TEMPERATURE EFFECTS ON THE MECHANICAL PROPERTIES OF WELDS IN THREE TYPICAL STRUCTURAL STEELS

by

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INTRODUCTION

Numerous failures of welded steel structures under low temperature conditions have emphasized the need for a clear concept of the behavior of metals at low temperatures. During the past fifteen years, such failures have occurred, for example, in ships, bridges, and large tanks. Prior to this time, fabrication of such structures rarely involved welding. The structures were riveted and in most cases safety factors based on the accepted standard of allowable tensile strength were sufficient to insure satisfactory service under normal conditions. Fabrication by welding of large steel structures is more economical and less time-consuming than riveting; the imminence of a second World War placed the attempted solution to this problem high on the research list.

The subject of this investigation was proposed by Professor S. H. Graf as part of an investigation for the Corps of Engineers, into the relative suitability of Mayari-R, 0.11 percent plain carbon, and 0.33 percent plain carbon steels for use in all-welded navigation locks and spillway gates for McNary Dam. In service these gates would be subjected to atmospheric temperatures ranging from about -20 F to perhaps 110 F. It was intended that a successful completion of this investigation should serve as a basis for selection of the proper steel for the above service, as well as to assist in arriving at a better understanding of the mechanics of the lower temperature fractures in welded steels.

HISTORY OF PRIOR INVESTIGATIONS

Dewar in 1905 was one of the first to institute research into the behavior of metals at temperatures below normal atmospheric temperatures. However, it was not until the middle of 1930 that extensive research was undertaken in this field. With the advent of fabrication of steel structures by welding, came scattered reports of structural failures, especially in bridges.

In most cases the fractures exhibited brittle appearance. It had been known for some time that riveted structures, upon being loaded, tended to deform slightly at the joints. It was at first believed that the sole cause of failure in the welded structure lay in the inability of such structures to deform at the joints under load, thus creating high "locked up" stress within the structure itself. Later investigation has shown this to be partially true. However, also important is the ductility of the steel itself. Early investigations revealed that steels which exhibited satisfactory tensile strengths, impact values, and bend angles in bend tests at room temperature gave greatly different values at reduced temperatures. In most cases the tensile strength increased with the reduction in temperature, but impact values and bend angles decreased greatly. Obviously, there was some minimum temperature below which the steels would yield impact values and bend angles unsatisfactory for service.

Prior to this time the design engineer was concerned with two groups of properties; strength and ductility. The strength property was determined by static tensile tests of the material and could be easily specified. The ductility was determined by a measurement of elongation and reduction in area. These values were generally determined at room temperatures. As long as riveting was used as a means of fabrication, little difficulty was experienced in structures designed with safety factors based on the above values. Any deformation required to relieve "locked up" stresses could take place at the riveted joints. With the introduction of welding as a means of fabrication of structures, plastic flow of the metal itself was required in order to relieve the stresses. Under normal temperature conditions, most steels have the ability to deform in such a manner. In other words, the steels are ductile. However, under low temperature conditions some steels do not deform prior to failure, that is, they are brittle steels. Static tests indicate that steels become harder and stronger with a decrease in temperature. These results could be very misleading to the designer, since ductility usually decreases correspondingly. In addition, fabrication by welding often creates fine notches or cracks in the weld metal or in the adjacent heat-affected area. Such cracks act as points of localized stress concentration. Unless there is plastic deformation to relieve concentrated stresses existing, cracks are rapidly enlarged and can propagate rapidly throughout the entire structure. Such failures have often been described as being similar to an explosion. Since failure without plastic deformation has an extremely low time factor, the forces involved are of a very high order (11). Under conditions of local stress concentrations associated with notches or sharp changes in section, low temperatures at time of loading, or rapid rates of loading, load bearing capacity of steel depends on its ability to resist stress where plastic deformation is more restricted than it is in the tensile test (9). Kinzel (11) noted that the decrease of ductility with a decrease in temperature was in no instance a proportional relationship, and found that an increased rate of load increases the temperature at which brittle behavior occurs, as does increased restraint (sharpness of notch).

Ludwik postulated a theory for brittle failure of steels when he stated that for a given material brittle failure takes place when the stress necessary for yielding (the flow stress) exceeds the stress necessary for fracture (the fracture stress). That is, if a material is stressed below the flow stress it will deform elastically, if stressed between the flow and fracture stress it will deform plastically, and if stressed above the fracture stress it will fail. In materials subject to low temperature embrittlement, the flow stress increases faster than the fracture stress with a reduction in temperature. When a temperature is reached at which the flow stress exceeds the fracture stress, the metal has become completely brittle. This temperature of embrittlement is designated "the transition temperature of the metal." Metals could become brittle in a similar manner if the fracture stress were to decrease faster than the flow stress with a decrease in temperature. However, such cases are rare. Anderson and Wagner (1), MacAdam, and numerous other investigators have concurred in this theory.

A notch has the effect of raising the strain rate at the base of the notch, as well as increasing stress concentration and, therefore, should raise the transition or embrittling temperature. Also, sharper and deeper notches cause additional restraint restricting material contraction (11).

Now it remained to be determined which metals were subject to this so-called low temperature embrittlement. Investigation has shown that this embrittlement occurred in ferritic steels but was almost entirely absent in austenitic, copper base, or nickel base steels (7). Seigle and Brick (16) state that low temperature ductility appears to be the property of only the face-centered cubic lattice (nickel, aluminum, lead, most of the austenitic steels, copper, et cetera). Ferritic steels being of the body-centered cubic lattice, are subject to low temperature embrittlement. The problem then was to investigate the mechanics of low temperature fractures and to devise a method of testing metals in order to standardize the selection of the proper material for use in structures where low temperatures might be encountered. As previously mentioned, in riveted structures slippage could take place at the joints as necessary; whereas, in welded structures this cannot occur. In addition, no detrimental heat effects such as accompany the welding process, occur during the riveting process.

It is a generally accepted theory that steels under normal conditions, when subjected to a load, reach first a yield point after which there is a considerable amount of deformation or plastic flow prior to fracture. Upon reduction of temperature, in the case of ferritic steels, the stress required to produce flow exceeds the stress required to produce fracture. In the first case, the fracture is of the ductile type, in the second case, brittle (5). The temperature at which the fracture changes from ductile to brittle, the transition temperature, is of extreme importance in the design of welded steel structures. If the structure is never exposed to temperatures in the vicinity of this transition temperature, it would be expected that it would react normally. The determination of this transition temperature has been the subject of much controversy for the past few years. Many opinions exist concerning types of test specimens and the procedures to be used in such determinations.

1. Testing Procedures

Most authorities agree that tension tests on un-notched specimens have little or no value in the determination of the behavior of steels at low temperatures. For many years, investigations were based almost entirely upon results of notched bar impact tests. These specimens made use of various types of notches, including Charpy key-hole notch, standard ASTM 45 degree notch, and in Germany the German Charpy key-hole notch. The German Charpy differed from the American Charpy in that the breaking area was 10 by 7 mm instead of 10 by 5 mm. Much controversy has arisen as to the best type of notch to be used with the impact specimen. The standard V-notch Charpy specimen approaches very closely the most severe conditions of loading which may be imposed on standard impact bars. The V-notch also is often credited with great selectivity and more readily showing transition temperature. However, Hoyt (10) remarks, " For tough metals the V-notch is too shallow for true notch-bar tests and gives fictitiously high impact values." The key-hole notch was the one most widely used in 1940, although not so sensitive to differences in composition and temperature as the V-notch (2). Many investigators used the key-hole notch for no better reason than the large amount of data available for comparison. It can be seen that correlation of impact data is exceedingly difficult with these three specimens in wide use.

(a) Impact tests

In service the rate of loading ordinarily is similar to that encountered in static testing. The rate of loading in impact tests is much greater than that usually encountered in service. For this reason correlation between impact values and performance of plate in service is somewhat doubtful. MacGregor and Grossman (15) believe that the Charpy impact test does not yield values which can be used directly in design. Its use is mainly restricted to the determination of the effects of metallurgical and structural changes on the energy absorbed at a fixed strain rate and for an idealized condition of constraint. There is no exact impact level at which fracture changes sharply from tough to brittle, but rather a transition zone. In other words, there is a range of temperatures in which the

Charpy test might yield values ranging from extremely ductile to extremely brittle for the same metal. For this reason, research using the Charpy test must, of necessity, involve a large number of specimens in order to establish a set curve. Obviously, this imposes considerable restriction upon the testing program, since the Charpy specimen involves a great deal of machining. It is necessary that this transition zone be completely defined in the case of impact tests, since high impact values could be obtained at temperatures of the order of one to two degrees above the transition zone.

Armstrong and Gagnebin in their survey of work on steels suitable for temperatures down to -200 F (19) set an arbitrary 15 ft-lb of energy absorption in the Charpy test as a desired temperature requirement. Such a requirement was to be a satisfactory basis for acceptance of steels, inasmuch as many factors control values given in the Charpy test. The transition temperature has been found to increase with an increase in sharpness of the notch, with an increase in striking velocity of the pendulum, and with a change in method of forming notch (machining or pressing). In summary then, it can be seen that the transition temperature of a steel, as determined by impact tests, does not mean that the steel will show brittle failures in service at this temperature. Klier, Wagner, and Gensamer (12) have concluded that the Charpy test cannot serve to indicate the acceptability of a given ship plate steel. Wiley (18) feels that at the present time there is no satisfactory test for the determination of the transition temperature, but that the Charpy notched-bar impact gives a better indication of the resistance of the steel to fracture under low temperatures than the tensile test specified at present.

Recently a new type of impact specimen, the Schnadt specimen, has been introduced (Figure 1) (17). Schnadt used three impact specimens, two of which were notched, to evaluate the brittleness of steel. Brittle metal gives low values in all three specimens. Semi-brittle steel has a high impact value only in the un-notched specimen, whereas the tough steel exhibits high values in all three specimens.

The Izod impact test has not been used extensively since it is not practical for use at low temperatures unless the entire testing machine can be placed in a cold room. The Charpy test has been quite convenient for low temperature use since the specimen could be removed from the cooling unit, placed in the machine, and broken in a matter of two or three seconds. This could not be done with the Izod machine.

