THROUGH-THICKNESS TENSION TESTING OF STEEL

R. J. Glodowski, *editor*

ASTM STP 794

THROUGH-THICKNESS TENSION TESTING OF STEEL

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Committee A-1 on
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and Related Alloys
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Foreword

The Symposium on Through-Thickness Tension Testing of Steel was held in St. Louis, Missouri, on 17–18 November 1981. ASTM Committee A-1 on Steel, Stainless Steel, and Related Alloys was sponsor. R. J. Glodowski served as symposium chairman and has edited this publication. G. J. Roe, Bethlehem Steel Corporation, and Michael Wheatcroft, American Bureau of Shipping, served as session chairmen.

Related ASTM Publications

Rolling Contact Fatigue Testing of Bearing Steels, STP 771 (1982), 04-771000-02

Stainless Steel Castings, STP 756 (1982), 04-756000-01

Application of 2¼Cr-1Mo Steel for Thick-Wall Pressure Vessels, STP 755 (1982), 04-755000-02

Toughness of Ferritic Stainless Steels, STP 706 (1980), 04-706000-02

Properties of Austenitic Stainless Steels and Their Weld Metals (Influence of Slight Chemistry Variations), STP 679 (1979), 04-679000-02

Intergranular Corrosion of Stainless Alloys, STP 656 (1978), 04-656000-27

Rail Steels—Developments, Processing, and Use, STP 644 (1978), 04-644000-01

Structures, Constitution, and General Characteristics of Wrought Ferritic Stainless Steels, STP 619 (1976), 04-619000-02

A Note of Appreciation to Reviewers

The quality of the papers that appear in this publication reflects not only the obvious efforts of the authors but also the unheralded, though essential, work of the reviewers. On behalf of ASTM we acknowledge with appreciation their dedication to high professional standards and their sacrifice of time and effort.

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SUMMARY

Introduction

Through-thickness tension testing of steel is concerned with the evaluation of tensile properties in the direction perpendicular to the rolled surface of a steel plate. This through-thickness orientation has also been referred to as the short transverse or "Z" direction.

It has long been recognized that the mechanical properties of commercially available steels are anisotropic. However, the significance of mechanical properties in the through-thickness direction only became of engineering importance when a particular type of weldment cracking known as lamellar tearing became a serious problem. The susceptibility of a given welded joint of lamellar tearing depends on many factors including design details, restraint levels, welding conditions, and material ductility. The most widely accepted method of relating the material ductility factor to lamellar tearing has been the reduction of area of a round tension test specimen, oriented perpendicular to the planes along which much of a lamellar tear propagates. Since lamellar tearing occurs in planes roughly parallel to the plate surface, the test specimen orientation of concern was in the direction perpendicular to that plane, namely, the through-thickness direction.

About five years ago ASTM recognized the need to address the subject of through-thickness tension testing. A task group was formed to write a specification for testing procedures and acceptance standards for the determination of through-thickness reduction of area values in plates over 25.4 mm (1 in.) thick. The principle purpose of the testing was to provide a steel plate with increased resistance to lamellar tearing. This work resulted in ASTM Specification for Through-Thickness Tension Testing of Steel Plate for Special Applications (A 770), approved by the Society on 28 March 1980.

In the process of writing ASTM A 770 it became clear to those involved that through-thickness tension testing had a set of characteristics quite different from those normally associated with in-plane testing (longitudinal or transverse to the rolling direction). Some of the factors considered were the effects of specimen design, preparation, and location in the plate, and the inherent variability of the test results. Because it was felt that knowledge of these factors could be very useful to users of the specification, a symposium was organized in which different investigators shared their experience and knowledge of through-thickness testing. The symposium was held in St. Louis, Missouri, on 17–18 November 1981. It is hoped that the symposium and this resulting volume provide workers involved in through-thickness tension testing with some insights they might not otherwise obtain.

The contents of this publication are divided into two sections, similar to the arrangement of the two symposium sessions. The first group of papers is primarily concerned with test methods and, in particular, the design and preparation of the test specimen. The second group of papers emphasizes relations between the through-thickness tension test results and metallurgical factors such as the role of inclusion types and distribution, strength levels, plate thickness and location effects. This division of papers is not rigorous, however, since several papers deal with test methods and metallurgical factors.

This publication is a contribution of the Joint Task Group on Through-Thickness Tension Testing of Subcommittee A01.02 on Structural Steel for Bridges, Buildings, Rolling Stock, and Ships, and Subcommittee A01.11 on Steel Plates for Boilers and Pressure Vessels, both Subcommittees of ASTM Committee A-1 on Steel, Stainless Steel, and Related Alloys. As Chairman of the Joint Task Group, I would like to acknowledge the contributions of all the members of the Task Group in assisting with the organization of the symposium and serving as reviewers of the papers. In particular, Michael Wheatcroft and Gerald Roe deserve recognition for their review efforts and for serving as session chairmen.

The goal of this publication is to provide information to metallurgists who are concerned with providing steel plates with improved through-thickness properties, and particularly to design engineers who may be interested in what is involved in testing the through-thickness properties of steels. The results of these tests need to be viewed somewhat differently than normal mechanical property data. The information in this publication should provide some insight for these evaluations.

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Senior Staff Metallurgist, Armco Inc., Middletown, Ohio; symposium chairman and editor

Test Methods

J. M. Holt[1]

Effect of Specimen Type on Reduction-of-Area Measurements

REFERENCE: Holt, J. M., "**Effect of Specimen Type on Reduction-of-Area Measurements,**" *Through-Thickness Tension Testing of Steel, ASTM STP 794,* R. J. Glodowski, Ed., American Society for Testing and Materials, 1983, pp. 5–24.

ABSTRACT: Because the susceptibility of plate material to lamellar tearing is believed to be related to the amount of reduction of area measured by a tension test specimen oriented in the through-thickness (Z) direction, tests were conducted to determine the influence of specimen dimensions on the tensile properties of ASTM A36, A588, and A514 Grade F steels for the two types of specimens commonly used for testing in the Z-direction. The first is the standard specimen with the length of the reduced section shortened so that the overall length of the specimen is equal to the thickness of the plate (stub specimen). The second is the standard specimen machined from a blank that has been prepared by welding prolongations to the plate surfaces so that the plate forms a full-plate-thickness insert at the midlength of the specimen (tab specimen). Because the intent was to compare only the trends in the changes of the tensile strength values and the reduction-of-area values for the different specimens, and because variability obtained in the longitudinal direction is less than that obtained in the through-thickness direction, the specimens were oriented in the longitudinal direction of the plate.

The results indicated a significant decrease in the reduction of area and a significant increase in the tensile strength of both types of specimens as the thickness of the insert or the length of the reduced section is decreased to less than two specimen diameters. These trends are due to constraint in plastic flow caused by the higher strength of the weld area of the tab specimens or by the shoulders of the stub specimens.

KEY WORDS: lamellar tearing, materials testing, reduction-of-area measurements, steel plates, tensile strength, tension test, test methods

Susceptibility of plate material to lamellar tearing appears to be related to the amount of reduction of area (RA) determined with a tension test specimen oriented in the thickness (Z) direction [*1,2*].[2] Consequently, specifications are being written that require through-thickness (Z-direction) tension tests [*3*]. An ASTM standard 12.7-mm (0.50-in.)-diameter tension test specimen (A370) can be obtained in the Z-direction for plates having a thickness of about 114 mm (4½ in.) or greater. To test lighter-gage plate, some investi-

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[2] The italic numbers in brackets refer to the list of references appended to this paper.

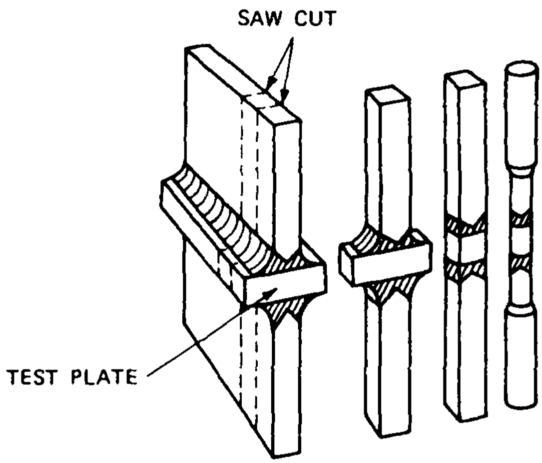
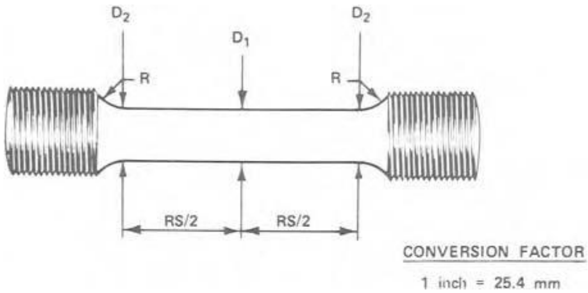


FIG. 1—*Tension test specimen with welded extensions for through-thickness tensile strength and ductility measurements.*

gators have used small-size specimens with dimensions that are proportional to those of the standard specimen. Other investigators have designed specimens (often called stub specimens) in which the length of the reduced section of the standard specimen is made shorter, while the other dimensions remain unchanged, so that the overall length of the specimen does not exceed the plate thickness. Still other investigators have welded extension prolongations (tabs) to the plate surfaces (Fig. 1) to obtain sufficient length for the standard-size specimen; these specimens are often called tab specimens.

There are problems with each of these three approaches. The primary drawback to the use of the small-size specimen (with dimensions proportional to those of the standard specimen) is that the cross-sectional area becomes so small that it may not be representative of the bulk material. For example, inhomogeneities (such as inclusions) in the specimen at the point of fracture may be a large fraction of the specimen cross-sectional area, and can therefore result in misleading test data. Conversely, because the cross section is so small, some specimens may contain less than a representative amount of inhomogeneities, again with misleading test results. A large number of specimens can be tested to attempt to obtain a representative average, but the cost of testing becomes prohibitive. Another drawback to the small-size specimen is that many test facilities are not equipped to machine or test such specimens.

The stub specimen usually has the advantage of a larger cross section and "standard" grip ends. Machine-shop automation cannot always be readily utilized with this specimen, however, because of the many different lengths of reduced sections. Also, the specimen cannot be positioned in the desired location within the plate thickness.



SPECIMEN GEOMETRY DESIGNATION	NOMINAL SECTION LENGTH, inches	REDUCED-SECTION LENGTH, diameters	SPECIMEN DIMENSIONS, inches				
			RS/2	D_1	D_2	R	THREAD
1	1/2	1	0.250 ± 0.005	0.505 ± 0.005	$D_1{}^{+0.001}_{-0.000}$	$0.50^{+0.06}_{-0.00}$	3/4-16
2	1	2	0.500 ± 0.005	0.505 ± 0.005	$D_1{}^{+0.001}_{-0.000}$	$0.50^{+0.06}_{-0.00}$	3/4-16
3*	2-1/4	4-1/2	1.125 ± 0.06	0.505 ± 0.005	$D_1{}^{+0.003}_{+0.005}$	$0.50^{+0.06}_{-0.00}$	3/4-16
4	4-1/2	4-1/2	$2.250^{+0.06}_{-0.00}$	0.900 ± 0.010	$D_1{}^{+0.005}_{+0.008}$	$1.00^{+0.06}_{-0.00}$	1-1/2-6

* STANDARD ASTM SPECIMEN

FIG. 2—*Dimensions of specimens tested.*

The tab specimen offers the convenience of a standard-size specimen for machining and testing and if necessary permits positioning the reduced section at any location within the plate thickness. However, the tab specimen requires equipment and personnel to prepare the tabs and to perform the welding. Furthermore, the heat-affected zone can cause anomalies in testing plate less than 25.4 mm (1 in.) in thickness.[3]

Most plate-producing mills in the United States are tooled to produce and to test the ASTM standard 12.7-mm (0.50-in.)-diameter round tension test specimen with a 51-mm (2-in.) gage length (Geometry 3 of Fig. 2). The overall length of this specimen is approximately 127 mm (5 in.), depending on the type of grip ends required by the test laboratory, and thus tabs must be welded to any plate thinner than 127 mm (5 in.). The object of the present investigation was to determine the effect on reduction-of-area values of (*1*) stub specimens with reduced sections of different lengths and of (*2*) tab specimens with extensions welded to inserts of varying lengths to simulate plates of different thicknesses.

Materials and Experimental Work

The present investigation was conducted on 25.4-mm (1-in.)-thick plates of ASTM A36, ASTM A588, and ASTM A514 Grade F steels. The chemical

[3] Domis, W. F., this publication, pp. 59–69.

TABLE 1—*Chemical composition of steels investigated.*

Steel Designation	Chemical Composition, % (Ladle Analysis)											
	C	Mn	P	S	Si	Cu	Ni	Cr	Mo	V	B	Al_{tot}
A36 Heat B	0.20	1.11	0.007	0.023	0.029	[a]	[a]	[a]	[a]	[a]	[a]	[a]
A36 Heat A	0.22	1.08	0.008	0.021	0.029	0.04	0.14	0.06	0.07	[a]	[a]	[a]
A588	0.14	1.09	0.018	0.028	0.26	0.31	0.04	0.60	0.02	0.04	[a]	0.04
A514 Grade F	0.16	0.83	0.010	0.166	0.27	0.27	0.80	0.49	0.41	0.05	0.004	[a]

[a] Not determined.

composition and room-temperature tensile properties of these plates are given in Tables 1 and 2, respectively. Specimens of ASTM standard geometry were machined from the three steels for use as controls.

Although the use of specimens with short reduced sections is not an attractive procedure, such specimens were included in this study because stub specimens are used by some investigators and because the shoulders of the specimens restrain the reduced section from contracting (necking) during tensile loading. In a similar manner, the harder heat-affected zone of tab specimens restrains necking. Stub specimens were machined from the three steels with reduced sections 12.7 mm (½ in.) long and 25.4 mm (1 in.) long (Geometries 1 and 2 of Fig. 2). In order to investigate any variability in trends between different heats of the same steel grade, a second set of stub specimens was machined from a 25.4-mm (1-in.)-thick plate from another heat of A36 steel.

The longitudinal axis of the stub specimens was oriented parallel to the rolling direction of the steels, rather than in the *Z*-direction, for the following reasons: (*1*) the tensile data obtained for specimens oriented in this direction show less variability, (*2*) all specimens would have a similar metallurgical structure (that is, there would be less effect of the gradation of properties between surface and midthickness in the rolling direction than in the *Z*-direction), and (*3*) only trends in behavior were of interest in the present investigation, rather than the absolute levels of strength and ductility. It is recognized that the through-thickness reduction-of-area values would be appreciably

TABLE 2—*Tensile properties of steels investigated.*

Steel Designation	Longitudinal Tensile Properties					
	Heat No.	Plate No.	Yield Strength, ksi[a]	Tensile Strength, ksi	Elongation, %	Reduction of Area %
A36 Heat B	68E428	166 957	37.2	65.1	34.2	70.5
A36 Heat A	70E908	347 748	36.7	65.3	34.5	70.1
A588	71D905	464	59.5	86.5	26.7	65.6
A514 Grade F	74A090	41 765	108.5	117.5	21.8	65.1

[a] 1 ksi = 6.895 MPa.

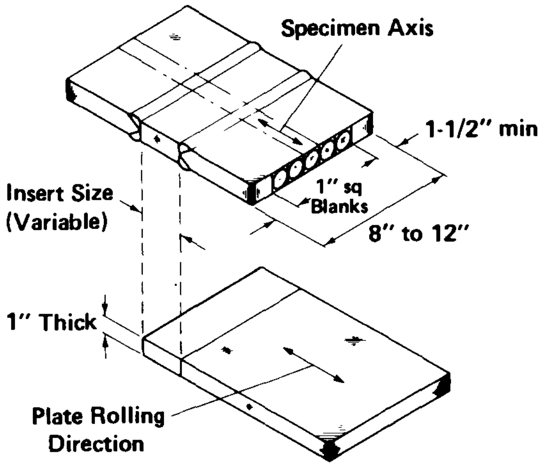


FIG. 3—*Schematic of method of preparing 12.7-mm (0.50)-in.-diameter tab specimens.*

lower and would have greater scatter than the reduction-of-area values determined in the longitudinal direction.

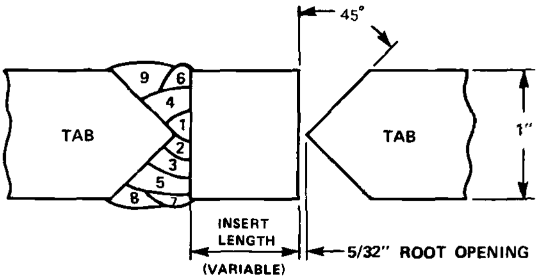
The tab specimen was given the largest emphasis in the investigation because it appeared that specifications for Z-direction testing would require the use of this specimen. [ASTM Specification for Through-Thickness Tension Testing of Steel Plates for Special Applications (A 770) has since been adopted and designates the "tab" specimen as the standard test specimen.] To determine the minimum thickness of plate that can be tested with the tab specimen, inserts with lengths simulating plates with thicknesses of 12.7, 25.4, 38.1, and 63.5 mm (½, 1, 1½, and 2½ in.) were shielded-metal-arc welded to tabs of A514 steel.[4] ASTM standard geometry specimens were then machined from blanks, and the inserts were centered at midlength of the specimens. Figure 3 schematically depicts the method of preparing the tab specimens. The rolling direction of the insert material was parallel to the longitudinal axis of the specimen for the same reasons previously discussed for the stub specimens.

For reasons explained later, 23-mm (0.90-in.)-diameter specimens (Geometry 4 of Fig. 2) were prepared from 12.7- and 25.4-mm (½- and 1-in.)-thick inserts of A36 steel welded to A514 steel tabs. These specimens are geometrically equivalent to 6.4 and 12.7 mm (¼ and ½ in.) inserts in the standard specimen.

The welding procedures are summarized in Table 3. These procedures produced welds with a tensile strength on the order of 895 MPa (130 ksi) (based on conversion of Rockwell A hardness numbers). Macrographs of welded specimen blanks of the steels used are shown in Figs. 4 to 7.

[4] At the time the present investigation was initiated, the stud-welding technique described by Domis (Footnote 3) had not yet been developed at our laboratory.

TABLE 3—*Shielded-metal-arc welding procedures used to attach tabs to inserts.*[a]



Pass No.	Electrode Diameter, in.	Arc Voltage, v	Welding Current, A	Arc Travel Speed, in./min	Heat Input, J/in.
1	5/32	25	130	2.33	83 700
2	1/8	25	140	3.04	69 100
3	5/32	25	160	4.83	49 700
4	5/32	25	160	3.50	68 600
5	5/32	25	160	3.50	68 600
6	5/32	25	160	5.83	41 200
7	5/32	25	160	5.83	41 200
8	5/32	25	160	5.00	48 000
9	5/32	25	160	5.00	48 000

[a] 1 in. = 25.4 mm. Edges machine-beveled; direct current-reverse polarity; preheat temperature: 25°C (75°F); interpass temperature: 25°C (75°F); electrode: E11018M. Rootpass (No. 1) made at an angle of 45 deg ($\pi/4$ rad); that is, the figure shown here rotated 45 deg clockwise.

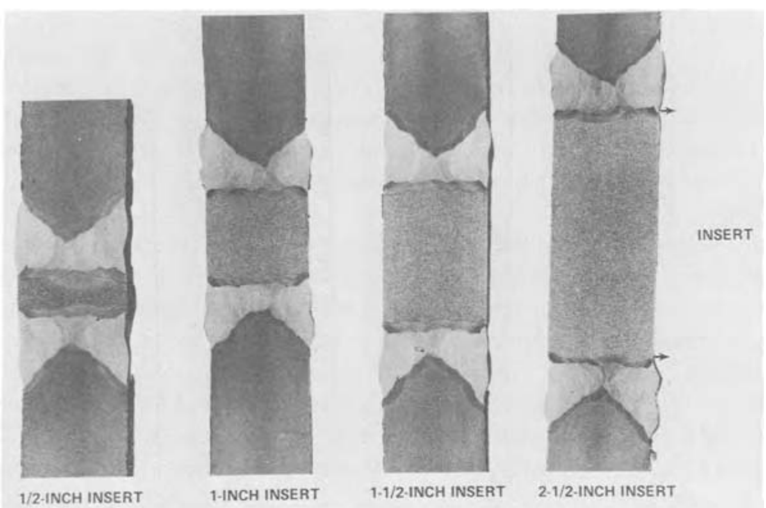


FIG. 4—*Material from which 12.7-mm (0.50-in.)-diameter tab specimens of A36 steel were machined (one half actual size).*

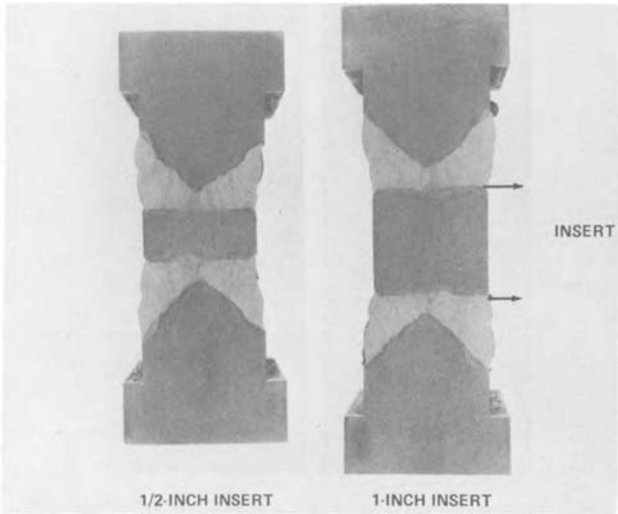


FIG. 5—*Material from which 22.9-mm (0.90-in.)-diameter tab specimens of A36 steel were machined (one half actual size).*

Results and Discussion

The results of the tension tests on the stub specimens (those with different reduced-section lengths) are summarized in Table 4 and plotted in Figure 8. Results for individual specimens are listed in Table 5.

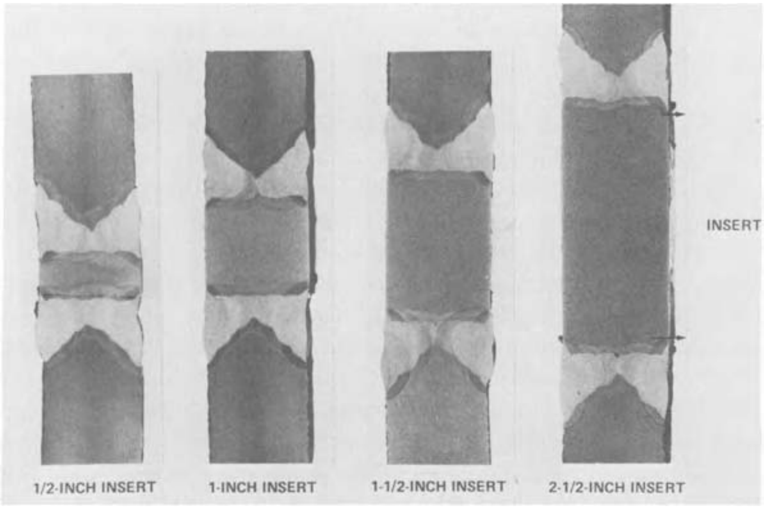


FIG. 6—*Material from which 12.7-mm (0.50-in.)-diameter tab specimens of A588 steel were machined (one half actual size).*

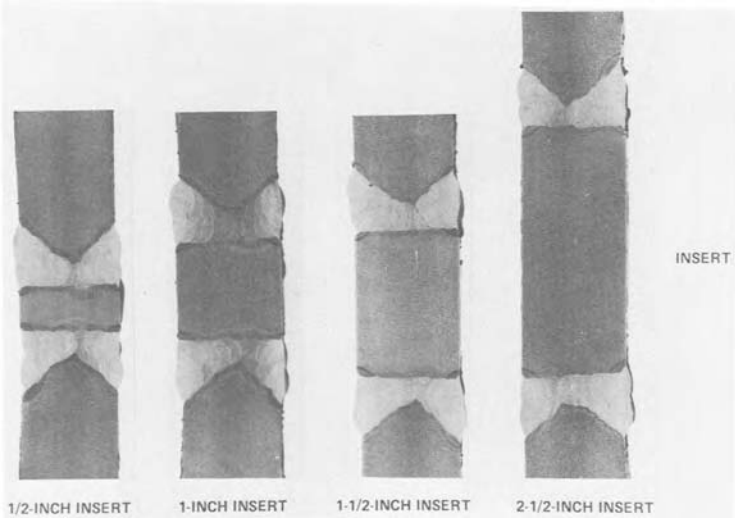


FIG. 7—*Material from which 12.7-mm (0.50-in.)-diameter tab specimens of A514 Grade F steel were machined (one half actual size).*

The data indicate that as the length of the reduced section was decreased from 4½ specimen diameters to 1 specimen diameter, the tensile strength increased by about 15 MPa (2 ksi) for A36 steel and by about 20 MPa (3 ksi) for A588 and A514 steels, whereas the reduction of area (RA) decreased (on an absolute basis) by about 2 to 3 percentage points for all steels investigated. These results are similar to those obtained in another investigation [*1*], which are also plotted in Fig. 8. These trends are caused by the constraint from the grip ends, which induce triaxial stresses in the reduced section.

Results of the tension tests on the tab specimens are summarized in Table 6 and plotted in Fig. 9. Results for individual specimens are listed in Table 7. The term "valid test", as used in Table 7 means that the specimen fractured in the material being tested and not in the weld. Fractures in the weld were associated with porosity, entrapped slag, etc.

The data for the tab specimens show that as the length of the insert was decreased from 4½ specimen diameters to 1 specimen diameter, the tensile strength increased by about 70 MPa (10 ksi) for A36 steel, by 170 MPa (25 ksi) for A588 steel, and by about 15 MPa (2 ksi) for A514 steel, and that the RA decreased (on an absolute basis) by about 9, 9, and 4 percent, respectively. This behavior is caused by the proximity of the higher strength weld areas, which inhibit plastic deformation and thus cause triaxial stresses in the insert. This effect was less for the A 514 steel because the tabs and welds were approximately the same strength as the insert. The data also show, however, that the maximum difference between the values obtained with an insert

TABLE 4—*Effect of length of reduced section on tensile strength and reduction of area of 12.7-mm (0.50-in.)-diameter tension test specimens (stub specimens).*[a]

	Tensile Strength, ksi[b]			Reduction of Area, %		
	Reduced-Section Length, diameters[c]			Reduced-Section Length, diameters		
Material	1	2	4½ (Standard)	1	2	4¼ (Standard)
A36 Heat B	67.5	67.1	65.1	68.5	69.5	70.5
A36 Heat A	67.5	65.6	65.3	67.8	69.2	70.1
A588	89.0	89.1	89.5	62.3	64.6	65.6
A514 Grade F	122.5	120.9	119.0	61.6	63.8	64.0

[a] 1 in. = 25.4 mm.
[b] 1 ksi = 6.89 MPa.
[c] 1 diameter = 0.5 in.

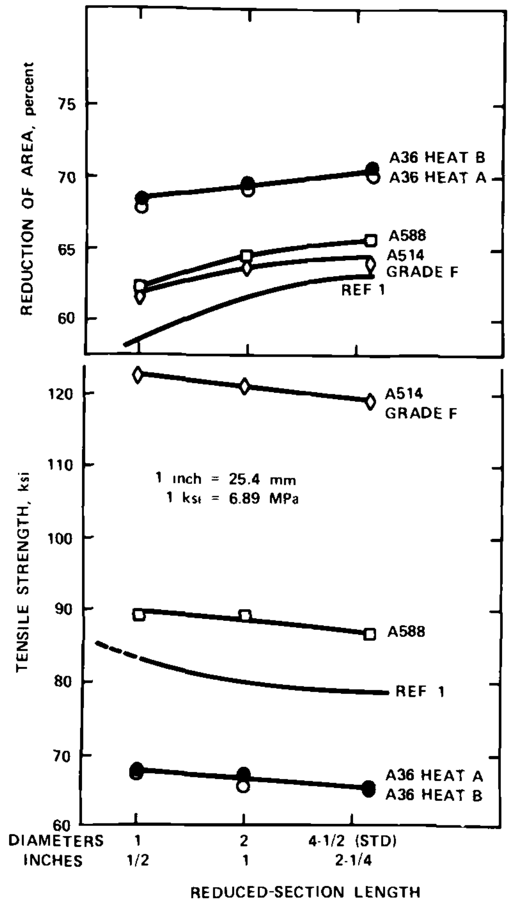


FIG. 8—*Effect of length of reduced section on tensile strength and reduction of area obtained with 12.7-mm (0.50-in.)-diameter stub-type tension test specimens.*

length of 2 specimen diameters and the values obtained with an insert length of 4½ specimen diameters was 21 MPa (3 ksi) in tensile strength and 2 percent in RA. Also shown in Fig. 9 are data obtained from a similar study by Kanazawa et al [*4*] on 12.7 to 100 mm (½ to 4 in.) thick plates of a steel having yield and tensile strengths of approximately 295 and 440 MPa (43 and 64 ksi), respectively. The trends shown by Kanazawa for both RA values and tensile strength values are similar to the trends observed in the present investigation except that the Kanazawa data showed no change in values with insert lengths greater than about 1¼ specimen diameters.

It should be noted that for the standard 12.7-mm (0.50-in.)-diameter specimens of both the A36 steel (Heat A) and the A588 steel, the RA and tensile strength values obtained for the stub specimens (Table 4) were different from the corresponding values obtained for the tab specimens (Table 6), even

TABLE 5—*Individual results for tension tests conducted with stub specimens.*

Specimen No.	Tensile Strength, ksi[a]	Reduction of Area, %	Length of Reduced Section, in.[b]
		A36 Heat B	
631	65.1	71.5	2.25 (standard geometry)
632	65.0	70.3	
633	65.2	67.8	
Average	65.1	70.5	
621	67.0	69.3	1.0
622	66.7	69.2	
623	67.5	70.0	
Average	67.1	69.5	
611	67.5	68.4	0.5
612	67.4	68.3	
613	67.6	68.8	
Average	67.5	68.5	
		A36 Heat A	
731	65.3	71.0	2.25 (standard geometry)
732	65.2	69.7	
733	65.4	69.7	
Average	65.3	70.1	
721	65.3	68.5	1.0
722	65.4	69.8	
723	66.1	69.2	
Average	65.6	69.2	
711	67.5	67.3	0.5
712	67.4	68.3	
713	67.6	67.8	
Average	67.5	67.8	
		A588	
531	86.9	65.9	2.25 (standard geometery)
532	86.9	64.4	
533	85.8	66.5	
Average	86.5	65.6	
521	89.7	64.7	1.0
522	89.0	65.2	
523	88.5	63.9	
Average	89.1	64.6	
511	89.1	61.0	0.5
512	89.7	62.8	
513	88.1	63.0	
Average	89.0	62.3	

TABLE 5—*Continued.*

Specimen No.	Tensile Strength, ksi[a]	Reduction of Area, %	Length of Reduced Section, in.[b]
		A514 Grade F	
Highest value	119.3	64.5	2.25 (standard geometry)
Lowest value	118.8	63.6	
Average of five	119.0	64.0	
121	120.6	64.6	1.0
122	120.9	63.6	
123	121.3	63.2	
Average	120.9	63.8	
111	123.1	61.8	0.5
112	122.8	61.4	
113	121.7	61.5	
Average	122.5	61.6	

[a] 1 ksi = 6.89 MPa.
[b] 1 in. = 25.4 mm.

though the samples were taken from the same general areas of the plates. Therefore, to permit a direct comparison between the results for the stub and tab specimens of either of these three steels, the data for the tab specimens (Table 6) were normalized by multiplying the value of interest in Table 6 by the ratio between the corresponding standard specimen value in Table 4 and the standard specimen value in Table 6. For example, the normalized RA-value for the three-diameter insert of the 12.7-mm (0.50-in.)-diameter A36 steel specimen was calculated as

$$65.6 \times \frac{70.1}{66.6} = 69.0$$

These normalized data are plotted in Fig. 10 and show that the restraint of the weldment of the tab specimen is more severe than that offered by the shoulders of the stub specimen probably because, for the insert, the weldment decreases the length of the base-metal test section. As can be seen in Fig. 10, the change in the properties is more pronounced after the reduced-section size or the insert size decreases in length to less than 2 specimen diameters. Hence this indicates that, especially for the tab specimen, the minimum length of the insert should not be less than 2 specimen diameters [25.4 mm (1.0 in.)] for the 12.7-mm (0.50-in.)-diameter specimen.

Because yielding occurs on 45-deg ($\pi/4$ rad) planes, plastic deformation is restrained from occurring when the height of the base-metal test section is less than 1 diameter for a round specimen (Fig. 11). Thus, to investigate the effect of a smaller insert on the behavior of the tab specimens, the insert size

TABLE 6—*Results of tension tests conducted by using 12.7-mm (0.50-in.)-diameter specimens with inserts of varying sizes (tab specimens).*[a]

	Tensile Strength, ksi[b]					Reduction of Area, %				
	Insert Length, diameters[c]					Insert Length, diameters				
Material	1	2	3	5	4½ (Standard)[d]	1	2	3	5	4½ (Standard)
A36, Heat A	81.8	74.1	72.8	72.3	71.4	57.6	64.6	65.6	67.0	66.6
A588	109.8	87.1	85.7	84.7	84.4	58.9	67.1	67.8	68.4	68.3
A514, Grade F	121.3	119.5	119.2	118.4	119.0	60.4	63.7	63.8	64.7	64.2

[a] 1 in. = 25.4 mm.
[b] 1 ksi = 6.89 MPa.
[c] 1 diameter = 0.5 in.
[d] "Standard" denotes the values obtained for specimens without ends welded to them.

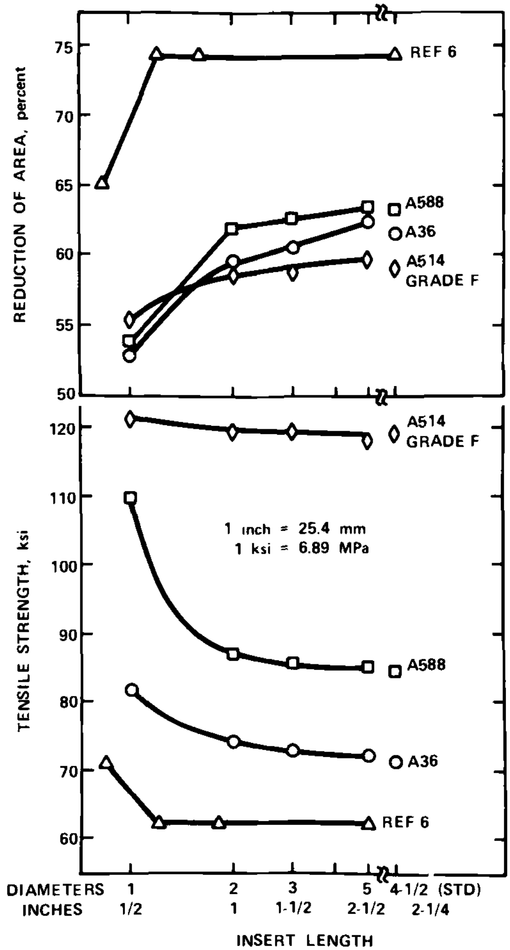


FIG. 9—*Effect of insert size on tensile strength and reduction of area obtained with ASTM standard 12.7-mm (0.5-in.)-diameter tab-type tension test specimens.*

was reduced to ½ diameter. Because the heat-affected zone (HAZ) extends toward the center of the insert, meaningful 6.35-mm (¼-in.)-thick inserts for the 12.7-mm (0.50-in.)-diameter specimen could not be prepared; however, similar results could be obtained by preparing geometrically similar 22.9-mm (0.90-in.)-diameter specimens with 25.4 and 12.7 mm (1 and ½ in.) thick inserts. As can be noted (Geometry 4 of Fig. 2), all dimensions were twice those of the standard specimen except the diameter, which was 22.9 mm (0.90 in.) instead of 25.4 mm (1.00 in.) because of scale, pits, etc., on the surface of the 25.4-mm (1-in.)-thick plate. Therefore these specimens may be thought of as simulating 6.35 and 12.7 mm (¼ and ½ in.) thick (½ and 1 diameter long) inserts in the standard 12.7-mm (0.50-in.)-diameter specimen but with a smaller HAZ.

TABLE 7—*Individual results of tension tests conducted by using standard 12.7-mm (0.50-in.)-diameter specimens with inserts of varying sizes that simulate through-thickness orientation.*[a]

Specimen No.	Insert Size, in.[a]	Tensile Strength, ksi[b]	Reduction of Area, %
	A36 Heat A		
711	not welded	72.8	65.9
712		72.1	66.7
713		71.0	66.7
714		70.1	67.8
715		70.8	65.7
Average		71.4	66.6
721	½	82.5	57.1
722		81.6	57.0
723		81.2	58.6
724		81.6	47.5[c]
725		82.0	57.8
Average		81.8	57.6
731	1	75.3	64.5
732		73.6	64.9
733		73.3	64.4
734		74.1	64.5
735		74.0	64.7
Average		74.1	64.6
741	1½	71.9	65.8
742		72.6	66.2
743		74.9	64.7
744		71.7	65.5
745		72.9	65.9
Average		72.8	65.6
751	2½	72.6	67.4
752		71.3	67.3
753		71.9	66.5
754		72.1	67.6
755		73.6	66.2
Average		72.3	67.0
	A588		
811	not welded	83.8	67.6
812		84.5	68.5
813		84.9	68.8
814		84.0	68.3
815		84.9	68.4
Average		84.4	68.3
821	½	110.8	56.8
822		106.2	11.6[c]
823		108.7	37.2[c]
824		108.7	61.0
825		108.2	49.0[c]
Average		109.8	58.9
831	1	87.3	67.4
832		87.2	66.8
833		87.2	66.4
834		87.0	68.1
835		87.0	66.7
Average		87.1	67.1

TABLE 7—*Continued.*

Specimen No.	Insert Size, in.[a]	Tensile Strength, ksi[b]	Reduction of Area, %
841	1½	85.7	67.5
842		85.4	67.7
843		86.2	68.4
844		85.9	67.1
845		85.5	68.5
Average		85.7	67.8
851	2½	84.8	68.5
852		84.5	69.4
853		85.4	67.5
854		84.4	68.4
855		84.2	68.0
Average		84.7	68.4
	A514 Grade F		
111	not welded	118.8	64.5
112		119.1	64.4
113		118.8	64.2
114		119.3	64.5
115		118.9	63.6
Average		119.0	64.2
121	½	120.1	19.5[c]
122		120.8	61.5
123		121.6	60.0
124		121.3	61.0
125		121.4	59.1
Average		121.3	60.4
131	1	118.9	63.0
132		119.9	63.3
133		120.3	62.8
134		119.0	63.1
135		119.3	66.2
Average		119.5	63.7
141	1½	119.0	65.1
142		119.3	63.8
143		119.3	63.1
144		119.6	64.2
145		118.8	62.8
Average		119.2	63.8
151	2½	118.1	63.5
152		118.4	65.7
153		118.4	65.5
154		118.1	65.7
155		119.1	63.3
Average		118.4	64.7

[a] 1 in. = 25.4 mm.
[b] 1 ksi = 6.89 MPa
[c] Not valid.

