American Welding Society (AWS) Committee on Resistance Welding, 2000, *Recommended Practices for Resistance Welding*, AWS C1.1M/C1.1:2000, Miami: American Welding Society, Figure 3.

Figure 6.16—Peel Test Procedure



Source: Adapted from American Welding Society (AWS) Committee on Resistance Welding, 2000, *Recommended Practices for Resistance Welding*, AWS C1.1M/C1.1:2000, Miami: American Welding Society, Figure 16.

Figure 6.17—Test Specimen and Typical Equipment for the Torsion-Shear Test



Source: Adapted from American Welding Society (AWS) Committee on Resistance Welding, 2000, Recommended Practices for Resistance Welding, AWS C1.1M/C1.1:2000, Miami: American Welding Society, Figure 22.

Figure 6.18—Pillow Test for Seam Welds

HARDNESS TESTS

Hardness tests determine the resistance of a material to penetration. Nonetheless, hardness test results are often used as a quick method of approximating ultimate tensile strength in the local area tested. Hardness measurements can also provide information about metallurgical changes caused by welding. In alloy steels, a high hardness could indicate the presence of martensite in the weld's heat-affected zone, while a low hardness may indicate an overtempered condition. Welding can cause significantly lower hardness in the heat-affected zone of cold-worked metal because of recovery and recrystallization. In age-hardened metal, welding can result in a lower heat-affected-zone hardness because of overaging.

Hardness tests are performed using a penetrator that is forced against the surface of the test specimen to form an indentation. The type of material, the geometry, and the size of the penetrator depend on the test method and hardness range and include hardened-steel spheres and diamond pyramids. Hardness test methods for metals include the Brinell, Knoop, Vickers, and Rockwell tests. The first three tests utilize the area of indentation under load as the measure of hardness. The Rockwell test uses the depth of indentation under load as a hardness measure. The diameter or depth of the indentation is then measured and converted to a hardness number using a standardized procedure for each method as defined in *Standard Test Methods and Definitions for Mechanical Testing of Steel Products,* ASTM A 370.[20] The hardness number must always be reported along with the method, test load, and type and size of penetrator used, either explicitly or using standard abbreviations such as those defined in the document cited above.

The selection of a hardness test method depends primarily on the hardness or strength of the metal, the size of the welded joint, and the type of information desired. Hardness tests measure the average hardness of the material under the indentation. Tests that make larger indentations are more representative of the bulk properties of a metal. The Brinell test produces a large indentation, typically 0.08 in. to 0.22 in. (2 mm to 5.6 mm) in diameter, yielding an average hardness for the largest sample of metal. The Rockwell test produces a much smaller indentation, which is suited to hardness traverses. However, these indentations are still macroscopic and may be larger than the precise areas of interest, such as a fusion zone or a coarse-grain region in the heat-affected zone.

For microscopic areas, the Vickers and Knoop microhardness tests make small indentations that are well suited for hardness measurements of the various regions of the heat-affected zone and for closely spaced traverses. These tests, which are used with a metallograph, can measure the hardness of individual grains and inclusions in the metal.

Hardness tests can be performed on ground, polished, and polished-and-etched cross sections of a weld joint. Measurements can be made on any specific area of the weld or base metal, depending on the test method and purpose. Frequently, hardness indentations are made at regular intervals across an entire weld cross section, as shown in Figure 6.19. Hardness traverses of a weld cross section are often performed using the Vickers method because the very small indentation provides information on local microstructural changes in the weld metal and heat-affected zone.

An approximate interrelationship exists among the results of the different hardness tests and the tensile strength of some metals. For example, the approximate ultimate tensile strength of carbon and low-alloy steel