The notched-bar impact tests can be useful in determining the general characteristics of a steel. However, until such time as specifications are devised, standardizing the specimen including type and depth of notch, there will be little basis for correlation of values so obtained. It must be emphasized that impact results are not indicative of service characteristics of the metal, but are peculiar to the particular metal involved and the conditions imposed upon that metal. Some authorities have noted variations in these

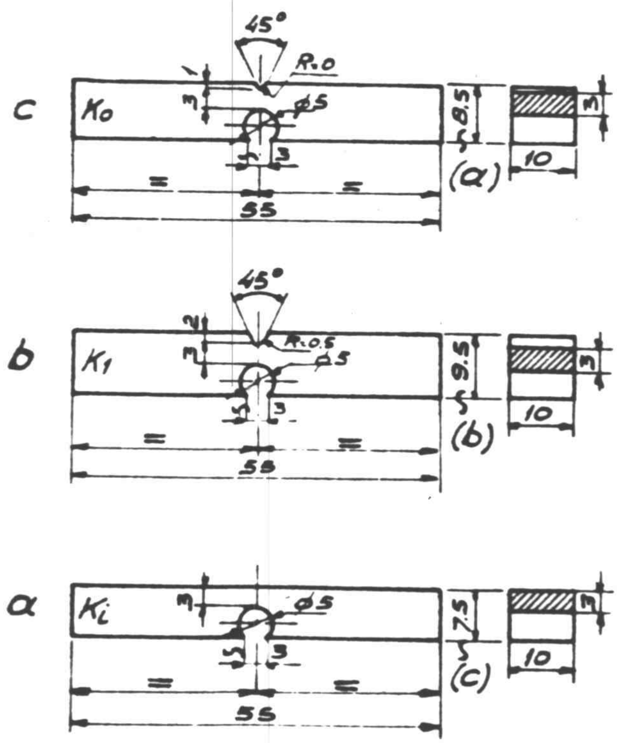


Figure 1. **The three Schnadt impact specimens. A hardened steel pin is fitted tightly into the 5 mm holes. The hammer of the impact machine strikes the pin. Accordingly, the fractured section is entirely in tension. Dimensions in millimeters.**

values among two steels exhibiting identical microstructure and chemical composition but of different heats.

(b) Notched bend tests

Notched bend tests involving many variations in notch position, direction of notch (longitudinal or transverse) and direction of bead (longitudinal or transverse) have been proposed. These bend tests tend to give a transition temperature rather than a transition zone. Obviously this is very desirable. However, many of the difficulties encountered in the Charpy tests are encountered in the bend tests. Variations in values of bend angles at fracture are obtained with variations in sharpness and depth of the V-notch. These variations are not so pronounced as in the case of the impact test values.

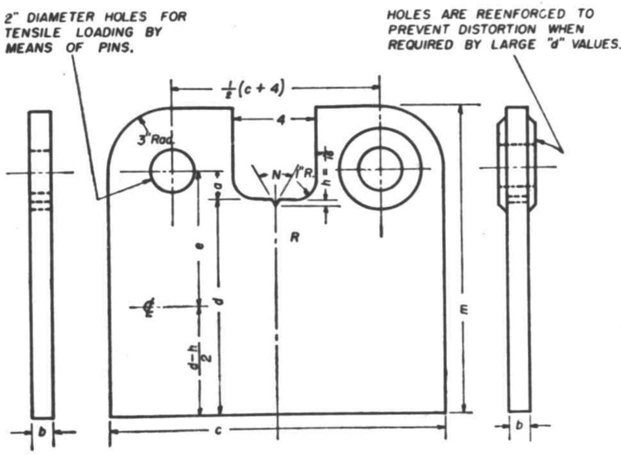
Kinzel (11) determined the transition temperature by measuring one percent lateral contraction obtained in notched bend tests. His results were quite consistent for similar steels. He feels that results obtained by this method of testing are much more easily correlated with actual service conditions. He points out that he has found fractures in service showing lateral contractions of the order of one percent.

The M.I.T. slow-bend test has given transition temperatures corresponding to the upper portion of the transition zone obtained by the impact tests. The transition temperature obtained in this manner is defined as the highest temperature at which fracture is obtained without noticeable deformation as determined by the load deflection diagram. This value then is a conservative one which might be well adaptable to design specifications (15).

Otto Graf (8) after much research on structural failures, such as the failure of the Rudersdorf Bridge in 1938, proposed a longitudinally welded specimen notched at right angles to the bead. This specimen tests the unaffected plate metal, the heat-affected zone, and the plate metal. Most of his failures started at the junction of the plate and weld metal. On the other hand, M.I.T. slow-bend tests found that the zone of lowest ductility occurred as much as one-half inch away from the weld in some cases.

Bagsar (3) has investigated cleavage or brittle fractures in mild steels, using a test coupon with an eccentric load applied to cause fracture, Figure 2. Use of such a test coupon is more time consuming, since the test set-up is more complicated and larger specimens are necessary. However, he feels that the results justify these disadvantages. Transition temperatures determined by this method have been found to run 85-100 F higher, in some cases, than those obtained by Charpy impact tests, and therefore appear to more nearly indicate the behavior of the steel in service. Since most welded structures involve minute cracks, and are therefore subject to cleavage fractures, this type of a test should be considered unless further investigation indicates otherwise.

MacGregor and Grossman (14) used notched bar bend tests and tests on circular discs and were able to obtain excellent correlation between these two. From this they conclude that general correlation



"b" = FULL PLATE THICKNESS.
"e" = ECCENTRICITY = $a + \left(\frac{d+h}{2}\right)$

Variable:- ECCENTRICITY.

COUPON TYPE	a	d	m	c
3A*	−2	4	7	16
2A	−2	6	7	16
15A	−1.5	6	7.5	16
B	0	6	9	16
D	1.5	6	10.5	16
F	3	6	12	16
K	6	6	15	16
H	10	6	19	18

Variable:- COUPON DEPTH.

COUPON TYPE	a	d	m	c
1	1.5	1.19	5	16
3	1.5	3.19	7	16
D	1.5	6	10.5	16
12	1.5	12	18	20
16	1.5	16	22	22
18	1.5	18	24	24
22	1.5	22	28	30
24	1.5	24	30	30

*Coupon Recessed On Both Edges Leaving Coupon Depth 4". (See Fig. 7A.)

ALL DIMENSIONS IN INCHES.

Figure 2. **Details of Cleavage-Tear Test Coupons for Various Eccentricities of Loading and Coupon Depths**

of properly notched bars and structures, or machine parts, is possible as regards the transition to brittle fracture.

In summary, the bend specimens are easier to test at low temperature than the tension specimens, but somewhat more difficult than the impact specimens. Large bend specimens can be loaded to failure in the testing machines ordinarily available. Bend angles at the weld for different steels are relatively large, facilitating the comparison of tests.

2. Grain Size

Fine grained ferritic steels lose their ductility at lower temperatures than coarse grained steels. However, both become completely embrittled at sufficiently low temperatures. It has been found that coarse grain generally accompanies brittle fractures at low temperatures but is not necessarily the cause of such fractures. Fine McQuaid-Ehn grain size usually indicates better impact properties at low temperatures. However, fine McQuaid-Ehn grain steels usually have been treated with sufficient aluminum to retain definite quantities in solution (2).

3. Carbon

Carbon has been felt to be the greatest single factor in the loss of ductility at lower temperatures. In general, an increase in carbon is accompanied by an increase in the transition temperature.

Ziegler (19) obtained best results with a maximum of 0.05 to 0.07 percent carbon. The difficulty is that reduced percentage of carbon reduces the tensile strength to somewhat below the desired limit. In an effort to overcome this difficulty, investigation of the effect of alloys was undertaken. It was found that the addition of vanadium increased the tensile strength but decreased the impact values. Addition of molybdenum decreased the impact values at all temperatures, but a proper balance of nickel and molybdenum will give fair low temperature impact resistance. Hardness alone is not a determining factor. However, for the same type of microstructure embrittlement will occur at higher temperatures at the higher hardness levels.

4. Section Size

Brown, Lubahn, and Evert (5) have conducted extensive investigations into the effect of section size on static notched bar tensile properties. They found that an increase in the tested specimen size may result in a pronounced decrease in the unit properties of the presumably geometrically similar specimens. The effects of section size as an embrittling factor can best be explained by a statistical theory that considers the metal volume to contain defects of various degrees of severity which determine the local properties.

5. Principles of Test

The specimens should involve actual welding and the power input, speed of welding, and mass of specimen should be varied to match the application in question. Mass effect is automatically matched if the thickness of the test specimen is that of the plate (11).

Kinzel (11) suggests that the bead be longitudinal and that the notch be at right angles to the weld, and therefore test all zones. His suggestion for a standardized test was the setting of an one percent contraction as the determining factor in the transition temperature. He found that this gave the best correlation to transition temperatures found in service conditions, and further, that the one percent contraction also broadly corresponds to measured deformations in service failures. This disagrees considerably with the opinions of some other authorities.

It has been shown in welded structures that the elimination of small cracks either in the weld metal or heat-affected zone adjacent to the weld metal is almost impossible. A crack is a notch of almost infinite sharpness, and may result due to hardening in the heat-affected zone or due to stresses produced by combination of the normal temperature restraint and the effect of volume change due to transformation of the steel.

Thermal cycles may supplement stresses tending to crack the heat-affected zone as well as the deposited metal. There is a tendency for stress concentration at the base of such cracks. Therefore, the question of notch sensitivity of the steel is highly important. It is for this reason that investigations concerning the transition temperature of steels using un-notched specimens have been almost entirely abandoned.

6. <u>Summary</u>

Graf (8) upon investigations of actual failures of structures in service, concluded that the following factors are important in explaining these failures:

(a) Chemical composition of the steels, their method of production, ingot practice, probably also the treatment of the steel during rolling and fabrication

(b) The size of the welded elements, particularly their thickness (before the accidents commenced to occur, flanges of structures were thinner and narrower)

(c) The shape of the structure, especially the kind of welds and their location

(d) The sequence of welding, the speed of welding, the restraint to expansion and contraction offered by the surrounding steel during heating and cooling (web stiffeners with ends wedged tight or with free ends) and also the temperature of the air and the steel during welding, et cetera

(e) The shrinkage stresses in the completed structure, particularly in the welds

(f) The temperature of the structure in service

(g) The type and magnitude of loading in service and in the tests

The material of which the girder is built must be of such quality that it will undergo a great deal of deformation without fractures when overloaded despite the presence of fine, short cracks.

In view of the variety of factors involved in low temperature embrittlement of steel, it can be seen that the problem of selection of a test method to be used as a standard in specifications is exceedingly complex. Many authorities, including Luther (13) and Wiley (18) feel that there is no satisfactory method available at the present time for evaluating the low temperature properties from a design standpoint. Luther states that each originator of a new method feels that his is approaching perfection and that all others are not completely satisfactory. This appears to be the most definite conclusion which can be made at the present time.