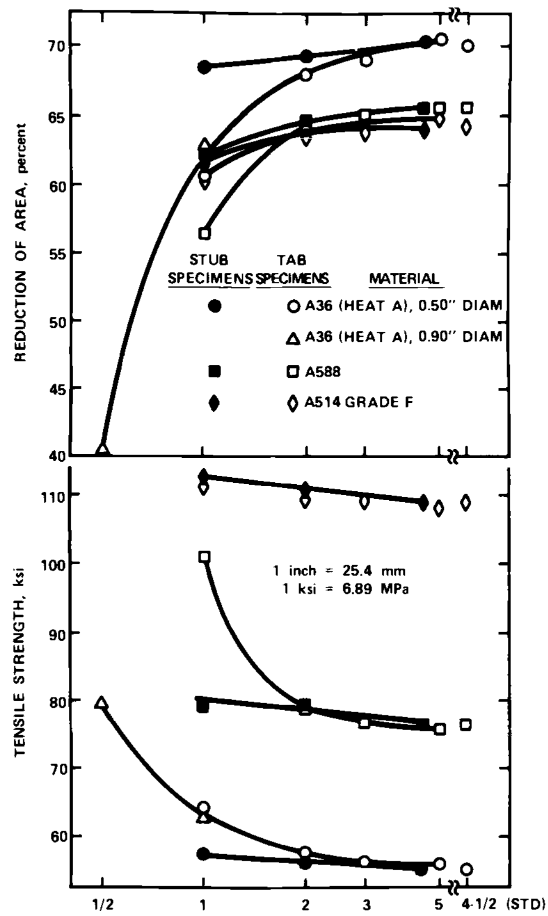


FIG. 10—*Effect of length of reduced section (stub specimens) and insert size (tab specimens) on tensile strength and reduction of area.*

The results of the tests on the 22.9-mm (0.90-in.)-diameter specimens are summarized in Table 8 and plotted in Figure 10. Results for individual specimens are listed in Table 9. The RA showed a considerable decrease and the tensile strength a corresponding increase as the insert length was decreased from 1 to ½ diameter. These results, and the fact that the HAZ may extend as deep as 6.35 mm (¼ in.), indicate that in the tab specimens the weld promotes constraint to plastic deformation.

Conclusions

The present study was conducted to evaluate the effect of gage length on the tensile-strength and reduction-of-area values obtained for stub and tab

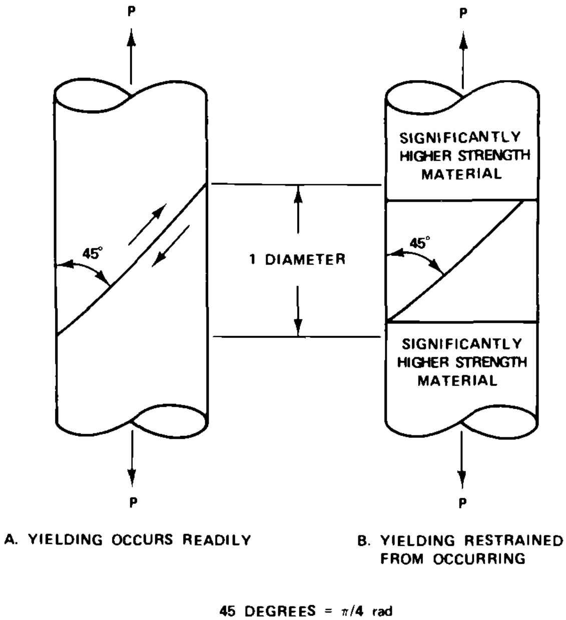


FIG. 11—*Schematic of yielding mechanism.*

specimens used to measure the through-thickness tensile properties of plate steels. The tests were conducted on specimens oriented parallel to the rolling direction, not the thickness. The results may be summarized as follows:

1. Both specimen types exhibited the same trends; namely, the measured reduction-of-area values decreased and the measured tensile-strength values increased as the length of the reduced section of the stub specimens, or the thickness (length) of the insert of the tab specimens, was decreased.
2. These trends are caused by the constraint of the shoulders of the stub specimens or by the welds in the tab specimens, both of which prevent plastic flow from occurring in the center section of the specimens.

TABLE 8—*Results of tension tests on A36 steel (Heat A) conducted by using geometrically similar specimens with inserts of varying sizes (tab specimens).*[a]

Diameter of Specimen Tested, in.	Tensile Strength, ksi[b]		Reduction of Area, %	
	Insert Length, diameters[c]		Insert Length, diameters	
	½	1	½	1
0.90	89.9	72.9	40.6	62.9

[a] 1 in. = 25.4 mm.
[b] 1 ksi = 6.89 MPa.
[c] 1 diameter ≅ 1 in.

TABLE 9—*Individual results of tension tests conducted on A36 steel by using 22.9-mm (0.90-in.)-diameter specimens with inserts of varying sizes that simulate through-thickness orientation.*[a]

Specimen No.	Insert Size, in.	Tensile Strength, ksi[b]	Reduction of Area, %
911	½	90.2	40.5
912		89.2	32.2[c]
913		90.7	38.8
914		89.3	40.5
915		89.3	42.4
Average		89.9	40.6
921	1	72.5	64.3
922		72.8	61.3
923		73.5	61.9
924		73.0	60.5
925		72.5	66.5
Average		72.9	62.9

[a] 1 in. = 25.4 mm.
[b] 1 ksi = 6.89 MPa
[c] Not valid.

3. For the same reduced-section length and insert length, the constraint caused by the welds in the tab specimens was somewhat greater than that caused by the shoulders of the stub specimens.
4. If the thickness of the insert was less than two specimen diameters [25.4 mm (1 in.)], lower reduction-of-area values and higher tensile-strength values were obtained.

Therefore, when through-thickness tension tests are performed with tab specimens on plates less than two specimen diameters thick, or with stub specimens with reduced sections less than two diameters long, lower reduction-of-area values and higher tensile-strength values will be obtained due to the effects of the welds or of the shoulders. These effects must be taken into account in determining through-thickness properties of plates. Ways of attempting to minimize these effects include (*1*) use of small-size specimens, (*2*) use of correction curves,[5] and (*3*) "adjustment" in the RA value required for "thin" plates. Each of these methods must be used with care, however, and none is recommended as being universally applicable.

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A Comparison of Short Transverse Tension Test Methods

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ABSTRACT: There are several methods presently being used to measure the short transverse tensile properties of light gage (<50 mm) steel plate. The methods can be divided into two categories: miniature specimens machined from the plate and short transverse specimens with welded prolongations. Both test methods give reliable information about the material. Recently, however, the use of the miniature specimen has been questioned because the surfaces of the plates are not tested. Since one purpose of the short transverse test is to assess susceptibility to lamellar tearing, this is a valid criticism. On the other hand, the welded prolongations, while testing the plate from surface to surface, have fusion zones and heat-affected zones present that may affect the testing of the plate surfaces. Proponents of both test methods argue the benefits of each test and are convinced theirs is the more accurate.

This study presents comparisons of both test methods. The results show the advantages of each method as well as its limitations. The miniature specimen is ideally suited for light gage plates since the button ends are only 3 mm thick. The disruption in microstructure due to welding can be greater than 3 mm, thereby affecting test results, and these specimens are better suited for short transverse tests.

Another advantage of the miniature specimen is the ability to test specific regions of a plate such as surface, quarterline, or centerline, through positioning of the specimen. Data show the value of this approach, particularly when highly stressed weld joints are to be made on the surface of plates.

It is concluded that the miniature specimen provides valuable test data unobtainable from the welded specimen. Generally, both tests give comparable results. There are optimum gage ranges for each type of specimen.

KEY WORDS: lamellar tearing, miniature button head tension specimen, short transverse testing, stud-welded tension specimen, tension test, through gage

Modern designs of pressure vessels and structures are placing greater demands on materials. This has resulted in the need for an increased awareness of lamellar tearing in weld joints. The highly constrained weld joints used in contemporary structures have the potential for this problem. This can be reduced if the proper materials and fabrication procedures are used. Before the materials can be specified, however, suitable test methods have to be devised

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to determine the material properties and fabrication parameters that most significantly affect lamellar tearing [*1–5*].[2] Then a rapid, reproducible, reliable test method has to be developed for material qualification that will indicate a reduced susceptibility to lamellar tearing [*1,6*].

The outgrowth of much of this work [*1–5*] is that the through-gage, or short transverse (ST), reduction of area (%RA) is the one relatively easily obtainable property that correlates with lamellar-tearing susceptibility. A major problem is the designing of a test specimen that tests the region of the plate most susceptible to lamellar tearing, gives reproducible results, and provides minimum disruption of the material integrity to ensure testing of the material itself and not specimen preparation techniques.

To satisfy these needs, several short transverse tension specimens are presently in use [*6*]. Each has advantages and disadvantages. The most commonly used configuration has a prolongation welded on the opposite surfaces of the plates. Welding is usually stud or friction welding. A standard tension specimen is then machined from this configuration.

Another specimen configuration is a miniature button head (MBH) [*6*]. This specimen is usually machined from the full thickness of the plate. It can also be located throughout the plate gage to test specific locations.

It is the purpose of this paper to compare these two types of specimens in order to show the suitability of both. The advantages of each type are discussed as well as reproducibility of data, versatility, adaptability, and ease of preparation.

Materials

The steels used in this study were vacuum-degassed, low-sulfur (0.010 percent maximum), calcium-treated ASTM A 516 Grades 60 and 70. The extra processing and sulfur restriction are usually specified for steels requiring

TABLE 1—*Steel composition, %.*

Heat	C	Mn	S	P	Cu	Ni	Cr	Mo	Al	Si	Steel Grade[a]
1	0.23	0.95	0.005	0.008	0.16	0.13	0.12	0.04	0.022	0.23	70
2	0.15	0.97	0.006	0.010	0.17	0.12	0.12	0.04	0.012	0.23	60
3	0.24	0.96	0.004	0.008	0.11	0.14	0.12	0.04	0.027	0.23	70
4	0.21	0.98	0.003	0.006	0.08	0.05	0.08	0.01	0.034	0.23	70
5	0.15	1.01	0.003	0.005	0.16	0.13	0.13	0.03	0.030	0.24	60
6	0.23	0.98	0.004	0.009	0.16	0.12	0.11	0.03	0.028	0.20	70
7	0.15	0.98	0.004	0.010	0.12	0.11	0.14	0.03	0.024	0.20	60
8	0.23	1.00	0.005	0.008	0.32	0.14	0.17	0.04	0.024	0.19	70
9	0.22	0.93	0.003	0.010	0.12	0.14	0.15	0.04	0.022	0.20	70
10	0.22	0.97	0.006	0.008	0.10	0.08	0.10	0.02	0.039	0.25	70

[a]In accordance with ASTM A 516.

[2]The italic numbers in brackets refer to the list of references appended to this paper.

good short transverse properties. The steels selected are commonly used structural steels produced to these tighter restrictions.

All tests came from 13 to 83 mm production plates. A total of ten heats were required to get the eleven gages tested. Table 1 lists their compositions. To minimize variability effects, all test specimens (76 mm by 228 mm by gage) were cut from the plate location corresponding to the bottom end of the original ingot or slab after the plate had been normalized at 900°C and air-cooled.

To further reduce variation, so as to improve the confidence in comparisons of different specimen configurations, short transverse test coupons were cut adjacent to each other from the same 76 by 228 mm test coupon.

Two types of short transverse tension specimens are presently being used. One is machined entirely from the test plate. This is the miniature button head (MBH) specimen. The second type has welded prolongations, usually stud-welded, although other types of welding operations are acceptable.

Miniature Button Head

The design of the MBH is based on the work of DeArdo at the University of Pittsburgh.[3] There are three sizes, each representing a particular gage of plate ranging from 13 to 57 mm. Figure 1 shows the dimensions of each size MBH and representative specimens; also shown is the ASTM standard A370 9-mm-ϕ specimen.

The axis of the MBH is perpendicular to the rolled surfaces of the plate and the overall length usually corresponds to the gage of the plate. The mid-

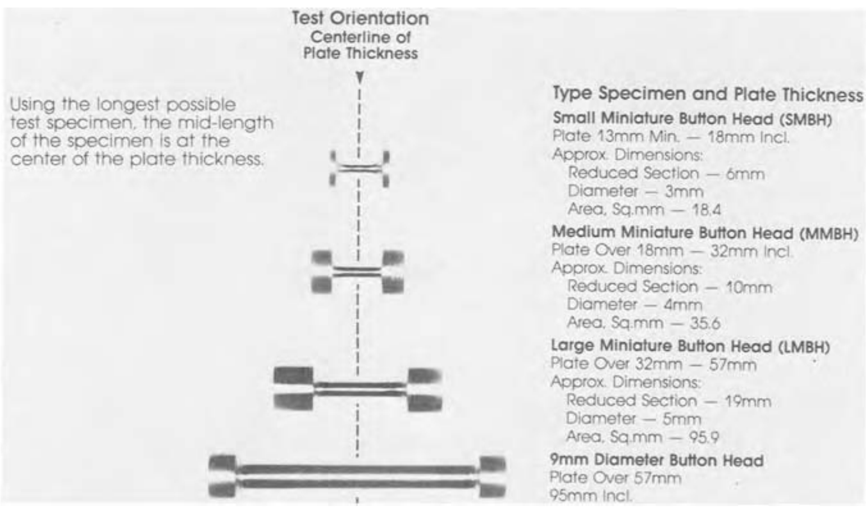


FIG. 1—*Dimensions of various button head specimens used for short transverse tension tests.*

[3] Private communication from A. J. DeArdo to D. A. Boe, 1976.

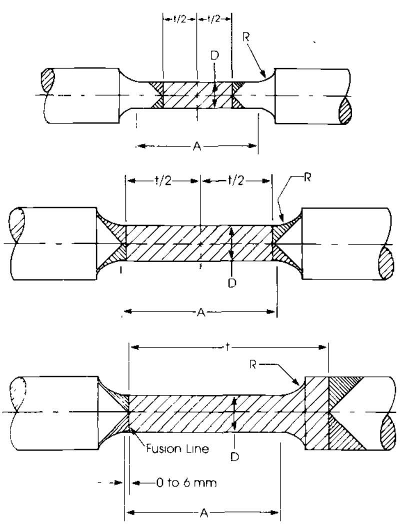
length of the MBH is located at the centerline of the plate. The size of the small MBH, however, allows for testing of specific locations through the thickness of the plate; for example, quarterline tests can be performed on plates as light as 25-mm gage. Also, because of the dimensions of the small MBH, near-surface material (3 mm below the surface) can be tested on all plates.

It should be noted that elongation measurements cannot be obtained on MBH specimens owing to their short length. Yield strengths are also unattainable because the extensometer, used to measure strain rates, cannot be attached to the specimens. Care is taken during testing, however, to ensure that strain rates conform to the ASTM standard strain rate of 0.0625 mm/min of gage length [6].

Miniature button head tension specimens are machined completely from the test coupons without the addition of prolongations. Because there is no weld, the properties obtained are those of the material and are not affected by weld quality. The absence of welded prolongations also enhances the validity of the results by eliminating alignment problems associated with welding.

Stud-Welded

Three types of welded tension specimens are specified in ASTM (A 770). Types 1 and 2 (Fig. 2) require the centerlength of the reduced section to correspond to the midgage of the plate. The Type 3 tension specimen has the weld fusion line of one plate surface located within 6 mm of one end of the



	t	D	R	A
Type 1	25≤t≤31	8.75	6	45
Type 2	31≤t≤51	12.5	10	60
Type 3	51<t	12.5	10	60

FIG. 2—*Configurations of welded specimens used for short transverse tension tests.*

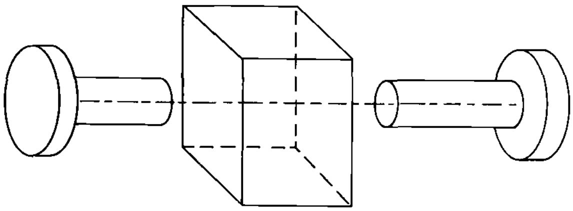


FIG. 3—*Schematic of stud weld-plate setup.*

reduced section. Although Type 1 specimens are not applicable for gages less than 25 mm, plates lighter than 25 mm were tested using this configuration. The primary purposes were to determine if the Type 1 specimen could be effectively used at the lighter gages, and to make additional comparisons with the MBH specimen.

For this study, the prolongations were stud-welded using standard studs and stud-welding techniques. The studs overmatched the plate for strength to ensure fracture between plate surfaces. Care had to be exercised to ensure correct alignment of the studs. The test specimens were rough machined to produce 30 mm by 30 mm by gage blocks having parallel sides, after which welded prolongations were joined to the surfaces (Fig. 3). All test specimens were then turned on a lathe in accordance with ASTM A 770 and tested per ASTM A 370.

Data and Discussion

Short transverse tension tests were performed on ASTM A 516 Grade 60 or 70 steel from 13 to 83 mm in gage. Both the MBH and the stud-welded (SW) specimens were used for all plates. Table 1 lists the compositions and Tables 2 to 5 show the tensile data.

TABLE 2—*Comparison of tensile properties obtained with small miniature button head and Type 1 (modified) stud-welded specimens.*

		Small Miniature Button Head				Stud Weld		
Gage, mm	Heat	*n*		UTS, MPa	%RA	*n*	UTS, MPa	%RA
13	3	6	average	530	55.2	2	545	63.0
			minimum	511	43.5		544	60.8
			maximum	551	60.0		547	65.1
18	7	4	average	518	66.7	5	516	37.6
			minimum	482	60.0		502	29.9
			maximum	551	70.0		531	46.9

TABLE 3—*Comparison of tensile properties obtained with medium miniature button head and Type 1 and Type 1 (modified) stud-welded specimens.*

		Medium Miniature Button Head				Stud Weld			
Gage, mm	Heat	n		UTS, MPa	%RA	Specimen Type	n	UTS, MPa	%RA
22	9	3	average	528	50.6	1 (modified)	9	518	33.1
			minimum	510	38.5			506	29.9
			maximum	546	60.0			526	40.0
25	4	9	average	518	63.3	1	4	517	48.5
			minimum	495	57.1			511	31.2
			maximum	546	75.0			524	66.3

TABLE 4—*Comparison of tensile properties obtained with large miniature button head and Type 2 stud-welded specimens.*

		Large Miniature Button Head				Stud Weld		
Gage, mm	Heat	n		UTS, MPa	%RA	n	UTS, MPa	%RA
35	9	2	average	532	67.9	2	566	68.4
			minimum	522	66.7		553	66.7
			maximum	541	69.0		579	70.0
38	5	4	average	500	68.4	1	508	67.2
			minimum	496	66.7		...	...
			maximum	503	70.0		...	...
51	1	2	average	558	62.7	4	552	60.7
			minimum	556	62.1		551	59.2
			maximum	561	63.3		555	62.8

TABLE 5—*Comparison of tensile properties obtained with 9-mm ϕ and Type 3 stud-welded specimens.*

		9 mm ϕ						Type 3 Stud Weld				
Gage, mm	Heat	n		YS, MPa	UTS, MPa	%E	%RA	n	YS, MPa	UTS, MPa	%E	%RA
64	6	4	average	255	455	25.9	57.0	4	298	456	26.5	58.7
			minimum	207	452	22.1	47.9		283	440	20.0	51.3
			maximum	307	460	28.4	64.5		308	473	35.5	68.0
67	2	10	average	271	460	29.5	64.0	2	319	479	26.0	69.3
			minimum	250	450	25.0	61.3		314	479	23.0	67.0
			maximum	298	466	31.9	66.7		325	479	29.0	71.5
76	8	9	average	305	532	24.3	55.6	2	334	528	24.5	61.7
			minimum	260	526	19.3	35.9		326	521	22.0	56.0
			maximum	340	537	28.4	64.1		342	535	27.0	67.3
83	10	12	average	300	526	29.3	56.6	2	321	531	31.7	61.2
			minimum	287	513	26.6	52.1		316	529	31.4	61.1
			maximum	322	528	33.7	67.5		325	532	31.9	61.3

TABLE 6—*Ratio of tensile strength and %RA of MBH and SW specimens for each plate.*

Gage, mm	$r_{UTS} = \dfrac{UTS_{SW}}{UTS_{MBH}}$	$r_{RA} = \dfrac{\%RA_{SW}}{\%RA_{MBH}}$
13	1.029	1.142
19	0.996	0.567
22	0.981	0.654
25	0.998	0.766
35	1.064	1.007
38	1.016	0.982
51	0.989	0.968
64	1.002	1.030
67	1.042	1.082
76	0.992	1.110
83	1.009	1.081

Effect of Specimen Type

There is a close correlation of ultimate tensile strength (UTS) between both specimen types for all gages. The ratio

$$r_{UTS} = \frac{UTS_{SW}}{UTS_{MBH}} \tag{1}$$

for each gage is shown in Table 6 and plotted in Fig. 4. The minor variations in r_{UTS} are well within experimental scatter.

The reduction of area (%RA), however, is affected by the specimen type.

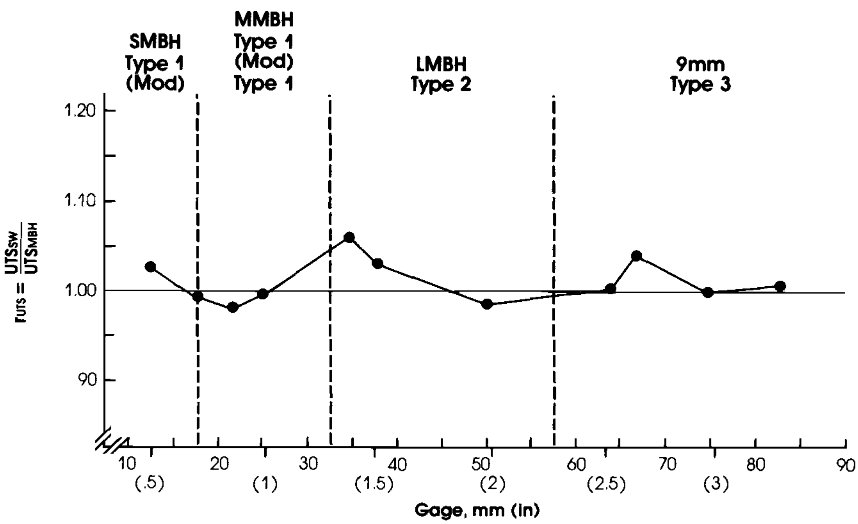


FIG. 4—*Effect of plate gage on the ratio of tensile strengths* (r_{UTS}) *obtained with stud welded to button head specimens.*

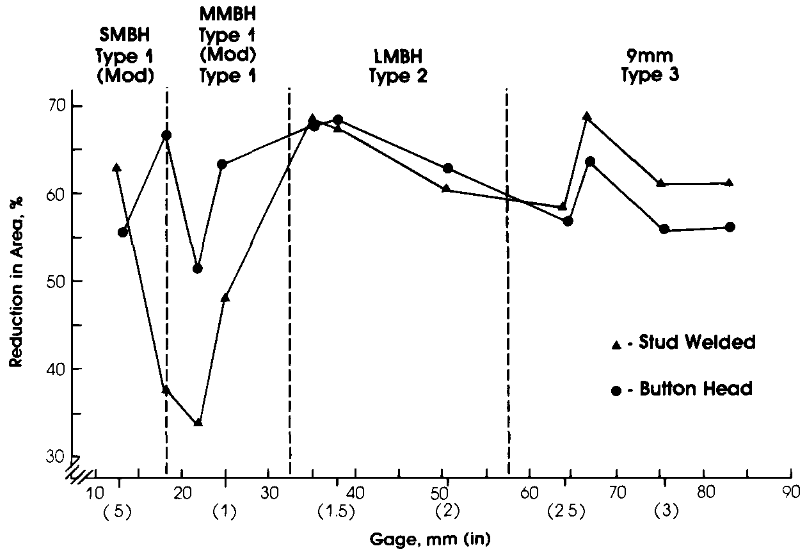


FIG. 5—*Effect of plate gage on the short transverse %RA obtained with the stud welded and button head specimens.*

Figure 5 is a graph of %RA for each specimen type for each gage. The SW has a significantly lower %RA than either the small MBH (SMBH) or medium MBH (MMBH) for the same gage range of from 18 to 25 mm. The 13-mm SW specimen has better ductility than the 13-mm MBH. This is contrary to the exhibited trend and no explanation for this can be offered.

The effect of gage is accentuated when the ratio

$$r_{RA} = \frac{\%RA_{SW}}{\%RA_{MBH}} \qquad (2)$$

is plotted (Fig. 6). The low %RA in SW specimens may be the result of constraints imposed by the weld and stud. The studs have a greater strength than the test plate. This, coupled with the inherent higher strength of the heat-affected zone, restricts deformation of the near surfaces of the test plate. By doing so, the stress state is no longer similar to that in a standard tension specimen. This altering of the stress state causes a premature shift from uniaxial to triaxial tensile stress. In doing so, the localized strain rate increases. This, coupled with the triaxial tensile stresses, reduces the ability of the material to sustain localized plastic deformation, that is, reduced %RA. This is analogous to, but not as severe as, the effect of a notch within the gage length of a test specimen.

The data in Figs. 5 and 6 substantiate this hypothesis on the effects of welding on the short transverse ductility. In Fig. 5, the same trends in %RA with gage are evident for both specimen types, although the %RA for the SW specimens is considerably lower than that for the MBH from 18 to 25 mm in

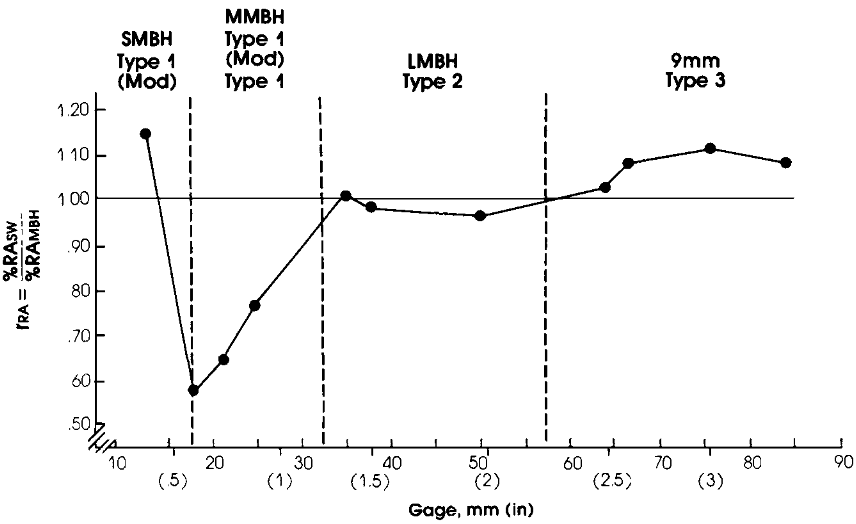


FIG. 6—*Effect of plate gage on the ratio of %RA obtained with the stud weld to %RA obtained with the button head specimens* (r_{RA}).

gage. Above 25 mm, both specimens give equivalent values of %RA. The variations in %RA with gage reflect plate-to-plate and heat-to-heat variations. Since both specimen types give similar trends, it is possible to normalize the %RA (Eq 2). The MBH was chosen for the denominator since it has the more constant gage length/diameter ($G/\phi = \rho$) ratio.

Table 7 lists ρ for the MBH and SW specimens. Also included are the effective ρ_E (G_E/ϕ) for the SW specimens, which assumes a 1-mm heat-affected zone (HAZ) on each surface of the test plate that constrains deformation. Because of this, G is further reduced. It should be noted that ASTM A 770 does not include welded short transverse tests for plates lighter than 25 mm. In this study, however, Type 1 specimen dimensions were used for the lighter gages to complete the comparison of specimen types.

To determine if there is any correlation between %RA and ρ, the data were plotted as shown in Fig. 7. The %RA could not be used because of inherent plate-to-plate variations (Fig. 5). The ratio ρ eliminates this fluctuation and allows for valid comparisons between the specimens, since tests were taken from the same location of each test plate for each gage. Figure 7 shows that r_{RA} increases with ρ to $\rho \simeq 2.5$. Thereafter r_{RA} is independent of ρ. These data show that the configuration of the SW specimens can adversely affect ductility for plates <25 mm, whereas the MBH can give a more correct ductility measure for gages as light as 13 mm.

It can be argued that the MBH does not give a valid test since it tests the center of the gage, is incapable of testing the near surface, does not have any weld zone to accentuate near-surface weaknesses, and, due to its small diameter, gives an inflated %RA. The SW specimen does not necessarily sat-

TABLE 7—*Ratio of plate gage* (G) *to specimen diameter* (ϕ) ($G/\phi = \rho$).

Plate Gage	Button Head	ρ, Stud Weld, Surface-to-Surface	ρ_E, HAZ-to-HAZ[a]
13	2:1	1.49:1[b]	1.26:1
18	2.5:1	2.06:1[b]	1.83:1
22	2.5:1	2.5 :1[b]	2.29:1
25	2.5:1	2.86:1	2.63:1
35	3.8:1	2.80:1	2.64:1
38	3.8:1	3.04	2.88:1
51	3.8:1	4.08	3.92:1
≥64	4:1	≥5.12	≥4.96:1

[a] HAZ = heat-affected zone.
[b] Plate gage too light for ASTM A 770; therefore these are modified Type 1 specimens to accommodate the lighter gages.

isfy these criteria either. The stress state imposed by the stud and HAZ is triaxial tension. The stress state in highly constrained weld joints subject to lamellar tearing is the result of bending stresses and plane strain. Also, the stress state set up by the SW configuration favors fracture near the center of the test specimen, except in cases of extremely low quality plate. These plates would also be identified by the MBH test. Finally, several investigators have found that lamellar tearing occurs below the HAZ and not at the near surface [*1,2*], although cracking can be initiated at a surface welding defect. Because of this, it may not be necessary to test the surface as long as the "near" surface is tested.

Figure 8 shows fractures of the MBH and SW specimens in 18-mm (Fig. 8*a*) and 22-mm (Fig. 8*b*) gage plates. The fracture location in each plate is independent of specimen type. The primary difference is the significantly lower ductility in the SW specimen (33.3 %RA versus 70.0 %RA and 29.9 %RA versus 60.0 %RA), probably due to the constraints mentioned pre-

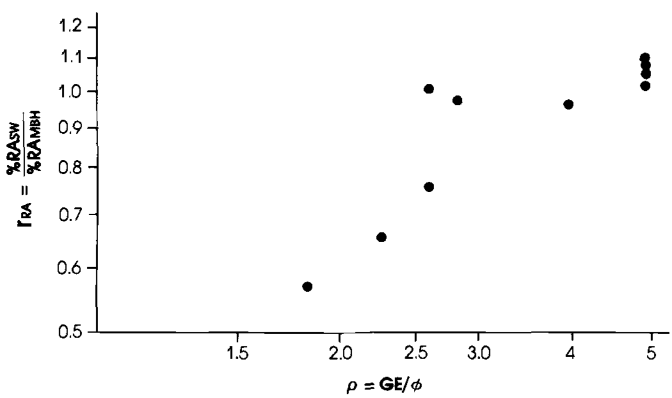


FIG. 7—*Effect of* ρ *on* r_{RA}.

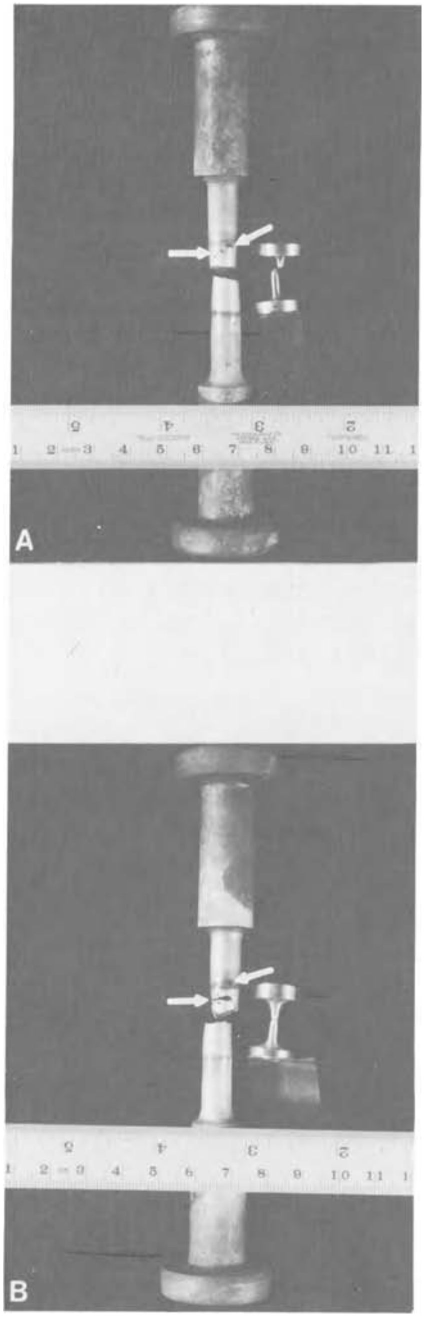


FIG. 8—*Fractured short transverse specimens showing the effect of end constraints on the ductility of stud-welded tests for 18-mm* (a) *and 22-mm* (b) *plates.*

viously. Owing to these constraints, a plate with sufficient ductility to reduce the susceptibility to lamellar tearing may be summarily rejected, not because of materials properties but because of deficiencies in specimen design.

Figures 8*a* and 8*b* also show subcritical surface cracks in the SW specimens. These cracks are generally below the HAZ and probably result from the end constraints. Even with these near-surface cracks, failure occurred near the quarterline of the plates: the same location as in the MBH specimens.

Finally, the question of inflated ductility as a function of reduced diameter must be addressed. Boe and Swift [*6*] compared the MBH with two types of stud-welded specimens. In that study, all specimens came from the same plate, were oriented parallel to the final rolling direction (*not short transverse*) so as to remove material variables as much as possible, and were tested by ASTM A 360 procedures. The data show comparable ductilities for the 13, 18, and 32 mm long MBH specimens (75 to 78%RA). Also, the same trends with respect to ρ are shown. These data show, however, that scatter in %RA with the MBH decreases with increasing diameter. Even then, the largest scatter is only ±3.8 percent of the %RA obtained from a standard 13-mm-diameter specimen. From that study, it was concluded that, if care is exercised in specimen preparation and testing, specimen diameter will not adversely affect data interpretation.

Near Surface-Tests

Oates and Stout [*1*] used welded specimens to test through-gage ductility and found a wide variation in ductility with through-thickness location of the fracture. More recently, Kaufman et al [*5*] reconfirmed this in their study of lamellar tearing. The data of Oates and Stout (Table 8) show that plates

TABLE 8—*Short transverse tensile properties for 6-mm-diameter, 25-mm gage length specimens* [1].

Steel Grade	Gage, mm	Distance of Fracture from Fusion Line, mm	Tensile Strength, MPa	Yield Strength, MPa	%RA
A515-70[a]	54	16	529	272	18.5
A515-70	...	25	531	269	23.4
A515-70	...	13	539	273	17.9
A515-70	...	22	525	269	17.3
A515-70[b]	54	5	350	287	3.9
A515-70	...	6	324	274	1.3
A515-70	...	5	406	274	3.5
A515-70	...	5	428	339	2.5

[a] Center of gage length at center of plate.
[b] Center of gage length at quarterline of plate.

TABLE 9—*Tensile property variations through the thickness in a 76-mm plate.*

Location	n	Specimen Type	Parameter	UTS, MPa	%RA
Surface	3	SMBH	average	528	66.9
			minimum	508	62.5
			maximum	551	71.4
Quarterline	3	SMBH	average	559	62.2
			minimum	551	60.0
			maximum	565	66.7
Centerline	3	SMBH	average	548	71.1
			minimum	537	66.7
			maximum	556	73.3
	9	9 mm ϕ	average	532	55.6
			minimum	526	35.6
			maximum	537	64.1
	2	SW Type 3	average	528	61.7
			minimum	521	56.0
			maximum	535	67.3

with high susceptibility to lamellar tearing have very low %RA at the quarterline, whereas the centerline %RA is good.

An advantage of the MBH specimens is that the near-surface properties can be measured. Table 9 shows the results of tests at the surface, quarterline, and centerline of a 76-mm plate using the SMBH. Figure 9 shows the location of the specimens. These data show excellent uniformity of properties and correlate well with the 9-mm and SW data. Because of this, the SMBH can be used to test various locations through the thickness while still maintaining a uniaxial stress distribution in the specimen, a condition not always attainable with an SW specimen.

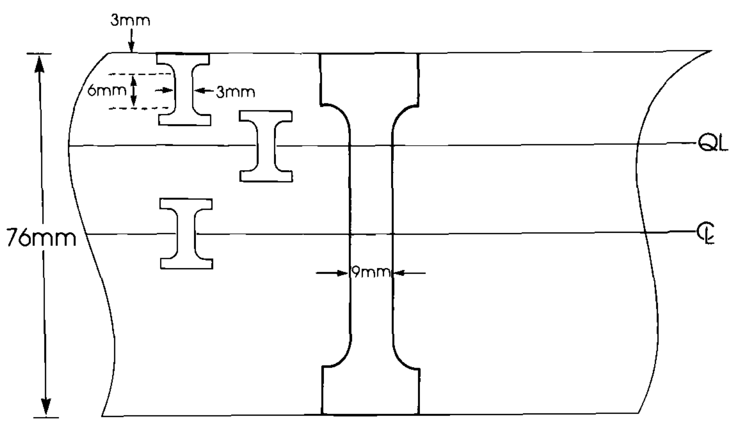


FIG. 9—*Schematic showing the location of button head specimens to test various locations through the thickness of rolled plates.*

TABLE 10—*Man-hours per test for MBH and SW specimens.*[a]

Procedure	MBH	SW
Milling	...	0.263
Turning	0.350	0.300
Stud welding	...	0.100
Testing	0.141	0.075
Total hours	0.491	0.738
Manpower savings	44%	

[a]Test sorting and cutting are equivalent for both specimens. Not included is the cost of the studs.