20. See Reference 8.

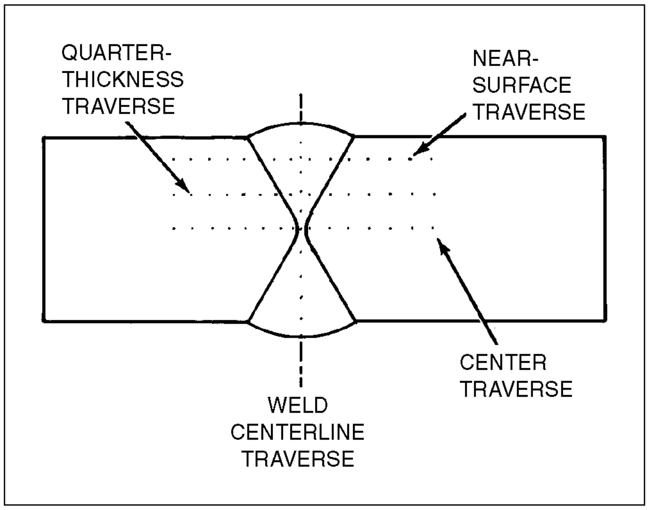


Figure 6.19—Typical Hardness Traverses for Double-V Groove Welded Joints

in ksi (MPa) is approximately one half (3-1/3) the Brinell hardness number. Table 6.2 provides the relationship for nonaustenitic steels, while Table 6.3 provides hardness conversions for austenitic steels. These correlations should be used with caution when applied to welded joints or any metal with a heterogeneous structure.

In hardness testing, proper specimen preparation is important for reliable results. The surface should be flat and reasonably free of scratches. In addition, it must be perpendicular to the applied load for uniform indentations. With thin, soft metals, the testing machine must produce a shallow indentation that is not restricted by the anvil of the testing machine. This can be accomplished (particularly with a Rockwell testing machine) with a small indenter and a light load.

BRINELL HARDNESS TEST

The Brinell hardness test consists of impressing a hardened steel ball into the test surface using a specified load for a definite time. Following this, the diameter of the impression is accurately measured and converted to a hardness number from a table. Examination should be performed according to the requirements of *Standard Test Method for Brinell Hardness of Metallic Metals,* ASTM E 10.[21] Stationary machines impress a ball 0.4 in. (10 mm) in diameter into the test object. The load for steel is 6600 pound-force (lbf) (3000 kilograms [kg]), whereas it is 1100 lbf or 3300 lbf (500 kg or 1500 kg) for softer metals. Two measurements of the impression diameters are taken at 90° from one another using a special Brinell microscope. The mean diameter is used to determine the Brinell hardness from the table.

To test larger components, portable Brinell equipment consisting of a 0.3 in. or 0.4 in. (7 mm or 10 mm) ball and a calibrated reference bar is available. A hammer blow is used to indent simultaneously both the indenter bar and the material being tested. The hardness of the material being tested can be measured using a special slide rule or inserting the hardness of the reference bar and the diameters of the two indentations into a formula. The accuracy of this method is enhanced by selecting a reference bar of approximately the same hardness as the unknown test material.

ROCKWELL HARDNESS TEST

The Rockwell hardness test measures the depth of residual penetration made by a small hardened steel ball or diamond cone. The test is performed by applying a minor load of 22 lbf (10 kg) to seat the penetrator in the surface of the specimen and hold it in position. The machine dial is turned to a set point, and a major load is applied. After the pointer comes to a rest, the major load is released, while the minor load remains.

The Rockwell hardness number is read directly on the dial. Hardened steel balls 1/8 in. or 1/16 in. (3.2 mm or 1.6 mm) in diameter are used for soft metals, whereas a cone-shaped diamond penetrator is used for hard metals. Testing is conducted in accordance with *Standard Test Method for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials,* ASTM E 18.[22]

MICROHARDNESS TESTS

The Knoop and Vickers microhardness tests determine the hardness of a very small area that is on the order of a few grains wide. The polished sample is viewed under a microscope at magnifications up to 800X. In these tests, the area of interest is located under the microscope, and the turret is then rotated to bring the indenter over the area. A calibrated machine is used to force a diamond indenter with a specified geometry into the sample using test loads of 1 gram-force (gf) to 100 gf. The turret is rotated back, and the diagonal of

21. American Society for Testing and Materials (ASTM) Subcommittee E28.06, *Standard Test Method for Brinell Hardness of Metallic Materials,* ASTM E 10, West Conshohocken, Pennsylvania: American Society for Testing and Materials.

22. American Society for Testing and Materials (ASTM) Subcommittee E28.06, *Standard Test Method for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials,* ASTM E 18, West Conshohocken, Pennsylvania: American Society for Testing and Materials.