Obviously, there is a great need for research in this field. Battelle Memorial Institute is at the present time conducting an investigation into the problem of selection of the most suitable type of test specimen. M.I.T., which has some of the most extensive equipment for low temperature work in the United States, is conducting several investigations into the behavior of metals at low temperatures. Many others, too numerous to mention, have some form of research project in this field under way.

As previously mentioned, most austenitic and nickel base steels are not subject to low temperature embrittlement. This problem could be by-passed then by replacing the usual structural steels with one of these two. However, in most instances the cost would be prohibitive.

Bagsar (4) suggests the following precautions to be taken in designing in order to partially counteract the properties of embrittlement:

(a) Use, for construction of critical sections, a steel which possesses the necessary resistance to development of cleavage fractures under service conditions. Heat treatments also may be necessary.

(b) Increase factor of safety for critical sections.

(c) Include in design a sufficient number of crack-arrestors.

(d) Modify design so as to eliminate as much as possible stress raisers or notches.

In addition, Brown and co-workers (5) recommend:

(a) Pre-treatment of plate structure, such as hardening or tempering, and

(b) Post-heating--probably mostly because of metallurgical improvement to the steel

TEST PROGRAM

1. General

A 30 degree double bevel (60 degrees included angle of weld) weld consisting of four passes, two on each side, was selected as the most suitable type for this investigation. One of the desirable qualities of such a weld is that an equal quantity of deposited metal lies on each side of the plate.

After a survey of previous work in this field, the following types of test specimens were selected:

(a) Tension specimens (welded and plate) 1 3/16 in. by 12 in. by 1/2 in., necked section 1 in.

(b) Free bend specimens 1 in. by 12 in. by 1/2 in., welded to be tested on the flat and on the edge

(c) Notched bend specimens 1 in. by 12 in. by 1/2 in. standard ASTM 45 degree V-notch, welded and plate, to be tested on the flat and on the edge

(d) Impact specimens, standard Charpy impact specimens, welded and plate, to be tested un-notched on flat and edge and notched on flat and edge.

There were many other possibilities in the selection of specimens to be used. However, it was felt that these specimens would best serve the purpose, as well as facilitate preparation of the specimens and testing. In addition there was a limited amount of material available, and selection of these specimens permitted a maximum number of tests.

The ASTM 45 degree V-notch was selected for all notched specimens, since it was felt that this type notch imposes nearly the most severe conditions possible in service, and further, in the case of ductile materials, the key-hole notch has been proven quite unsatisfactory.

Testing temperatures of 70 F, 0 F, and -20 F were selected, this being the expected critical range of temperatures in service. Later it was found necessary to test six of the impact specimens at 120 F, since results indicated that even 70 F was below the transition temperature of the 0.33 percent plain carbon steel.

OUTLINE OF TEST PROGRAM

"A" Specimens - Mayari-R, 0.10% C Steel
"B" Specimens - 0.11% Plain Carbon Steel
"C" Specimens - 0.33% Plain Carbon Steel

Tests on Original Material as Received

Tension, 70 F	A-1, B-2, C-2
Notched Bend, 70 F	A-2, B-1, C-1
Notched Bend, -20 F	A-3, B-3, C-3

Tension, Bend, and Impact Tests on Welded Specimens

NB - Notched Bend, FB - Free Bend, T - Tension, I - Impact

Ends Discards	As Welded (A,B,C)		Type & Temp.	As Welded (A,B,C)		Type & Temp.	Unwelded Impact Specimens					
							70 F		0 F		-20 F	
1-1	1-2	FB	Flat 70 F	4-2	T	70 F	A-1-3	U-F	A-1-9	F	A-1-7	U-F
1-12	1-3	I	(S) 70 F	4-3	FB	Edge 70 F	B-1-3	U-F	B-1-9	F	B-1-7	U-F
2-1	1-4	NB	(S) 70 F	4-4	I	(E) 70 F	C-1-3	U-F	C-1-9	F	C-1-7	U-F
2-12	1-5	T	70 F	4-5	T	0 F	A-2-3	U-E	A-2-9	E	A-2-7	U-E
3-1	1-6	FB	Edge 70 F	4-6	I	(S) 0 F	B-2-3	U-E	B-2-9	E	B-2-7	U-E
3-12	1-7	I	(E) 70 F	4-7	FB	Flat 0 F	C-2-3	U-E	C-2-9	E	C-2-7	U-E
4-1	1-8	NB	(E) 70 F	4-8	NB	(E) 70 F	A-3-7	F	A-3-3	U-F	A-3-9	F
4-13	1-9	I	(S) 0 F	4-9	FB	Edge 0 F	B-3-7	F	B-3-3	U-F	B-3-9	F
5-1	1-10	FB	Flat 0 F	4-10	NB	(S) 0 F	C-3-7	F	C-3-3	U-F	C-3-9	F
5-13	1-11	NB	(S) 0 F	4-11	I	(E) 0 F	A-4-6	E	A-4-4	U-E	A-4-11	E
6-1	2-2	FB	Edge 0 F	4-12	NB	(E) 0 F	B-4-6	E	B-4-4	U-E	B-4-11	E
6-13	2-3	I	(E) 0 F	5-2	T	-20 F	C-4-6	E	C-4-4	U-E	C-4-11	E
	2-4	NB	(E) 0 F	5-3	FB	Flat -20 F	A-5-4	U-F	A-5-6	F	A-5-11	F
	2-5	T	0 F	5-4	I	(S) -20 F	B-5-4	U-F	B-5-6	F	B-5-11	F
	2-6	FB	Flat -20 F	5-5	T	-20 F	C-5-4	U-F	C-5-6	F	C-5-11	F
	2-7	I	(S) -20 F	5-6	I	(E) -20 F	A-5-4	U-E	A-5-6	E	A-5-6	E

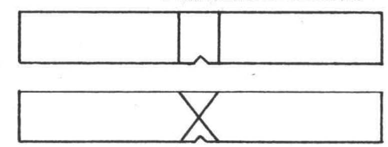
OUTLINE OF TEST PROGRAM (Cont'd)

Ends Discards	As Welded (A,B,C)	Type & Temp.	As Welded (A,B,C)	Type & Temp.	Unwelded Impact Specimens 70 F	0 F	-20 F
	2-8 NB	(S) -20 F	5-7 FB	Edge -20 F	B-5-4 U-E	B-5-6 E	B-5-6 E
	2-9 I	(E) -20 F	5-8 NB	(S) -20 F	C-5-4 U-E	C-5-6 E	C-5-6 E
	2-10 FB	Edge -20 F	5-9 FB	Flat 70 F			
	2-11 NB	(E) -20 F	5-10 NB	(E) -20 F			
	3-2 FB	Flat 0 F	5-11 I	(S) 70 F			
	3-3 I(U)	Spare	5-12 NB	(S) 70 F			
	3-4 NB	(S) 70 F	6-2 T	70 F			
	3-5 T	0 F	6-3 FB	Flat -20 F			
	3-6 FB	Edge 0 F	6-4 I	(E) -20 F			
	3-7 I	(E) 0 F	6-5 T	-20 F			
	3-8 NB	Spare	6-6 I	(S) -20 F			
	3-9 I	(S) 0 F	6-7 FB	Flat 70 F			
	3-10 NB	(E) 0 F	6-8 NB	(E) 70 F			
	3-11 NB	(S) 0 F	6-9 FB	Edge -20 F			
			6-10 NB	(S) -20 F			
			6-11 I(U)	-20 F			
			6-12 NB	(E) -20 F			

Unwelded impact specimens cut from ends of pieces for welded impact specimens. Second group of specimens from plates No. 5, cut from other end.
U - un-notched.

Notch Position

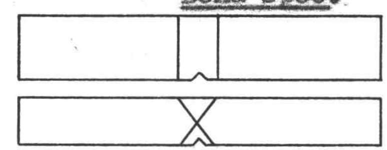
Impact Spec.



Edge (E)

Side (S)

Bend Spec.



Edge (E)

Side (S)

Hardness surveys across the weld and heat-affected zones were desired in order to correlate points of embrittlement with location of hard spots. Brinell hardness tests were to be made in order to classify the material. X-ray inspections were made of each weld in order to insure satisfactory fusion between the weld and parent metals. Metallographic examinations were to be made of the structure in the unaffected plate, heat-affected zone, line of fusion between the weld and parent metal, and weld metal.

2. Material

Three types of steel, Mayari-R, 0.11 percent plain carbon and 0.33 percent plain carbon steel were to be investigated. The following chemical compositions of these steels were supplied by the manufacturer:

%	C	Mn	P	S	Si	Ni	Cr	Cu
Mayari-R	0.10	0.70	0.099	0.033	0.25	0.38	0.51	0.55
Plain Carbon	0.11	0.51	0.013	0.038				
Plain Carbon	0.33	0.74	0.015	0.044				

The welding rod used was Fleetweld 85, with the following composition: C - 0.10-0.14, Mn - 0.40-0.45, Si - 0.01 max., S - 0.035 max., P - 0.030 max., Cu - 0.1 max., coating, Mo - 0.5%.

3. Preparation of Specimens

Three 12 in. by 12 in. by 1/2 in., and three 6 in. by 24 in. by 1/2 in. plates of each of the three steels were available for this test program. A 1 1/4 in. by 12 in. section was cut from each of the

12 in. square plates in order to provide specimens of the unwelded plate for tension and bend tests. This left three 10 3/4 in. by 12 in. by 2 in. plates of each of the steels, which were cut in the middle the long way in the direction of rolling. The plates were then beveled along the cut and welded. The remaining three plates of each steel were cut in the middle perpendicular to the two-foot dimension, beveled along the present one-foot dimension, and welded so as to form plates 12 in. by 12 in. by 1/2 in. The plates were welded using a Lincoln-Shield Arc Welder, 150 amperes, using an average current of approximately 27 volts and 132 amperes. This left plates with all welds in the direction of rolling, from which test specimens were to be cut. Figure 3 shows the approximate position of each specimen in the original plate.

The letter designation "A" was given to the Mayari-R plate, "B" to the 0.11 percent plain carbon steel plates, and "C" to the 0.33 percent plain carbon steel plates. Numerals from one to six were given to each of the plates, with one to three being given to the 10 1/4 in. by 12 in. by 1/2 in. plates, and four to six to the 12 in. by 12 in. by 1/2 in. plates in order to designate the individual plates. Plates A, B, and C-3 and 6 were stress relieved for one hour at 1100 F.