Relative Costs of Specimens

One consideration in using a particular test is the cost of manufacture and testing, assuming all other factors equal. It has been shown that the MBH is a less costly specimen to prepare and test than a variety of SW configurations [*6*]. Table 10 shows revised man-hour costs for the MBH and SW that still reflect a potential savings. The MBH specimen requires 29 min to machine and test compared with 44 min for the SW specimen. Additional costs for the SW are the cost of the studs and stud welder. The welder in particular is a costly item, since most steel mill test laboratories have little additional use for a stud welder.

Based upon the cost factors listed in Table 10 and the knowledge that the MBH gives data at least as credible as the SW, the MBH provides the more favorable total cost/quality benefits.

Other laboratories may have different equipment and, therefore, different cost factors. Also, as this type of testing becomes more popular, cost differentials will probably decrease. It should be noted, however, that generally both types of specimens are available, depending upon the preference of the performance specification.

Conclusions

The tensile data developed during the course of this study show that MBH and SW specimens give comparable results for plates of 25 mm and heavier. For lighter gage plates, the stress state in the SW specimen gives low ductility values, not necessarily associated with the factors known to cause lamellar tearing. The MBH specimen can be used to determine the distribution of properties through the thickness, an option not conveniently available with the SW specimen.

The MBH can be less costly than the SW in manpower, materials, and equipment. This is an important consideration in high-volume test laboratories where there are limited resources or space. The versatility of the MBH, along with its constancy of geometry and cost effectiveness, makes it the more desirable specimen for testing short transverse properties.

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D. C. Ludwigson[1]

Factors Affecting Variability in Through-Thickness Reduction-of-Area Measurements

REFERENCE: Ludwigson, D. C., "**Factors Affecting Variability in Through-Thickness Reduction-of-Area Measurements,**" *Through-Thickness Tension Testing of Steel, ASTM STP 794,* R. J. Glodowski, Ed., American Society for Testing and Materials, 1983, pp. 40–47.

ABSTRACT: Plate steels are frequently subjected to through-thickness tension tests to assess their susceptibility to lamellar tearing. In the use of test data, however, the technologist is often hindered by a large variability in measured through-thickness reduction-of-area (TTRA) values. In particular, a group of reduction-of-area values from through-thickness specimens may exhibit a standard deviation 5 to 10 times that exhibited by a group from adjacent planar specimens. The technologist must either accept an inability to discern small differences in test results or increase the number of specimens in replicate tests.

Accordingly, an analysis was made of standard deviation values obtained in through-thickness tension testing of plate. In particular, six coupons were taken from each of 108 samples of various plate steels. Prolongs were stud-welded to both surfaces of each coupon, and 12.83-mm (0.500-in.)-diameter by 127-mm (5-in.)-long tension test specimens were strained to failure in a universal testing machine at a crosshead-separation speed of 0.1 mm/s (¼ in./min). Reduction of area was measured for each specimen and for each group of six specimens representing a sample, a mean value and a standard deviation value were calculated.

Regression analysis of the data produced the model

$$\text{standard deviation, \%} = 4.614 + 1.136\ (\text{plate thickness, in.}) - 0.004778\ (\text{TTRA\%} - 38)^2$$

Variability among test results increased with increasing plate thickness and decreased as the mean TTRA value departed in either direction from 38 percent.

The overall standard deviation in TTRA values observed was about 5.1 percentage points. This figure indicates that mean TTRA values resulting from sextuplicate tests must differ by more than about 6.5 percentage points to be judged statistically different at the 97.5 percent confidence level. More tests would be required if finer discrimination were desired; fewer tests could be tolerated if lack of certainty about differences in TTRA values greater than 6.5 percentage points were tolerable.

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KEY WORDS: plate, lamellar tearing, ductility, through-thickness tension test, statistical analysis

Plate steels are frequently subjected to through-thickness tension tests to assess their susceptibility to lamellar tearing. Low through-thickness reduction-of-area (TTRA) values, less than about 20 percent, are thought to be associated with lamellar-tearing susceptibility, and ASTM Specification A 770 requires a 20 percent minimum TTRA. In the use of TTRA data, however, the technologist is often hindered by a large variability in measured values. In particular, a group of reduction-of-area values from through-thickness specimens may exhibit a standard deviation 5 to 10 times that exhibited by a group from adjacent planar specimens. Standard deviation in reduction-of-area values for planar specimens is often about 1 percentage point; the corresponding standard deviation for through-thickness specimens is often in the range of 5 to 10 percentage points.

High levels of variability in TTRA can lead to difficulty in the interpretation of through-thickness tension tests performed either for acceptance-test purposes or for research-evaluation purposes. ASTM A 770 contains retest provisions for those instances in which one acceptance-test result is below the aforementioned 20 percent level, and the other of two is above this level. In the research setting the technologist must either accept an inability to discern small differences in test results or, at some expense, increase the number of specimens in replicate tests.

In the present paper, variability in TTRA values is explored, and two factors that influence this variability, plate thickness and the mean value of TTRA, are identified.

Materials and Experimental Work

During a recent production period, 108 samples of commercial rare-earth-treated, lamellar-tearing-resistant steel plate were gathered. These plate samples were from ASTM A 516 Grade 70, A 588 Grade A, and A 633 Grade C steels; product thicknesses ranged from 25 to 102 mm (1 to 4 in.). Six 51-mm (2-in.)-square coupons were taken from each of the 108 samples. Hardened prolongs were stud-welded to both surfaces of each coupon, and 12.83-mm (0.505-in.)-diameter by 127.0-mm (5-in.)-long tension test specimens were prepared by plunge-grinding the welded assemblies. The specimens were strained to failure in a universal testing machine at a crosshead-separation speed of 6.35 mm (¼ in.) per minute. Reduction of area was measured for each specimen and, for each group of six specimens representing a sample, a mean value and a standard deviation value were calculated.

The 108 data sets were analyzed by multiple linear regression to discern influences of plate thickness and mean TTRA value on standard deviation.

Results and Discussion

Observed mean TTRA values of the samples (Table 1) ranged from 8.3 to 70.6 percent and averaged 46.6 percent. Standard deviations of the six individual TTRA measurements about their mean ranged from 0.8 to 17.0 percentage points and averaged 5.1 percentage points.

Inspection of the data indicated that standard-deviation values tended to increase with increasing plate thickness. Also, it appeared that standard-deviation values were smaller than average when the mean TTRA value was near either extreme of its range. Accordingly, the model selected encompassed these two features. Regression analysis then provided the numerical values given in the equation

$$\text{standard deviation, \%} = 4.614 + 1.136\,(\text{plate thickness, in.}) - 0.004778\,(\text{TTRA\%} - 38)^2 \quad (1)$$

Equation 1 indicates that standard deviation about mean TTRA values increases with increasing plate thickness. The student's τ-value associated with plate thickness, 2.69, indicates a significant effect. For illustration, examples of the influence of thickness on estimated standard deviation are shown in Fig. 1. Although no effort was made to discover the reason for this effect, it may have its origin in the homogenizing influence of the greater amount of hot work represented by the thinner plates.

Equation 1 also indicates that standard deviation decreases as the mean TTRA value departs, in either direction, from a level of 38 percent. The student's τ-value associated with TTRA, −4.87, indicates a very significant effect. For illustration, an example of the extent of this influence of mean TTRA value on estimated standard deviation is shown in Fig. 2. Once again no research effort was aimed at an explanation of this effect. However, some collapse of the standard deviation of any variable as that variable approaches the limits of its range may not be entirely unexpected.

No significant association of standard deviation with steel grade could be discerned. This finding should not be surprising, because the three plate grades have similar properties; their yield strengths generally are in the range of 241 to 379 MPa (35 to 55 ksi). Other plate grades of similar strength may also be encompassed by the foregoing results. However, a plate grade with substantially different properties, for example, ASTM A 514 Grade F, which yields at about 758 MPa (110 ksi), might not be properly modeled by Eq 1.

In the research setting, the observed standard-deviation value is an important determinant of experimental design. This figure is used to estimate the minimum separation between two mean TTRA values, termed Δ, that indicates a statistically significant difference. In the sample calculation given as Eq 2, the value of τ selected from a textbook table is for 97.5 percent confidence and 11 degrees of freedom. The standard-deviation value used in the calculation, 5.1 percentage points, is the arithmetic mean of the values ob-

TABLE 1—*Mean and standard deviation values for groups of six TTRA measurements on A 516, A 633, and A 588 plates of varying thickness.*

Plate Thickness, in.[a]	Mean TTRA, %	Standard Deviation in TTRA Measurement, %
1.00	32.4	2.7
	32.6	3.8
	34.3	5.0
	35.4	1.6
	38.5	5.4
	46.9	7.7
	48.3	3.9
	49.1	7.1
	49.6	5.2
1.25	8.3	2.5
	10.2	2.5
	18.8	3.5
	19.0	7.4
	22.9	5.5
	23.9	8.9
	28.4	5.3
	33.2	4.3
	35.8	2.9
	37.2	3.5
	37.5	5.9
	40.2	2.2
	41.4	5.8
	42.0	0.8
	46.4	8.2
	50.4	7.2
	54.7	4.3
	54.9	2.4
	57.9	1.3
	58.7	4.1
	59.3	1.6
	64.2	2.7
	66.0	2.9
	66.2	3.0
1.34	9.3	3.8
	10.8	4.9
	30.2	5.0
	37.3	4.5
	48.5	9.8
	58.9	1.5
1.50	49.1	5.0
	49.8	3.6
	66.3	1.7
1.63	35.9	4.3
	39.1	2.9
	54.9	1.7

TABLE 1—*Continued.*

Plate Thickness, in.[a]	Mean TTRA, %	Standard Deviation in TTRA Measurement, %
1.75	33.5	8.6
	37.9	7.8
	47.4	8.6
	47.8	13.4
	49.2	5.7
	49.5	7.3
	51.2	7.0
	53.8	7.8
	53.9	6.8
	54.8	6.4
	55.4	14.5
	55.6	10.2
	56.5	1.1
	57.5	8.7
	57.8	4.5
	57.8	5.9
	60.7	3.0
	60.7	8.5
	60.8	2.9
	61.0	5.8
	61.7	2.5
	65.0	2.8
	65.4	1.8
	67.0	3.0
	69.8	2.4
2.00	10.8	4.3
	13.5	5.2
	16.2	3.0
	16.3	3.9
	28.5	2.3
	30.4	2.8
	32.0	4.2
	32.7	1.6
	34.7	5.9
	40.1	4.4
	48.6	13.0
	48.8	11.7
	49.2	7.9
	49.4	5.9
	51.2	10.6
	51.6	9.8
	53.7	4.0
	54.1	3.7
	55.1	8.9
	55.4	8.2
	58.5	3.5
	58.9	6.9
	61.9	1.0
	64.0	2.2
	65.5	2.7
	68.7	0.9
	70.6	1.2

TABLE 1—*Continued.*

Plate Thickness, in.[a]	Mean TTRA, %	Standard Deviation in TTRA Measurement, %
3.00	28.4	5.4
	64.2	3.3
	64.5	3.0
	65.6	3.0
3.25	58.5	3.0
3.50	36.7	17.0
	53.1	6.4
3.75	56.0	11.6
	58.8	2.9
4.00	50.9	7.3
	61.8	2.4
	MEAN VALUES	
1.78	46.6	5.1

[a] 1 in. = 25.4 mm.

served in the present work. The number of specimens for which the calculation is made, six, is also the number used in the present work. The calculation yields

$$\begin{aligned} \Delta &= (\tau_{N_1+N_2-1})\sqrt{(S_1^2/N_1) + (S_2^2/N_2)} \\ \Delta &= 2.201\sqrt{(5.1^2/6) + (5.1^2/6)} \\ &= 6.5 \end{aligned} \tag{2}$$

where S = standard deviation. For these values, the minimum difference between two mean TTRA values that can be said to be statistically significant is

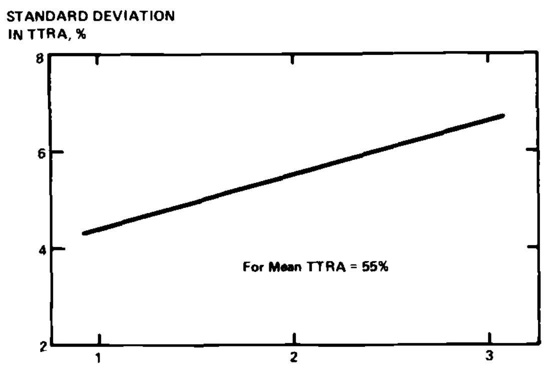

FIG. 1—*Effect of plate thickness on standard deviation (mean TTRA = 55 percent).*

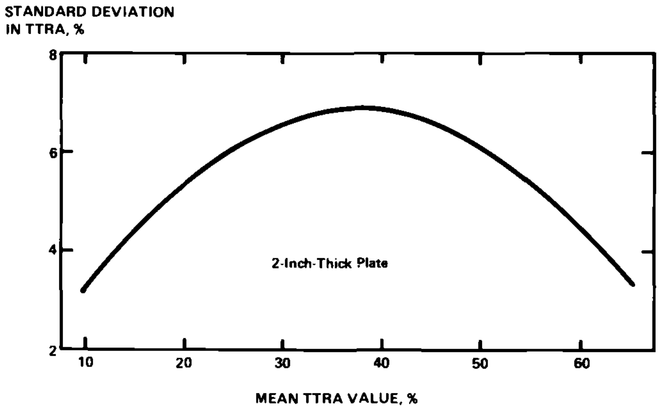

FIG. 2—*Effect of mean TTRA value on standard deviation (51-mm (2-in.)-thick plate).*

6.5 percentage points. More tests would be required if finer discrimination were desired; fewer tests could be tolerated if lack of certainty about differences in TTRA values greater than 6.5 percentage points were tolerable. Equation 2 can also be used to calculate the number of tests required to obtain a given level of discrimination; and, of course, values of τ representing levels of confidence other than the one used in the example can be used. Moreover, other observed levels of standard deviation, perhaps from Eq 1, can be used.

In our laboratory, Eq 1 is used in the design and analysis of experiments on factors influencing TTRA. The equation is also used to check on the quality of testing at our laboratory and, on occasion, the quality of testing done elsewhere.

Summary

An analysis has been made of standard-deviation data associated with sextuplicate measurements of through-thickness reduction-of-area values representing 108 rare-earth-treated steel plates. These values were obtained by testing 12.83-mm (0.505-in.)-diameter specimens prepared from stud-welded assemblies. A grand average standard deviation of 5.1 percentage points was observed. This value, of course, is much greater than its planar-direction counterparts and justifies the retest provision in ASTM A 770.

Regression analysis indicated that standard deviation increased with increasing plate thickness and decreased as mean TTRA value departed in either direction from 38 percent. These two effects were very significant.

A statistical computation indicates that, when six tests are used to obtain a mean TTRA value, discrimination between two mean TTRA values can be made with more than 95 percent confidence if these two values differ by more than 6.5 percentage points.

Knowledge of expected levels for standard deviation in TTRA measurements can be used in the design and analysis of experiments and in the assessment of testing quality.

D. C. Ludwigson[1]

Plate Thickness and Specimen Size Considerations in Through-Thickness Tension Testing

REFERENCE: Ludwigson, D. C., "**Plate Thickness and Specimen Size Considerations in Through-Thickness Tension Testing,**" *Through-Thickness Tension Testing of Steel, ASTM STP 794,* R. J. Glodowski, Ed., American Society for Testing and Materials, 1983, pp. 48–58.

ABSTRACT: The through-thickness tension test to assess the resistance of plate steels to lamellar tearing often involves the welding of prolongs to either surface of coupons from a plate and the preparation of round through-thickness tension test specimens from the resulting weldments. Specimens are strained to failure in a universal testing machine, and reduction of area is calculated from before-and-after test measurements of minimum specimen diameter.

Experiments have been performed to evaluate the influence of coupon thickness on tensile properties measured with axisymmetric through-thickness specimens prepared from stud-welded assemblies. Results indicate that the influence of coupon thickness on tensile strength and reduction of area is small, provided that the separation between metallographically observable weld heat-affected zones in the coupon is at least as great as the specimen diameter. At smaller separations the intrusion of hardened prolongs and associated welds into the specimen gage length severely increases observed tensile strength and severely decreases observed reduction of area.

Test results led to an engineering rule of thumb for the minimum plate thickness that may properly be tested with welded through-thickness specimens of a given diameter:

$$\text{minimum plate thickness} = \text{specimen diameter} + 2\,(\text{penetration distance})$$

For a stud-welded specimen in which the penetration distance is about 0.457 mm (0.18 in.), the approximate minimum critical coupon thicknesses for 12.83, 9.07, and 6.40 mm (0.505, 0.357, and 0.252 in.) diameter specimens are 22.2, 19.1, and 15.9 mm (⅞, ¾, and ⅝ in.), respectively. Provided these minimums are observed, property differences attributable to specimen size are small.

KEY WORDS: plate, lamellar tearing, ductility, through-thickness tension test, specimen size

NOTE: It is understood that the material in this paper is intended for general information only and should not be used in relation to any specific application without independent examination and verification of its applicability and suitability by professionally qualified personnel. Those making use thereof or relying thereon assume all risk and liability arising from such use or reliance.

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The through-thickness tension test is in general use to assess the resistance of plate steels to lamellar tearing. A usual assessment procedure involves the welding of prolongs to either surface of coupons from the plate and the preparation of standard round through-thickness tension test specimens from the resulting weldments. The specimens are strained to failure in a universal testing machine, and reduction of area is calculated from before-and-after test measurements of minimum specimen diameter. Several investigations have shown that adequate resistance to lamellar tearing is associated with reduction-of-area values of 20 percent or more.[2-4]

The foregoing procedure is encompassed by ASTM Specification A 770. This specification permits the use of 12.83-mm (0.505-in.)-diameter specimens made from weldments containing plate coupons at least 31.75 mm (1¼ in.) thick, and the use of 9.07-mm (0.357-in.)-diameter specimens made from weldments containing plate coupons from 25.40 to 31.75 mm (1 to 1¼ in.) thick. Although it is sometimes desirable to assess lamellar-tearing resistance in thinner plates, the specification does not cover thicknesses less than 25.40 mm (1 in.). Information in this paper will provide the basis for extending the thickness limitation downward to 15.88 mm (⅝ in.).

Experimental Work: Stage I

In the first stage of the experimental work, through-thickness tension test specimens were prepared from a sample of 82.55-mm (3¼ in.)-thick ASTM A 633 Grade C steel plate, a normalized 344.7-MPa (50-ksi) yield strength product. Coupons 50.80 mm (2 in.) square were taken from the sample and reduced to coupons with a sequence of thicknesses down to 12.70 mm (½ in.) by machining and grinding equal amounts from either surface. Coupon thicknesses tested were 82.55, 76.20, 50.80, 38.1, 31.75, 25.40, 22.23, 19.05, 15.88, and 12.70 mm (3¼, 3, 2, 1½, 1¼, 1, ⅞, ¾, ⅝, and ½ in.). Hardened prolongs were welded to both surfaces of these coupons, and 12.83-mm (0.505-in.)-diameter axisymmetric through-thickness tension test specimens were prepared by plunge-grinding the weldments. In total, 83 specimens were prepared; there were as few as 5 and as many as 12 specimens for a given coupon thickness. Reduction of area and tensile strength were measured when these specimens were tension tested.

An additional weldment prepared for each coupon thickness was sectioned in half, polished, and etched. The separations between the weld heat-affected zones were measured on these etched sections, and weld-penetration

[2] Wold, G. and Kristoffersen, R., "Development of Method for Measuring Susceptibility of Steel Plate to Lamellar Tearing," Paper 1915, Offshore Technology Conference, AIME, Dallas, Tex., 1973.

[3] Farrar, J. C. M. and Dolby, R. E., "Lamellar Tearing in Welded Steel Fabrication, "Publication SBN 85300068, The Welding Institute, Cambridge, England, 1972.

[4] "Lamellar Tearing-Resistant Steels," Nippon Steel Corporation, Nov. 1979.

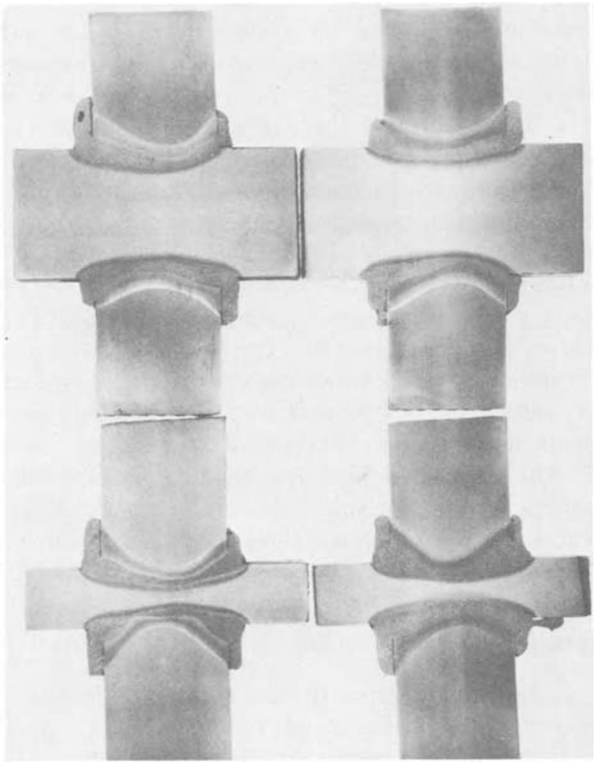

FIG. 1—*Appearance of macroetched stud-welded sections (nital etch).*

distances were calculated. A photograph of two section pairs is shown in Fig. 1.

Results

Results of the through-thickness tension tests are summarized in Fig. 2. Reduction of area and tensile strength are plotted on the vertical axis against coupon thickness on the horizontal axis. For coupon thicknesses ranging from 82.55 to 22.23 mm (3¼ to ⅞ in.), reduction of area declined only slightly with decreasing coupon thickness; the slope is about 2 percentage points for each 25.40 mm (1 in.) of thickness. This behavior changed abruptly at the 22.23-mm (⅞-in.) coupon thickness. For coupon thicknesses from 22.23 to 12.70 mm (⅞ to ½ in.), reduction of area declined very sharply with declining coupon thickness; the slope is about 61 percentage points per 25.40 mm (1 in.) of thickness. The intersection of the two straight-line segments representing these two contrasting behaviors was found analytically. The two lines met at a coupon thickness of 22.33 mm (0.879 in.), or very

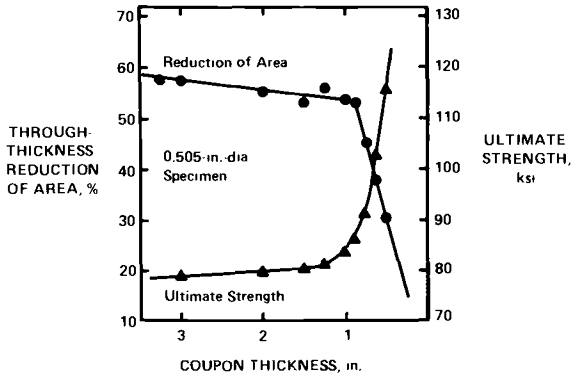

FIG. 2—*Influence of coupon thickness on through-thickness tensile properties of 12.83-mm (0.505-in.)-diameter specimens.*

nearly 22.2 mm (⅞ in.). Tensile strength appears to be nearly the mirror image of the reduction-of-area behavior.

The reason for the decrease in reduction of area and the increase in tensile strength with decreasing coupon thickness is, of course, the increasing protrusion of studs and weld heat-affected zones into the deforming region of the through-thickness tension test specimen. In Fig. 3 the separation between heat-affected zones in the coupon is plotted against coupon thickness. A linear decrease in separation distance with decreasing coupon thickness was noted. This plot is also the key to the observed abrupt change in reduction-of-area behavior at the 22.23-mm (⅞-in.) coupon thickness. If the specimen

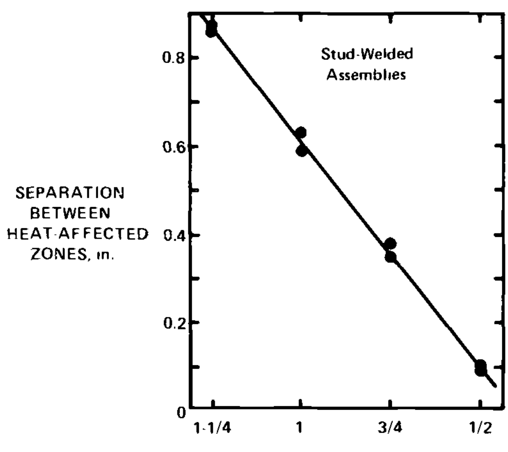

FIG. 3—*Relation between test coupon thickness and separation between heat-affected zones in stud-welded assemblies for tension test specimen preparation.*

diameter—in this case 12.83 mm (0.505 in.)—is set equal to the separation distance, the corresponding coupon thickness is found analytically to be 22.76 mm (0.896 in.) or, once again, nearly 22.23 mm (⅞ in.).

This limiting coupon thickness, 22.23 mm (⅞ in.) for the 12.83-mm (0.505-in.)-diameter specimen, could be discerned rather distinctly with the ductile material used. When a less ductile plate material was used, the results were consistent with the foregoing finding; however, owing to a greater variability in through-thickness reduction of area (TTRA) values and a smaller change in TTRA with coupon thickness, the limiting coupon thickness could not be discerned as distinctly.

The aforementioned observations were used to formulate a working hypothesis. If the separation between weld heat-affected zones in a weldment for preparation of an axisymmetric through-thickness tension test specimen is greater than the diameter of the specimen, reduction of area is only slightly sensitive to coupon thickness. For most practical purposes, the observed slight sensitivity can be neglected, and the test results can be said to represent the coupon. If the separation distance is smaller than the specimen diameter, stud and weld protrusion severely influence measured reduction-of-area values and make the test an invalid measure of coupon properties. Therefore through-thickness tests on specimens prepared from weldments provide valid measures of base-metal properties only if the distance separating the weld heat-affected zones in the weldment exceeds the minimum specimen diameter.

Experimental Work: Stage II

To verify the hypothesis and to find the critical coupon thicknesses for 9.07 and 6.40 mm (0.357 and 0.252 in.) diameter specimens, the experimental work was extended. Coupons were made from a sample of 25.40-mm (1-in.)-thick plate of ASTM A 633 Grade C steel. This steel was from a different heat than that used previously. As before, a sequence of coupon thicknesses, this time ranging from 23.81 to 11.11 mm ($^{15}/_{16}$ to $^{7}/_{16}$ in.) in 1.59-mm ($^{1}/_{16}$-in.) intervals, was prepared. Forty-five 9.07-mm (0.357-in.)-diameter and forty-five 6.40-mm (0.252-in.)-diameter axisymmetric specimens were prepared as before from stud-welded assemblies prepared from these coupons. In addition, six 12.83-mm (0.505-in.)-diameter specimens were prepared from welded assemblies encompassing 25.40-mm (1-in.)-thick coupons. Reduction of area and tensile strength were measured. In addition, separation distances were measured on an additional welded assembly.

Results

Figure 4 shows the relation between separation distance and coupon thickness observed in the extended experimental work. For a given coupon thickness, separation distances somewhat greater than those previously ob-

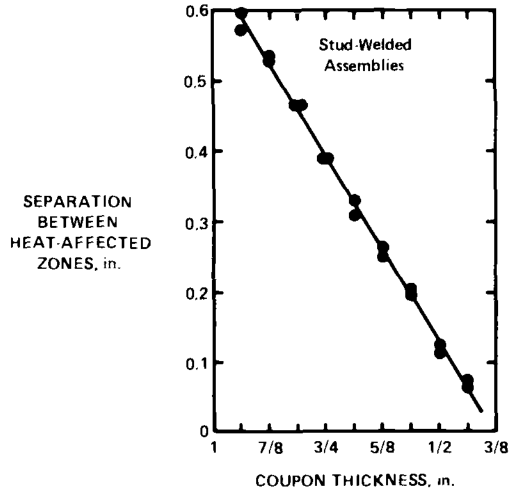

FIG. 4—*Relation between test coupon thickness and separation between heat-affected zones in stud-welded assemblies for tension test specimen preparation.*

tained were observed. This finding is a result of a deliberate reduction in energy input in the stud-welding process made subsequent to the first stage of the experimental work.

The influence of coupon thickness on through-thickness tensile properties as measured with 9.07-mm (0.357-in.)-diameter specimens is summarized in Fig. 5. As before, there is a sharp break in the slope of the reduction-of-area versus coupon thickness relation at an intermediate coupon thickness. The intersection of the two line segments, obtained analytically, is at 18.29 mm

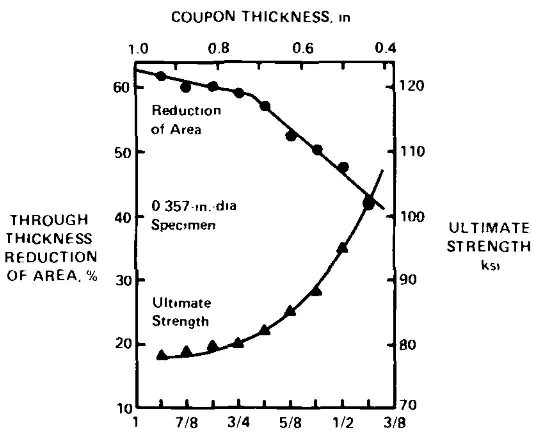

FIG. 5—*Influence of coupon thickness on through-thickness tensile properties of 9.07-mm (0.357-in.)-diameter specimens.*

(0.720 in.), or somewhat less than 19.05 mm (¾ in.). The 9.07-mm (0.357-in.) separation distance, obtained analytically from the data shown in Fig. 4, corresponds to a coupon thickness of 18.2 mm (0.717 in.). The close agreement between these two coupon thickness determinations tends to confirm the hypothesis and establishes a critical coupon thickness, about 19.05 mm (¾ in.), for the 9.07-mm (0.357-in.)-diameter specimen.

The influence of coupon thickness on through-thickness tensile properties as measured with 6.40-mm (0.252-in.)-diameter specimens is summarized in Fig. 6. As before, a break in slope of the reduction-of-area versus coupon thickness relation can be discerned. When analytic methods are applied to the data, the intersection is placed at 15.90 mm (0.626 in.), or very nearly 15.88 mm (⅝ in.). The 6.40-mm (0.252-in.) separation distance, once again obtained analytically from the data shown in Fig. 4, corresponds to a coupon thickness of 15.67 mm (0.617 in.). The close agreement between these two coupon thickness determinations further confirms the hypothesis and establishes 15.88 mm (⅝ in.) as the lower limit for use of 6.40-mm (0.252-in.)-diameter specimens made from stud-welded assemblies.

Discussion

The aforementioned findings are easily translated into a practical engineering rule for required coupon thickness:

$$\text{separation distance} \geq \text{specimen diameter}$$
$$\text{separation distance} = \text{coupon thickness} - 2\,(\text{penetration distance})$$
$$\text{coupon thickness} \geq \text{specimen diameter} + 2\,(\text{penetration distance})$$

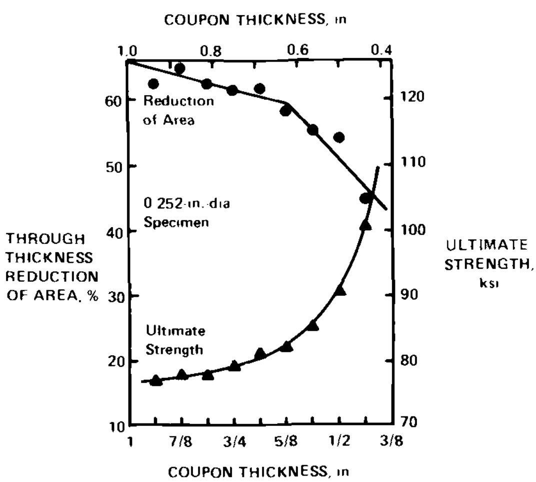

FIG. 6—*Influence of coupon thickness on through-thickness tensile properties of 6.4-mm (0.252-in.)-diameter specimens.*

For three specimen sizes it has been shown that reduction-of-area values change only slightly with coupon thickness if separation distance is greater than the specimen diameter. The separation distance can be expressed as the coupon thickness minus two times the penetration distance of the weld heat-affected zone below the plate surface. By substitution, then, the minimum coupon thickness is found to be the sum of the specimen diameter and two times the penetration distance.

Of course, penetration distance can vary with welding process and practice. In our experience, however, the penetration distance associated with stud welding averaged 4.57 mm (0.18 in.). The value changes slightly with coupon thickness, but it is very nearly 4.57 mm (0.18 in.) over the range of interest. Penetration distances measured on friction-welded assemblies averaged 4.06 mm (0.16 in.). For purposes of illustration, a penetration distance of 6.10 mm (0.24 in.) was selected as typical for shielded metal-arc welding.

Some examples of minimum plate thicknesses for valid through-thickness testing for three specimen diameters and three welding processes are given in Table 1. In round numbers, the 12.83, 9.07, and 6.40 mm (0.505, 0.357, and 0.252 in.) diameter specimens made from stud-welded assemblies may be used to make valid through-thickness tests on plates of 22.23, 19.05, and 15.88 mm (⅞, ¾, and ⅝ in.) thickness, respectively. For friction-welded assemblies, slightly thinner plates may be tested. If the shielded-metal-arc process is used to make weldments for specimen preparation, however, one should add about 3.18 mm (⅛ in.) to these thicknesses.

J. M. Holt has investigated the behavior of longitudinal specimens made from shielded metal-arc-welded assemblies.[5] His results, which predate the

TABLE 1—*Minimum plate thickness examples.*[a]

Specimen Diameter, in.	Welding Process and Associated Penetration Distance, in.[b]	Minimum Plate Thickness, in.
0.505	(FW) 0.16	0.83
	(SW) 0.18	0.87
	(SMA) 0.24	0.99
0.357	(FW) 0.16	0.68
	(SW) 0.18	0.72
	(SMA) 0.24	0.84
0.252	(FW) 0.16	0.57
	(SW) 0.18	0.61
	(SMA) 0.24	0.73

[a] 1 in. = 25.4 mm.
[b] FW = friction welding, SW = stud welding, and SMA = shielded-metal-arc welding.

[5] Holt, J. M., this publication, pp. 5–24.

present work, led him to express the concept that minimum plate thickness is associated with specimen diameter. In particular, he concluded that, "If the thickness of the insert was less than two specimen diameters, lower reduction-of-area values and higher tensile strength values were obtained." For the 12.83-mm (0.505-in.)-diameter specimen used frequently in that work, the generality is correct, and the concept of an association between specimen diameter on critical plate thickness has been confirmed in the present work. For the through-thickness orientation, however, the minimum plate thickness is generally a value other than twice the specimen diameter (Table 1).

The data developed during the exploration of specimen and coupon sizes provided the basis for some further comparisons. Shown in Fig. 7 are the through-thickness tensile properties obtained for a 25.40-mm (1-in.)-thick coupon insert in three differently sized specimens. Data for the two smaller size specimens actually represent very short, but analytic, extrapolations from 23.81 to 25.40 mm ($^{15}/_{16}$ to 1 in.) along the coupon thickness axis in Figs. 5 and 6. At this constant coupon thickness tensile strength decreased slightly and reduction of area increased slightly with decreasing specimen size. These property changes represent a decreasing influence of stud and weld intrusion into the gage length with decreasing specimen size. For the 12.83-mm (0.505-in.)-diameter specimen, the separation between weld heat-affected zones [16.66 mm (0.656 in.)] is about 1.3 times the specimen diameter. For the 9.07-mm (0.357-in.)-diameter specimen, this same separation represents about 1.8 specimen diameters; for the 6.40 mm (0.252-in.)-diameter specimen, the separation is about 2.6 specimen diameters.

The comparison changes, however, when test results are compared at a given ratio of separation (between weld heat-affected zones) to specimen diameter (Fig. 8). For the test results of the 12.83-mm (0.505-in.)-diameter specimens with a 25.40-mm (1-in.) insert, this ratio is 1.3. The same ratio applies to 9.07-mm (0.357-in.)-diameter specimens made from 20.64-mm ($^{13}/_{16}$-in.)-thick coupons and to 6.40-mm (0.252-in.)-diameter specimens

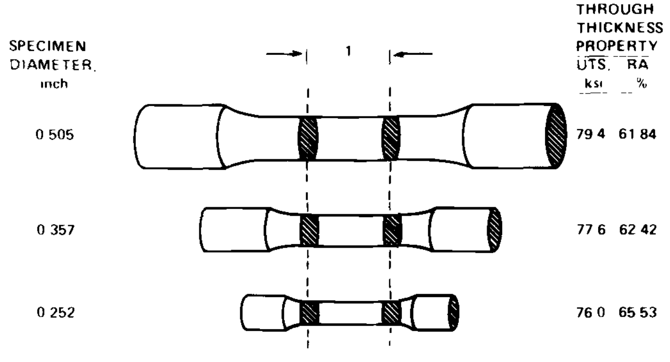

FIG. 7—*Association of through-thickness property changes with specimen dimensions.*

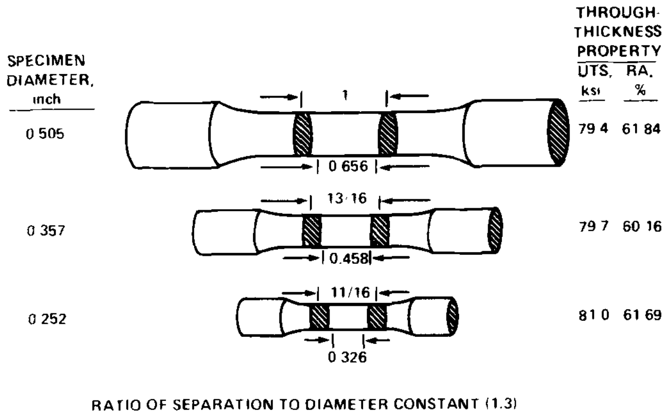

FIG. 8—*Association of through-thickness property changes with specimen dimensions.*

made from 17.46-mm ($^{11}/_{16}$-in.)-thick coupons. The comparison between three specimen sizes now indicates no substantial change in properties owing to specimen size when the deforming portion of the coupon is proportional to the specimen diameter.

At times in the research setting, it is desirable to compare test results for plates of different thicknesses. The data developed herein provide a basis for adjusting observed tensile-strength and reduction-of-area values to their equivalent at another thickness. For the 12.83-mm (0.505-in.)-diameter specimen a reference thickness of 88.90 mm (3½ in.) might be selected; this thickness puts the weld heat-affected zones into the threaded portion of the specimen or fully out of the deforming region of the specimen. The tensile property corrections given in Table 2 can then be used when comparing, for example,

TABLE 2—*Tensile property corrections for stud-welded 0.505-in.-diameter through-thickness specimens.*[a]

Plate Thickness, in.	Subtract Value Below from Tensile Strength, ksi	Add Value Below to Reduction of Area, %
3½	0	0
3	0.4	1.0
2¾	0.6	1.5
2½	0.8	2.0
2¼	1.0	2.5
2	1.2	2.9
1¾	1.6	3.4
1½	2.1	3.9
1¼	2.9	4.4
1	5.3	4.9
⅞	7.7	5.1

[a] 1 in. = 25.4 mm; 1 ksi = 6.8948 MPa.

plates of differing thickness from the same heat. Any substantial differences remaining after making these corrections would represent real property differences rather than some difference associated with test practice. The corrections are small enough, however, that for most plate-size differences they may be neglected.