The welded plates were cut transverse to the direction of rolling, as shown in Figure 3. The tension and bend specimens were then milled down to size. The impact specimens were cut from pieces indicated, with the weld in the center of the specimen. These were milled on all four sides, so as to place the center of the weld in

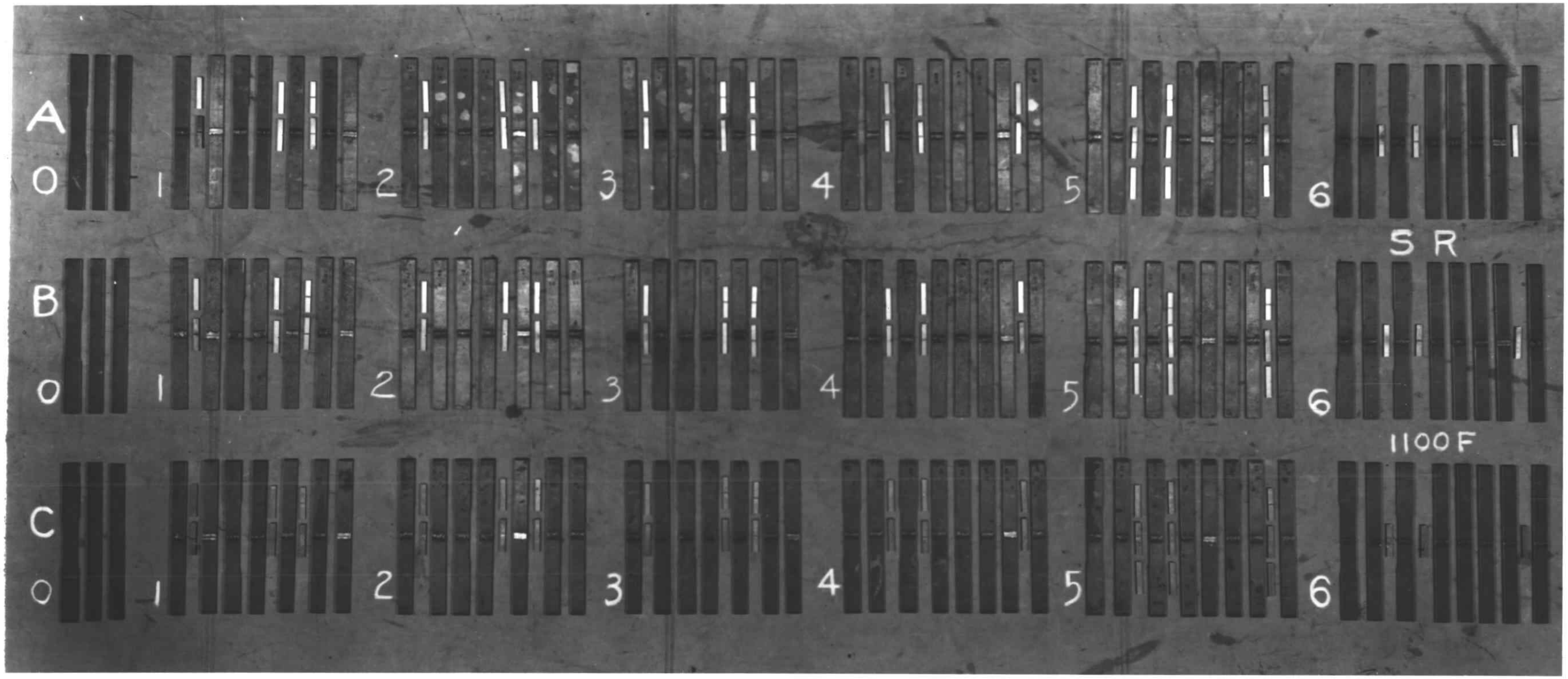


Figure 3. Specimens Used in Test Program, In Position as in Uncut Plate

the center of the specimen. In addition impact specimens from unwelded plates were cut from ends of these pieces. The ends of the plates, approximately 1/2 in. wide, were reserved for hardness surveys and metallographic examinations. ASTM 45 degree V-notches were cut in the notched-bend specimens, as indicated in the test program sheet. All machining was done in the mechanician's shop with the exception of the notching, which was done in the shop of the aeronautical division.

4. Metallographic Examination

Inspection of the plates indicated that some of the "C" plates, C-4 in particular, had extensive carbon segregation with an extremely high carbon sandwich resulting at the center of the plate. Metallographic examination verified this fact as did later hardness tests. Figure 4 is a micrograph of the high carbon center of plate C-4. Figure 5 is a micrograph of the heat-affected zone near the edge of the plate, Figure 6 at the junction of the parent and weld metals, and Figure 7 is a micrograph of the structure near the bottom of the first pass of deposited metal and the heat-affected zone. Micrographs were not made of the A and B specimens since the structures in similar portions of the plate would be quite similar with the exception of the high carbon sandwich. Figure 8 is a macrograph of the weld section showing deposited metal, heat-affected zone, and high carbon center.

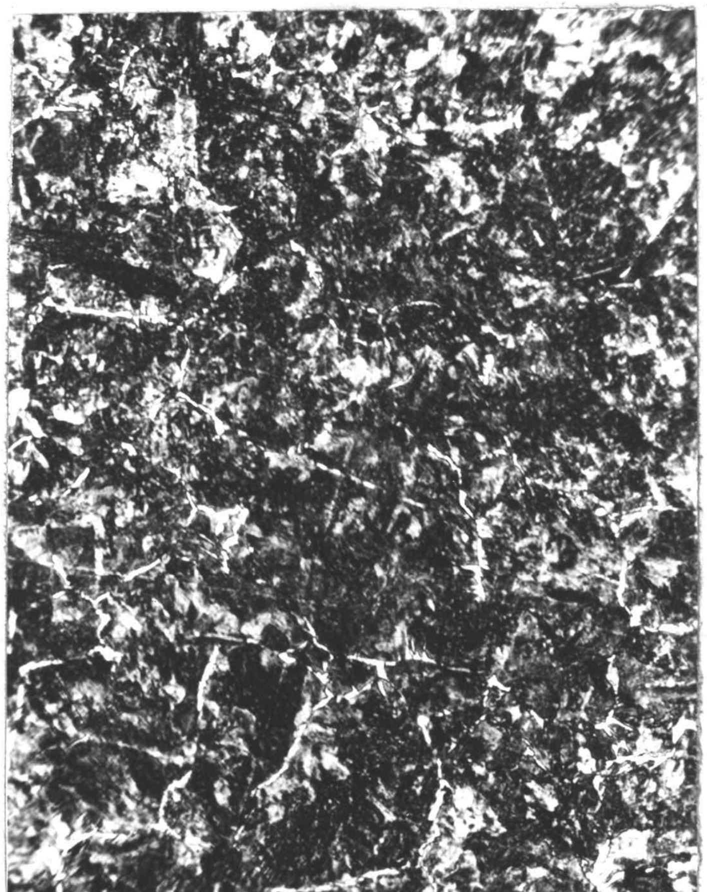


Figure 4. Micrograph of High Carbon Center. 0.33% Steel

Figure 5. Micrograph of Heat-Affected Zone Near Edge of Plate. 0.33% C Steel

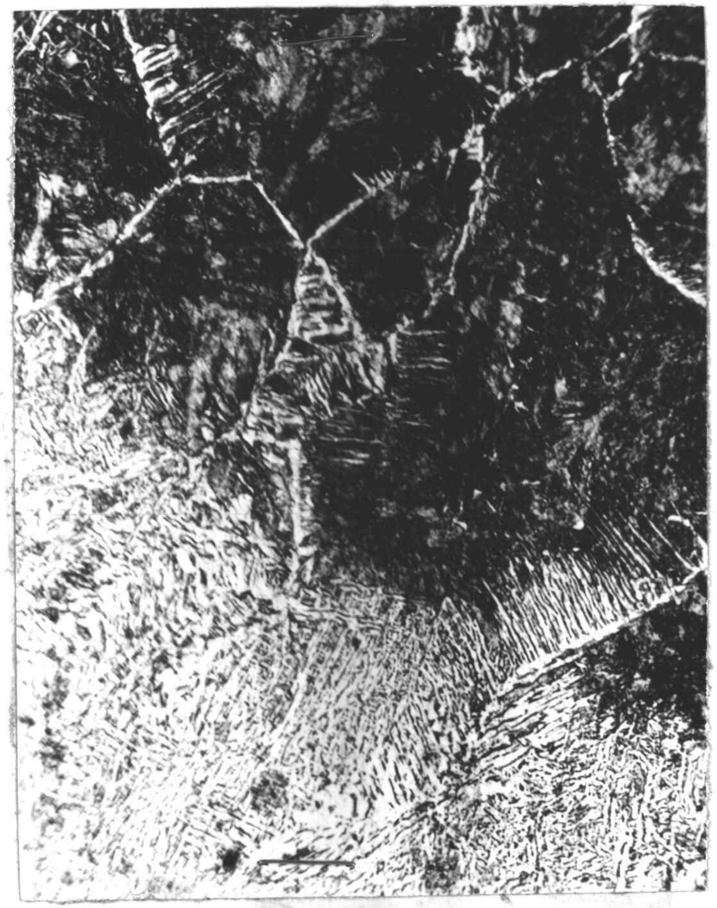


Figure 6. Micrograph at Junction of Parent and Weld Metal. 0.33% C Steel

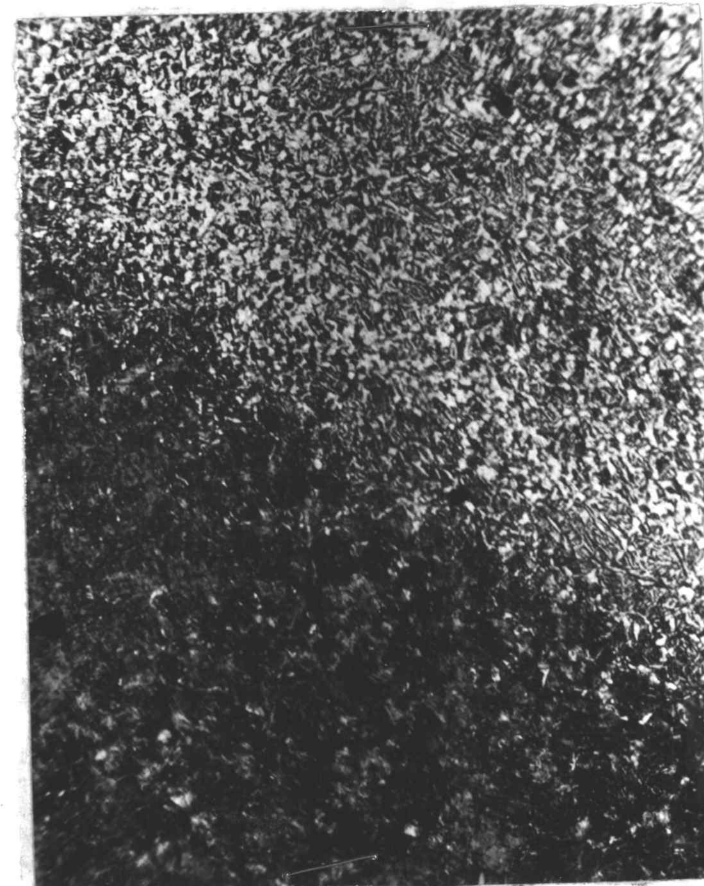


Figure 7. Micrograph Near Bottom of First Pass at Junction of Parent and Weld Metal. 0.33% C Steel

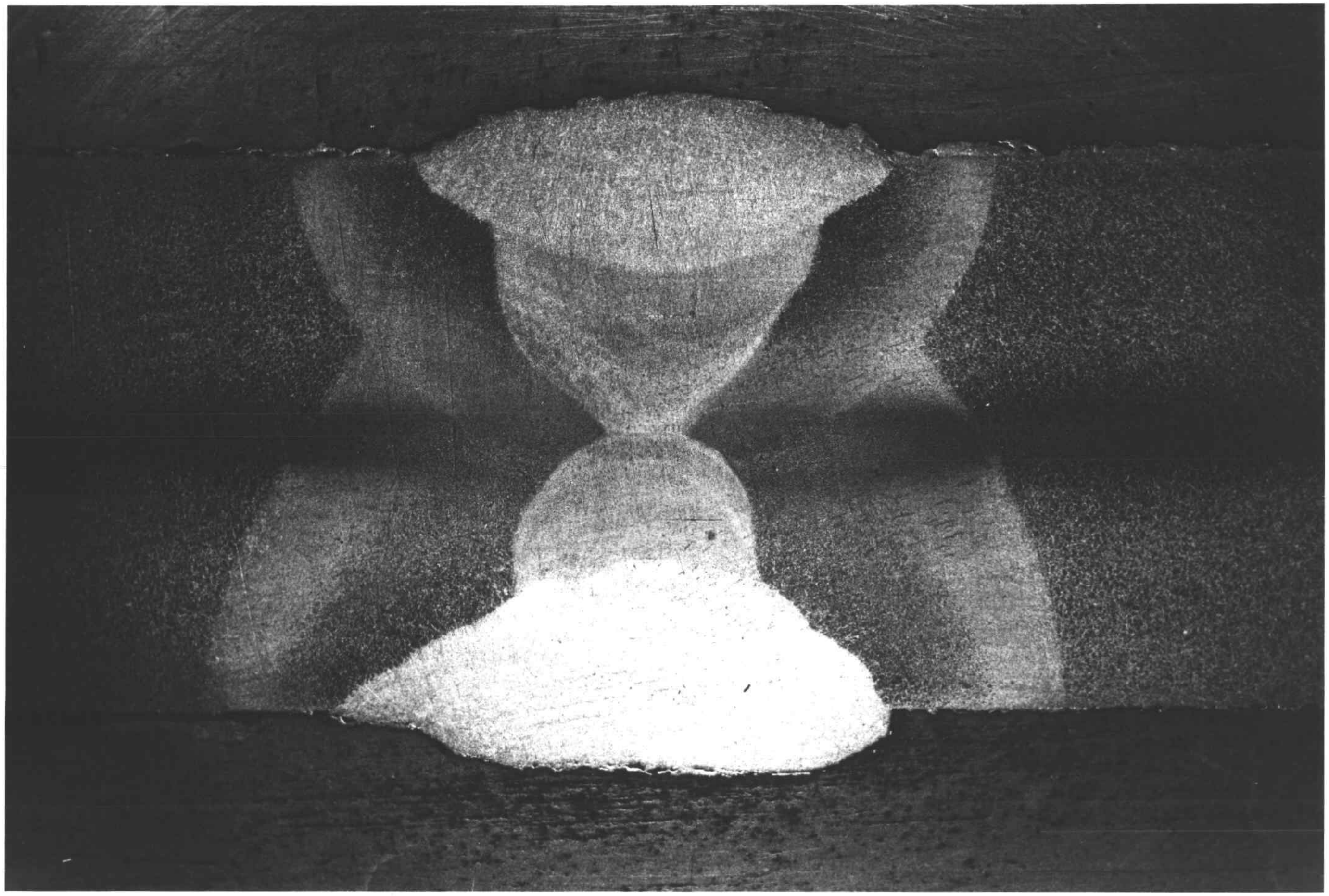


Figure 8. Macrograph of Weld Plate C Showing Deposited Metal, Heat-Affected Zone and High Carbon Center

5. Hardness Tests

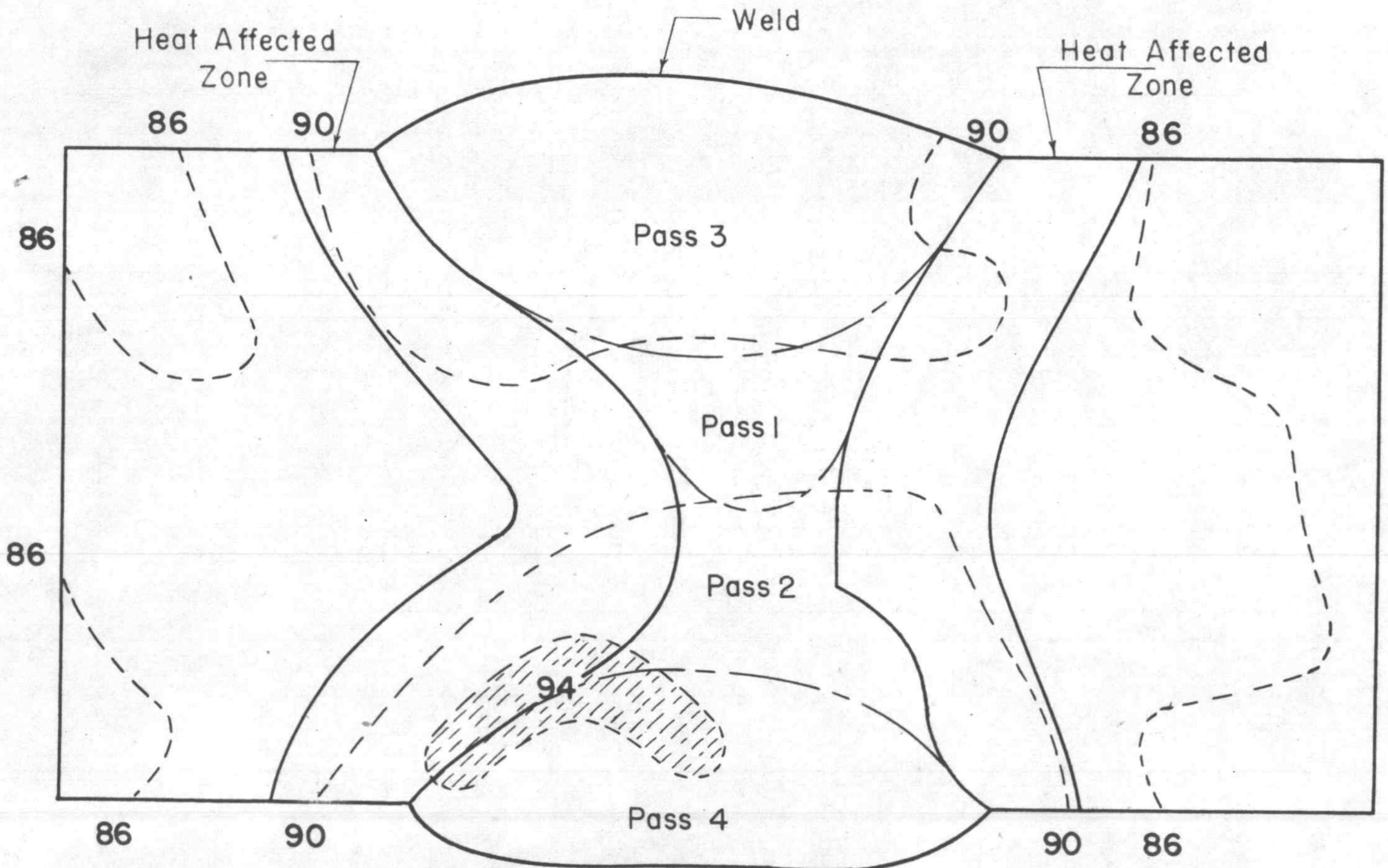
Hardness contours (Figures 9-12) across the welds were made for all three steels, two contours being made for the C plates; one of the specimens showing no carbon segregation, and the second with the high carbon center.

Figure 9 shows a zone of high hardness at the junction of the parent metal and the weld metal deposited in the last pass. This zone might be expected, since the last pass is not subjected to the annealing heat treatment by subsequent passes. A zone of low ductility would be expected to coincide with this zone of high hardness.

Figure 10, showing the hardness contours of the 0.11 percent carbon steel, indicates two zones of high hardness lying almost entirely in the third and fourth passes. Since the carbon content of the weld material was slightly higher than that of the plate metal, and pass number three received little heat treatment, while pass number four received no heat treatment due to the welding cycle, this might be expected.

Figure 11 (0.33 percent carbon steel without high carbon center) shows four zones of high hardness lying in the heat-affected zone at the fusion line. The zones of highest hardness are associated with pass number four, as might be expected. Failure in the bend tests, especially the free bend, would be expected in the heat-affected zone.