Summary

Experiments have been performed to evaluate the influence of coupon thickness on tensile properties measured with axisymmetric through-thickness specimens prepared from stud-welded assemblies. Results indicate that the influence of coupon thickness on tensile strength and reduction of area is small, provided that the separation between metallographically observable weld heat-affected zones in the coupon is at least as great as the specimen diameter. At smaller separations the intrusion of hardened prolongs and associated welds into the specimen gage length severely increases observed tensile strength and severely decreases observed reduction of area. Because the heat-affected zone associated with stud welding penetrates about 4.57 mm (0.18 in.) below the coupon surface, the approximate minimum critical coupon thicknesses for 12.83, 9.07, and 6.40 mm (0.505, 0.357, and 0.252 in.)-diameter specimens are 22.23, 19.05, and 15.88 mm (⅞, ¾, and ⅝ in.), respectively. Provided these minimums are observed, property differences attributable to specimen size are generally small.

W. F. Domis[1]

Stud Welding of Prolongations to Plate for Through-Thickness Tension Test Specimens

REFERENCE: Domis, W. F., "**Stud Welding of Prolongations to Plate for Through-Thickness Tension Test Specimens,**" *Through-Thickness Tension Testing of Steel, ASTM STP 794,* R. J. Glodowski, Ed., American Society for Testing and Materials, 1983, pp. 59–69.

ABSTRACT: The usual method of preparing specimens for through-thickness tension tests is to weld extensions (prolongations) to the plate by shielded metal-arc, electron-beam, or friction welding and to machine ASTM standard round tension specimens from these weldments. All three methods have disadvantages. Shielded metal-arc welding is time-consuming because small electrodes must be used and the sample must cool between weld passes to minimize the size of the heat-affected zone. The equipment for friction and electron-beam welding is relatively expensive. Consequently, a rapid and low-cost stud-welding method has been developed for attaching prolongations to plate coupons to produce weldments from which tension specimens up to 12.8 mm (0.505 in.) in diameter can be prepared.

A portable stud-welding gun, mounted in a drill press to ensure axial alignment, is being used for welding studs to plate to produce weldments suitable for through-thickness testing. Welds have been made successfully on A36, A588, A514, A516, A537, and A633 steel plates, and through-thickness tension specimens machined from these weldments have been tested with a stud- or weld-failure rate of less than 2 percent. A stud fabricated from AISI 8620 steel bar and quenched and tempered to a minimum hardness of 30 Rockwell C appears to be suitable for through-thickness testing of plate products having strength levels up to and including that of A514 steel. Data show that this procedure is suitable for determining through-thickness reduction-of-area values for plate of about 25.4-mm (1-in.) thickness or more.

Test results indicated that the strength level of studs does not have a significant effect on the tensile properties of the test plate (provided that the strength of the stud is greater than that of the test plate).

KEY WORDS: alloy steels, carbon steels, materials testing, plate, welding

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In recent years there has been an increased awareness on the part of fabricators and designers that wrought steel products such as plate exhibit lower ductility in the through-thickness (short transverse) direction than in the longitudinal or transverse rolling directions. Under certain conditions of weld-joint design, welding process, or welding procedure, a low through-thickness ductility may contribute to the formation of separations lying beneath the weld (not necessarily in the heat-affected zone) and parallel to the plane of the plate. These separations have been termed "lamellar tears".

Because of the increased concern regarding lamellar tears and the increased complexity of welded structures, there is increasing demand for steels that are resistant to lamellar tearing. Also, because there appears to be a correlation between resistance to lamellar tearing and reduction-of-area values determined in tests conducted with standard ASTM A370 round tension test specimens oriented in the through-thickness direction, the use of through-thickness testing is growing. The usual method of preparing such specimens has been to weld extensions (prolongations) to the test plate by conventional arc-welding, electron-beam welding, or friction welding and to machine ASTM standard round tension specimens from these weldments. However, conventional arc-welding processes, such as shielded metal-arc welding, are time-consuming because small electrodes must be used and the sample must cool between weld passes to minimize the size of the heat-affected zone. The equipment cost for friction welding ($100 000 and up) and electron-beam welding ($250 000 and up) is very high.

Consequently, stud welding has been evaluated as a rapid and economical method for attaching extensions to plates to provide 12.8-mm (0.505-in.)-diameter specimens suitable for through-thickness tension tests. Stud welding is an arc process in which a metal stud is welded to a plate by a high-current arc that heats the faying surfaces to the melting point; the surfaces are then brought together under pressure. The process is very rapid, with arc times of approximately 1-s duration, resulting in a relatively narrow heat-affected zone. The procedure appears to be a practical method for providing specimens for through-thickness testing. An evaluation of the stud-welding procedures is described herein.

Materials and Experimental Work

To provide weldments suitable for the machining of the through-thickness tension specimens, a portable stud-welding gun was used to weld studs to the test plates. The gun is powered by two 800-A generators wired in parallel, with an arc time of approximately 1 s. With this gun, a stud was welded to one side of the plate; after allowing time for the plate to cool, another stud was welded on the opposite side of the plate. To provide a weldment for subsequent machining of a tension specimen, it was necessary to weld the stud perpendicular to the plate surface and in axial alignment to the stud on the opposite face of the plate. To accomplish this, it was necessary to mount the stud gun in a fixture. A modified drill-press stand was the fixture used in the present work. Because commercially available studs with a nominal tensile strength of 415 MPa (60 ksi) do not exhibit the strength required to test plate products having strength levels up to and including that of A514 steel, the studs were made from AISI 8620 steel quenched and tempered to a suitable strength level.

To determine the effect of the stud-weld heat input on the test plate, temperature measurements were taken with thermocouples placed 6.4 and 12.7 mm (¼ and ½ in.) below the plate surface. Hardness traverses were made through the thickness of 19, 25.4, and 51 mm (¾, 1, and 2 in.) thick test blocks machined from 51-mm-thick A516 Grade 70 plate and through the thickness of 51-mm-thick A514 plate.[2] Also, to determine whether stud strength affects the tensile properties of the test plate, studs with two yield strength levels [345 and 860 MPa (50 and 125 ksi)] were welded to 51-mm-square by 25.4-mm-thick test blocks of A36 plate, with the test block oriented to provide a longitudinal tension test specimen. Finally, trial welds were produced on A36, A516 Grade 70, A588, and A514 steel plates, and tested to determine whether satisfactory through-thickness tension test specimens had been produced.

Results and Discussion

Figure 1 shows the portable stud-welding gun used to weld studs to plate for through-thickness tension test specimens, together with the control box (which controls arc duration) and the drill-press mounting. A closer view of the gun and components is shown in Fig. 2. This view shows the gun, the stud, the ceramic ferrule that contains the molten pool, the work piece or plate to be welded, and the alignment fixture. One limitation noted in initial trials was that, because of arc blow, the test plate must be a minimum of 51 mm square. Machining of the 51-mm-square block did not present a problem in preparation of tension test specimens.

An experimental stud of 8620 steel quenched and tempered to a hardness of 25 Rockwell C is shown in Fig. 3, along with a cross section of an experimental specimen with studs welded to 25.4-mm-thick plate. The flux embedded in the tip of the stud is used as an arc stabilizer and deoxidizing agent. Also, as shown in this figure, the depth of the weld heat-affected zone extends approximately 4.8 mm (3/16 in.) below the surface of the test plate. Results to date show that this heat-affected zone cannot be significantly reduced without affecting joint efficiency. The chemical composition of the 8620 cold-rolled bar used for the fabrication of these studs is shown in Table 1, along with the mechanical properties determined for the bar after heat treatment—

[2] The A516 Grade 70 steel was made to a fine grain practice and the plate was normalized.

quenching from 845°C (1550°F) and tempering in the range 650 to 370°C (1200 to 700°F).

To date, welds similar to those shown in Fig. 3 have been made successfully on A36, A588, A514, A516, A537, and A633 steels, and have been subsequently tested as 12.8-mm-diameter tension specimens with a stud-failure or weld-failure rate of less than 2 percent. A 22-mm-diameter by 76-mm-long (⅞ by 3 in.) stud, with a 0.43-rad (25-deg) bevel at the tip of the stud similar to that shown on the experimental stud in Fig. 3, is a suitable stud configuration for welding and subsequent machining of 12.8-mm-diameter tension specimens. Studs produced from 8620 bar stock quenched and tempered to a minimum hardness of 30 Rockwell C are suitable for through-thickness test-

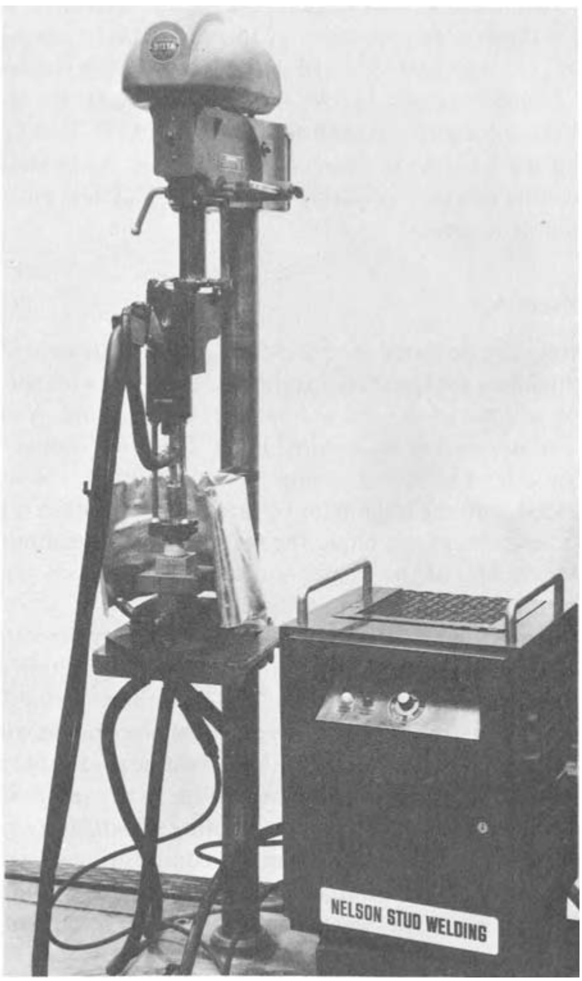

FIG. 1—*View of drill-press-mounted stud-welding gun and control box.*

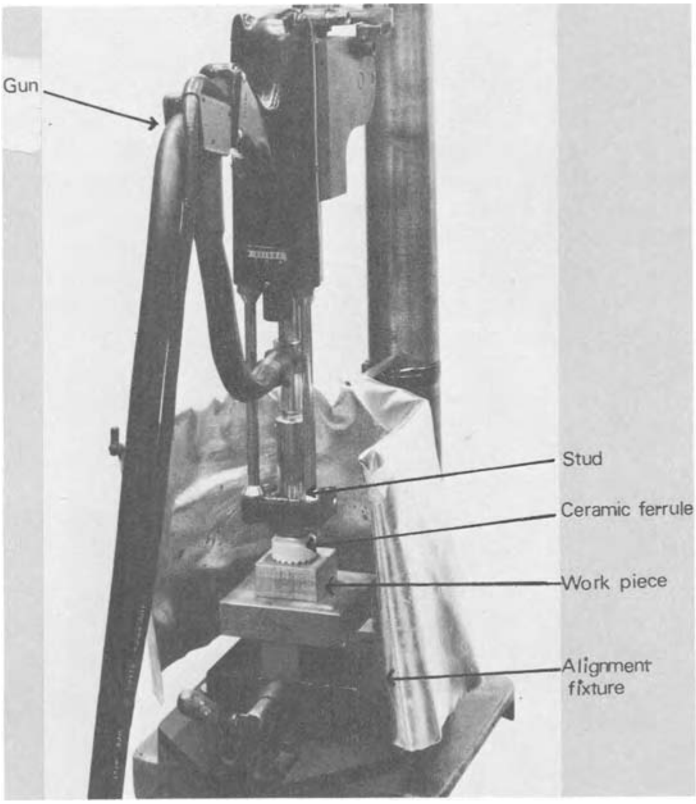

FIG. 2—*Close-up view of various components of stud welder.*

ing of plate products having strength levels up to and including that of A514 steel.

Although the visible heat-affected zone is a good measure of the depth below the plate surface affected by the heat input of the stud weld, temperature measurements were made that indicated that 25.4-mm-thick plate 51 mm square reached a maximum temperature of approximately 595°C (1100°F) during welding at a point directly under the stud and 6.4 mm below the original plate surface. At 12.8 mm (½ in.) below the plate surface (midthickness), the peak temperature recorded was 205°C (400°F).

More important, however, is the effect of the heat input on the plate hardness. To determine this, hardness traverses were made through the thickness of 19, 25.4, and 51 mm thick A516 Grade 70 test blocks and 51-mm-thick A514 plate before and after stud welding. These results are shown in Figs. 4 to 7 as plots of change in hardness versus distance from (depth below) the original plate surfaces. Figures 4, 5, and 6 show the effect of heat input on the through-thickness hardness of 19, 25.4, and 51 mm thick plates of A516

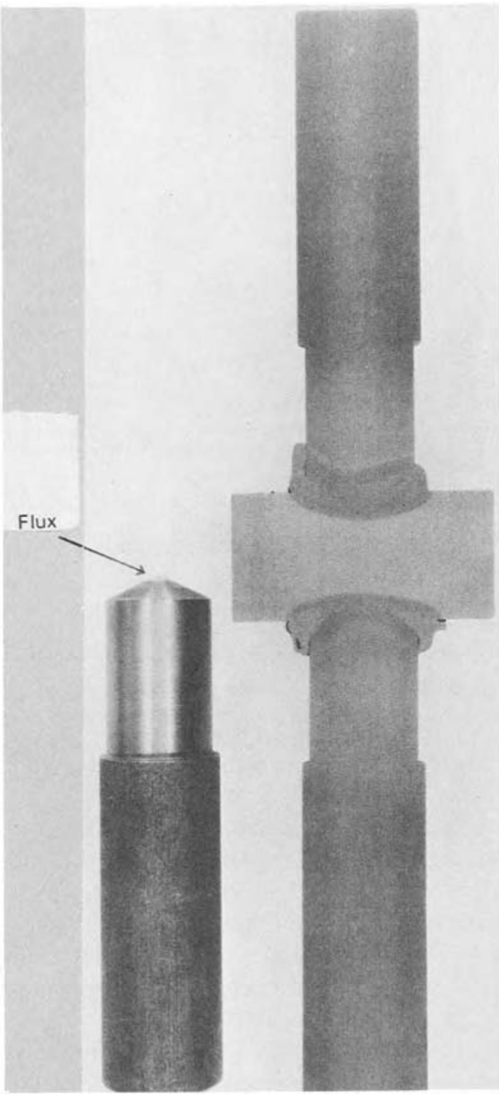

FIG. 3—*Experimental stud and cross section of stud-welded plate (one half actual size).*

TABLE 1—*Mechanical properties of 1-in. round AISI 8620 cold-rolled bar.*[a]

Heat Treatment, °F Quench	Heat Treatment, °F Temper	Yield Strength, ksi	Tensile Strength, ksi	Elongation in 2 in., %	Reduction of Area, %	Hardness, Rc
as-rolled		89.6	100.1	14.5	59.1	10
1550	1200	86.6	99.4	25.0	76.5	14
1550	1100	99.4	111.2	23.2	73.8	19
1550	1000	105.4	120.1	19.0	70.1	22
1550	900	116.4	130.1	18.0	68.6	25
1550	800	128.1	141.8	16.0	65.4	32
1550	700	132.8	158.0	15.8	61.8	36

Chemical Composition of AISI 8620 Bar Investigated, %

C	Mn	P	S	Si	Ni	Cr	Mo	Total Al
0.20	0.78	0.017	0.026	0.27	0.40	0.51	0.16	0.042

[a] °C = 5/9 (°F − 32); 1 in. = 25.4 mm; 1 ksi = 6.895 MPa.

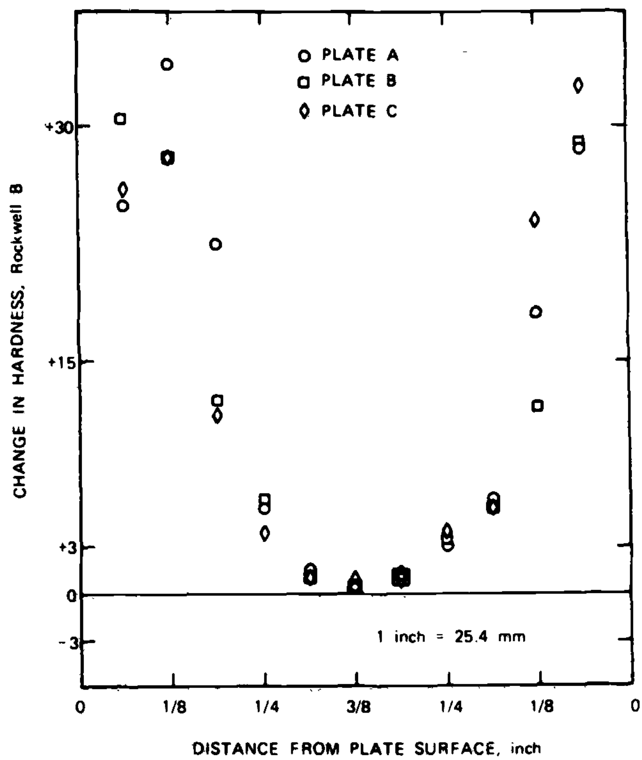

FIG. 4—*Effect of stud-welding heat input on hardness of 19-mm (3/4-in.)-thick test block of A516 Grade 70 plate steel.*

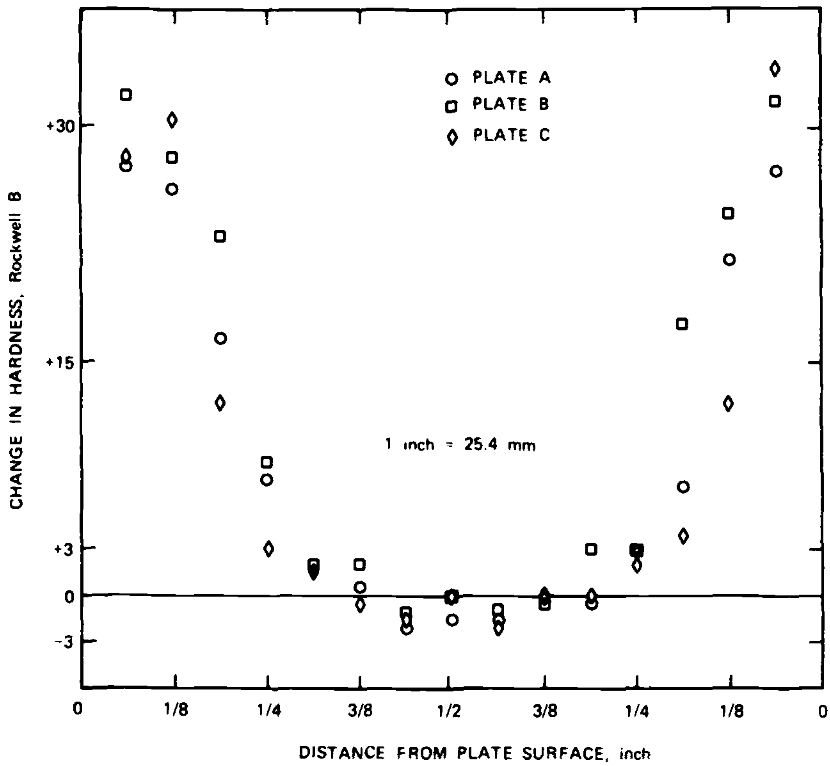

FIG. 5—*Effect of stud-welding heat input on hardness of 25.4-mm (1-in.)-thick test block of A516 Grade 70 plate steel.*

Grade 70 steel, respectively. These results show that the heat input from stud welding caused a significant increase in hardness to a distance of at least 6.4 mm below the plate surfaces. At a point 6.4 mm below the surface, the increase in hardness ranged from 2 to 9 Rockwell B points. For the 19-mm-thick A516 Grade 70 plate, some small increase in hardness due to heating was noted even in the central zone of the plate (Fig. 4). For A514 steel (Fig. 7), the hardness showed an increase at a point 3.2 mm (⅛ in.) below the plate surface; however, the stud-weld heat input did not have an effect on the hardness 6.4 mm below the plate surface.

The results, along with those obtained for the A516 Grade 70 plate, suggest that the effect of the stud-weld heat input on the change in hardness of the test plate is related, as would be expected, to the composition and heat treatment of the plate. These hardness traverses also indicate that the type of stud welding used for this study can result in metallurgical changes throughout the plate thickness (Fig. 4) when the plate is under 25.4 mm thick. More

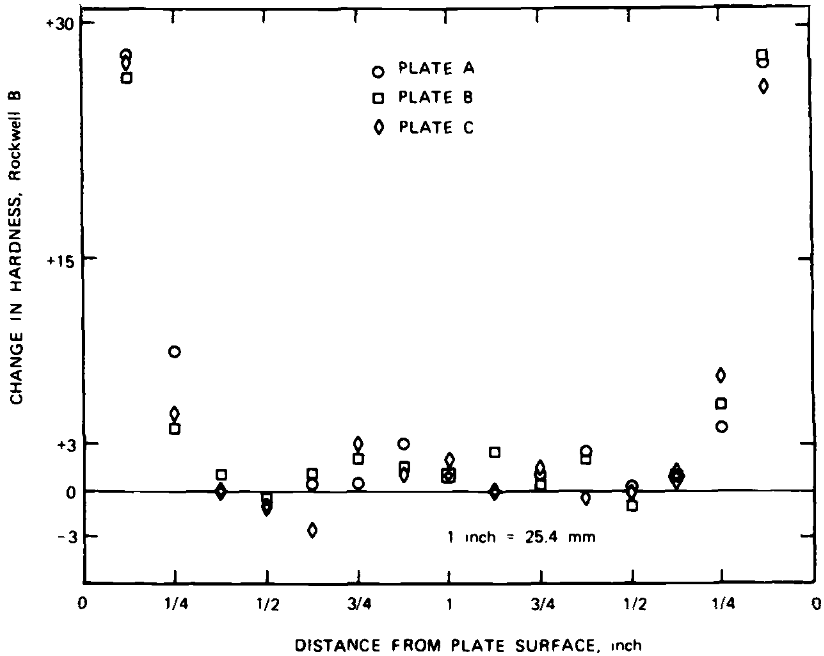

FIG. 6—*Effect of stud-welding heat input on hardness of 51-mm (2-in.)-thick test block of A516 Grade 70 plate steel.*

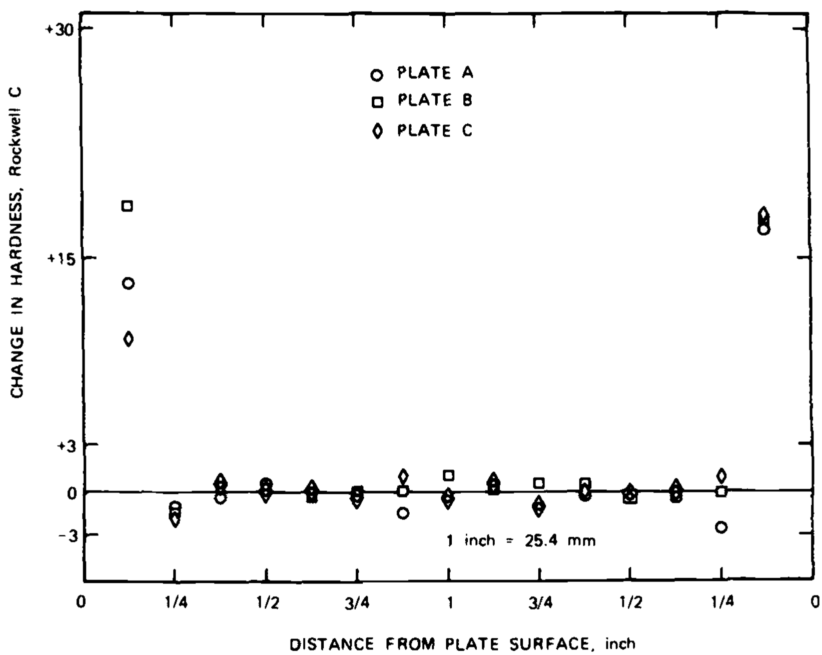

FIG. 7—*Effect of-stud welding heat input on hardness of 51-mm (2-in.)-thick test block of A514 steel plate.*

TABLE 2—*Effect of stud strength on longitudinal tensile properties of A36 plate.*[a]

Tensile Strength, ksi	Reduction of Area, %
50-ksi yield strength, stud-welded to A36 plate	
72.1	61.7
73.1	61.2
72.7	60.3
125-ksi yield strength, stud-welded to A36 plate	
72.6	61.6
72.5	62.2

[a] 1 ksi = 6.895 MPa.

recent work has shown this procedure to give accurate through-thickness reduction-of-area values for plates as thin as 22.4 mm (0.88 in.).[3]

The results of longitudinal tension tests on A36 plate welded with studs of two different yield strength levels are shown in Table 2. The measured tensile strengths and reductions of area were very similar for plate welded with studs having yield strengths of 345 and 860 MPa. The results show that the strength level of the studs did not have a significant effect on the tensile properties of the test plate (provided, of course, that the strength of the studs is greater than that of the test plate).

The equipment and procedures described in this report are currently being used on a routine basis at U.S. Steel Research for evaluating through-thickness ductility of steel plates.

Summary

The results of the present work indicate that a portable stud-welding gun, mounted in a drill press to ensure axial alignment, can be used to weld studs to plate to produce weldments suitable for through-thickness tension test specimens. To date, welds have been made successfully on A36, A588, A514, A516, A537, and A633 steel plates, and through-thickness tension specimens machined from these weldments have been tested with a stud-failure or weld-failure rate of less than 2 percent. A stud fabricated from AISI 8620 steel bar and quenched and tempered to a minimum hardness of 30 Rockwell C is suitable for through-thickness testing of plate products having strength levels up to and including that of A514 steel.

Examination of the visible heat-affected zone and hardness traverses through the plate thickness after stud welding showed that metallurgical changes can occur throughout 19-mm-thick plate. Thus this procedure appears to be suitable for determining through-thickness reduction-of-area

[3] Ludwigson, D. C., this publication, pp. 48–58.

values for plate thicknesses of about 25.4 mm (1 in.) or more. The test results also showed that the strength level of the studs does not have a significant effect on the tensile properties of the test plate (provided that the strength of the stud is greater than that of the test plate).

Equipment for stud welding is relatively inexpensive compared with the cost of other methods of welding extensions, such as friction welding and electron-beam welding. Stud welding for attaching prolongations to plate is now being used routinely at U.S. Steel Research.

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Characterizing the Through-Thickness Properties of Ultra-High-Strength Steel Plate

REFERENCE: Stotz, R. C., Berry, J. T., Anctil, A. A., and Oppenheimer, E. D., **"Characterizing the Through-Thickness Properties of Ultra-High-Strength Steel Plate,"** *Through-Thickness Tension Testing of Steel, ASTM STP 794,* R. J. Glodowski, Ed., American Society for Testing and Materials, 1983, pp. 70–84.

ABSTRACT: The Double-Ligament Test has been successfully used in the past to solve a number of practical problems relating to the ductility in the *Z*-direction of a variety of wrought and cast products, although much of the early experience was generated with high-strength low-alloy steels. More recently the test has been applied with considerable success to the evaluation of the through-thickness properties of forged and cross-rolled electroslag remelted AISI 4340 steel in the quenched and tempered condition with yield strengths in the vicinity of 2000 MPa (290 ksi). This paper describes the precautions necessary in testing steels of this particularly high strength-hardness-ductility level, and compares tensile properties of this type of material at three product thickness levels for all three principal directions. A comparison is also made between the properties determined using this test for longitudinal and transverse directions, with these employing conventional-type test bars. The paper concludes with a discussion of the results obtained and their interpretation using SEM-based fractography and other appropriate techniques.

KEY WORDS: anisotropy, short transverse ductility, lamellar tearing, rolled steel plate, through-thickness properties, ultra-high-strength steel plate

There are many design applications involving steel products in the form of either plate, bar, skelp, or thin-section forgings where the mechanical behavior of the material in the through-thickness or *Z*-direction is of salient importance. The instance of fracture by lamellar tearing in welded carbon and high-strength low-alloy steel has been discussed at some length in the literature [*1*],[4] as have the various techniques associated with determining the susceptibility of such steels to this type of failure using either an approach that

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[4] The italic numbers in brackets refer to the list of references appended to this paper.

embraces the welding process itself [1] or one wherein a specialized test piece is subjected to loading [2,3]. Less obvious are applications involving secondary or even tertiary processing, such as forge welding type operations on one hand and operations such as pocket milling complex forgings on the other, where lamellar-type inclusions or other anisotropic aspects of the microstructure of the alloy can affect the eventual performance of the product.

The problem of the assessment of the short transverse mechanical properties of sheet and plate material is one of a recurring nature. The significant factor hampering determination of such properties is test specimen size and geometry. Not surprisingly, several testing techniques have evolved over the years. This has been particularly true in those applications pertaining to constructional steels, where both texture and inclusion effects are of special interest to designers of critical welded structures such as bridges, ships, and offshore rigs. The present paper describes the modification and application of a test that has proved particularly useful in practice.

The Double-Ligament Test (DLT) [4,5] has found several areas of useful application, not only in the area of wrought plate or skelp-like materials [4-7], but also in that of cast materials [8,9], where both section thickness and location within a given section thickness are important factors. In the aforementioned work, however, all the materials concerned possessed yield stress levels no greater than 600 MPa (87 ksi). The current work indicates how this testing technique has been applied to an ultra-high-strength steel that was available in a variety of section thicknesses between 10 and 50 mm (0.4 and 2.0 in.).

Background of Double-Ligament Testing Technique

Several review articles dealing with short transverse, or through-thickness, testing techniques have appeared in the literature in recent years. Most of these have been specifically concerned with materials exhibiting lamellar tear problems [1,10,11]. Among the techniques used are those embracing subsize tension test specimens. Specimens have typically ranged from button-ended miniature variety [12] to the 15.9-mm (0.625-in.)-diameter short transverse bar [10]. Alternatively, where plate thickness has limited such approaches, projections or extension pieces attached by either welding [2,13,14] or silver-soldering [15] have been pressed into use. Finally, more specialized test bar configurations of the type to be discussed here or those proposed by European [3] and Japanese [16] workers have also been used.

Many of the tests mentioned in the literature have found only limited usage. The miniature test bar approaches are really only suitable for plate thickness of about 25 mm (1.0 in.) and up, while those tests involving welded projections invariably lead to heat-affected or poorly jointed interfacial zones which are generally deemed undesirable and virtually impossible to apply to ultra-high-strength heat-treated material. Thus there clearly exists a need for developing a technique that facilitates the determination of through-thickness stress-strain behavior in material as thin as 5.0 mm (0.2 in.). The technique developed by two of the present writers [4-6], which dates back to 1966, involves the machining of four parallel slots in a small bar, normally 19 by 5 by 5 mm (0.75 by 0.20 by 0.20 in.). Two outer slots are machined at right angles to the lower surface of the bar, and two overlapping inner slots from the upper surface of the bar (Fig. 1). The slot combination is such that two ligaments [1.5 mm (0.04 in.) long by ~0.6 mm (0.025 in.) thick] are obtained, one between each pair of outer and inner slots. The specimen is inserted into a specially designed rig which allows the two ligaments to be put into tension simultaneously (Fig. 2). A ram clamping the central portion of the bar carries a wand bearing an LVDT core, thus enabling a displacement signal to be obtained that accurately represents the average extension of the ligament pair. If the load upon the ram is monitored and displayed together with the displacement signal on an x-y recorder, a load-deflection curve can be obtained. The trace obtained, however, requires careful interpretation. Firstly, the test rig compliance must be ascertained and corrected for. Secondly, account must be taken of any bending and stress intensification occurring because of the slot-end configuration. The success or failure of any attempt to reduce stress intensification at the slot ends should be evident when the broken specimen is examined. If the fracture indeed occurs near the slot ends, stress concentration effects would seem to be operative and the results of the test would not be valid. When specimens are observed to break in or about the middle portion of the ligaments, the ultimate stress can be readily calculated by using the original area of this specimen, in spite of the fact that yielding may have been initiated at the slot

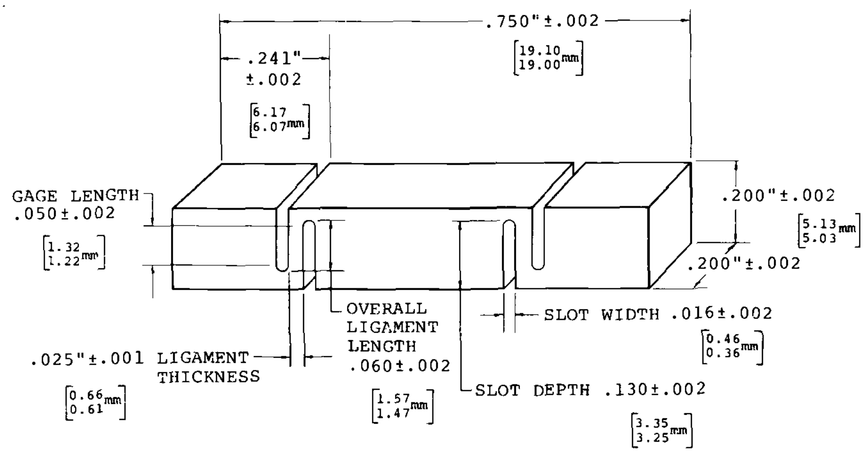

FIG. 1—*Detail of original DLT tension specimen. Specimens used in the present study have an increased length of 25.4 mm (1.00 in.) and round bottomed slots with 0.3-mm (0.012-in.) slot width, but are otherwise similar.*

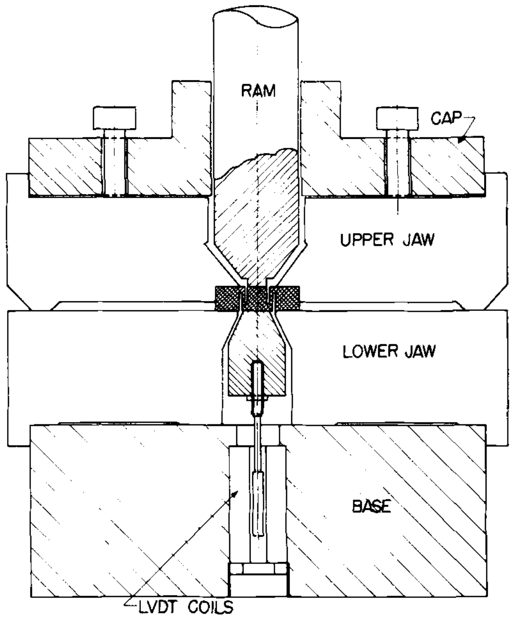

FIG. 2—*Front sectional view of DLT test fixture.*

ends. The last matter is important and has been examined in some detail [*17*]. By the use of a finite-element model of the ligament zone, an elastic stress analysis has yielded correction factors that can be applied to the various bar slot designs considered in the course of a broad investigation [*5*].

Utilization of the results of this stress analysis has allowed the collection of meaningful data not only upon low-alloy constructional steels in plate form but also upon high-strength aluminum alloy wrought plate and casting configurations. The efficacy of the technique in determining mechanical properties in various orientations has been effectively checked out by comparison with the results of full-size test bars, where the orientation and geometry permit.

As has been mentioned, the bulk of work to date has been in connection with low-carbon constructional-type steels 415 MPa (60 ksi) in yield strength, in thicknesses from 5 to 13 mm (0.2 to 0.5 in.). Consequently, applicability for use with an ultra-high-strength material, such as the electroslag remelted (ESR) and heat-treated AISI 4340 steel discussed here, had yet to be determined at the commencement of this investigation, and turned out to present some interesting problems that were solved by minor modifications of the specimen and apparatus.

The original DLT test rig (Fig. 2) was designed and constructed with a base and cap of mild steel, a ram of unhardened AISI 0-1 tool steel, jaws of hardened 0–1, and four standard mild steel bolts for clamping. During preliminary testing with standard size (Fig. 1) DLT specimens of AISI 4340 (H_{Rc} 57) steel, it was discovered that the specimens were showing an unacceptable amount of bending and that the ram itself was deforming. The ram was then heat treated to approximately H_{Rc} 61 and the loading fact resurfaced. To minimize specimen bending, the specimen length was increased to 25 mm (1.00 in.). New jaws were manufactured from AISI 4340 and heat-treated to H_{Rc} 55. To allow greater clamping force, the bolts were replaced with high-strength (≃200 ksi yield) aircraft-grade bolts. Specimen preparation (finish machining) was also an important consideration. The surface-grinding and slot-grinding operations can generate considerable heat; thus adequate cooling must be present in order to prevent grinding burns or grinding cracks and to prevent a secondary heat-treatment operation. Since the actual total cross-sectional area of a DLT specimen is small, [3.23 mm^2 (0.005 in.^{2}) for each ligament], grinding burns or cracks in the test area can be seriously detrimental to the test results.

Slot grinding resulted fortuitously in a rounded contour at the slot bottom rather than the square contour obtained from milling the earlier soft materials. Slot width was 0.3 mm (0.012 in.) rather than 0.4 mm (0.016 in.), which further improved the design.

Experimental Results

The material tested was available in the form of slabs cut from plates of the following thicknesses:

Plate S-I (Heat 2780): 10.0 mm (0.4 in.)
Plate S-II (Heat 9060): 25 mm (1.0 in.)
Plate S-III (Heat 9060): 45 mm (1.75 in.)

Chemical analyses in percent for the principal alloying elements and impurities were given for the Heat 2780 sample as carbon, 0.40; manganese, 0.77; silicon, 0.20; phosphorus, 0.010; sulfur, 0.003; nickel, 1.69; chromium, 0.85; molybdenum, 0.24; and vanadium, 0.003; and for the Heat 9060 samples as carbon, 0.40; manganese, 0.82; silicon, 0.25; phosphorus, 0.007; sulfur, 0.002; nickel, 1.76; chromium, 0.84; molybdenum, 0.26; and vanadium, 0.002. The 10.0-mm (0.4-in.) plate was produced from a 500-mm (20-in.)-diameter ESR ingot by reduction to a 300-mm (12-in.)-diameter cross section at 1110°C (2030°F), which was followed by hot-pressing to 300 by 125 mm (12 by 5 in.) section and finally cross-rolling to the 10-mm (0.4-in.) plate thickness.

The second and third plates, also reduced from 500-mm (20-in.)-diameter ESR ingot to approximately 240-mm (9.5-in.)-diameter cross section, were produced as parts of a step-forged bar of rectangular cross section. The steps concerned with the present material (S II and S III) used the thicknesses indicated previously.

After annealing at typically 870°C (1600°F) for 8 h, furnace cooling (FC) to 650°C (1200°F) over 12 h, and then air cooling (AC) to ambient, the plates were divided and blanks for the various specimens were prepared by milling. In addition to DLT bar blanks, tension specimen blanks were also cut. Heat treatment and oil quenching (00) was carried out in a controlled atmosphere furnace according to the following steps:

1. Normalize at 900°C (1650°F) for 1 h, followed by air cooling.
2. Austenitize 845°C (1550°F) for 1 h, followed immediately by oil quenching.
3. Temper at 170°C (340°F) for 1 h, followed by oil quenching.

Specimens were then fabricated by grinding under strictly controlled conditions. The design and fabrication of the tension test bars conformed to ASTM Tension Testing of Metallic Materials (E 8). The DLT specimens conformed to the modified design presented earlier in this paper.

The combinations afforded by the orientation of our DLT bar and the associated slots are illustrated in Fig. 3. The nomenclature used throughout all DLT work to date is also illustrated in this figure. The full-scale tensile bars were oriented in the longitudinal and long transverse directions only in the various plate samples.

Replication level for the DLT specimens depended upon availability of

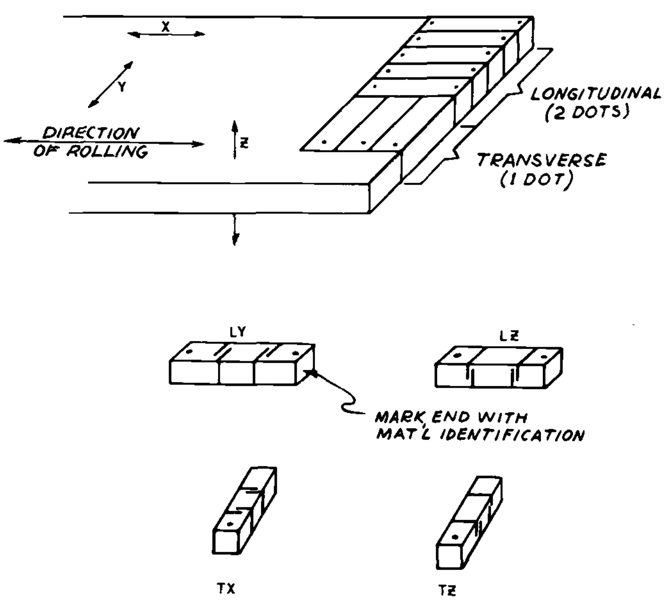

FIG. 3—*Specimen identification and nomenclature.*

TABLE 1—*Mechanical properties determined by DLT test from Plate S-1 of AISI 4340 steel* (H_{RC} = *57*) *with respect to location and orientation.*

			Yield Strength (σ_{ys}), MPa (ksi)			Ultimate Strength (σ_{UTS}), MPa (ksi)			Elongation, %		
			Range			Range			Range		
Specimen	Location	Orientation	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average
3, 5, 15, 16, 18	C	TX	1489 (216)	1407 (204)	1439 208.8)	2165 (314)	2055 (298)	2132 (309.2)	11.1	9.6	10.6
2, 6, 14, 20, 22	C	LY	1386 (201)	1358 (197)	1348 (195.5)	2220 (322)	2062 (299)	2151 (312)	14.9	11.5	13.5
1, 7, 17, 21	C	TZ	1441 (209)	1345 (195)	1348 (200.7)	2124 (308)	1869 (271)	2027 (294)	12.5	4.3	8.6
B, 4, 19, F	C	LZ	1489 (216)	1345 (195)	1406 (204)	2144 (311)	1806 (262)	2031 (294.5)	10.8	6.0	9.0
11, 13, 25, 26, 29, J	S	TX	1689 (245)	1255 (182)	1462 (212)	2303 (334)	1951 (283)	2131 (309)	16.7	7.8	12.6
9,[a] 23, 27, 28, 32	X	LY	1538 (223)	1338 (194)	1425 (206.7)	2172 (315)	2082 (302)	2136 (309.8)	13.4	10.8	12.2
C, 8, 10, 24, 31, G	S	TZ	1496 (217)	1214 (176)	1354 (196.4)	2213 (321)	1758 (255)	1951 (283)	11.2	4.6	6.7
12, 30, H, D	S	LZ	1606 (233)	1345 (195)	1515 (219)	2110 (306)	1758 (255)	1894 (274.75)	15.0	3.0	7.1

[a] Invalid test.

TABLE 2—*Results of tension tests on ESR 4340 steel.*

Bar	Orientation	From Plate	Original Diameter, mm	Original Area, mm^2	Yield Strength, MPa (ksi)	Ultimate Tensile Strength, MPa (ksi)	Fracture Strength, MPa (ksi)	Elongation, %, 2-in. gage Length[a]
A	longitudinal	S-I	0.2497	0.0490	1393 (202)	2110 (306)	1620 (235)	15
B	longitudinal	S-I	0.2497	0.0490	1386 (201)	2137 (310)	1544 (224)	15
D	long transverse	S-I	0.2503	0.0492	1393 (202)	2131 (309)	1751 (254)	13
C	long transverse	S-I	0.2496	0.0489	1407 (204)	2131 (309)	1689 (245)	14
U	longitudinal	S-III-2	0.2490	0.0487	1358 (197)	2248 (326)	1744 (253)	16
V	long transverse	S-II-2	0.2492	0.0488	1331 (193)	2220 (322)	1910 (277)	12
W	long transverse	S-III-2	0.2490	0.0487	1379 (200)	2220 (322)	1869 (271)	11
X	longitudinal	S-III-1	0.2496	0.0489	1365 (198)	2227 (323)	1738 (252)	15
Y	long transverse	S-II-1	0.2488	0.0486	1372 (199)	2241 (325)	1882 (273)	12
Z	longitudinal	S-II-1	0.2488	0.0486	1358 (197)	2227 (323)	1772 (257)	12

[a] 1 in. = 25.4 mm.

TABLE 3—*Summary of mechanical property averages determined by DLT test for specimens from different plates of ESR AISI 4340 steel ($H_{RC} \approx 57$) with respect to orientation.*

	Orientation								
	TX			LY			TZ and LY		
ates	Yield Strength (σ_{ys}), MPa (ksi)	Ultimate Tensile Strength (σ_{UTS}), MPa (ksi)	Elongation %	Yield Strength (σ_{ys}), MPa (ksi)	Ultimate Tensile Strength (σ_{UTS}), MPa (ksi)	Elongation, %	Yield Strength (σ_{ys}), MPa (ksi)	Ultimate Tensile Strength (σ_{UTS}), MPa (ksi)	Elongation, %
I	1422 (206.3)	2115 (306.7)	11.6	1381 (200.3)	2144 (311)	12.9	1395 (202.3)	1966 (285.1)	7.4
II	1401 (203.2)	2176 (315.6)	12.2	1425 (206.7)	2262 (328)	13.6	1400 (203.1)	2108 (305.8)	8.8
III	1439 (208.7)	2253 (326.8)	13.5	1433 (209.3)	2161 (313.38)	12.6	1442 (209.2)	2122 (307.7)	7.9

TABLE 4—*DLT elongation distribution for various orientations: Plate S-I (10 mm).*

Orientation	Elongation, %[a]		
	Individual Values	Range	Average
Longitudinal (TX)	7.8, 9.4, 9.5, 10.5, 10.9, 10.9, 11.1, 13.1, 13.5, 14.5, 16.7	7.8 to 16.7 (8.9)	11.6 [15]
Long transverse (LY)	10.8, 11.5, 11.7, 12.8, 12.9, 13.4, 14.2, 14.3, 14.9	10.8 to 14.9 (4.1)	12.9 [13.5]
All short transverse (TZ and LZ)	3.4, 3.9, 4.3, 4.6, 5.1, 5.1, 5.4, 6.0, 7.3, 8.9, 9.6, 9.7, 10.2, 10.8, 11.2, 12.5	3.4 to 12.5 (9.1)	7.4

[a] Parentheses ( ) = magnitude of range; brackets [ ] = average elongation observed in round tension test bars per ASTM E 8.

TABLE 5—*DLT elongation distribution for various orientations: Plate S-II (25 mm).*

Orientation	Elongation, %[a]		
	Individual Values	Range	Average
Longitudinal (TX)	1.9, 12.5, 12.7, 13.9, 14.3, 14.8, 15.0	1.9 to 15.0 (13.1)	12.1 [16]
Long transverse (LY)	12.6, 12.8, 13.7, 13.9, 14.1, 14.4	12.6 to 14.4 (1.8)	13.6 [11.5]
All short transverse (TZ plus LZ)	2.6, 4.2, 5.5, 5.7, 8.8, 9.9, 10.4, 11.6, 12.3, 12.5, 13.5	2.6 to 13.5 (10.9)	8.8

[a] Parentheses ( ) = magnitude of range; brackets [ ] = average elongation observed in round tension test bars per ASTM E 8.

TABLE 6—*DLT elongation distribution for various orientations: Plate S-III (45 mm).*

Orientation	Elongation, %[a]		
	Individual Values	Range	Average
Longitudinal (TX)	10.9, 11.4, 13.5, 13.7, 14.4, 17.2	10.9 to 14.2 (3.3)	13.5 [15]
Long transverse (LY)	11.8, 11.9, 11.9, 12.3, 13.2, 13.3, 13.7	11.8 to 13.7 (1.9)	12.6 [12]
All short transverse (TX plus LZ)	4.5, 5.0, 5.0, 5.2, 5.3, 5.4, 7.3, 11.4, 12.1, 12.4, 13.5	4.5 to 13.5 (9.0)	7.9

[a] Parentheses ( ) = magnitude of range; brackets [ ] = average elongation observed in round tension test bars per ASTM E 8.

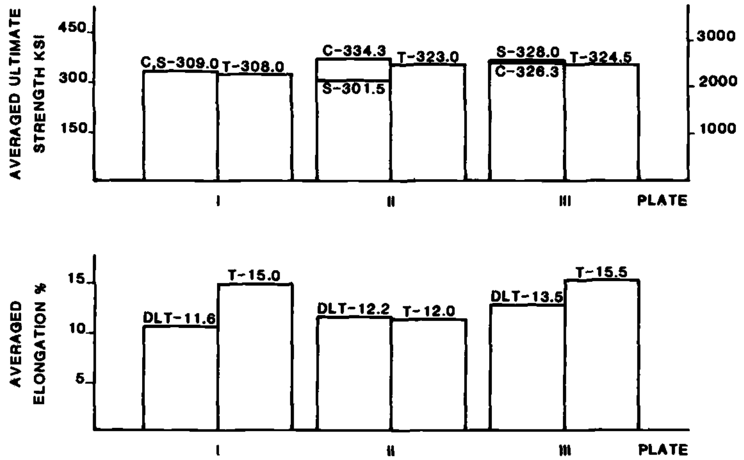

FIG. 4—*Longitudinal properties of Plates S-I, S-II, and S-III of AISI 4340 ESR steel* $H_{RC} = 57$) *as determined by DLT and regular tension test procedures.* C = *DLT specimens located near surface,* S = *DLT specimens located near central plane, and* T = *tension specimens centrally located.*

plate, since a parallel fracture toughness study also had to be undertaken [*18*]. However, as many as six (but on an average four) specimens for any particular orientation were prepared and tested. Opportunity was also taken to sample the materials concerned just below the surface as well as in the central plane of the plates concerned, although it was later determined the ranges of results obtained did not indicate any pronounced differences between the properties of DLT bars sampled at these respective locations.

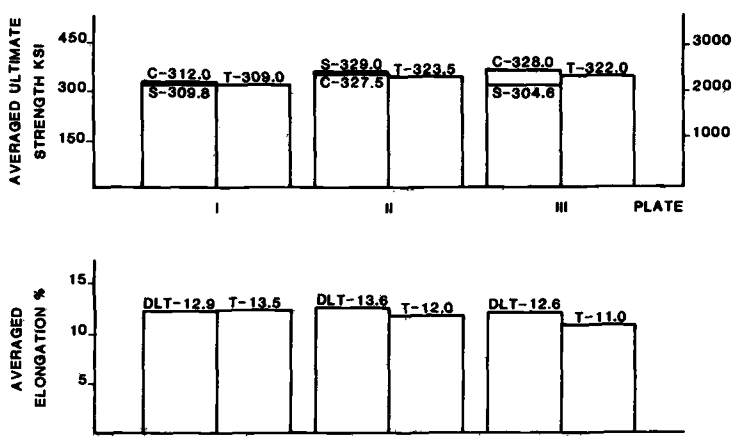

FIG. 5—*Transverse properties of Plates S-I, S-II, and S-III of AISI 4340 ESR steel* ($H_{RC} = 57$) *as determined by DLT and regular tension test procedures.* C = *DLT specimens located near surface,* S = *DLT specimens located near central place, and* T = *tension specimens centrally located.*

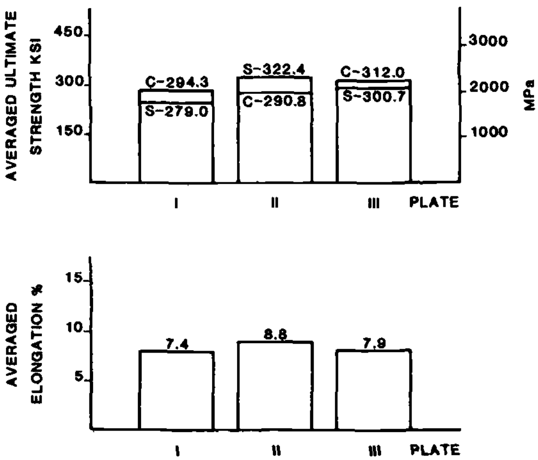

FIG. 6—*Short transverse properties of Plates S-I, S-II, and S-III of AISI 4340 ESR steel* (H_{RC} = 57) *as determined by DLT procedures.* C = *DLT specimens located near surface, and* S = *DLT specimens located near central plane.*

Duplicate tension tests of the materials in the longitudinal and long transverse directions were repeated in accordance with ASTM E 8.

The DLT testing procedure was essentially that described previously [*4,5*] with the exceptions noted earlier regarding the DLT rig modifications. Comparative DLT and regular tensile data are contained in Tables 1 and 2 for the properties of the 10-mm (0.4-in.) plate. Similar ranges of properties were obtained for the thicker plate materials. Table 3 summarizes average DLT properties for all plates. Tables 4 to 6 illustrate the individual elongation distributions for the various plate-orientation combinations obtained using the DLT technique. Figures 4, 5, and 6 show averaged data and range information graphically for the DLT experiments.

Discussion

Previous investigations employing the DLT technique [*4–8*] had indicated that yield strength, ultimate strength, and elongation values could be expected that were close to those obtained by the conventional ASTM E 8 methods, subject of course to the limitation that the full-scale bars could indeed be sampled.

It should be noted here that in examination of the yield stress it was found that, although some localized yielding occurred in the slot-end regions, the rounding afforded by the grinding did not make the stress concentration correction (utilized previously in tests with lower strength steels) necessary in the calculations concerned.

It may be concluded from Tables 2 and 3 that the present results bear out the previous supposition regarding agreement, provided precautions are taken as noted earlier [5]. These precautions, as reiterated in the present paper, are that a sufficiently large number of samples must be taken to be representative of the cross section being studied and that rotation or bending must be avoided in testing. In the present study, which was conducted with a very high-strength, low-inclusion-count material, the first precaution could be readily undertaken where material was available, while the second was promoted not only by using a bar of increased length (25 mm) but by the fixturing changes detailed earlier.

Although both sets of precautions are important in obtaining meaningful strength values, the degree of replication in sampling emerged as being especially important in correctly presenting information on elongation. Since the onset of necking in a material of this hardness level was very close to fracture, little difficulty was experienced in estimating the elongation level in the majority of cases. In some instances, especially in the short transverse testing, the two ligaments were seen to sometimes break separately; in such cases the elongation reported represented the first break observed.

In the course of investigation of the reasons for the promotion of the separate breaks, as well as of those ligaments showing particularly low elongation values generally, it was decided to undertake a limited amount of scanning electron microscopy. Several candidate fracture surfaces were examined. Results indicated that ligaments falling in the foregoing categories showed unusual fracture features, in particular exhibiting flat spots on an otherwise classical slant fracture type surface. Higher-resolution examination indicated that the flat spots were associated with areas displaying a high degree of colonization of inclusions, which in the aggregate are expected to be of a very low level in ESR material.

This degree of colonization, together with the necessity of specifying a high degree of replication of specimens, is particularly borne out if one examines the dispersion of the elongation values evidenced in Tables 4 to 6. This is especially true when one studies this width of dispersion for the short transverse elongation values in comparison with those for the other orientations for all three plate thicknesses.

Conclusions

It is concluded that, provided appropriate precautions regarding sample replication and fixturing are strictly observed, meaningful data on the tensile behavior of the subject ultra-high-strength steel can be obtained by using the Double-Ligament Test.

It is further concluded that for the steel concerned, an ESR grade of AISI 4340, the colonization of inclusions can strongly affect the ductility behavior observed.

Acknowledgments

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Relations Between Material Factors and Through-Thickness Tension Test Results

R. J. Jesseman[1] *and G. J. Murphy*[2]

Some Effects of Specimen Design, Sample Location, and Material Strength on Through-Thickness Tensile Properties

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ABSTRACT: The percent reduction of area for tension specimens made in the through-thickness direction of plates (%RA_Z) is often determined to give a relative measure of the resistance to lamellar tearing. Testing variables can affect the %RA_Z measured. Results are presented of investigations designed to examine some effects of (*1*) tension specimen design, (*2*) specimen location relative to the original ingot, (*3*) steel microstructure, (*4*) material strength level, (*5*) specimen-to-specimen variability, and (*6*) final diameter measurement reproducibility. Tension specimens in the *Z*-direction with an 8.9 mm (0.350 in.) diameter and 50.8 to 63.5 mm (2 to 2½ in.) parallel section gave the highest average %RA_Z and smallest variability. Specimen location had a very marked effect on the %RA_Z, with the lowest values found along the ingot centerline and highest levels at the ingot corners and edges. Normalized ASTM A537 Class 1 steel gave higher %RA_Z than when quenched and tempered to nearly the same ultimate tensile strength. Material strength level varied by changing the tempering temperature after quenching had only a small effect on the %RA_Z. Considerable specimen-to-specimen variability in the %RA_Z can exist even within a small area of a plate and reduce the significance of a single specimen result. Final specimen diameters can be difficult to measure and reproducibility of the %RA_Z calculated by different testing personnel for an individual specimen is sometimes poor.

Results indicate that specifications covering the through-thickness tension testing of rolled steel plates should reference the test location to the original as-cast ingot or slab if the region of lowest %RA_Z is to be reported. Specifications need to address the problem of specimen-to-specimen variability and %RA_Z reproducibility when determining the number of specimens to be tested and establishing acceptance criteria.

KEY WORDS: through-thickness tension test, reduction of area, lamellar tearing, plates, tension testing variables, material variables

Several investigators report that the percent reduction-of-area (%RA) measured on a tension specimen machined from the through-thickness direction (*Z*-direction) provides a good measure of the relative lamellar tearing suscep-

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tibility of a steel plate.[3-6] Generally, reduction-of-area levels above 20 to 25 percent in Z-direction tension tests indicate a low risk of lamellar tearing, except in very highly restrained weldments. The lamellar tearing risk increases rapidly at lower $\%RA_Z$ unless the restraint level or the amount of strain imposed on the Z-direction of the plate is reduced.

The technical literature abounds with studies concerning the mechanisms by which lamellar tearing develops and with methods that help to prevent it from occurring during fabrication. Most plate producers have developed specially processed steels that help accommodate welding strains in the Z-direction without cracking. Although through-thickness tension testing specifications such as ASTM A770 or API No. 2H have been adopted, little work concerning the details of the Z-direction tension test itself has been published. Differences in nonmetallic inclusion distributions may change the specimen design effects on ductility or alter the certainty with which the final diameter can be measured compared with conventional longitudinal (L) and transverse (T) specimens. Test location relative to the as-cast position in an ingot or a slab may be more significant in Z-direction tests than in the L or T direction. Specimen-to-specimen variability, even in a small section of a plate, may be different. Also, material strength level or microstructure effects on the %RA may be changed by these same inclusion distribution differences.

Results are presented of investigations designed to examine some effects of (*1*) Z-direction tension specimen design, (*2*) specimen location relative to the original ingot, (*3*) steel microstructure, (*4*) material strength level, (*5*) specimen-to-specimen variability within a small area of a plate, and (*6*) reproducibility of the final diameter measurement. Plates for these studies were specially selected to give about 25 to 40 percent RA_Z.

Material

Two production plates desulfurized by injecting calcium silicide into the ladle of molten steel were obtained for these studies. Each plate represented the product of an entire ingot so that the test specimen location effects could be investigated. Both plates were specially selected because preliminary Z-direction tension tests made in accordance with ASTM Specification for Through-Thickness Tension Testing of Steel Plates for Special Applications (A770) showed reduction-of-area levels of about 25 to 40 percent. Intermediate $\%RA_Z$ values were considered desirable because this range would allow

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TABLE 1—*Chemical composition of ASTM A131 Grade CS and ASTM A537 plates.*

Steel	Test	Chemical Composition, Weight Percent									
		C	Mn	P	S	Si	Cr	Ni	Mo	Cu	Al
A131, Grade CS	heat	0.10	1.05	0.010	0.005	0.19	0.12	0.16	0.04	0.14	0.020
	Coupon 1	0.11	1.05	0.010	0.006	0.20	0.12	0.16	0.04	0.14	0.022
	Coupon 2	0.11	1.06	0.010	0.005	0.19	0.12	0.16	0.04	0.14	0.019
	Coupon 3	0.11	1.07	0.010	0.005	0.19	0.12	0.16	0.04	0.14	0.019
	Coupon 4	0.11	1.05	0.010	0.005	0.20	0.11	0.16	0.04	0.14	0.023
	Coupon 5	0.11	1.07	0.010	0.006	0.20	0.12	0.16	0.04	0.14	0.022
	Coupon 6	0.11	1.05	0.010	0.007	0.20	0.11	0.16	0.04	0.14	0.019
	Coupon 7	0.10	1.06	0.010	0.007	0.20	0.12	0.16	0.04	0.14	0.018
	Coupon 8	0.11	1.06	0.010	0.005	0.19	0.11	0.16	0.04	0.14	0.016
A537	heat	0.18	1.36	0.010	0.009	0.32	0.19	0.23	0.07	0.14	0.056
	Coupon 9	0.19	1.36	0.010	0.009	0.32	0.19	0.23	0.07	0.14	0.051
	Coupon 10	0.20	1.37	0.010	0.007	0.32	0.20	0.23	0.07	0.14	0.053
	Coupon 11	0.19	1.38	0.010	0.007	0.32	0.19	0.23	0.07	0.14	0.045
	Coupon 12	0.20	1.40	0.010	0.008	0.33	0.20	0.23	0.07	0.14	0.049

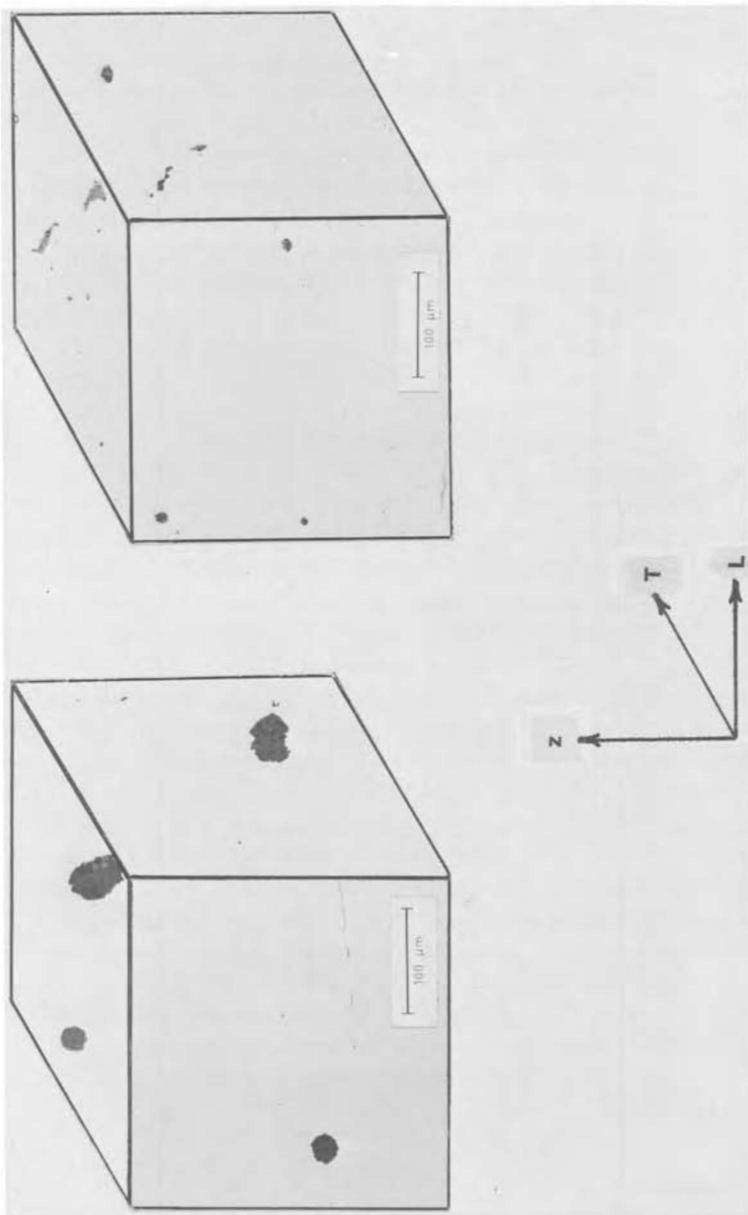

FIG. 1—*Nonmetallic inclusion types and sizes. (left) ASTM A131 Grade CS plate. (right) ASTM A537 plate.*

either increases or decreases caused by the tension testing and material variables to be observed. This %RA_Z range also represented the level that usually is the most critical from the standpoint of material rejection or acceptance, according to several testing specifications.

One of the plates was a 76-mm (3-in.)-thick ASTM A131 Grade CS. It was used to study the effects of tension specimen design and effects of sample location relative to the original ingot. The other plate was a 64-mm (2½-in.) thick ASTM A537 pressure vessel quality. Residual chromium, nickel, and molybdenum levels were purposely on the high side of the A537 specification range to help give the hardenability needed to determine the effects of steel microstructure and strength level. Both grades were used for evaluating the specimen-to-specimen variability that can be found in a small area of a plate and for studying reproducibility of the final diameter measurement. These plate thicknesses were chosen so that the test material comprised most of the parallel section in many of the tension specimen designs evaluated.

Heat chemical compositions included in Table 1 show that the A131 Grade CS steel had 0.005 percent sulfur while the A537 grade had 0.009 percent sulfur. This sulfur was combined as both elongated manganese sulfide inclusions and as spherical calcium-oxygen-sulfur inclusions. Incomplete sulfide inclusion shape control in these heats was probably responsible for the 25 to 40 percent RA_Z levels found in the preliminary *Z*-direction tension tests. Figure 1 shows the nonmetallic inclusion types and sizes in both plates, although the number of each inclusion type is not necessarily representative. Differences in inclusion shape between *L*, *T*, and *Z* directions can be seen in this figure.

The ASTM A131 and ASTM A537 plates were sampled as sketched in Fig. 2. All coupons represented portions of prime plate and neither the normal discard nor the locations required for tension tests in ASTM Specification for General Requirements for Rolled Steel Plates, Shapes, Sheet Piling, and Bars for Structural Use (A6) or ASTM Specification for General Requirements for Steel Plates for Pressure Vessels (A20). The A131 plate had been production-normalized as required for Grade CS steel, while the A537 plate was obtained in the as-rolled condition to allow various laboratory heat treatments to be performed. Both were ultrasonically inspected in accordance with ASTM Specification for Straight-Beam Ultrasonic Examination of Plain and Clad Steel Plates for Special Applications (A578) Level II to assure freedom from large exogenous inclusions. Each coupon was later ultrasonically tested by hand, and localized areas showing even small losses in back reflection were marked and discarded.

Procedure

Specimen Design Study

The A131 Grade CS plate was used to examine some *Z*-direction tension test specimen design effects on %RA_Z. All samples were machined from the

TABLE 2—*Slenderness ratios* (L/D) *for each specimen configuration.*

Specimen Type	L/D Ratio
A	12[a]
B	8.5[a]
C	6[a]
D	2.5[b]
E	4[b]
F	4[b]

[a]Based on 76 mm (3 in.) plate thickness.
[b]Based on actual length of the parallel section.

coupon (No. 8 in Fig. 2) representing the centerline at the ingot bottom. A total of 42 full-thickness blanks with a 30-mm (1⅛ in.)-square cross section were cut. The position of each blank was recorded so that a random sample location could be assured for each of the specimen designs examined. Prolongations were inertia-welded to both surfaces of each blank.

Six different through-thickness tension specimen configurations were machined. The specific designs are identified as Types A, B, C, D, E, and F in Fig. 3. Note that these samples allowed evaluation of three diameters at a constant 127-mm (5-in.)-long parallel section and study of three parallel section lengths at a constant 12.7 mm (0.500 in.) diameter. The design designated as Type F in Fig. 3 was similar to the Type 3 specimen in ASTM Specification A770 except for the slightly shorter parallel section length needed to allow direct comparison with the Type E specimen. Slenderness ratios (L/D) for the six specimen configurations are summarized in Table 2. These are based on either the parallel section length or 76 mm (3 in.) plate thickness, whichever was shorter. All had L/D ratios that equalled or exceeded 2.5. Seven specimens of each type were tested.

Specimen Location Study

Seven of the Z-direction tension specimens denoted as Type C in Fig. 3 were machined from each of the eight coupons from the A131 Grade CS plate. These represented the corner, quarter-width, centerline, and three-quarter-width positions at the plate end corresponding to the top of the ingot; corner, quarter-thickness, and centerline for the plate end representing the bottom of the ingot; and the plate edge at ingot midheight. Detailed locations are shown in Fig. 2*a*. Coupons 3 and 8 represented those positions that would be tested in accordance with ASTM Specification A770 for this plate. If the plate size had been such that the ingot width would have made the plate length, however, Coupon 5 would have been one of the locations required by ASTM A770.

A standard transverse 12.7-mm (0.500-in.)-diameter tension specimen was also machined from the quarter-thickness location of each plate to document the effect of test location relative to the original ingot. Product chemical composition near the midthickness was also determined.

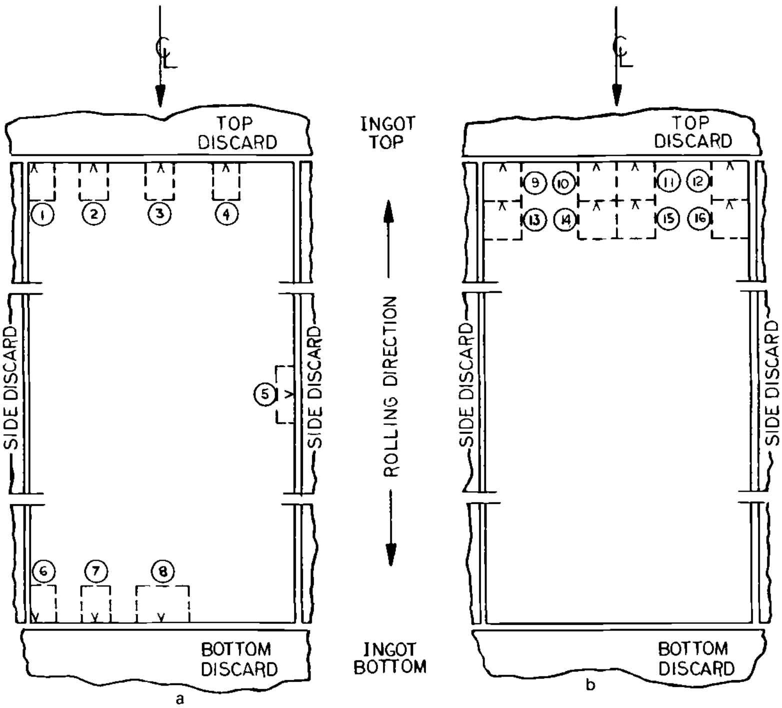

FIG. 2—*Sketch showing test locations and test coupon identification (not to scale).* (a) *ASTM A131 Grade CS plate.* (b) *ASTM A537 plate.*

Microstructure and Strength Level Studies

The A537 plate coupons (Nos. 9 to 16 in Fig. 2*b*) were laboratory-normalized or quenched and tempered (Q&T) as shown in Table 3. Normalizing gives a ferrite and pearlite microstructure, while quenching develops a predominately lower-bainite microstructure containing a little martensite and polygonal ferrite. Note that a plate edge sample and a plate centerline sample were heat-treated for each condition. This was done to examine the effect of relatively few inclusions (edge coupons) and areas of maximum number of inclusions (centerline coupons). Austenitizing for either normalizing or quenching and tempering involved 30 min at 900°C (1650°F). All tempering was for 30 min at the three temperatures indicated in Table 3.

Tempering at 680°C (1260°F) was intended to give an ultimate tensile strength for the Q&T condition which was nearly identical to that developed by normalizing this same plate. Yield strength would be somewhat higher for the Q&T condition, but since specimen necking occurs after the ultimate load is reached, the tensile strength should be the parameter to be equalized when %RA effects are being studied. Tempering at 650°C (1200°F) is the temperature normally used for production ASTM A537 Class 2 plates. The

TABLE 3—*Heat treatments for ASTM A537 plate coupons.*

Coupon Number		
Edge	Centerline	Laboratory Heat Treatment
9	10	normalize
13	11	Q&T at 680°C (1260°F)
16	15	Q&T at 650°C (1200°F)
12	14	Q&T at 480°C (900°F)

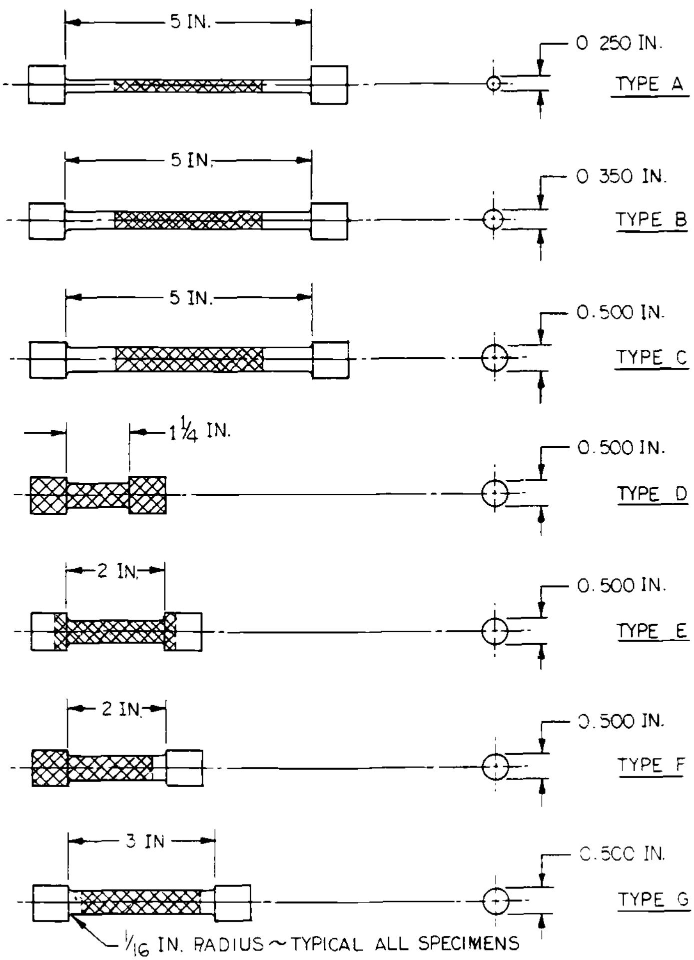

FIG. 3—*Z-direction tension test specimen designs. Cross-hatched areas represent test plate material.*

480°C (900°F) temper was used to maximize the tensile strength possible in this grade and still maintain a completely ductile fracture mode. Normalizing is the heat treatment specified for ASTM A537 Class 1 plates.

Eight full-thickness Z-direction tension specimen blanks with a 30-mm (1⅛-in.)-square cross section were cut from each coupon. High-strength prolongations were inertia-welded to both surfaces and Type G specimens were machined. As shown in Fig. 3, this particular specimen had a 12.7 mm (0.500 in.) diameter and allowed testing the full plate thickness with an effective *L/D* ratio of 5.0. Standard transverse tensiles of the same diameter were machined from the quarter-thickness location of each coupon. Product chemical composition was determined at the midthickness for each location across the plate (Coupons 9, 10, 11, and 12 in Fig. 2*b*).

Specimen-to-Specimen Variability Study

Testing either seven or eight specimens for each of the various designs or plate locations gives some indication as to the variability that can be expected within a relatively small area of a plate. Such information is helpful in determining the significance of an individual result on the overall plate quality.

Final Diameter Reproducibility Study

Not all Z-direction tension specimens break with the cup–cone type fracture usually found for conventional *L* or *T* tension tests. To provide some information on the reproducibility of the final specimen diameter measurement, and therefore the $\%RA_Z$, three independent measurements were made on all broken Z-direction tension specimens. All diameters were determined with pointed micrometers. Three measurements were also made for the standard transverse tensiles from the A537 plate.

Results

Product Chemical Composition

Product chemical compositions run on the ASTM A131 Grade CS and ASTM A537 plate coupons are shown in Table 1. All product checks were in good agreement with the heat analyses and indicated good chemical homogeneity. Differences in Z-direction tension test properties between coupons cannot be related to variations in the sulfur content or any alloying element.