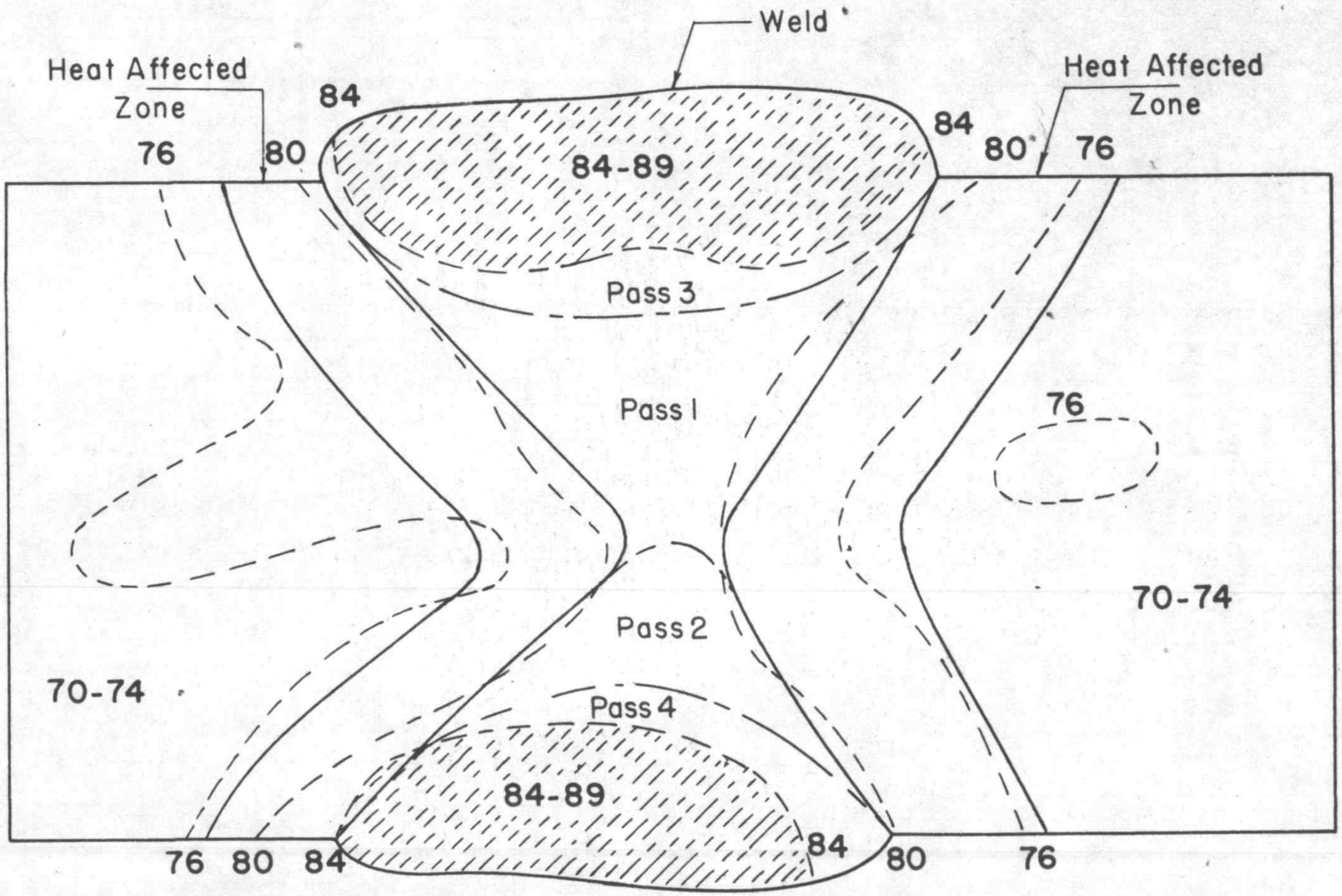
Figure 12 (0.33 percent carbon steel with high carbon center)



HARDNESS CONTOURS ACROSS WELD

ROCKWELL "B" SCALE

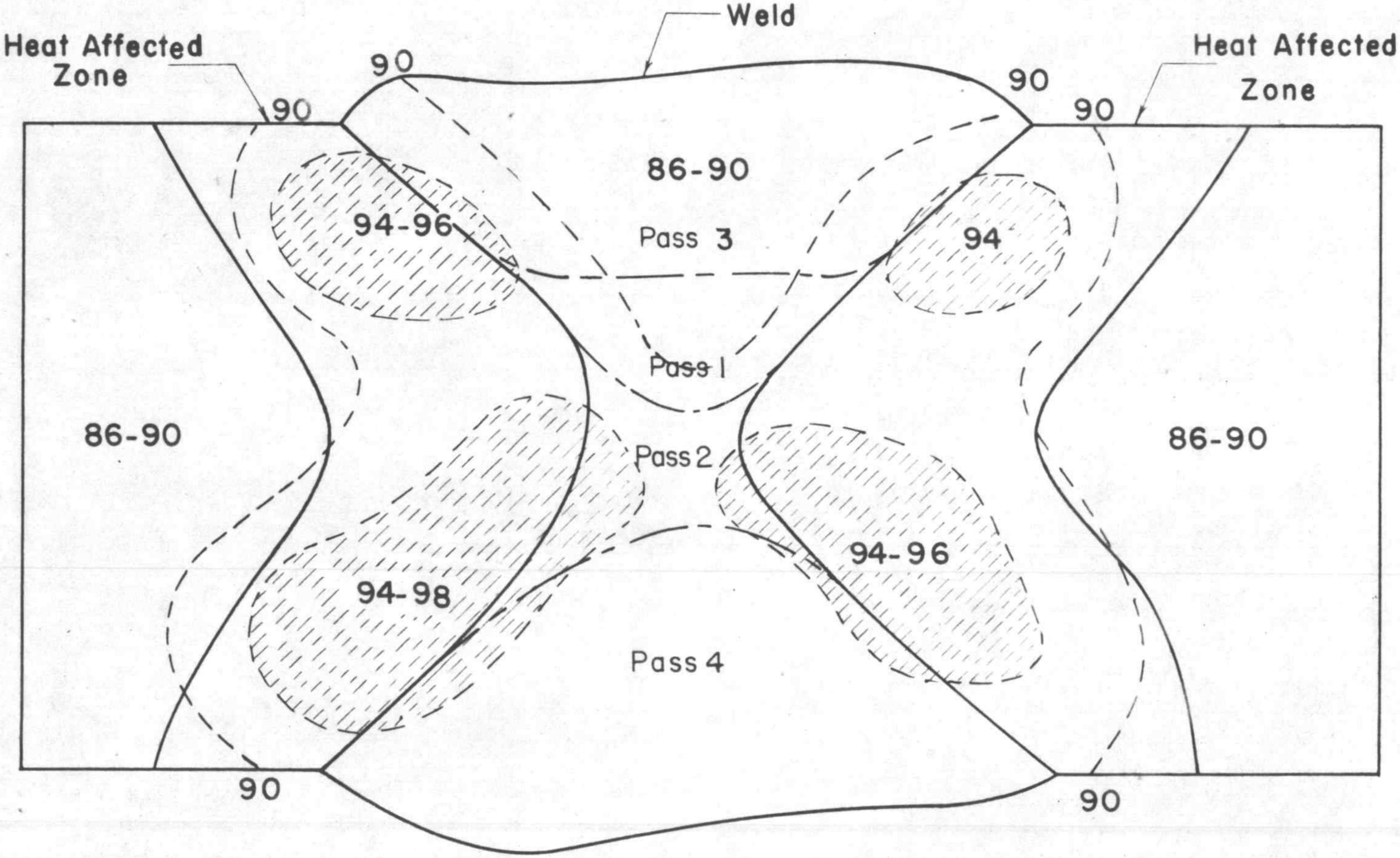
Specimen No. A-5-13 Figure 9. Scale - 7" = 1"



HARDNESS CONTOURS ACROSS WELD

ROCKWELL "B" SCALE

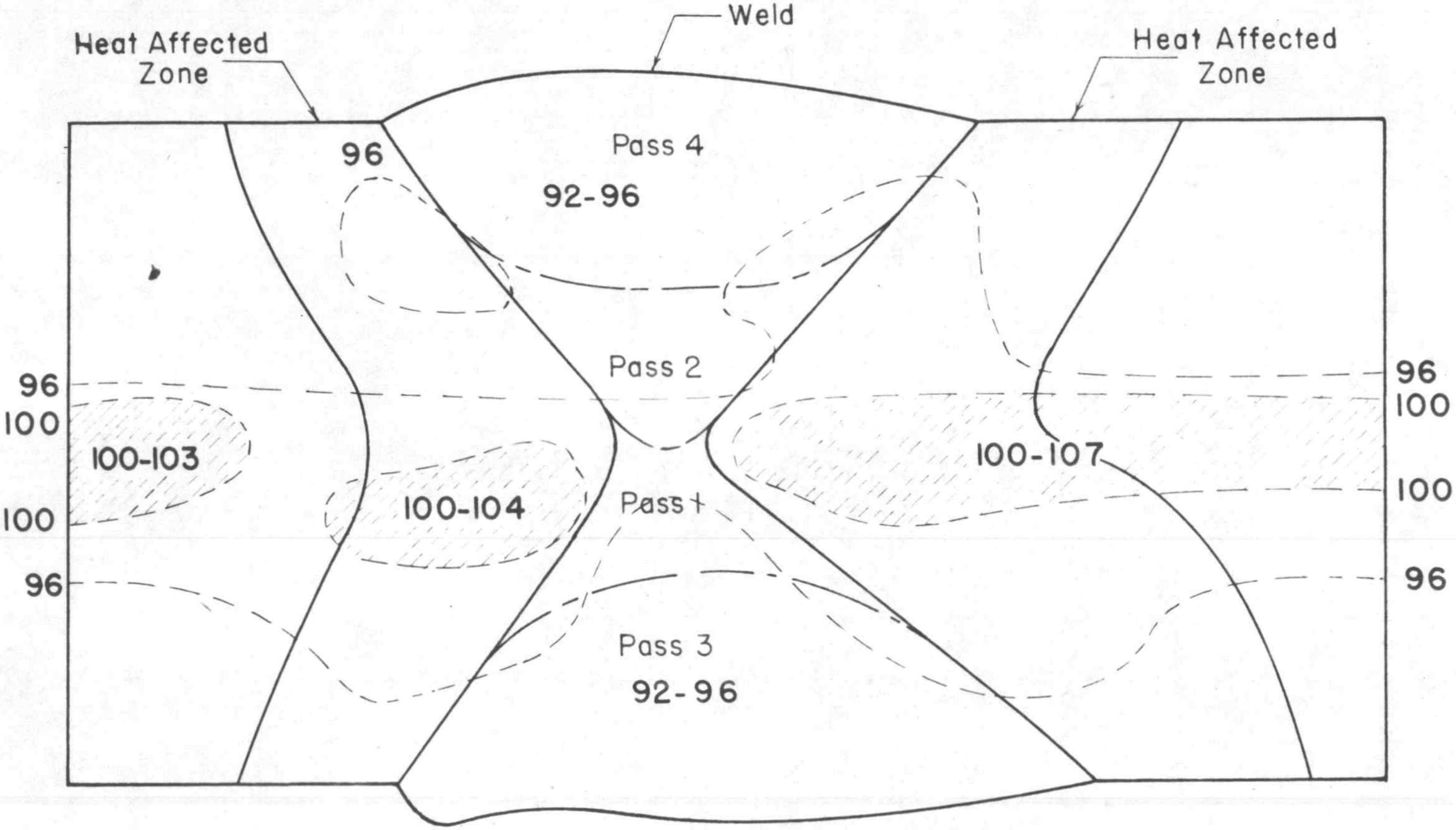
Specimen No. B-2-12 Figure 10. Scale - 7" = 1"



HARDNESS CONTOURS ACROSS WELD

ROCKWELL "B" SCALE

Specimen No. C-1-1 Figure 11. Scale - 7" = 1"



HARDNESS CONTOURS ACROSS WELD

ROCKWELL "B" SCALE

Specimen No. C-4-13 Figure 12. Scale - 7"= 1" indicates a zone of extremely high hardness throughout the center of the plate and weld. Carbon migration into the weld is apparent by the relatively higher hardness of the weld metal. Fracture in free bend might be anticipated in the heat-affected zone, exhibiting a lesser degree of ductility than might be expected in similar specimens without the high carbon center.