Transverse Tensile Properties

Table 4 summarizes the conventional transverse tensile properties for each of the 16 coupons. The A131 Grade CS plate had average yield and tensile strengths of 295 and 442 MPa (42.8 and 64.1 ksi), respectively. Ductility lev-

TABLE 4—*Transverse tensile properties of ASTM A131 Grade CS and ASTM A537 plates.*

	Test Location		Yield Strength		Tensile Strength			Reduction of Area, %		
Steel	Ingot Position or Heat Treatment	Coupon	ksi	MPa	ksi	MPa	Elongation in 50.8 mm (2 in.), %	Measurement A	Measurement B	Measurement C
A131, Grade CS	top edge	1	41.9	289	64.4	444	37	74	[a]	[a]
	top ¼-width	2	43.2	298	64.2	443	35	72	[a]	[a]
	top ½-width	3	42.2	291	64.0	441	37	71	[a]	[a]
	top ¾-width	4	41.7	287	64.1	442	36	75	[a]	[a]
	midheight edge	5	45.1	311	64.6	445	37	74	[a]	[a]
	bottom edge	6	42.3	292	64.4	444	37	75	[a]	[a]
	bottom ¼-width	7	44.7	308	63.8	440	37	74	[a]	[a]
	bottom ½-width	8	41.7	287	63.3	436	36	74	[a]	[a]
A537	normalized									
	edge	9	[b]	[b]	83.9	578	31	70	69	70
	½-width	10	52.8	364	82.5	569	31	69	68	68
	Q&T at 680°C (1260°F)									
	edge	13	66.4	458	87.4	603	27	69	68	68
	½-width	11	65.9	454	86.5	596	28	68	68	68
	Q&T at 650°C (1200°F)									
	edge	16	69.8	481	90.5	624	26	66	66	66
	½-width	15	70.7	487	90.4	623	27	67	66	68
	Q&T at 480°C (900°F)									
	edge	12	83.4	575	103.4	713	22	66	66	65
	½-width	14	82.4	568	103.2	711	21	66	65	65

[a] Only one %RA measurement made.
[b] Testing error prevented determination.

els were about 36 percent elongation and 74 percent RA in this plate. Testing location relative to the original ingot did not appear to have much effect on the transverse tensile properties.

Microstructure and strength variations were intentionally introduced into the A537 steel coupons by the four heat treatments. However, for each heat treatment there was little difference in transverse tensile properties between plate edge and centerline test locations. Compared with normalizing, tempering at 680°C (1260°F) after quenching developed about 30 MPa (4 ksi) higher tensile strength and slightly lower %RA. Lowered tempering temperature raised yield and tensile strengths and decreased ductility of the quenched coupons.

The three sets of transverse %RA values shown for each A537 steel specimen in Table 4 were in good agreement. Measurement of the final specimen diameter was reproducible and did not appear to be affected very much by testing personnel.

Specimen Design

Reduction-of-area values determined using Types A, B, C, D, E, and F specimens are given in Table 5. Average values for each specimen design are shown in addition to the individual results. Because the two smaller specimen diameters caused problems during machining, the average results for Type A and Type B are each based on six rather than seven tests.

Specimen diameter effects on the $\%RA_Z$ (Measurement A) determined for Types A, B, and C samples are graphically shown in Fig. 4. For this A131 plate and test location, the standard 12.7-mm (0.500-in.)-diameter specimen gave the lowest average $\%RA_Z$. It also exhibited the greatest specimen-to-specimen variability, with two results not meeting the 20 percent requirement included in ASTM A770. The specimen with an 8.9 mm (0.350 in.) diameter gave the highest average $\%RA_Z$ (66 percent) and the lowest specimen-to-specimen variation. An intermediate average $\%RA_Z$ was found for the 6.4-mm (0.250-in.)-diameter specimen, but the variability was almost as large as encountered with the Type C design.

Figure 5 illustrates the effect of the parallel section length on the $\%RA_Z$ determined with 12.7-mm (0.500-in.)-diameter specimens. Type E specimens with a 50.8-mm (2-in.)-long parallel section gave the highest average %RA and smallest specimen-to-specimen variations. Reducing the parallel section to 31.8 mm (1.25 in.) resulted in both a slightly lower average $\%RA_Z$ and greater variability. The Type C specimen that tested the entire 76 mm (3 in.) plate thickness had considerably lower $\%RA_Z$ and a very large specimen-to-specimen variation.

Comparison of results in Table 5 for the Type E and Type F specimens shows that testing to include only one plate surface gave a slightly higher average $\%RA_Z$. Specimen-to-specimen variability was also reduced somewhat for the Type F specimen.

TABLE 5—*Effect of Z-direction tension specimen configuration on the* %RA_Z *in ASTM A131 Grade CS plate.*

Specimen Configuration[a]	Test No.	Reduction of Area, % Measurement A	Measurement B	Measurement C
Type A	1	68	67	67
	2	67	68	67
	3	63	63	63
	4	63	62	58
	5	53	46	40
	6	20	15	13
	Average	56	54	51
Type B	1	74	73	72
	2	72	70	69
	3	70	71	70
	4	69	65	67
	5	68	68	68
	6	44	42	39
	Average	66	65	64
Type C	1	70	68	68
	2	67	65	65
	3	62	64	64
	4	58	62	63
	5	50	48	44
	6	19	18	18
	7	16	19	18
	Average	49	49	49
Type D	1	72	65	65
	2	66	67	67
	3	64	63	61
	4	63	69	70
	5	61	65	65
	6	45	41	41
	7	39	33	32
	Average	58	58	57
Type E	1	69	68	68
	2	68	70	71
	3	66	69	68
	4	64	68	68
	5	61	62	59
	6	58	52	49
	7	48	47	48
	Average	62	62	62
Type F	1	70	67	66
	2	68	69	68
	3	68	68	68
	4	67	65	63
	5	66	66	65
	6	66	68	67
	7	55	51	52
	Average	66	65	64

[a] See Fig. 3 for specimen dimensions.

Specimen Location

Individual and average %RA_Z results for the eight ingot locations tested in the A131 Grade CS plate are summarized in Table 6. Figure 6 illustrates the effect of ingot location on the average %RA_Z.

Considerable ingot location effects are readily apparent. The highest average %RA_Z was obtained at the locations representing ingot corners. Along the ingot edge, RA_Z decreased from 69 percent at the corners to 53 percent at the midheight position (Coupon 5). The bottom of this ingot provided higher %RA_Z than the top. At either the ingot top or bottom, the average %RA_Z decreased towards the centerline. The decrease at the ingot top was well underway at the quarter-width testing location, while very high values were still found at the ingot bottom. Specimen-to-specimen variability could not be directly associated with test position relative to either ingot width or ingot height.

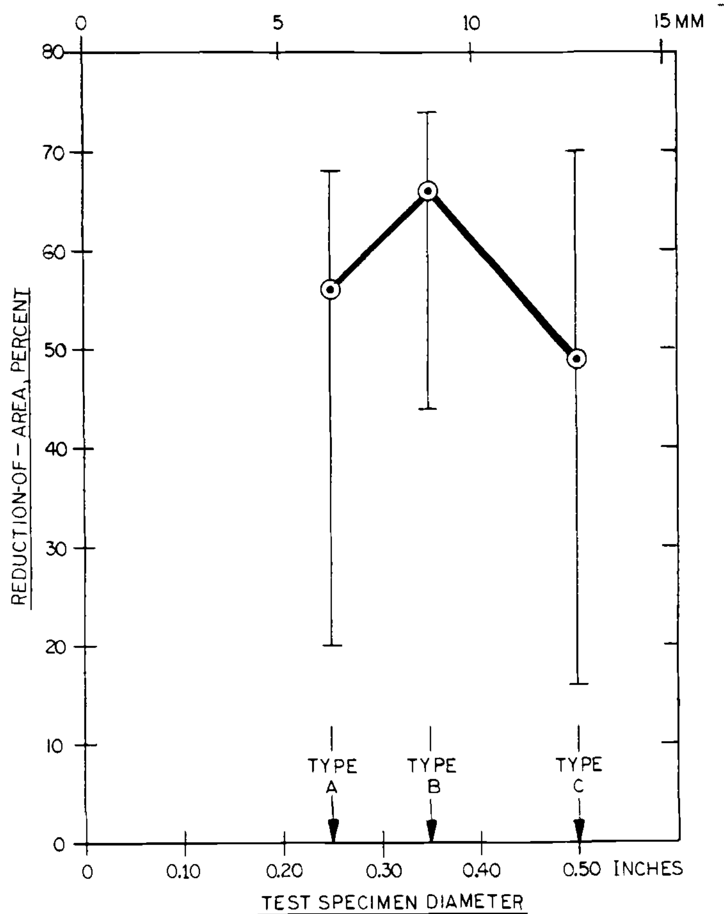

FIG. 4—*Effect of Z-direction tension specimen diameter on* %RA_Z *in ASTM A131 Grade CS plate.*

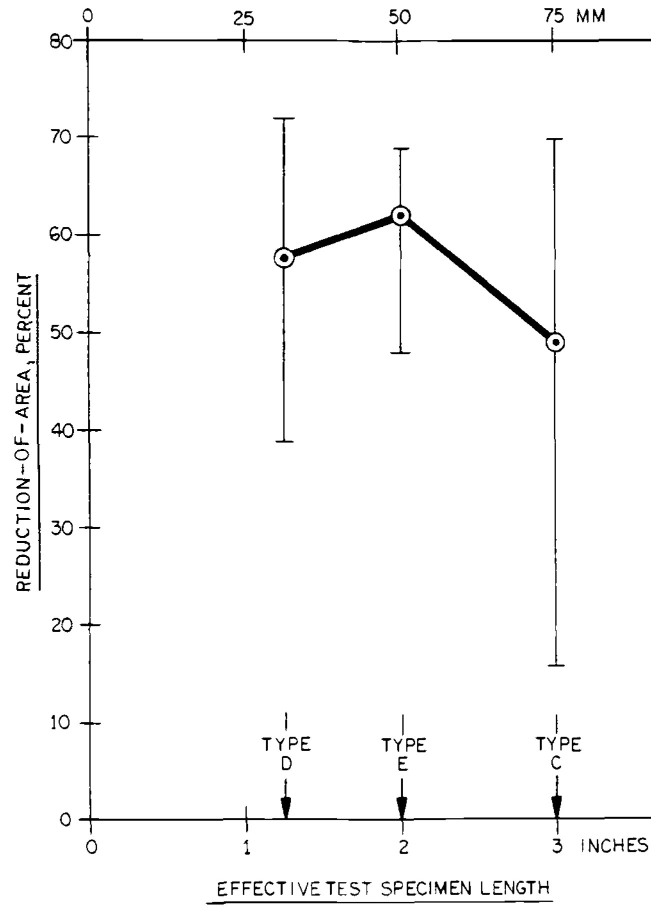

FIG. 5—*Effect of Z-direction tension specimen parallel section length on* %RA_Z *in ASTM A131 Grade CS plate.*

Microstructure and Strength Level

Tension test results for the eight heat-treated A537 plate coupons (Nos. 9 to 16) are given in Table 7. Yield strength, tensile strength, and elongation values for the Z-direction are included in addition to the three sets of %RA_Z results. Figure 7 shows the average %RA_Z (Measurement A) as a function of the average tensile strength for both plate edge and plate centerline testing locations. Similar relationships for the standard transverse results are also indicated in Fig. 7. The averaged Z-direction tensile properties are presented in Table 8 as a percent of the transverse values given in Table 4. Microstructures for the normalized and quenched and 650°C (1200°F) tempered A537 plates are shown in Fig. 8. Normalizing resulted in a polygonal ferrite and pearlite microstructure with an ASTM No. 8½ grain size, while quenching developed a microstructure containing mainly lower-bainite with smaller amounts of fine polygonal ferrite, upper-bainite, and martensite. Changes in the tempering temperature only slightly affected the size of the carbides formed.

Neither microstructure nor strength level had much effect on %RA in the standard transverse tests taken at either the plate edge or centerline locations. Figure 7 indicates that %RA decreased only about one percentage point for each 70 MPa (10 ksi) increase in the tensile strength.

Testing in the *Z*-direction resulted in lower reduction of area than in the transverse direction. As observed previously for the A131 Grade CS plate, the reduction was appreciably greater near the ingot centerline than at the edges. Table 8 shows that the through-thickness reduction of area was approximately three fourths of that in the transverse direction for plate edge tests, while it was only about half that for centerline tests.

Figure 7 shows that the microstructure seemed to have little or no effect on the $\%RA_Z$ at the plate edge, as evidenced by nearly identical results for the normalized and the quenched and 680°C (1260°F) tempered conditions.

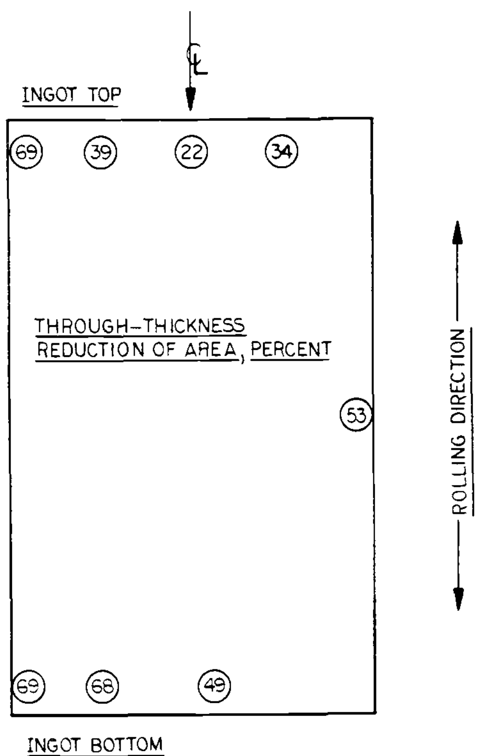

FIG. 6—*Effect of ingot location on* $\%RA_Z$ *in ASTM A131 Grade CS plate.*

TABLE 6—*Effect of test location on the %RAz in the ASTM A131 Grade CS plate.*

Ingot Position	Test No.	Reduction of Area, % Measurement A	Measurement B	Measurement C
Top edge (Coupon 1)	1	72	70	71
	2	70	69	69
	3	70	70	70
	4	69	70	70
	5	67	67	67
	6	67	68	68
	7	67	68	68
	Average	69	69	69
Top ¼-width (Coupon 2)	1	46	47	48
	2	46	47	48
	3	46	50	52
	4	42	44	43
	5	41	42	42
	6	31	32	32
	7	23	32	27
	Average	39	42	42
Top ½-width (Coupon 3)	1	26	27	30
	2	25	30	31
	3	25	27	27
	4	24	28	27
	5	21	19	18
	6	21	24	21
	7	16	19	16
	Average	22	25	24
Top ¾-width (Coupon 4)	1	48	46	46
	2	42	38	32
	3	34	40	43
	4	32	28	27
	5	31	29	30
	6	30	33	37
	7	19	14	17
	Average	34	33	33
Midheight edge (Coupon 5)	1	70	70	68
	2	64	65	63
	3	52	50	50
	4	52	50	50
	5	50	53	50
	6	45	38	39
	7	38	42	39
	Average	53	53	51
Bottom edge (Coupon 6)	1	74	73	71
	2	70	70	72
	3	70	69	66
	4	69	67	67
	5	68	68	67
	6	66	65	65
	7	64	65	63
	Average	69	68	67

TABLE 6—*Continued.*

Ingot Position	Test No.	Reduction of Area, % Measurement A	Measurement B	Measurement C
Bottom ¼-width (Coupon 7)	1	70	70	70
	2	70	69	69
	3	70	69	69
	4	69	68	68
	5	68	66	68
	6	68	68	68
	7	66	65	65
	Average	68	68	68
Bottom ½-width (Coupon 8)	1	70	68	68
	2	67	65	65
	3	62	64	64
	4	58	62	63
	5	50	48	44
	6	19	18	18
	7	16	19	18
	Average	49	49	49

However, at the ingot centerline where the heaviest inclusion concentrations can be expected, the normalized plate provided an average 46 percent RA_Z, while the quenched and tempered condition had only 36 percent RA_Z.

Higher strengths obtained by lowering the tempering temperature after quenching generally resulted in decreased $\%RA_Z$. The magnitude of the $\%RA_Z$ decrease averaged about four percentage points for each 70 MPa (10 ksi) increase in the tensile strength. This rate of decrease was larger than that determined for the transverse testing direction. No edge or centerline test location effects on the strength level trend were observed.

Specimen-to-Specimen Variability

Some observations concerning the specimen-to-specimen variability in the $\%RA_Z$ have already been mentioned for the A131 Grade CS tests. It was noted that the 8.9-mm (0.350-in.)-diameter specimen (Type B) and the specimen that emphasized testing of the surface (Type F) seemed to help reduce the variability. Testing location relative to the ingot could not be directly correlated with the specimen-to-specimen variations. However, regions of the plate that gave average RA_Z levels below about 50 percent had much larger variability.

Tests for the A537 steel plate generally exhibited less specimen-to-specimen variability than did the A131 Grade CS plate. This was probably related to the overall greater sulfide inclusion shape control in the A537 plate (Fig. 1).

TABLE 7—*Effect of microstructure and strength level on the Z-direction tensile properties of ASTM A537 plate.*

Heat Treatment	Ingot Position	Test No.	Yield Strength		Tensile Strength		Elongation in 50.8 mm (2 in.), %	Reduction of Area, %		
			ksi	MPa	ksi	MPa		Measurement A	Measurement B	Measurement C
Normalized	edge (Coupon 9)	1	55.7	384	83.7	577	25	56	58	58
		2	57.4	396	83.8	578	28.5	56	55	55
		3	55.0	379	84.0	579	25	55	55	55
		4	57.3	395	84.6	583	24	55	50	50
		5	55.0	379	84.4	582	23	52	49	50
		6	56.3	388	84.3	581	25	52	51	51
		7	54.7	377	84.0	579	25	51	52	50
		8	56.0	386	84.4	582	25	46	44	43
		Average	55.9	386	84.2	580	25	53	52	52
	½-width (Coupon 10)	1	56.4	389	82.4	568	21	55	54	53
		2	54.4	375	83.4	575	22	54	53	53
		3	54.4	375	83.4	575	22	49	38	35
		4	56.7	391	83.2	574	19	47	43	42
		5	55.1	380	83.5	576	19	45	41	40
		6	57.6	397	83.3	574	15	44	32	31
		7	56.1	387	83.3	574	21	40	40	35
		8	56.6	390	83.2	574	18	37	39	37
		Average	55.9	385	83.2	574	20	46	42	41
Q&T at 680°C (1260°F)	edge (Coupon 13)	1	63.9	441	84.9	585	22	53	51	52
		2	62.2	429	84.0	579	22	52	52	51
		3	63.1	435	84.2	580	21	52	52	49
		4	62.4	430	84.3	581	23	51	48	50
		5	66.1	456	84.5	483	22	51	50	50
		6	64.9	447	84.9	585	23	51	51	51
		7	59.5	410	85.5	589	22	50	53	52
		8	61.4	423	84.4	582	22	40	51	45
		Average	62.9	434	84.6	583	22	50	51	50

	½-width (Coupon 11)	1	63.7	439	85.4	589	20	43	44	42
		2	64.4	444	84.4	582	15	42	32	36
		3	63.5	438	85.0	586	19	40	36	34
		4	65.9	454	85.3	588	20	37	36	34
		5	64.7	446	85.8	591	14	37	36	30
		6	63.4	437	85.2	587	17	35	30	28
		7	63.5	438	84.9	585	14	33	30	24
		8	64.0	441	84.9	585	13	25	21	20
		Average	64.1	442	85.1	587	16	36	33	31
Q&T at 650°C (1200°F)	edge (Coupon 16)	1	60.7	418	86.4	596	22	62	63	63
		2	62.4	430	85.6	590	21	60	59	60
		3	61.4	423	85.9	592	21	60	58	57
		4	63.1	435	86.5	596	21	58	60	60
		5	66.5	458	87.4	603	20	54	54	54
		6	68.0	469	86.8	598	17	46	43	45
		7	62.4	430	86.4	596	17	41	42	39
		8	64.5	445	87.6	604	18	39	40	40
		Average	63.6	439	86.6	597	20	52	52	52
	½-width (Coupon 15)	1	66.3	457	88.2	608	18	41	41	39
		2	67.2	463	88.1	607	16	37	34	31
		3	66.5	458	87.3	602	17	36	34	33
		4	61.4	423	87.5	603	13	33	22	22
		5	66.7	460	87.4	603	15	31	30	26
		6	66.0	455	87.8	605	14	30	28	25
		7	66.8	461	87.7	605	14	28	28	23
		8	66.2	463	88.0	607	15	27	34	35
		Average	66.0	455	87.8	605	15	33	31	29
Q&T at 480°C (900°F)	edge (Coupon 12)	1	77.4	534	100.3	691	19	54	54	52
		2	74.8	516	99.4	685	18	52	50	50
		3	76.5	527	103.0	710	15	50	48	48
		4	76.1	525	99.8	688	17	48	47	47
		5	76.2	525	100.0	689	17	46	42	46
		6	76.8	529	99.5	686	19	45	46	48
		7	77.1	531	104.5	720	16	44	38	36
		8	76.4	527	99.4	685	16	43	45	44
		Average	76.4	527	100.7	694	17	48	46	46

TABLE 7—*Continued.*

Heat Treatment	Ingot Position	Test No.	Yield Strength		Tensile Strength		Elongation in 50.8 mm (2 in.), %	Reduction of Area, %		
			ksi	MPa	ksi	MPa		Measurement A	Measurement B	Measurement C
	½-width (Coupon 14)	1	80.7	556	102.0	703	14	36	37	34
		2	82.2	567	100.6	694	13	35	30	31
		3	78.1	538	101.0	696	13	34	32	34
		4	81.2	560	101.5	700	11	30	25	25
		5	79.9	551	101.6	700	11	30	27	28
		6	78.9	544	101.8	702	11	30	28	30
		7	80.5	555	100.9	702	10	27	27	26
		8	80.6	556	100.6	694	13	27	24	23
		Average	80.3	553	101.2	698	12	31	29	29

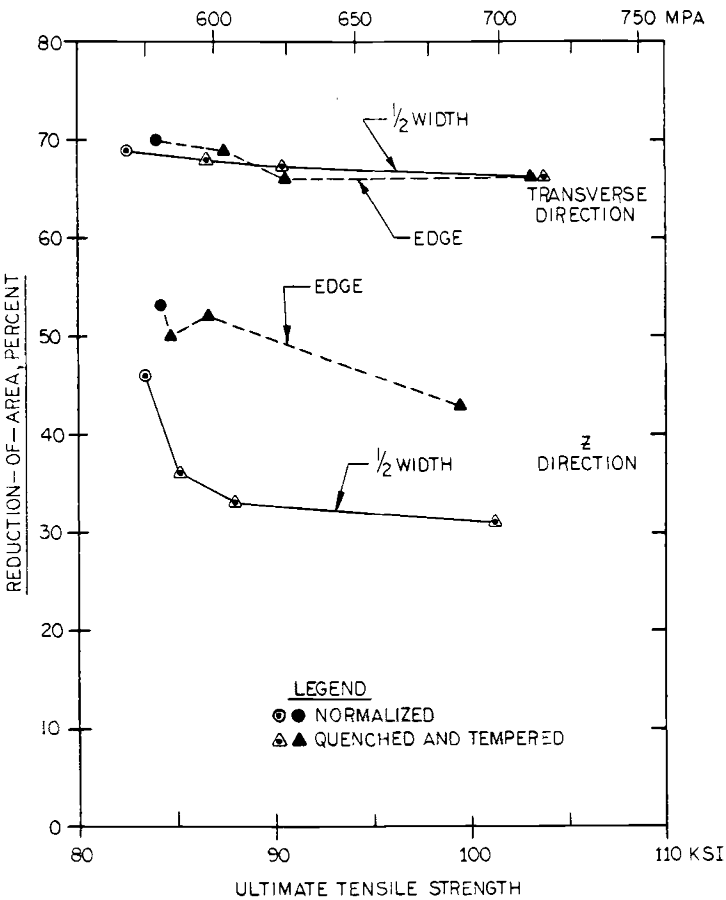

FIG. 7—*Effect of microstructure, strength level, and ingot location on* %RA_Z *in ASTM A537 plate.*

Neither average %RA_Z, testing location, microstructure, nor strength level could be correlated with the overall magnitude of the variability in the A537 plate.

Final Diameter Reproducibility

Tables 4 to 7 include three sets of reduction-of-area determinations. Individual results for the transverse tension tests in the A537 plate (Table 4) exhibited little variation between the measurements. In the *Z*-direction tests, similar good agreement was observed for the three values when the RA_Z was above about 60 percent. Reproducibility of RA_Z often became poor at lower levels, especially in the range of 20 to 40 percent. In at least one instance, acceptance or rejection using a single test requirement of 20 percent RA_Z could

TABLE 8—*Z-direction tensile properties in ASTM A537 plate as a percent of the transverse tensile properties.*

Heat Treatment	Ingot Position	Percent of the Transverse Tensile Properties[a] Yield Strength	Tensile Strength	Elongation in 50.8 mm (2 in.)	Reduction of Area[b]
Normalized	edge	97	100	93	76
	½-width	106	101	74	67
Q&T at 680°C (1260°F)	edge	95	97	81	72
	½-width	97	98	57	53
Q&T at 650°C (1200°F)	edge	91	96	77	79
	½-width	93	97	56	50
Q&T at 480°C (900°F)	edge	92	97	77	73
	½-width	97	98	57	47

[a] Average of the eight Z-direction tension tests used in these comparisons.
[b] Measurement A used for both test orientations.

be changed simply by selecting the diameter measurement used.

Although reproducibility was sometimes very poor for individual specimens, the use of an average $\%RA_Z$ for the six to eight specimens tested for each variable generally gave good agreement. Use of an average for several specimens seems to reduce the measurement variability at least to acceptable levels, even though it can still be high for one or more of the specimens included in the average.

Discussion

The through-thickness tension test results obtained for the 76-mm (3-in.)-thick ASTM A131 Grade CS and 64-mm (2½-in.)-thick ASTM A537 plates suggest that there are some testing and material factors that can affect the reduction of area determined. Some of these variables cause similar effects in conventional transverse tension tests, while others seem to be observed only in the *Z*-direction. Differences in the nonmetallic inclusion shape and distribution between *Z*-direction and *L* or *T* tests are suspected to be a primary factor.

Specimen Design

Smaller specimen diameters generally raise the reduction of area found in conventional *L* and *T* tests. However, competing effects seem to be present for *Z*-direction tension specimens that help keep the $\%RA_Z$ relatively constant for diameters between 6.4 and 12.7 mm (0.250 and 0.500 in.). For any planar inclusion population, larger *Z*-direction specimen diameters would be expected to have a greater probability of containing more inclusions. This would tend to lower the average $\%RA_Z$ for larger diameters. A given inclusion contained within a diameter would represent a larger proportion of the

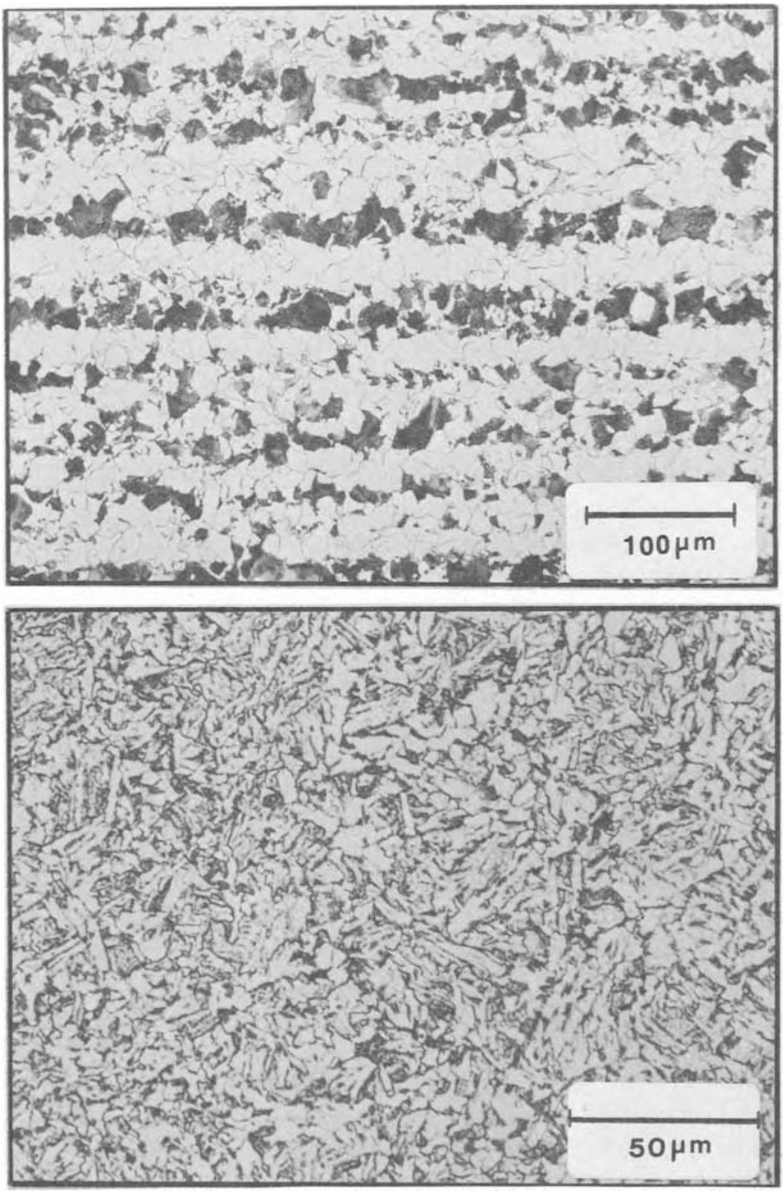

FIG. 8—*Microstructures in ASTM A537 plate developed by heat treatment (nital etch).* (top) *Normalizing gave a polygonal ferrite and pearlite microstructure.* (bottom) *Quenching and tempering at 650°C (1200°F) gave a lower-bainite microstructure with some fine polygonal ferrite and tempered martensite.*

cross-sectional area with smaller diameters and thereby would tend to lower the average $\%RA_Z$. It is believed that these two opposing effects resulted in the intermediate 8.9-mm (0.350-in.)-diameter specimen giving the slightly higher average $\%RA_Z$. When either of the opposing factors predominated, the specimen-to-specimen variability could be expected to become larger, just as observed by these series of tests.

Longer parallel sections in a Z-direction tension specimen appeared to act similarly to increased diameter; that is, the probability of greater inclusion populations would be higher when long parallel sections are used. However, since steel-making practices normally result in greater inclusion concentrations in the center third of a plate thickness than nearer either surface, the effect from longer parallel sections can be expected to be small. Testing near the plate surface, as with the Type F specimen, also gives higher, less variable $\%RA_Z$ results because fewer inclusions are likely to be present. The reason for the slightly lower average $\%RA_Z$ with the 32-mm (1.25-in.) parallel section (Type D) is not known, unless it is related to the planar inclusions effectively reducing the slenderness ratio below the 2.0 to 2.5 level often considered to be critical.

From a through-thickness tension testing specification viewpoint, it would seem that the specimen diameter and the length of the parallel section should be selected to assure that the length-to-diameter ratio exceeds 2.0 to 2.5. This ratio should be based on the length of test material contained within the parallel section, not the overall length of the parallel section, which can include portions of the welds or welded prolongations. Within these restrictions, the choice of the specimen design should be left to agreement between the purchaser and producer. Results obtained should give reasonably similar measures of the relative lamellar tearing resistance.

Specimen Location

The large ingot location effects are also believed to be related to the probability that planar inclusions will be contained within a Z-direction tension test area.

Specifications for Z-direction tension tests should make reference to the original ingot or cast slab position from which the plate was rolled. Otherwise a given $\%RA_Z$ may not provide the same measure of lamellar tearing resistance. For plates rolled such that the ingot or slab width becomes the length, simply testing the centerline at the top and bottom of a plate would avoid the area expected to have the lowest $\%RA_Z$. By referencing the as-cast centerline in testing specifications, some differences in the quality measured may still be present between plates rolled from continuously cast slabs and those rolled from ingots. However, those differences would be expected to be much smaller than can be encountered when the top and bottom of the plate represent the ingot edges.

Microstructure and Strength Level

Based on results for the four A537 plate heat treatments, *Z*-direction tension tests should be conducted on coupons laboratory heat-treated to the microstructure and strength level to be present at the time of welding. Testing as-rolled or normalized plates with a ferrite and pearlite microstructure could give higher $\%RA_Z$ than the component would have after a quenching and tempering heat treatment.

The apparent microstructural effect was probably caused by a strength gradient in the thickness direction of the quenched and tempered condition. This gradient would be smaller in normalized steels that have ferrite and pearlite microstructures. Strength gradients concentrate strains and make any inclusions present in these areas much more influential.

Specimen-to-Specimen Variability

The specimen-to-specimen variability observed seems to have relevance in selecting the testing frequency and the retest criteria. Use of two tension specimens, one from each end of a plate (or an ingot), may not give the purchaser adequate quality assurance. This situation could occur when, by chance, the two tests are taken from regions that give high $\%RA_Z$, while much of the remainder of the plate has 20 percent or less RA_Z. Similarly, such limited testing could result in a plate producer having to reject overall high-quality plates just because the initial and retest areas included localized inclusion concentrations. Some plates rejected might be superior to those accepted if only because of the large specimen-to-specimen variability which can be encountered between adjacent samples.

More *Z*-direction testing seems to be required to reduce the specimen-to-specimen variability. One possible approach is the use of six or more specimens, at least three representing each end of an ingot. The average of all six specimens must exceed the required minimum reduction-of-area value, with no individual specimen giving less than half. Retesting would be required only when individual specimens gave less than half of the minimum $\%RA_Z$. Additional specimens would raise testing costs, but this would usually be a small price when compared with the expenses involved when lamellar tearing is encountered during fabrication.

Another possible approach that would help keep the number of specimens tested for each plate low, but still help minimize potential problems caused by large specimen-to-specimen variation, involves the use of a heat lot average. In this case, one specimen from each end of a plate would still be tested, but acceptance would be based on the average of all plates produced from the heat. Retesting would be mandatory for any plate that had an individual $\%RA_Z$ result less than half of the required average.

For situations where fewer than three plates would be *Z*-direction tension tested, additional tests could be made for each plate so that at least six results were available from the heat to determine the average $\%RA_Z$.

Final Diameter Reproducibility

For Z-direction tension specimens that had about 20 to 40 percent RA_Z, the final diameter was sometimes difficult to measure. This difficulty resulted in poor reproducibility of the final diameter recorded for a specimen by different testing personnel. Average diameters for three sets of measurements generally resulted in much less variability. The use of average results either for each plate or for all plates produced from a heat would also help decrease the somewhat subjective nature of the final diameter measurement, in addition to the specimen-to-specimen variability discussed previously.

Conclusions

Testing and material variables have been found to have different effects in tension tests made in the through-thickness direction of plates than in the conventional L or T orientations. These differences seem to be at least partially caused by variations in the shape and distribution of nonmetallic inclusions. Based on results presented, the following aspects should be considered in Z-direction tension testing specifications:

1. Testing in the Z-direction should reference the as-cast centerline of plate if the region of lowest ductility is to be sampled. Testing along ingot edges can give much higher $\%RA_Z$ than testing at the ingot centerline. Meeting a minimum $\%RA_Z$ requirement may not give the same measure of the relative lamellar tearing resistance, unless the same testing location is always used.
2. The minimum $\%RA_Z$ requirement should be based on the average of multiple tension tests rather than each of two tests. Only in this way can the possible problems from large specimen-to-specimen variations and final specimen diameter measurement reproducibility be reduced to reasonable levels. Averaging the results of at least six specimens from each plate or using the average of fewer tests from all plates of each heat are suggested means of reasonably increasing the sample population.
3. Test specimens should be machined from plate coupons heat-treated to the same microstructure and strength level that will be encountered during fabrication.

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Relation of Through-Thickness Ductility to Inclusion Prevalence, Matrix Toughness, and Matrix Strength

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ABSTRACT: Through-thickness ductility is used as a measure of the resistance of steel plate to lamellar tearing during and after welding. Lamellar tearing is initiated by delamination at inclusion/matrix interfaces in response to weld thermal-contraction strain, and this behavior is simulated in the through-thickness tension test. Although initiated at inclusions, lamellar tearing proceeds by microvoid growth and coalescense into terraces and, finally, by shear between terraces. These latter stages of lamellar tearing are thought to be sensitive to matrix strength and toughness. Accordingly, an attempt was made to investigate the influence of changes in strength and toughness on through-thickness reduction of area (TTRA).

Six high-strength low-alloy steel plates with a range of inclusion fractions were selected and heat-treated to develop ranges of strength and toughness. Measurements of inclusion fraction, longitudinal tensile properties, longitudinal Charpy impact properties, and TTRA were made. Analyses of these results indicated the following associations:

1. Doubling the inclusion concentration (for example, from 0.1 to 0.2 percent) resulted in a decrease in TTRA of about 12 percentage points.
2. Increasing the transition temperature (decreasing the toughness) by 56°C (100°F) resulted in a decrease in TTRA of about 4 to 12 percentage points and an average of about 7 percentage points.
3. Increasing the yield strength by 68.9 MPa (10 ksi) resulted in a decrease in TTRA of 1 to 8 percentage points and an average of about 4 percentage points.

These findings indicate that inclusions are the principal factors in restricting through-thickness ductility, but that high strength or low toughness may also be appreciably associated with reduced TTRA.

KEY WORDS: lamellar tearing, through-thickness tension test, matrix toughness, matrix strength, inclusion prevalence, transition temperature

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Through-thickness ductility is used as a measure of the resistance of steel plate to lamellar tearing during and after welding. In particular, it has been found that a through-thickness reduction of area (TTRA) of 20 percent or more, now a part of ASTM Specification for Through-Thickness Tension Testing of Steel Plates for Special Applications (A 770) is associated with resistance to lamellar tearing. Lamellar tears initiate parallel to the plate surface under welds by delamination at inclusion/matrix interfaces in response to weld thermal-contraction strain. Accordingly, high resistance to lamellar tearing, or high TTRA, can be built into plate products by minimizing inclusion prevalence. This technology has recently been reviewed by Sommella.[2]

Although lamellar tearing is initiated at inclusions, it proceeds by microvoid growth and coalescence into terraces and, finally, by shear between terraces. These latter stages of lamellar tearing are thought to be sensitive to matrix toughness and strength. Indeed, several laboratory investigations have indicated that low toughness and high strength abet inclusions in restricting TTRA. Accordingly, an attempt was made to investigate the influence of changes in matrix toughness and matrix strength on TTRA.

Materials and Experimental Work

The experimental work consisted largely of selecting a group of plate steels with different inclusion-prevalence levels; heat-treating them to obtain different matrix-toughness and strength levels; measuring inclusion prevalence, toughness, strength, and through-thickness ductility; and attempting to find associations among these measures.

The experimental materials were selected from commercial plate stocks as follows:

1. Plate samples from two heats of ASTM A514 Grade F steel.
2. Plate samples from two heats of ASTM A588 Grade A steel.
3. Plate samples from two heats of ASTM A537 steel.