Brinell hardness tests were made on the sides and edges of representative samples of all plates in order to classify the plate material.

6. Tension Tests

Tension tests were made on one unwelded specimen of each plate at 70 F and on two welded as rolled and welded stress-relieved specimens of each plate at 70 F, 0 F, and -20 F. Average values of results are shown in Table I. The tensile tests of the steels showed that the ultimate and yield points increased slightly with a decrease in temperature, while the ductility, as determined by elongation in a two-inch gage length and reduction in area, decreased. The stress-relieved specimens exhibited slightly higher values of yield point and ultimate strength. These results are consistent with the findings of other investigators. The impossibility of determining the brittle transition temperature from tension tests is apparent. The tension specimens are shown in Figure 13.

TABLE I
TENSION TESTS (70 F, 0 F, -20 F)

Most values are average of two tests. Details of test included in original data sheets, Appendix.

"A" Specimens - Mayari-R 0.10% C Steel
"B" Specimens - 0.11% Plain Carbon Steel
"C" Specimens - 0.33% Plain Carbon Steel

Material & testing temperature	Original Material 70 F			Weld 70 F			Weld 0 F			Weld -20 F		
Specimens	A	B	C	A	B	C	A	B	C	A	B	C
Y.P., psi	49,500	33,100	47,600	50,300	35,150	48,350+	54,200	37,000	49,950++	53,400	37,250	54,200
Ultimate, psi	78,670	58,800	85,100	78,550	59,950	87,330	81,100	61,700	90,600	82,500	62,200	89,600
Break, psi	71,000	48,600	74,300	71,650	49,400	82,400	74,000	52,400	85,080	73,100	53,000	89,600
Elong. in 2" over fracture - %	31.5	42.0	29.5	21.2	34.0	17.0	17.2	35.5	17.0	25.5	38.8	9.0
Red. area - %	37.2	55.9	43.0	31.2	55.4	28.0	36.2	47.5	22.7	36.2	34.4	3.0

+One of C specimens fractured in weld (bead ground off).
++One of C specimens fractured in weld.
Remainder of specimens fractured outside of weld and heat-affected zone.

STRESS RELIEVED

Material and testing temperature	Weld 70 F			Weld 0 F			Weld -20 F		
Specimens	A	B	C	A	B	C	A	B	C
Y.P., psi	51,200	32,700	47,500	58,000	33,800	45,600	55,700	37,400	50,300
Ultimate, psi	78,100	57,600	84,300	81,700	60,700	90,500	82,900	60,700	87,900
Break, psi	68,600	49,200	74,600	80,600	55,100	84,000	72,300	50,200	77,200
Elong. in 2" over fracture - %	25.5	34.5	29.0	12.5	28.0	20.0	27.5	34.5	24.0
Red. area - %	39.7	52.2	43.8	14.8	37.8	32.9	38.4	48.2	38.1

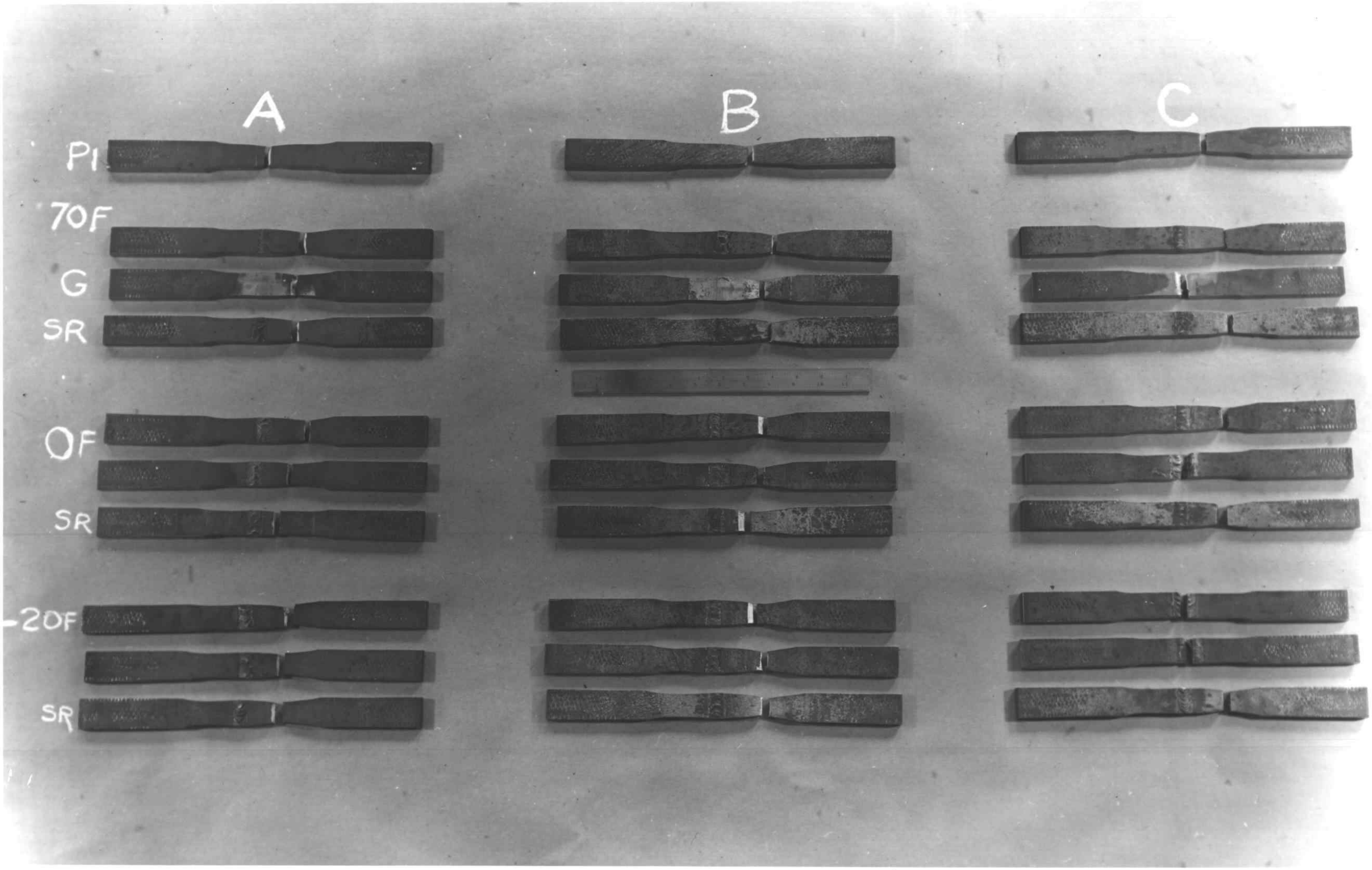


Figure 13. Tension Specimens After Fracture

7. <u>Free Bend Tests</u>

Two welded specimens, as rolled, and one welded stress-relieved specimen of each material were tested at 70 F, 0 F, and -20 F, both on the flat and on the edge. Average values of results are shown in Table II. The testing machine and setup used for low temperature bend tests is shown in Figure 14. This photograph shows the cooling unit used to produce testing temperatures and the potentiometer used to measure the temperature. Dry ice and kerosene were used in the cooling unit for the 0 F and -20 F tests.

The bend angles in fracture are not believed to be greatly significant. They do indicate a trend that is from ductile to brittle. However, they cannot easily be correlated with service conditions due to the presence of minute cracks or notches under service conditions. In addition, the materials in the ductile state were rarely fractured. More significant was the location of the formation of the crack in those specimens which did fracture in this test and the appearance of such fractures. The results obtained in these tests in some cases tend to bear out the findings of MacGregor and Grossman in the M.I.T. slow bend tests. That is, that some fractures occurred outside the heat-affected zone in the unaffected plate metal, indicating a zone of low ductility. In general, however, most of the fractures occurred in the heat-affected zone. Material "B", the 0.11 percent carbon steel, exhibited a definite superiority over the other two materials, both in the tests on edge and the tests on the flat, with respect to

TABLE II

FREE BEND TESTS (70 F, 0 F, -20 F)

"A" Specimens - Mayari-R 0.10% C Steel
"B" Specimens - 0.11% Plain Carbon Steel
"C" Specimens - 0.33% Plain Carbon Steel

TESTED ON FLAT

	70 F		0 F		-20 F	
Specimen	Bend Angle	Fracture	Bend Angle	Fracture	Bend Angle	Fracture
As rolled A	180°	At edge of weld	59°	Br.F.Gr. near edge,HAZ	46°	Br.F.Gr.at edge of weld
	58°	At edge of W into plate	74°	Br.F.Gr. near edge,HAZ	103°	Not broken, ductile
As rolled B	180°	At edge of weld	120°	Not broken	116°	Not broken, ductile
			120°	Not broken	111°	Not broken, ductile
As rolled C	80°	In HAZ	120°	Not broken	91°	Br.F.Gr. in HAZ
	180°	At edge of weld	120°	Not broken	114°	Not broken, ductile
Stress relieved A	93°	1/4" from edge weld	70°	Br.F.Gr. in HAZ	101°	Br. in HAZ
Stress relieved B	180°	Edge of weld	120°	Not broken, ductile	112°	Not broken, ductile
Stress relieved C	180°	Edge of weld	95°	Br.F.Gr. in HAZ	65°	Br. 1/4" into HAZ from weld

TABLE II (Cont'd)

		70 F		0 F		-20 F	
Specimen		Bend Angle	Fracture	Bend Angle	Fracture	Bend Angle	Fracture
As rolled	A	42°	Diag. across weld	45°	Br. at edge W in HAZ	20°	Br. edge W in HAZ
		23°	Diag. across weld	41°	Br. diag. across weld	38°	Sl.D.,F.Gr. edge of W
	B	119°	Along one edge	85°	Br.-R in HAZ	99°	Ductile, W & HAZ
		180°	Partial crack	115°	Not broken, ductile	98°	Duct.-R.F.Gr. in W & HAZ
	C	45°	Br. at edge of W & HAZ	44°	Br.-R diag. across W	47°	Sl.duct. F.G. in HAZ
		22°	Br. thru weld	28°	Br.-R partly in W	23°	Br.-R start in HAZ thru weld
Stress relieved	A			51°	Br.-R along HAZ	39°	Br.-R HAZ & edge of W
	B			113°	Not broken, ductile	114°	Not broken, ductile
	C			42°	Br. in HAZ	36°	Br. HAZ F.Gr.