These three grades have inherently different strength levels and responses to heat treatments. An attempt was made to find samples of each grade with different levels of inclusion prevalence; but, as will be shown later, the two samples of A514 steel had about the same level of inclusions. All samples were hot-rolled on a laboratory mill from thicknesses of 38.1 to 101.6 mm (1½ to 4 in.) to a thickness of 25.4 mm (1 in.), with a finishing pass at 982°C (1800°F).

In an effort to create different toughness and strength levels, five treatments were applied to sections of 25.4-mm (1-in.)-thick plate rolled from each sample:

[2] Sommella, J., "Significance and Control of Lamellar Tearing of Steel Plate in the Shipbuilding Industry," Ship Structure Committee Report 290, U.S. Coast Guard, Washington, D.C., 1979.

1. As-rolled.
2. Austenitized for 1 h at 913°C (1675°F), water-quenched, and tempered for 1 h at 593°C (1100°F).
3. Austenitized for 1 h at 913°C (1675°F), water-quenched, and tempered for 1 h at 677°C (1250°F).
4. Normalized for 1 h at 913°C (1675°F).
5. Spheroidized by soaking for 1 h at 746°C (1375°F) plus 24 h at 690°C (1275°F).

Matrix toughness and matrix strength, in addition to inclusion prevalence, were the independent variables in the research program. For one treatment or condition, product was left in the as-rolled condition. Quenched-and-tempered material, at two strength levels—achieved through the use of 593 and 677°C (1100 and 1250°F) tempering temperatures—comprised two more of the five conditions. Normalized product and spheroidized product completed the list of five conditions.

It should be emphasized at this point that, after laboratory rolling and a variety of laboratory heat treatments, it is no longer appropriate to refer to the sample materials as A514, A588, and A537. Accordingly, the samples that began as A514, A588, and A537 will be termed A1 and A2, B1 and B2, and C1 and C2, respectively, in the rest of this paper.

Three kinds of independent variables (inclusion prevalence, Charpy V-notch impact properties, and longitudinal tensile properties) were measured, along with one kind of dependent variable (through-thickness tensile properties). Among the independent variables, inclusion prevalence was measured metallographically with a quantitative television microscope for longitudinal sections as inclusion-area fraction and as projected inclusion length. Charpy V-notch impact tests were made by using a series of 16 longitudinal specimens for each sample and condition. Analytical methods were then used to extract transition temperatures and shelf heights from the data. Duplicate longitudinal tension tests were made for each sample in each condition; test results were then analyzed for yield and tensile strengths, elongation, and reduction of area. Toughness and strength measurements were made for longitudinal specimens in an effort to maximize the contribution of matrix properties and to minimize the contribution of inclusions to these measurements. The dependent variable, through-thickness reduction of area (TTRA), was obtained by testing six 12.83-mm (0.505-in.)-diameter through-thickness specimens made from stud-welded assemblies of each sample and condition.

Results and Discussion

Results of inclusion-prevalence measurements are shown in Table 1. As indicated earlier, the A samples had similar inclusion levels; however, as desired, the B and C samples had different inclusion levels. The two higher inclusion levels represent normal values of inclusions in plate steel; the four

TABLE 1—*Inclusion-prevalence measurements.*

Sample	Inclusion Area Fraction, %	Projected Inclusion Length, μm/0.5 mm²
A1	0.069	50
A2	0.069	51
B1	0.089	60
B2	0.229	157
C1	0.222	194
C2	0.093	64

lower inclusion levels represent values typical of lamellar-tearing-resistant plate.

Some selected matrix-toughness measurements are shown in Table 2. These results are for Sample B1. Although only the transition temperatures at 20.4 J (15 ft-lb), 381 μm (15 mils), and 50 percent shear are shown here, energy and ductility shelf heights and room-temperature energy absorption, lateral expansion, and fracture appearance were also examined, not only for this sample, but for all six samples. Of these measures, the transition temperatures appeared to be the most discriminating among the several conditions; on further examination, no particular transition-temperature criterion appeared to be superior to the others as a general measure of matrix toughness. For Sample B1, the 381-μm (15-mil) transition temperatures were on average about 16°F higher than the 20.4-J (15-ft-lb) transition temperatures, and the 50 percent shear transition temperatures were on average about 77°F higher than the 20.4-J (15-ft-lb) transition temperatures. Arbitrarily, the 20.4-J (15-ft-lb) transition temperatures were chosen as values to represent the independent-variable matrix toughness.

The matrix-toughness values for all six samples used as independent variables in the analysis are shown in Table 3. Overall the values ranged from

TABLE 2—*Selected matrix-toughness measurements.*[a]

	Transition Temperature, °F		
Condition of Sample B1	Energy Absorbed, 15 ft-lb	Lateral Expansion, 15 mils	Fracture Appearance, 50% Shear
As-rolled	+31	+41	+103
Quenched and tempered (1100°F)	−107	−78	−23
Quenched and tempered (1250°F)	−141	−128	−76
Normalized	−104	−91	−12
Spheroidized	−7	+6	+77

[a] °C = 5/9(°F − 32); 1 ft-lb = 1.36 J; 1 mil = 25.4 μm.

TABLE 3—*Independent variables: matrix toughness.*[a]

Condition	15-ft-lb Transition Temperature, °F					
	A1	A2	B1	B2	C1	C2
As-rolled	+59	+82	+31	+25	+29	+39
Quenched and tempered (1100°F)	−104	−108	−107	−100	−123	−208
Quenched and tempered (1250°F)	−208	−178	−141	−147	−139	−194
Normalized	+67	+98	−104	−110	−95	−101
Spheroidized	+18	+17	−7	−15	+37	+42

[a] °C = 5/9(°F − 32); 1 ft-lb = 1.36 J.

−133 to +37°C (−208 to +98°F). For any particular sample, the range of values was at least 94°C (170°F) wide. This diversity of values was sought and is a good characteristic in a set of independent-variable values.

Some selected matrix-strength measurements are shown in Table 4. These results also are for Sample B1. For this sample, yield strengths ranging from 311.6 to 675.7 MPa (45.2 to 98.0 ksi) and tensile strengths ranging from 501.9 to 777.0 MPa (72.8 to 112.7 ksi) were measured. Arbitrarily, yield strength was selected to represent the independent-variable matrix strength.

The matrix-strength values used as independent variables in the analysis are shown in Table 5 for all six sample materials. Overall these longitudinal yield strength values ranged from 213.7 to 993.5 MPa (31.0 to 144.1 ksi). Wide variations were also noted for each sample or for each condition. This range of values was judged to provide good diversity for the matrix-strength variable.

Values of the dependent variable, TTRA, used in the analysis are given in Table 6. Overall these values encompassed a range from about 16 to about 58 percent. This range approximately spans the range of TTRA values encountered in engineering practice, but both higher and lower values are sometimes encountered. In some cases, as with Sample B1 for example, there was substantial variation in TTRA associated with the different conditions; in other cases, as with Sample C1 for example, there was little variation asso-

TABLE 4—*Selected matrix-strength measurements.*[a]

Condition of Sample B1	Yield Strength, ksi	Tensile Strength, ksi
As-rolled	67.3	96.6
Quenched and tempered (1100°F)[b]	98.0	112.7
Quenched and tempered (1250°F)	78.2	94.0
Normalized	56.0	82.5
Spheroidized	45.2	72.8

[a] 1 ksi = 6.8948 MPa.
[b] °C = 5/9(°F − 32).

TABLE 5—*Independent variable: matrix strength.*

Condition	Yield Strength, ksi[a]					
	A1	A2	B1	B2	C1	C2
As-rolled	81.1	79.0	67.3	58.9	45.0	51.7
Quenched and tempered (1100°F)[b]	142.8	144.1	98.0	83.5	62.5	75.9
Quenched and tempered (1250°F)	112.1	109.5	78.2	72.3	59.3	68.8
Normalized	80.6	79.8	56.0	51.4	49.3	56.5
Spheroidized	60.4	58.6	45.2	42.7	35.8	31.0

[a] 1 ksi = 6.8948 MPa.
[b] °C = 5/9(°F − 32).

ciated with condition. For any given condition there was a substantial variation in TTRA among the several samples. The two missing values represent matrix tensile strengths that exceeded that of the prolong material.

Analytic methods, including multiple linear regression,[3] were used to assess the magnitude of changes in TTRA associated with increases in inclusion area, transition temperature, and yield strength. These results are given in Table 7. As expected, inclusion-area fraction had a very substantial effect. Also, the data indicated that the effect decreased with increasing inclusion area. Accordingly, the inclusion effect was modeled with a logarithmic function. Doubling the inclusion area fraction, for example from 0.10 to 0.20 percent, accounted for a 12 percentage point reduction in TTRA. For the materials in the present investigation, the four low-inclusion samples averaged 0.080 percent inclusions and their two high-inclusion counterparts averaged 0.225 percent inclusions. This difference in inclusion level translates to an 18 percentage point difference in TTRA.

Transition temperature also significantly influenced TTRA. A 56°C (100°F) increase in transition temperature, or decrease in toughness, accounted for an average 7-percentage point decrease (range of 4 to 12 percent) in TTRA. This effect, too, is appreciable. For example, for Samples B1

TABLE 6—*Dependent variable: TTRA.*[a]

Condition	A1	A2	B1	B2	C1	C2
As-rolled	38.10	21.79	38.52	21.27	15.86	27.70
Quenched and tempered (1100°F)[b]	...	...	41.41	17.70	15.64	29.23
Quenched and tempered (1250°F)	45.75	31.76	57.75	23.00	18.36	36.43
Normalized	35.21	22.23	49.17	28.59	18.88	31.22
Spheroidized	53.44	47.30	57.49	30.90	16.72	23.25

[a] Values represent the mean of measurements on six specimens.
[b] °C = 5/9(°F − 32).

[3] Draper, N. R. and Smith, H., *Applied Regression Analysis*, Wiley, New York, 1966.

TABLE 7—*Causal effects.*

Change in Independent Variable	Effect on TTRA, %	
	Range	Mean
Doubling inclusion fraction[a]	...	−12
Increasing transition temperature by 100°F[b]	−4 to −12	−7
Increasing yield strength by 10 ksi[c]	−1 to −8	−4

[a] For example, from 0.1 to 0.2 percent.
[b] °C = 5/9(°F − 32).
[c] 1 ksi = 6.8948 MPa.

and B2, transition temperature decreased by 75°C (135°F) when as-rolled samples were normalized. This treatment would account for a 9.5 percentage point improvement in TTRA because of improved toughness.

Yield strength also significantly influenced TTRA. On average, a 68.9-MPa (10-ksi) increase in yield strength accounted for a 4 percentage point decrease (range of 1 to 8 percent) in TTRA. In continuing the aforementioned example of normalizing Sample B1 or B2, the average 64.8-MPa (9.4-ksi) yield strength reduction associated with normalizing translates into a 3.8 percentage point improvement in TTRA. With contributions from toughness improvement and yield strength reduction, a 13.3 percentage point improvement in TTRA might be expected from normalizing an as-rolled A588 steel plate. Indeed, in separate work, the ductility of a group of eight A588 samples with an average TTRA of 11 percent was improved by normalizing. The observed average TTRA after treatment was 24 percent or, as predicted, about 13 percentage points higher.

These results show that, to achieve a given level of TTRA, more attention must be given to inclusion control as product strength increases or as product toughness decreases. In addition, substantial changes in TTRA can be achieved through thermal treatments that alter strength and toughness.

Summary

An attempt was made to demonstrate an association between differing matrix toughness, matrix strength, and inclusion levels in plate steels and their through-thickness ductility. Six steel plates with a range of inclusion fractions were selected and heat-treated to develop ranges of matrix toughness and matrix strength. Measurements of inclusion fraction, longitudinal Charpy impact properties, longitudinal tensile properties, and through-thickness reduction of area were made. Analyses of these results indicated the following associations:

1. Doubling the inclusion concentration, for example from 0.1 to 0.2 percent, was associated with a TTRA reduction of about 12 percentage points.

2. Increasing the transition temperature (decreasing the toughness) by 56°C (100°F) was associated with TTRA reductions of about 4 to 12 percentage points and an average of about 7 percentage points.

3. Increasing the yield strength by 68.9 MPa (10 ksi) was associated with TTRA reductions of 1 to 8 percentage points and an average of about 4 percentage points.

These findings indicate that, although inclusions are the principal factor in restricting through-thickness ductility, high strength or low toughness may also be appreciably associated with reduced TTRA.

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Dependence of Through-Thickness Ductility on Location in Plate Length, Width, and Thickness

REFERENCE: Ludwigson, D. C., "**Dependence of Through-Thickness Ductility on Location in Plate Length, Width, and Thickness,**" *Through-Thickness Tension Testing of Steel, ASTM STP 794,* R. J. Glodowski, Ed., American Society for Testing and Materials, 1983, pp. 121–129.

ABSTRACT: Substantial differences in the variation of through-thickness ductility with location in plate length, width, and thickness have been observed. Some rare-earth-treated steel plates made for lamellar-tearing-resistant applications exhibit large variations in ductility with location, whereas other plates are much more uniform. Data are given to illustrate both patterns of behavior.

When variation is encountered, the poorest ductility is found in that portion of the plate that represents the bottom/midwidth/midthickness of the ingot. Rare-earth-oxysulfide inclusions tend to cluster and segregate to that location and reduce ductility there. If such inclusions are sufficiently prevalent, the consequent variation in ductility can be substantial. If inclusion prevalence is very low, however, good uniformity of properties is observed.

KEY WORDS: plate, lamellar tearing, ductility, through-thickness tension test, inclusions

It is well known that plate products may not always be uniform in properties throughout their length, width, and thickness, or among the many plates from a single heat [*1–3*].[2] Therefore, in the acceptance testing or research evaluation of plate products, the selection of a test-coupon location may present a problem. For acceptance testing, ASTM Specification for Through-Thickness Tension Testing of Steel Plates for Special Applications (A 770) requires that one coupon be taken from the midwidth at each end of each plate. As will be shown, the lowest through-thickness ductility is often encountered at one of these two locations. If lamellar-tearing resistance during

NOTE: It is understood that the material in this paper is intended for general information only and should not be used in relation to any specific application without independent examination and verification of its applicability and suitability by professionally qualified personnel. Those making use thereof or relying thereon assume all risk and liability arising from such use or reliance.

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[2] The italic numbers in brackets refer to the list of references appended to this paper.

fabrication is to be assessed, the coupon should contain a plate surface, since lamellar tearing is usually a near-surface phenomenon. The specification also contains an option for full-thickness through-thickness tension testing to assess fitness for through-thickness loading during service. As will be shown, midthickness ductility in very thick plates may not be as good as the near-surface ductility. Some observations that have been made on the variation of through-thickness reduction of area (TTRA) with test-coupon location in rare-earth-treated plate steels are the subject of this paper.

Results and Discussion

Position in Plate Length and Width

For many plates, position in plate length reflects location in ingot height, and position in plate width reflects location across the broad face of an ingot. Accordingly, for plates of ASTM A516 Grade 70 and A633 Grade C rolled from big-end-up hot-topped ingots, TTRA was measured at plate positions representing the top, midheight, and bottom locations in ingot height in combination with edge, quarter-width, and midwidth locations across the broad face of the ingot. Six tests were made at each location. Full-thickness TTRA results for the 31.8-mm (1¼-in.)-thick plate of A516 steel are summarized in Fig. 1. Ductility values became progressively poorer with distance from ingot edge to midwidth; bottom-of-ingot specimens exhibited the poorest ductility.

The pattern of ductility in this plate reflects the pattern of rare-earth-oxysulfide inclusion segregation in the ingot. These inclusions are formed in the ladle when the rare-earth addition is made. They are solid at steelmaking temperatures and globular in shape [4]. Most of the inclusions float

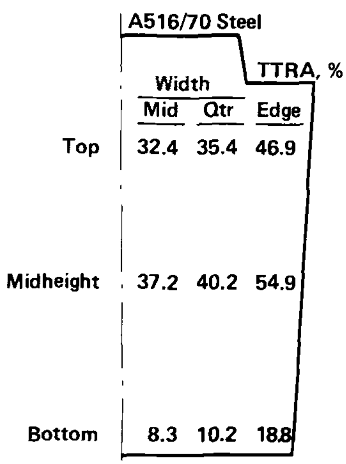

FIG. 1—*Profile of TTRA values in an A516/70 ingot.*

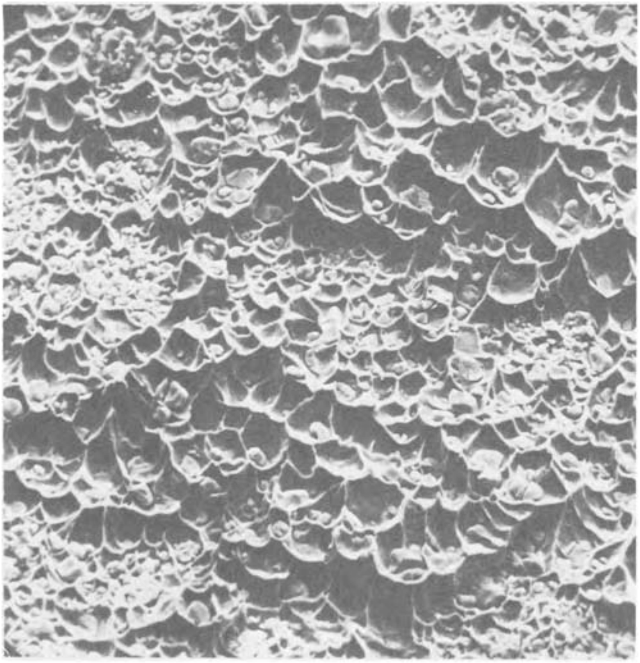

FIG. 2—*SEM fractograph of A516/70 fracture surface; bottom/midwidth;* ×600.

up into the ladle slag and are trapped there because they are somewhat less dense than the molten steel. However, some of the smaller inclusions—those less than about 5 μm in diameter—may remain in suspension. After teeming, some of these small rare-earth-oxysulfide inclusions rise up into the hot top, but others become nuclei for iron solidification. As the solid iron builds up on these inclusion nuclei, the growing composite particle becomes denser than the liquid steel and begins to descend. Thermal-convection currents in the ingot mold, downward along the mold walls and upward at the ingot axis, tend to shape the aggregation of composite particles into the form of a cone at the ingot bottom. Figure 2 shows a scanning electron microscope (SEM) fractograph of a fracture surface of a broken full-thickness through-thickness tension test specimen from the bottom/midwidth of the A516/70 steel ingot. Individual inclusion particles, identified by energy-dispersive radiation analysis as rare-earth sulfides or oxysulfides, reside in dimples and are surrounded by iron that exhibits ductile fracture. This particular specimen exhibited a TTRA of 5.9 percent.

By contrast, the fracture surface of a full-thickness through-thickness tension test specimen from the top/edge location of the same plate—shown in Fig. 3, again as seen in the SEM at ×600—exhibits only ductile dimples; no aggregations of inclusions are evident. This particular specimen exhibited a TTRA of 48.0 percent.

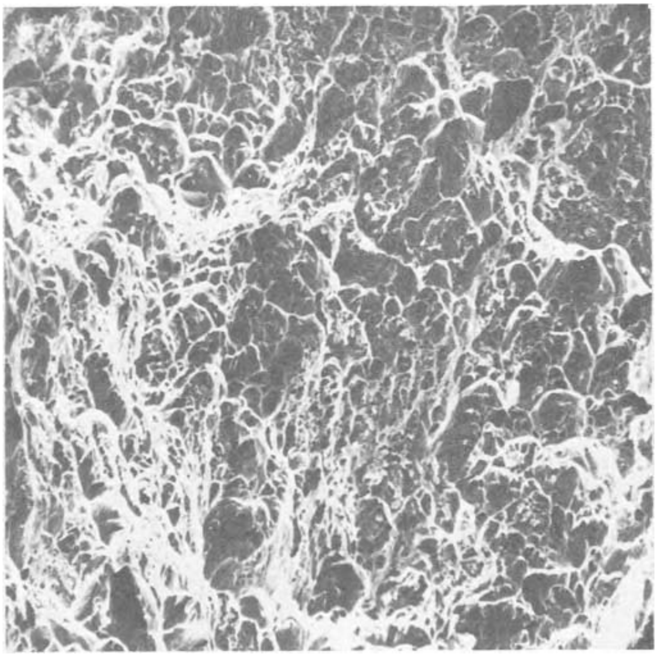

FIG. 3—*SEM fractograph of A516/70 fracture surface; top/edge; ×600.*

A633/C Steel

	Width: Mid	Width: Qtr	Edge
Top	57.8	57.8	57.5
Midheight	54.8	51.2	60.7
Bottom	37.9	53.9	61.7

TTRA, %

FIG. 4—*Profile of TTRA values in an A633/C ingot.*

Variation in through-thickness ductility in plate length and width can be reduced by minimizing the amounts of inclusion-forming ingredients, principally sulfur, in the steel. If the inclusion levels are low enough, even segregation will not concentrate inclusions to the extent that TTRA falls below 20 percent, the minimum level specified in ASTM Specification A 770. The formal criterion for evaluating the concentrating potential of inclusion ingredients has been established in Japan by Sanbongi [5]. When translated into practical terms, Sanbongi's criterion requires that the steel contain about 0.010 percent sulfur or less at the time of the rare-earth addition. Our experience confirms this finding. Figure 4, for example, is a chart of the distribution of TTRA values in a 44.5-mm (1¾-in.)-thick plate of A633 steel that was made from a heat with a 0.010 percent sulfur at the time of the rare-earth addition. Although there is still a noticeable drop in ductility at the bottom/midwidth location, TTRA values are more uniform than those shown previously for the A516 steel and are always well above the 20 percent specification level. The A516 steel plate that exhibited substantial nonuniformity of properties was made from a heat that contained 0.023 percent sulfur at the time of the rare-earth addition.

Position in Plate Thickness

Segregation of inclusions to the ingot axis also influences the variation in through-thickness ductility at different positions in the plate thickness. This variation can be detected by making specimens from coupons representing only a fraction of the plate thickness. Naturally, for good sensitivity to location in plate thickness, it is best to evaluate this variation in very thick plates. Figure 5 shows TTRA profiles through the thickness of 178 and 203 mm (7 and 8 in.) plates from different heats of A633 steel. The 178-mm (7-in.) plate declined in TTRA from about 70 percent at either near-surface location to 15 percent at midthickness. The low ductility at midthickness was traced to inclusion concentrations that were formed because sulfur was not reduced sufficiently before the rare-earth addition. By contrast, the 203-mm (8-in.) plate exhibited 60 to 70 percent TTRA throughout its thickness. This plate came from a heat with a low level of inclusions achieved through sulfur reduction to 0.009 percent prior to the rare-earth addition.

It is interesting to note that either plate would be resistant to lamellar tearing. At near-surface locations, where lamellar tearing would usually appear, both plates exhibited TTRA values well above the 20 percent specification level and would be resistant to lamellar tearing. The 203-mm (8-in.) plate would also have good through-thickness load-carrying capability.

Although inclusion concentrations are the usual source of poor through-thickness ductility in plates, unhealed or partially healed solidification microvoids may be another source. Shown in Fig. 6, as observed in the SEM at ×100, is the fracture surface of a through-thickness tension test specimen

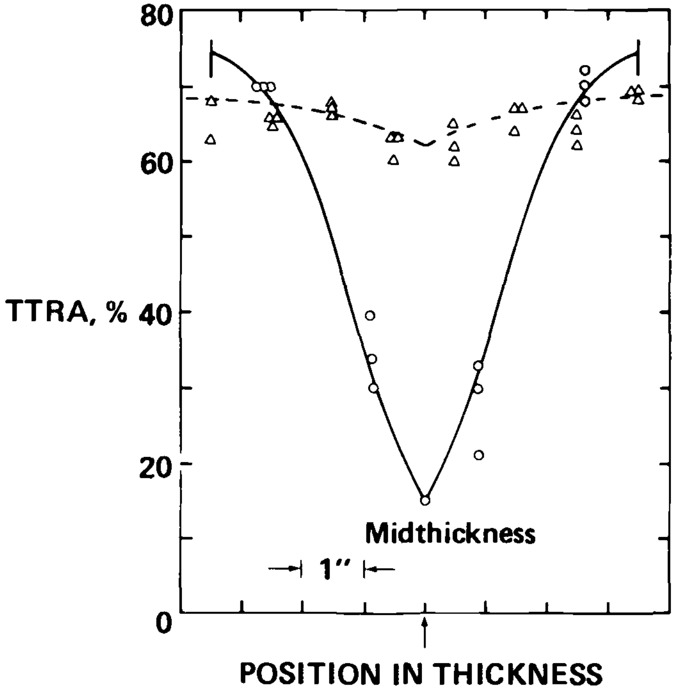

FIG. 5—*Influence of position through plate thickness on the TTRA values of two A633/C heats.*

FIG. 6—*SEM fractograph of A588/A steel fracture surface, showing incompletely healed solidification microvoid;* ×100.

from the midthickness of a 193.7-mm (7⅝-in.)-thick plate of A588/A steel. Several microvoids, elongated and partially healed by rolling, can be seen here. These microvoids form during the final stages of solidification because of shrinkage and blocked flow of liquid steel into the resulting cavities. There is a tendency for inclusions to be associated with microvoids, but in the present example there is no appreciable concentration of inclusions in or near these microvoids. Only in very thick plate might one expect to see microvoids and associated low ductility at midthickness. Even in very thick plate, however, solidification microvoids can usually be healed through altered rolling schedules.

The manifestation of partially healed microvoids on TTRA is illustrated in Table 1. These results represent slices approximately 25.4 mm (1 in.) in thickness at equally spaced intervals through 193.7, 76.2, and 46.0 mm (7⅝, 3, and 1¹³⁄₁₆ in.) thick plates rolled from the same heat of A588 steel. In the 193.7-mm (7⅝-in.) plate, TTRA was substantially lower at near-midthickness positions—23 to 25 percent—than at near-surface positions—54 to 62 percent. For the 76.2-mm (3-in.) plate, the midthickness TTRA (36 percent) was again lower than that at surface positions (56 or 60 percent), but it was higher than the midthickness ductility for the thicker plate. For the 46-mm (1¹³⁄₁₆-in.) plate, TTRA values of 52 and 55 percent were recorded for the half-thickness coupons, and a TTRA of 55 percent (not shown here) was recorded for the full-thickness plate. The improvement in midthickness TTRA with decreasing plate thickness represents the further healing of microvoids with increased hot rolling.

Through-thickness tension tests are generally used to assess the ability of steel plates to resist lamellar tearing during fabrication. If TTRA values at near-surface locations are at least 20 percent, the plate might be judged resistant to lamellar tearing. An option in the specification allows through-thickness testing at other locations in thickness to assess fitness to accept

TABLE 1—*Profile of TTRA at 1-in. intervals through the thickness of plates from an A588 steel plate.*[a]

Average TTRA, %, at the Indicated Plate Thickness, in.		
7⅝	3	1¹³⁄₁₆
62	...	...
54	56	...
25	...	52
23[b]	36[b]	...
25	...	55
55	60	...
62	...	...

[a] 1 in. = 25.4 mm.
[b] Midthickness.

through-thickness design loads during service. It may be tempting to apply the same 20 percent criterion used in lamellar-tearing situations for the service-load situation. The data shown here for A516 steel, however, suggest the hazard in that extension of the lamellar-tearing criterion. When tensile strength in the through-thickness direction is plotted against reduction of area in the same test (Fig. 7), it is seen that tensile strength is impaired in product exhibiting 20 percent TTRA. Analytic treatment of these data indicates that full tensile strength is achieved only when TTRA exceeds 32 percent. Other investigators [*6–9*] have presented data indicating that tensile strength is impaired when TTRA values are less than about 18 to 30 percent.

Location in Heat

There are reasons why one might expect variations in TTRA among plates rolled from different ingots in a heat. An increasingly torn teeming stream, due to progressive nozzle deterioration, can entrain air and thereby favor the development of oxide inclusions in later ingots. Stratification of inclusions toward the upper portion of the steel in the teeming ladle can produce similar effect. Reduced superheat in later ingots might add to the effect. The

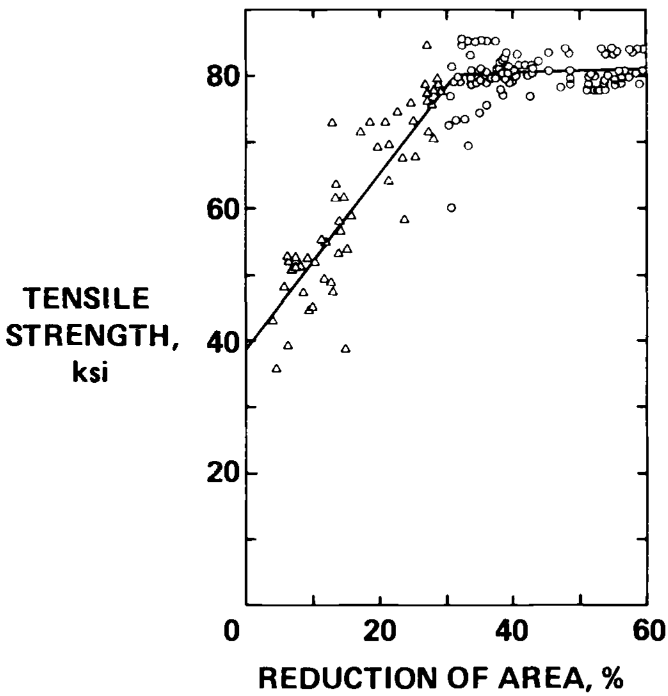

FIG. 7—*Association of tensile strength with reduction of area in A516/70 steel (individual measurements in four ingots).*

TABLE 2—*Variation in TTRA with position in heat.*

A516		A588		A633		A633	
Ingot	TTRA, %	Ingot	TTRA, %	Ingot	TTRA, %	Ingot	TTRA, %
2/8[a]	58.6	2/9	52.9	2/8	66.9	1/9	49.6
4/8	51.8	3/9	73.5	4/8	60.9	4/9	69.6
5/8	52.3	5/9	59.0	5/8	61.4	7/9	62.5
8/8	63.7	...	...	7/8	68.4	9/9	68.2

[a] Second ingot of eight teemed.

data shown in Table 2, however, fail to suggest that any consistent pattern in TTRA with position in heat is developed in commercial practice.

Summary

In rare-earth-treated steels made for lamellar-tearing-resistant applications, the segregation of rare-earth-oxysulfide inclusions toward ingot-bottom and central-axis locations has been observed to cause reduced TTRA values in plate positions representing the ingot bottom, midwidth, and midthickness. However, when the steelmaker reduces the sulfur level to about 0.010 percent or less prior to making the rare-earth addition, inclusion prevalence and segregation are minimized. In very thick plates, unhealed solidification microvoids may also reduce through-thickness ductility at near-midthickness plate positions. Among plates from different ingots in a given heat, some random variations in TTRA are usually observed, but a consistent pattern in TTRA with position in heat has yet to be discerned.

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A. D. Wilson[1]

Comparing the Effect of Inclusions on Ductility, Toughness, and Fatigue Properties

REFERENCE: Wilson, A. D., "**Comparing the Effect of Inclusions on Ductility, Toughness, and Fatigue Properties,**" *Through-Thickness Tension Testing of Steel, ASTM STP 794,* R. J. Glodowski, Ed., American Society for Testing and Materials, 1983, pp. 130–146.

ABSTRACT: The nonmetallic inclusion structure in a steel has been demonstrated to have a dramatic effect on mechanical properties and lamellar-tearing resistance. Although the through-thickness tension test has become widely used to assure a level of quality with regard to both of these items, the toughness and fatigue properties are also of concern. This study compares the tensile, Charpy V-notch impact, and fatigue crack propagation properties in the three major testing orientations of six plate steel grades in each of two quality levels (inclusion structures). The primary emphasis of the study was to establish which parameters from these test methods were most sensitive to inclusion structure. Generally, the Charpy V-notch upper shelf energy was found to be the most sensitive parameter to changes in inclusion structure. In steels with higher inclusion levels, however, the through-thickness tensile reduction of area was most sensitive. This appeared to take place when this value was less than 25 percent. Correlations among the various testing parameters were also identified.

KEY WORDS: through-thickness tension testing, inclusions, toughness, fatigue, inclusion effects, steel properties, anisotropy, steel quality

Although other factors in the welding process have been demonstrated to contribute to improved resistance from lamellar tearing [*1,2*],[2] the brunt of the concern has still been placed on the material properties. The through-thickness tension test (T^4) has been shown to be an excellent quality control test for steel to assure a level of lamellar-tearing resistance during the welding of structural steels [*3–5*]; see also ASTM Specification A 770. The results of this test, particularly the reduction-of-area determinations, have come to imply a certain level of overall quality of the material, which might be better expressed by other test methods. Furthermore, the results of T^4 cannot be directly applied to evaluating the service behavior of a joint with through-thickness stresses, which may or may not have lamellar tearing present. To

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[2] The italic numbers in brackets refer to the list of references appended to this paper.

do this the toughness and fatigue properties of the base steel are required.

The single most important factor controlling the lamellar-tearing resistance and the T^4 properties of steels is the nonmetallic inclusion structure [*1–3*]. The effect of nonmetallic inclusions on toughness and fatigue properties has also been shown [*6, 7*]. Of interest in this study are the relative differences shown in comparing the quality of steels with varying inclusion structures when measured by different test methods. To explore this question, six plate steel grades in two quality levels were evaluated by tension, Charpy V-notch impact (CVN), and fatigue crack propagation (FCP) testing in the full range of testing orientations of interest. These test plates were chosen to provide test materials having the different inclusion structures encountered in structural applications.

Experimental Procedures

Materials

The plate steel grades that were evaluated and their minimum yield strength requirements are listed in Table 1. Each grade was evaluated in two quality levels: conventional electric furnace practice (0.025 percent maximum sulfur) (CON) and calcium-treated electric furnace practice (0.010 percent maximum sulfur) (CaT). The latter has been demonstrated not only to result in a lower sulfur level, but to lead to minimization of manganese sulfide and aluminum oxide inclusion clusters and to inclusion shape control. These factors contribute to the improved ductility, toughness, and fatigue properties of steels produced by this technique [*8*]. All the CON steels except A 387 were produced to aluminum-killed fine-grain practice, and therefore had Type II

TABLE 1—*Plate steel grades evaluated and their minimum yield strength requirements.*

ASTM Specification and Grade	Specification Title	Required Minimum Yield Strength, MPa (ksi)
A516-70	Pressure Vessel Plates, Carbon Steel, for Moderate- and Lower-Temperature Service	262 (38)
A588A	High-Strength Low-Alloy Structural Steel with 50 000 psi Minimum Yield Point to 4 in. Thick	345 (50)[a]
A533B-1	Pressure Vessel Plates, Alloy Steel, Quenched and Tempered, Manganese-Molybdenum and Manganese-Molybdenum-Nickel	345 (50)
A633C	Normalized High-Strength Low-Alloy Structural Steel	345 (50)[a,b]
A387-22	Pressure Vessel Plates, Alloy Steel, Chromium-Molybdenum	310 (45)
A514F	High-Yield Strength, Quenched and Tempered Alloy Steel Plate, Suitable for Welding	690 (100)

[a] Minimum yield point.

[b] To 64 mm (2½ in.) thickness; for plates to 102 mm (4 in.), minimum yield point is 317 MPa (46 ksi).

MnS and Al_2O_3 inclusion clusters. The CON A 387 steel was produced to coarse grain practice and had clusters of MnS and complex silicate inclusions present. All the CaT steels showed a significant minimization of the foregoing inclusion types with the presence of calcium-modified, duplex, sulfide-aluminate inclusions.

The chemistries and plate thicknesses of the steels evaluated in this study are given in Table 2. Plate thicknesses from 57 to 305 mm (2¼ to 12 in.) were used in this investigation. The effect of CaT on lowering the sulfur level in these steels is particularly of note. The variety of casting thicknesses and rolling characteristics used for these plates additionally helps to produce the wide range of inclusion structures desired for this study. The A516-70, A633C, and A588A steels were all tested in the normalized condition. The A533B-1, A387-22, and A514F steels were all in the quenched, tempered, and stress-relieved conditions.[3]

Testing

The tension, CVN, and FCP tests were performed in accordance with the following applicable ASTM standards: Tension Testing of Metallic Materials (E-8), Notched Bar Impact Testing of Metallic Materials (E-23), and Test for Constant-Load-Amplitude Fatigue Crack Growth Rates Above 10^{-8} m/Cycle (E 647). The testing orientations used for all three test methods are given in Fig. 1. The tension tests were performed in the L, T, and S orientations; the CVN and FCP tests were performed in the LT, TL, ST, and SL orientations. Testing in the LS and TS orientations for these steels has been performed, but will not be reported since they do not add significantly to this study.

The tension tests were performed on 6.4-mm (0.252-in.)-diameter test specimens. At least two tension tests per orientation were conducted. The CVN results will be reported in the form of the upper shelf properties where inclusions have their greatest effect on toughness [*8*]. The average of three to five test results was used to establish the upper shelf energy (USE) and the upper shelf lateral expansion (USL). The FCP results were initially analyzed in the form of the Paris equation [*9*]

$$da/dN = C_o \Delta K^m \tag{1}$$

where da/dN is the growth rate, ΔK is the stress intensity factor range, and C_o and m are material constants. The values C_o and m are both required to characterize a particular steel, although various steels can be compared graphically in da/dN–ΔK plots. In this study the fatigue crack growth rate (FCGR) at a ΔK of 55 MPa$\sqrt{m}$ (50 ksi$\sqrt{in.}$) (FCGR-55) was used to sim-

[3] It is normally not recommended that A514F steel be stress-relieved; however, owing to the effect of residual stresses on FCP testing, stress relieving was required for the A514F plates in this study.

TABLE 2—*Chemistry of test materials, percent.*

Steel	Quality Level	Gage in.	Gage (mm)	C	S	Mn	P	Cu	Si	Ni	Cr	Mo	V	Al	Other
A516-70	CON	7½	(190)	0.23	0.013	0.98	0.013	0.13	0.25	0.14	0.08	0.03	0.002	0.039	...
	CaT	10	(254)	0.24	0.002	1.09	0.014	0.11	0.19	0.20	0.06	0.05	0.002	0.038	...
A633C	CON	4	(102)	0.13	0.021	1.41	0.011	0.23	0.24	0.23	0.20	0.06	0.001	0.049	0.026 Cb
	CaT	4	(102)	0.14	0.006	1.46	0.007	0.24	0.17	0.26	0.21	0.08	0.002	0.032	0.025 Cb
A588A	CON	3	(76)	0.15	0.020	1.07	0.006	0.27	0.24	0.16	0.58	0.07	0.051	0.026	...
	CaT	3	(76)	0.15	0.003	1.11	0.011	0.29	0.46	0.19	0.59	0.05	0.081	0.030	...
A387-22	CON	12	(305)	0.13	0.020	0.48	0.014	0.09	0.19	0.09	2.10	1.04	...	0.003	...
	CaT	12	(305)	0.11	0.009	0.33	0.012	0.18	0.03	0.21	2.28	0.96	0.004	0.019	...
A533B-1	CON	6½	(165)	0.18	0.009	1.41	0.008	0.13	0.23	0.48	0.11	0.48	...	0.045	...
	CaT	7½	(191)	0.20	0.009	1.27	0.012	0.11	0.18	0.61	0.08	0.55	...	0.046	...
A514F	CON	2¼	(57)	0.17	0.014	0.88	0.009	0.22	0.27	0.91	0.57	0.52	0.054	0.022	B added
	CaT	2¼	(57)	0.16	0.006	0.86	0.011	0.19	0.26	0.95	0.63	0.45	0.046	0.045	B added

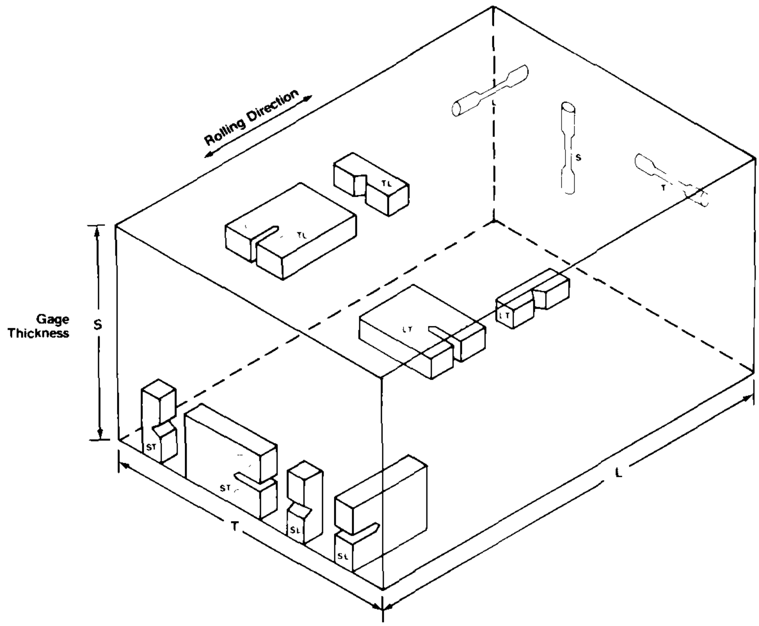

FIG. 1—*Testing orientations used in this study.*

plify comparisons. The effect of inclusion structure is most often noted at this ΔK-level [7].

Results

Test Data

The tension, CVN, and FCP results are given in Tables 3 and 4. Although the variation in results between the CON and CaT quality levels of these steels in the various test orientations can be noted in these tables, Fig. 2 summarizes some of the results. This figure compares the range of through-thickness and longitudinal test results. While significant variation in the tensile reduction of area (RA) is noted only in the S orientation for the A588A, A533B, and A514F steels, there is significant variation in the USE for all steels in both testing orientations. There is considerable variation in the FCGR-55 only in the SL orientation and for A588A and A514F.

Test Ratios

In order to normalize the results of the three test methods in some manner and to simplify comparisons, two types of ratios were used. Quality ratios demonstrated the differences between the CON and CaT quality levels of each steel grade in each testing orientation. For the tensile ductility and

TABLE 3—*Tensile properties.*

Steel	Quality Level	n[a]	0.2% Yield Strength, MPa[b]			Ultimate Tensile Strength, MPa[b]			Elongation, %			Reduction Of Area, %		
			L	T	S	L	T	S	L	T	S	L	T	S
A516	CON	0.271	254	253	261	519	504	510	33.2	32.7	27.7	64.6	63.7	44.2
	CaT	0.272	301	265	293	521	519	520	32.1	31.4	28.2	66.7	65.7	59.2
A633C	CON	0.240	332	339	322	516	521	512	36.1	31.6	22.7	77.5	70.7	46.4
	CaT	0.241	379	375	376	550	545	542	33.2	31.6	29.3	76.2	71.3	67.6
A588A	CON	0.234	348	335	336	525	512	468	31.8	29.4	10.1	74.9	60.0	8.2
	CaT	0.241	367	367	362	552	543	538	33.3	32.3	31.4	76.7	74.4	66.1
A387	CON	0.176	376	373	366	550	550	543	26.1	25.1	23.7	78.7	74.8	70.7
	CaT	0.181	406	403	396	539	537	531	25.8	25.3	24.3	81.5	79.0	75.0
A533B	CON	0.177	444	436	439	589	585	553	29.0	25.3	9.8	71.4	57.5	20.3
	CaT	0.173	494	494	496	603	601	601	27.9	27.0	25.5	72.8	70.2	66.9
A514F	CON	0.075	786	792	745	854	855	761	21.0	17.3	2.0	70.9	54.1	8.2
	CaT	0.067	799	784	781	855	845	847	19.4	18.9	13.5	71.8	64.9	51.8

[a] n = strain-hardening exponent determined in T orientation test.
[b] To obtain strength levels in ksi multiply these values by 0.145. Specimen orientations: L = longitudinal, T = transverse, S = through-thickness.

TABLE 4—*CVN and FCP results.*

		Charpy V-Notch Properties								Fatigue Crack Growth Rate at ΔK of 55 MPa$\sqrt{m}$ (50 ksi$\sqrt{in.}$), μm/cycle[c]			
		Upper Shelf Absorbed Energy, J[a]				Upper Shelf Lateral Expansion, mm[b]							
Steel	Quality Level	LT	TL	ST	SL	LT	TL	ST	SL	LT	TL	ST	SL
A516	CON	119	118	66	64	2.01	1.98	1.42	1.35	1.12	1.16	1.54	1.50
	CaT	172	160	126	122	2.24	2.24	1.98	1.93	1.06	1.05	1.18	1.25
A633C	CON	197	118	62	61	2.24	1.88	1.35	1.35	1.15	1.39	1.47	1.87
	CaT	304	213	134	138	2.13	2.31	1.85	1.96	0.845	0.917	1.02	0.809
A588A	CON	160	66	30	23	2.24	1.32	0.76	0.64	1.19	1.67	1.98	6.16
	CaT	279	206	140	149	2.34	2.34	2.01	2.08	1.09	1.11	1.24	1.32
A387-22	CON	188	137	111	107	2.29	2.01	1.83	1.85	0.740	0.811	0.963	0.950
	CaT	298	240	184	186	2.39	2.31	2.16	2.11	0.780	0.808	0.816	0.863
A533B-1	CON	172	95	57	56	2.26	1.68	1.22	1.22	0.684	0.721	1.29	1.73
	CaT	202	178	129	129	2.34	2.26	2.06	2.03	0.594	0.665	0.665	0.669
A514F	CON	111	56	19	16	1.58	0.86	0.36	0.28	0.773	1.03	2.20	4.92
	CaT	146	90	50	46	1.80	1.32	0.79	0.74	0.841	0.991	1.01	1.46

[a] To obtain energies in foot-pounds multiply these values by 0.737.
[b] To obtain expansions in milli-inches multiply these values by 39.4.
[c] To obtain growth rates in inch/cycle multiply these values by 3.94×10^{-5}.

CVN results, the ratios were established by dividing the CON results by the CaT results. For the FCGR-55 results, in order to keep values nominally between 0 and 1.0, the CaT results were divided by the CON results. Thus the quality ratios for RA for the A588A steel would be 0.98, 0.81, and 0.12 for the L, T, and S orientations, respectively. The quality ratios for FCGR-55 for A588A would be 0.92, 0.66, 0.63, and 0.21 for the LT, TL, ST, and SL orientations. These ratios indicated the extent of the improvement in quality

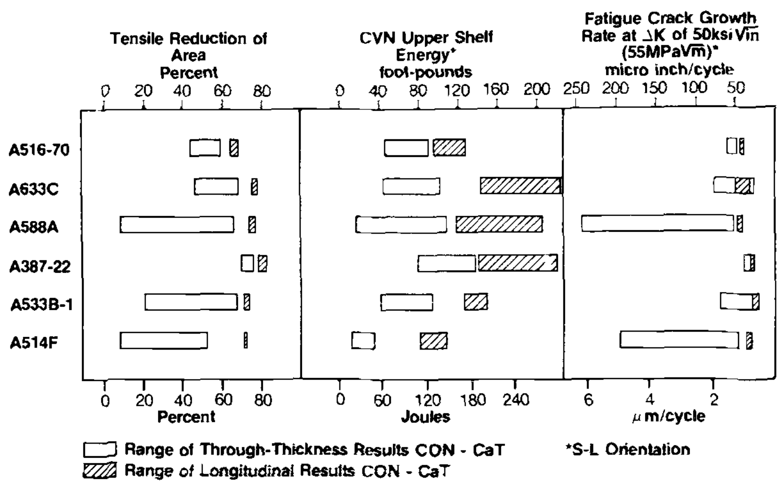

FIG. 2—*Bar graphs summarizing some of the testing results from Tables 3 and 4.*

resulting from the improved inclusion structure of the CaT steels for each type of test.

The anisotropy ratios demonstrated the variation in properties by testing orientation for each steel plate. For the tensile ductility and CVN data these anisotropy ratios were constructed by dividing the various testing orientations (T, S, TL, ST, SL) by the applicable longitudinal results (L, LT) for that plate. This division was once more reversed for the FCGR-55 results to keep the values roughly between 0 and 1.0. Thus the anisotropy ratios for RA for the A588A steel are 0.80 and 0.11 for the respective T and S orientations of the CON steel, while they are 0.97 and 0.86 respectively for the CaT steel. The FCGR-55 anisotropy ratios for the A588A steel are 0.71, 0.60, and 0.19 for the respective TL, ST, and SL orientations for the CON steel, while they are 0.98, 0.88, and 0.83 respectively for the CaT steel. These ratios defined the extent of the property anisotropy in each plate as a result of the inclusion structure as measured by each testing method.

The aforementioned ratios were then compared for the various testing parameters in order to establish which parameter(s) were most sensitive to changes in inclusion structure. The most important comparisons are given in Figs. 3 to 7. Figure 3 reveals that except for cases of low RA ratios the USE is more sensitive than the tensile RA. Figure 4 discloses that the USE is more sensitive than the FCGR-55. Figure 5 indicates that except for cases of low RA ratio, the FCGR-55 and the RA have a similar overall level of sensitivity. Figure 6 shows that generally the tensile reduction of area is more sensitive than the tensile elongation. Figure 7 demonstrates conclusively that the CVN

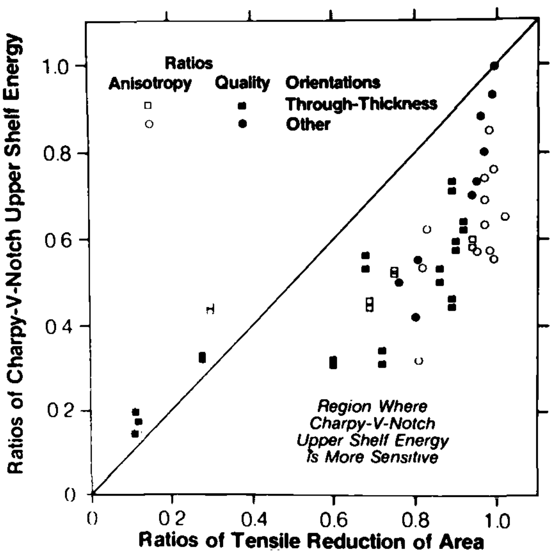

FIG. 3—*Comparison of anisotropy and quality ratios for Charpy V-notch upper shelf energy and tensile reduction of area.*

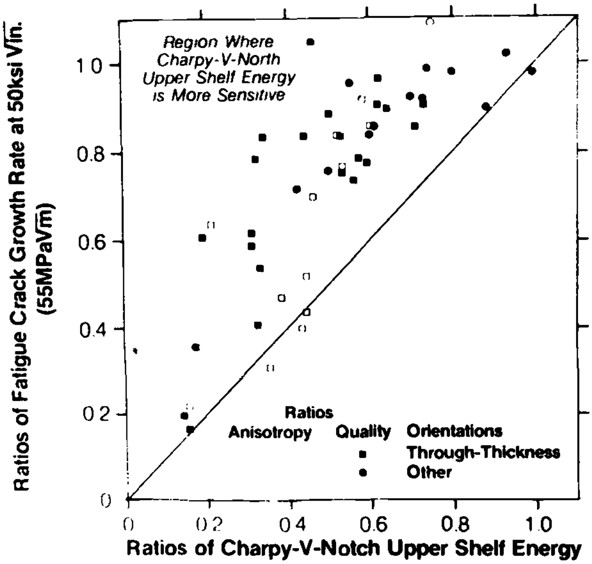

FIG. 4—*Comparison of anisotropy and quality ratios for fatigue crack growth rate at 55 MPa$\sqrt{m}$ and Charpy V-notch upper shelf energy.*

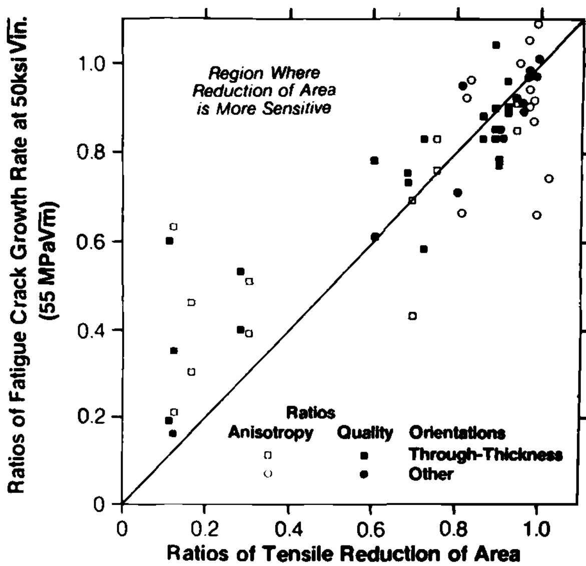

FIG. 5—*Comparison of anisotropy and quality ratios for fatigue crack growth rate at 55 MPa$\sqrt{m}$ and tensile reduction of area.*

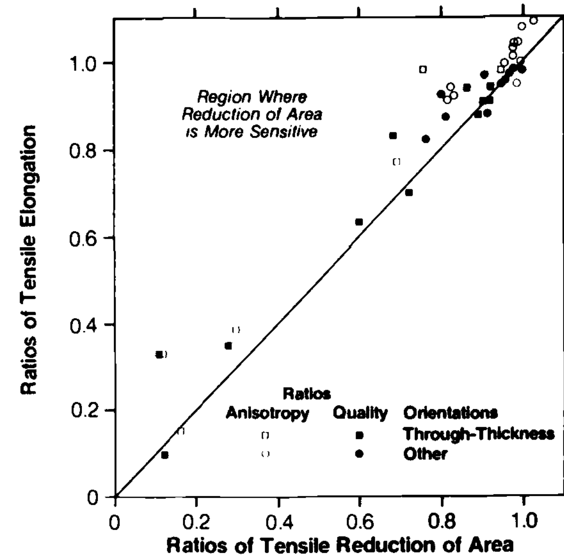

FIG. 6—*Comparison of anisotropy and quality ratios for tensile elongation and reduction of area.*

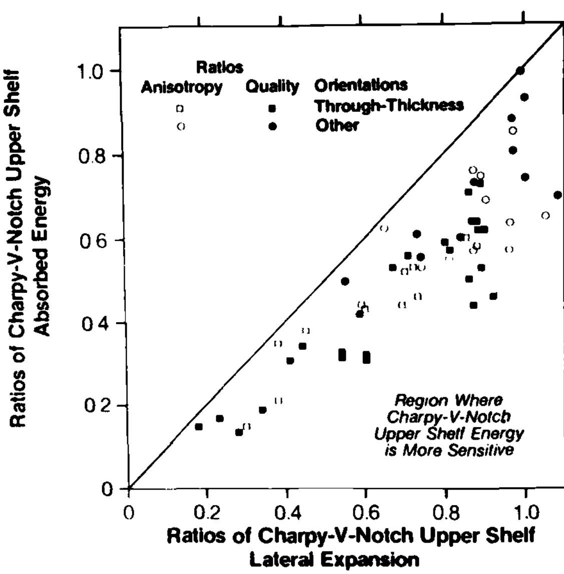

FIG. 7—*Comparison of anisotropy and quality ratios for Charpy V-notch upper shelf absorbed energy and lateral expansion.*

USE is more sensitive than the CVN USL. The reasons for these differences are discussed in the following section.

Discussion

The ductile fracture of most metals involves the nucleation, growth, and coalescence of voids, and is termed "microvoid coalescence" (MVC). In steels MVC takes place primarily at nonmetallic inclusions, although metal carbides play an important role as well. The spacing between these inclusions has been shown to be of particular importance during the void growth stage, since the linking together of adjacent voids leads to eventual failure [*10,11*]. The influence of specimen orientation is a result of this process in that cracking orientations on which inclusions are closer to one another tend to have poorer ductility and toughness. The interinclusion spacing is particularly critical when the inclusions are associated in clusters, such as for Type II MnS and alumina. The linkage of voids between inclusions of these groups happens relatively soon after they initiate, leading to poorer properties. This is demonstrated by the comparison fractographs shown in Fig. 8. Note that in Fig. 8*a* the Type II MnS inclusions are large and close together, while Fig. 8*b* shows the smaller Al_2O_3 inclusions which are also closely spaced. In contrast, CaT steel has small, widely spaced inclusions, which accounts for the improved properties. Similar effects, but to a smaller extent, have also been identified during FCP testing [*7*].

The comparison of the USE and RA ratios in Fig. 3 indicates that generally the CVN USE is more sensitive to inclusion structure than the tensile RA. This is directly related to the higher degree of constraint and triaxiality at the CVN notch tip, which contributes to void nucleation [*12*] and void growth [*13*] at inclusions. This reasoning is further supported by previous work concerning J_{Ic} upper shelf properties of steels of various inclusion contents [*6*]. In this case the J_{Ic} results on precracked 25-mm (1-in.)-thick specimens were found to be more sensitive than the CVN USE. However, research is still underway that is attempting to model upper shelf CVN fracture using void nucleation and growth data from tension specimens [*14*].

The CVN USE is not always the more sensitive. In cases of low through-thickness tensile RA, the RA is found to be more sensitive than the USE. This is a result of the different testing volume involved in each test. The tensile fracture can occur essentially anywhere in the specimen gage section [in this study, 25 mm (1-in.)] and thus can occur at the weakest cross section of the specimen. The CVN test is restricted by the notch to a relatively small volume of material. This only becomes a concern when there is a higher level of inclusions present, which varies through the plate thickness. Figure 9 points this out for the CON A588A material. Of the six through-thickness tension tests, three broke near the centerline and three broke near the one-third line of the plate. In each case the position with the greatest inclusion concentration has most likely lead to failure.

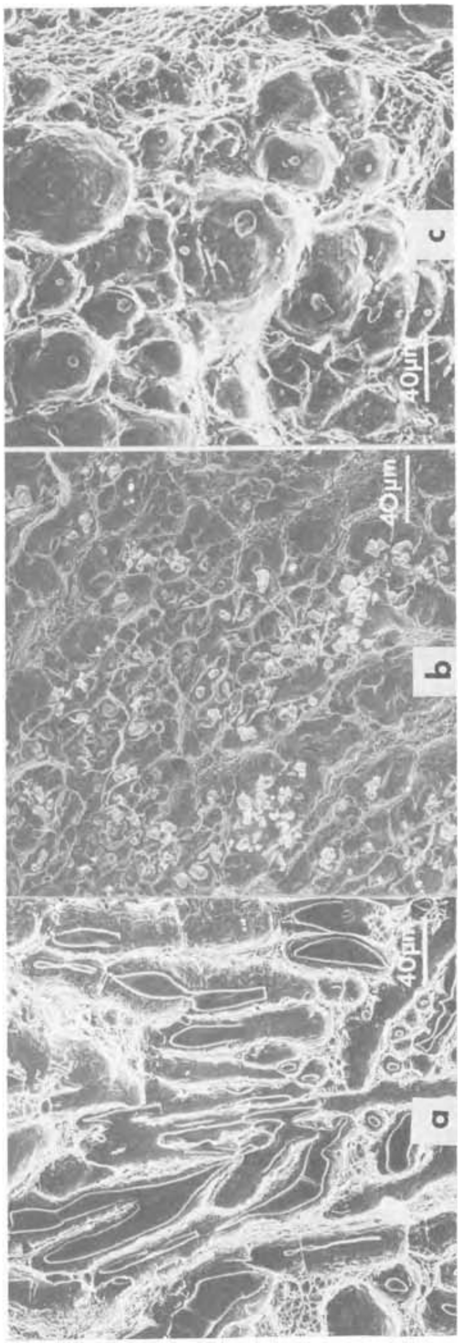

FIG. 8—*Scanning electron microscope fractographs from through-thickness-oriented fracture surfaces.* (a) *Type II MnS inclusions in CON steel.* (b) *Alumina cluster in CON steel.* (c) *Calcium-modified inclusions in CaT steel.*

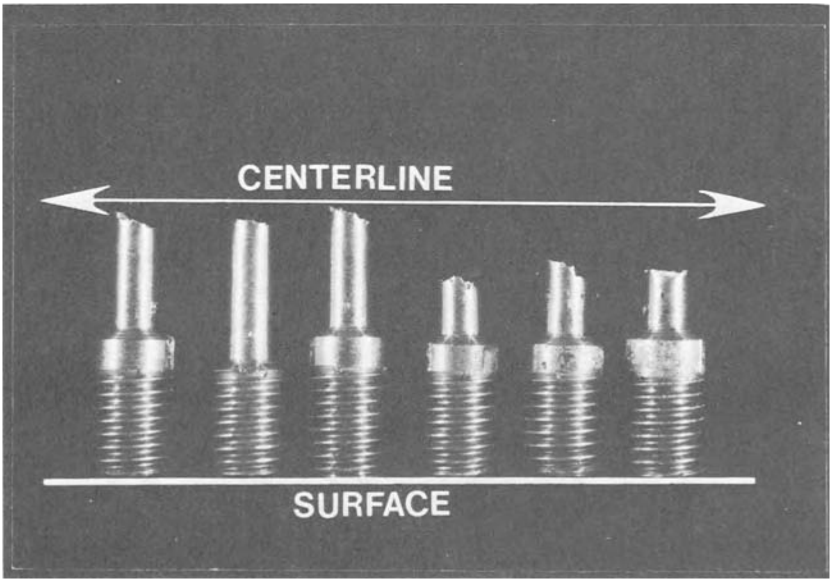

FIG. 9—*Through-thickness tension test specimens for CON-quality A588A plate.*

Even with the differences noted previously between RA and USE there is a correlation between the two properties (Fig. 10). The higher sensitivity of USE is further demonstrated by this graph, particularly at RA values greater than 60 percent. The equation given for the relation between these tested steels is similar to that reported for a study of carbon steels [*15*]. Some researchers have suggested that the use of the strain-hardening exponent n to the second power together with RA would improve this correlation [*10*]. This was not supported by this study. Previous work has found, however, that higher strength materials are more sensitive to inclusion structure for RA, CVN USE, and FCP properties [*7, 16*]. The influence on the RA and USE is directly related to void growth. A steel with a higher n will be capable of more work-hardening, which has been shown to decelerate void growth [*11*] and delay void coalescence.

Figure 4 demonstrates the greater sensitivity of USE over FCGR-55. This is not surprising, since the FCP crack is even more restricted than the notch in the CVN test. Furthermore, the FCP test is performed at ΔK-levels well below those indicative of a toughness test, and the plastic zone is significantly smaller and thus involves a smaller volume of test material. At the highest ΔK-levels during an FCP test, which is significantly below the K-level in a toughness test, there is still a significant portion of the fracture covered by ductile fatigue striations. The increasing presence of inclusions and inclusion clusters on the FCP fracture, however, is evidence of the mechanism

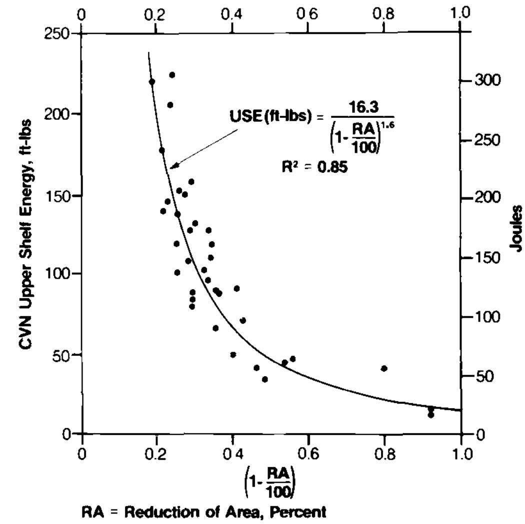

FIG. 10—*Plot of Charpy V-notch upper shelf energy versus tensile reduction of area for LT, TL, and SL orientations, with statistical best-fit equation given.*

leading to higher FCGR-55 values for orientations of greater inclusion involvement [7].

The differences between the interaction of the CVN test and FCP tests with inclusions is further revealed in Fig. 11. In both of these tests through-thickness fracture can take place in two directions, thus the ST and SL designations. Figure 11 shows that in the CVN test the USE values in the ST and SL orientations are identical, while in the FCP test the FCGR-55 in the SL

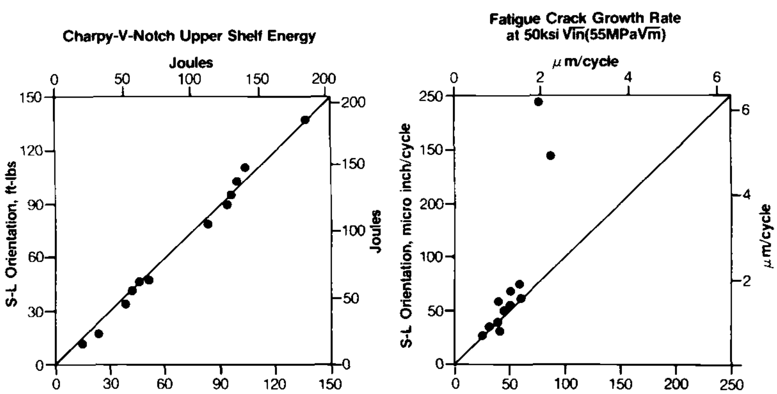

FIG. 11—*Plots comparing the ST and SL orientation results for both Charpy V-notch upper shelf energy and fatigue crack growth rate at 55 MPa$\sqrt{m}$.*

orientation can often be significantly faster than in the ST. This is again owing to the difference in the plastic zone acting in both tests. In the CVN test the elongated inclusions and inclusion clusters appear similar to the tearing crack in both orientations because of its large plastic zone. In the FCP test the smaller plastic zone sees only local variations and the elongated inclusion structure has a differing influence depending on cracking direction. This has been discussed in more detail elsewhere [*7*].

The comparison of the ratios for FCGR-55 and RA in Fig. 5 indicated a similar sensitivity at higher ratios. This is a result of the increased constraint of the FCP test being offset by its restricted volume of test metal and lower overall level of plasticity. At low ratios the RA is more sensitive because of the access to more test volume in material with high inclusion contents, as discussed previously.

Attempts to develop correlations between FCGR-55 and the tensile RA and CVN USE are given in Fig. 12. The SL orientation results are omitted in Fig. 12 because some of these results cannot be explained by those parameters (Fig. 11). Although the correlations are statistically significant, prediction of FCP performance from RA or USE data would not be a metallurgically sound practice without additional information on the microstructure.

The differing sensitivities for separate parameters determined by the same test method are shown by Figs. 6 and 7. In Fig. 6 the tensile RA was found to be more sensitive than the tensile elongation over the full range of results. One cause of this might be that fractures in tension specimens are often not centered between the punch marks on the gage section used to determine the elongation. Thus the full deformation of the specimen may not be noted by this parameter.

The CVN USE was shown to be more sensitive than the upper shelf lateral expansion (USL) (Fig. 7). The USL is more of a measure of ductility of the

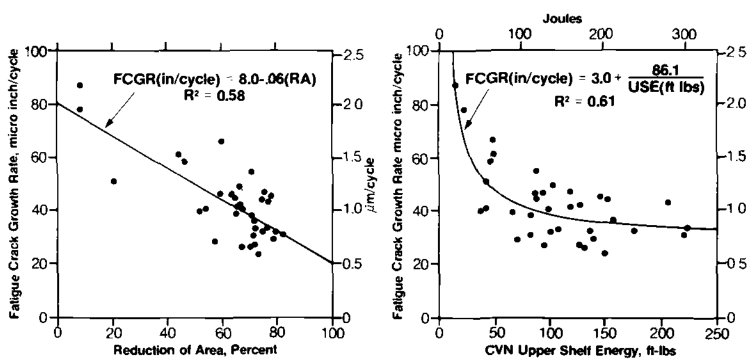

FIG. 12—*Plots of fatigue crack growth rate at* ΔK *of 55 MPa$\sqrt{m}$ (50 ksi$\sqrt{in.}$) versus tensile reduction of area and Charpy V-notch upper shelf energy, for LT, TL, and ST orientations only, with statistical best-fit equation given.*

specimen during fracture and records the deformation of the specimen primarily during the propagation of the fracture. The USE reports energy required for both initiation and propagation of the CVN fracture, and thus is more sensitive to inclusion structures which influence both stages of fracture. However, there is a reasonable correlation between the two parameters (Fig. 13). Note that the straight line fit that is often used for this relationship is not appropriate for the wide range of data in this study. Also, note the plateau effect for the USL results at about 2.3 mm (90 mills). This further supports the initiation-propagation discussion. Very high toughness steel (lower inclusion contents) would have greater energy requirements for initiation. This is detected only by the USE and not by the USL.

Conclusions

This study on a wide range of plate steel grades has revealed the differing sensitivities of the tension, Charpy V-notch (CVN), and fatigue crack propagation (FCP) tests to changes in inclusion structures. In particular the following conclusions have been established:

1. Generally the CVN upper shelf energy (USE) is the most sensitive parameter to changes in inclusion structures. In steels with higher levels of inclusions, however, the through-thickness tensile reduction of area (RA) is

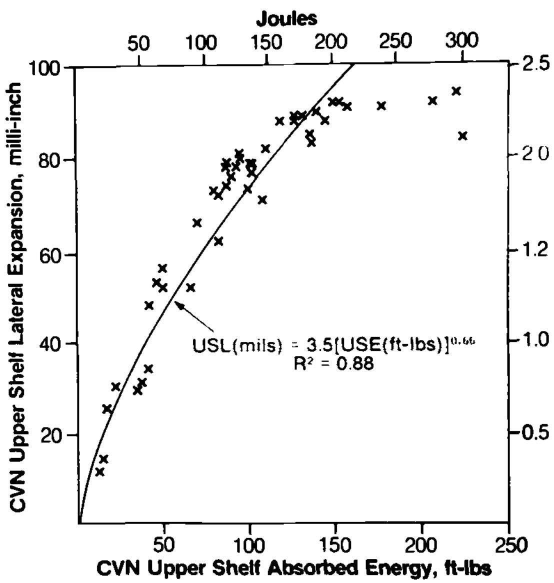

FIG. 13—*Plot of Charpy V-notch upper shelf lateral expansion versus upper shelf absorbed energy, with statistical best-fit equation given.*

most sensitive. This appears to apply when the RA is less than 25 percent.

2. The FCP properties are always less sensitive than the CVN USE results and are either equal in sensitivity or less sensitive than the RA, depending on the testing orientation and inclusion structure.

3. Correlations among the CVN USE, the tensile RA, and the FCP properties were obtained.

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Summary

Summary

The contents of this book are divided into two sections, though there is considerable interrelationship between these divisions. The first section deals with methods of through-thickness testing. Through-thickness (also called short-transverse or "Z" direction) tension testing has inherent difficulties quite separate from the more familiar in-plane testing procedures. Consequently, much of the work included in this section is concerned with the design and preparation of test specimens which will provide meaningful and repeatable results. The second section deals more with the metallurgical factors in steel plate manufacturing that will affect the results obtained in the through-thickness tension test.

Test Methods

Holt addresses the very important question of specimen dimensions, particularly the length of the reduced-section or insert length in the case of specimens with welded prolongations. Three steel plate materials with a wide strength range were used in his investigation. Holt used either 12.7 or 22.8 mm (0.5 or 0.9 in.) diameter specimens that were oriented in the longitudinal direction. This orientation was chosen to reduce the influence of the data scatter inherent in through-thickness direction testing results. He concluded that the measured reduction-of-area values decreased and the measured tensile strength values increased as the effective reduced section length was lowered to less than two specimen diameters. These changes were apparently caused by constraint effects of the shoulders or of the higher strength prolongations.

Reed et al examine the relative merits of two different through-thickness test specimen types. They compared miniature specimens machined entirely from the plate with specimens with stud-welded prolongations for gripping in the test machine. The material used was ASTM A516 specially processed for improved through-thickness properties. The small specimen, called the miniature button head (MBH), was machined entirely from the through-thickness direction of the test plate in diameters of either 3, 4, or 5 mm, depending on test plate thickness. Stud-welded test specimens were prepared in accordance with ASTM Specification A 770, with either Type 1, Type 2, or Type 3 specimens, again depending on plate thickness. The authors concluded that for plates of 25 mm (1 in.) or over, both specimen types gave comparable results. For lighter gage plates, the stud-welded specimens gave lower reduction of area values, most likely because of the low effective gage length to diameter ratios. It is noted that this ratio became important only for values less than 2.5, which is the minimum ratio value allowed in ASTM A 770. Reed et al also point out that the MBH specimen can test near the plate surface almost as well as the welded specimen, and that for some test laboratories the MBH specimen may be less costly to use.

The next two papers are by *Ludwigson.* In the first, the author reviews an analysis of a standard-deviation study made using through-thickness reduction-of-area measurement from six tests taken from each of 108 plate materials. He used 12.8-mm (0.505-in.)-diameter specimens with stud-welded prolongations. A grand average standard deviation of 5.1 percentage points was observed, a value much larger than expected for in-plane tension test results. Ludwigson noted that the standard deviation in six tests increased with increasing plate thickness. The standard deviation also exhibited a minimum at a mean value of 38% reduction of area, the standard deviation increasing at both lower and higher mean values.

In his second paper, Ludwigson investigates the relations between plate thickness and specimen diameter. Again, the problem of the restriction of deformation by the higher strength stud-welded prolongations was observed. Ludwigson recommends a minimum effective gage length equal to the test specimen diameter. Neither the prolongation nor the distance affected by the heat from welding the prolongation is included in the effective gage length.

Domis describes a procedure for stud-welding prolongations on plates for the preparation of through-thickness test specimens. Stud welding is one of several methods that may be used. According to Domis, stud welding offers several advantages over other welding procedures, including savings in time and cost. A stud fabricated from AISI 8620 steel bar and quenched and tempered to a minimum HRC 30 hardness was used for steels with strengths up to and including that of ASTM A514 steel. As long as the strength of the stud was greater than that of the test plate, the strength level of the stud had no apparent effect on the through-thickness tension test result.

Stotz et al discuss a completely different type of test specimen for determining through-thickness tensile properties. This test specimen is called the double-ligament specimen and tests a relatively small cross section. The authors describe the application of that test procedure to an AISI 4340 steel plate with a 2000 MPa (290 ksi) yield strength. The disadvantages of this test include a small test volume, a complex test set-up, and no local ductility results directly comparable with the reduction of area value obtained from a round tension specimen. This specimen would have some advantage in high-strength materials, particularly thin plates, where welding suitable prolongations may be very difficult.

Relations Between Material Factors and Through-Thickness Tension Test Results

Jesseman and Murphy examine the effects of test specimen design, variability of the test results, and reproducibility of the final area measurement, as well as the effects of material factors including strength level, microstructure, and sample location. Test plates of ASTM A131 Grade CS and A537 steel giving through-thickness reduction-of-area values from 25 to 40% were used. The authors presented a large amount of data evaluating the effects of the variables involved and presented recommendations for future through-thickness tension testing specifications. In particular, it was suggested that more than two tests per plate are necessary for a reasonable evaluation of the through-thickness reduction-of-area properties. Also, the authors recommend that the through-thickness test location should be referenced to the as-cast centerline of the plate to provide a consistent measurement of the relative lamellar tearing resistance of each plate.

Two papers by *Ludwigson* also evaluate the effects of microstructure and specimen location on the through-thickness tension test result. In his first paper in this section, Ludwigson quantifies the relations between the through-thickness reduction-of-area value and the inclusion concentration, Charpy V-notch transition temperatures, and yield strengths. He concludes that the inclusions are the principal factors in restricting through-thickness ductility, but that high strength and/or low toughness can also lower the reduction of area.

Ludwigson's second paper evaluates the variation of through-thickness ductility with location in the plate length, width, and thickness. The conclusion was that, when variation is encountered in rare-earth treated steels, the poorest ductility is found in the region of the plate corresponding to the bottom/midwidth/midthickness of the ingot. Both of these papers by Ludwigson present results that agree well with those in the Jesseman and Murphy paper.

Wilson compares the effects at inclusions on toughness and fatigue properties in the through-thickness direction as well as the tensile ductility. He found that the Charpy V-notch upper shelf energy was most sensitive to changes in inclusion structure for steels with through-thickness tensile reduction-of-area values above 25%. For steels with higher inclusion levels giving lower reduction of area values, the reduction-of-area value was the most sensitive test result. Fatigue crack propagation properties were shown to be either equal or less sensitive to inclusion structure than the through-thickness reduction of area values.

Final Remarks

The papers in this volume cover a number of factors involved in the through-thickness property evaluation of steel plates. Though all conclusions may not be in exact agreement, each author recognizes the problem of the inherent variability of the through-thickness test result. This observation has been recognized in the first revision of ASTM A 770, which received Society approval on 28 May 1982. The revised specification addresses the problem of variability in the Appendix. The effects of test specimen design, including diameter and slenderness ratios, are reviewed. The inherent variability of the distribution of nonmetallic inclusions is also discussed. In view of this potential variability of the through-thickness reduction of area test result, it is recognized in the Appendix that two tests per plate are not sufficient to fully characterize the through-thickness ductility of a plate. Even with the information in this publication, it will be difficult to establish the number of tests and test positions required to provide a good estimate of both the mean and the variability of the through-thickness tensile reduction of area values of a plate. Therefore the intent of ASTM A 770 is to qualify a plate according to the described testing procedure using only a minimum value requirement, without reference to an average value requirement. Also mentioned in the Appendix, and well supported by the information in this publication, is the fact that the high variability of the test results greatly increases the possibility that subsequent testing of a steel plate qualified according to ASTM A 770 may produce results which do not meet the specified acceptance standard.

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