Abbreviations: Br - Brittle
F.Gr. - Fine Grain
R - Rough
W - Weld
HAZ - Heat-Affected Zone

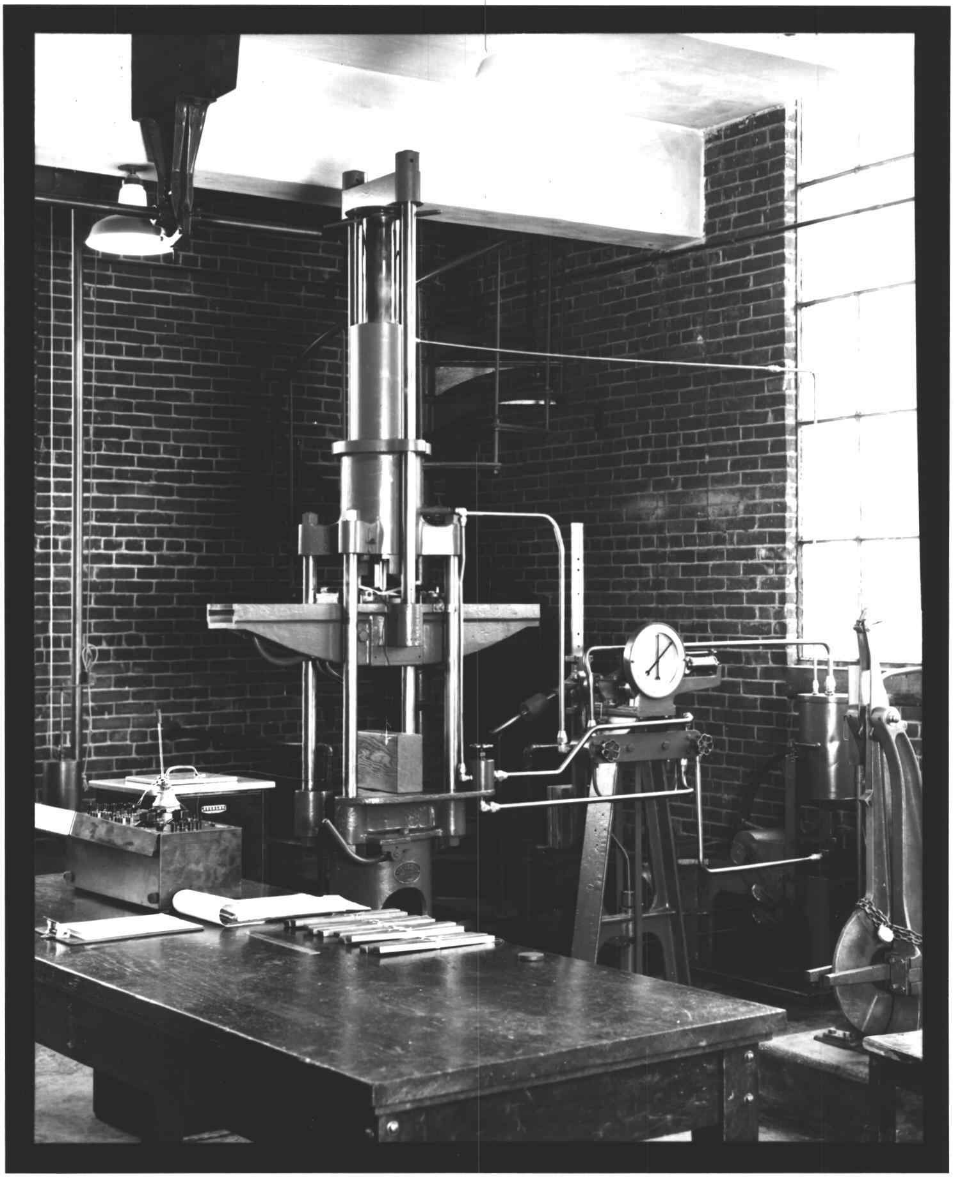


Figure 14. Amsler Testing Machine and Setup For Low Temperature, Free and Notched-Bend Tests, and Showing Cooling Unit and Potentiometer

ductility at all temperatures. Results obtained from tests of the stress-relieved plates indicated no noticeable improvement of ductility. Bend specimens are shown in Figures 15, 16, and 17.

8. Notched Bend Tests

Notched bend tests were made on one specimen of each material, unwelded, at 70 F and -20 F. These were notched and tested on the edge. Notched bend tests were also made on two welded as rolled specimens and one welded stress-relieved specimen at 70 F, 0 F, and -20 F notched and tested both on the flat and on the edge. In each case the notch was placed in the center of the weld. Such tests impose as severe conditions as could possibly exist in practice. The notched-bend specimens as fractured are shown in Figures 15, 16, and 17.

Had sufficient material been available, tests would have been conducted on specimens notched in the heat-affected zone in order to compare results. Average results may be found in Table III. Bar graphs of bend angles at fracture for these specimens are shown in Figures 18, 19, and 20. Inspection of the graph in Figure 18, Mayari-R steel, indicates that the transition temperature of the welded specimens was between 0 F and 70 F. The transition temperature of the unwelded plate was above 70 F. The stress-relieved specimens showed little superiority over the as-rolled specimens when tested on the flat. However, when tested on the edge, the increase in bend angles was five to ten degrees.

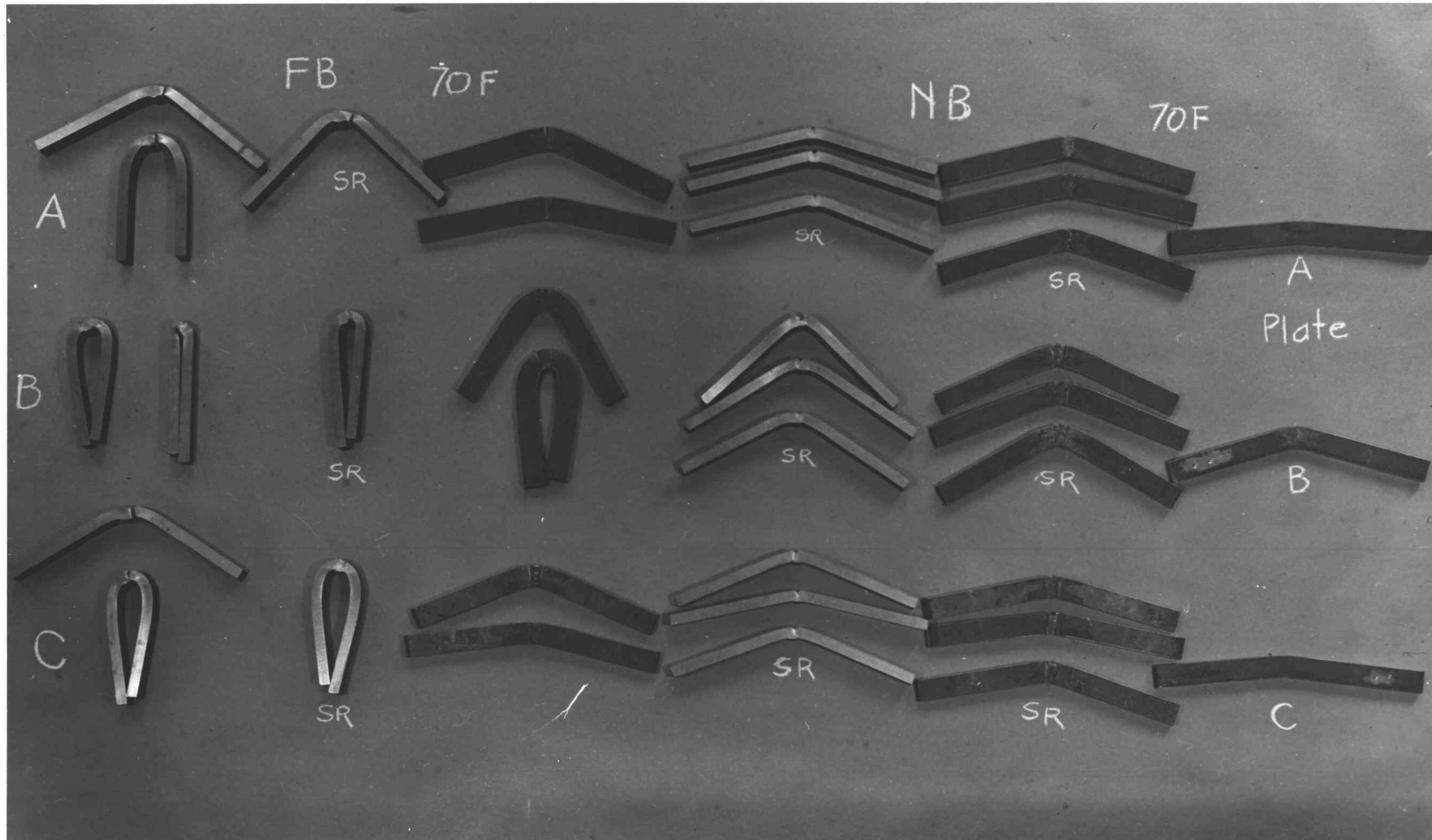


Figure 15. Notched and Free Bend Specimens After Fracture at 70 F

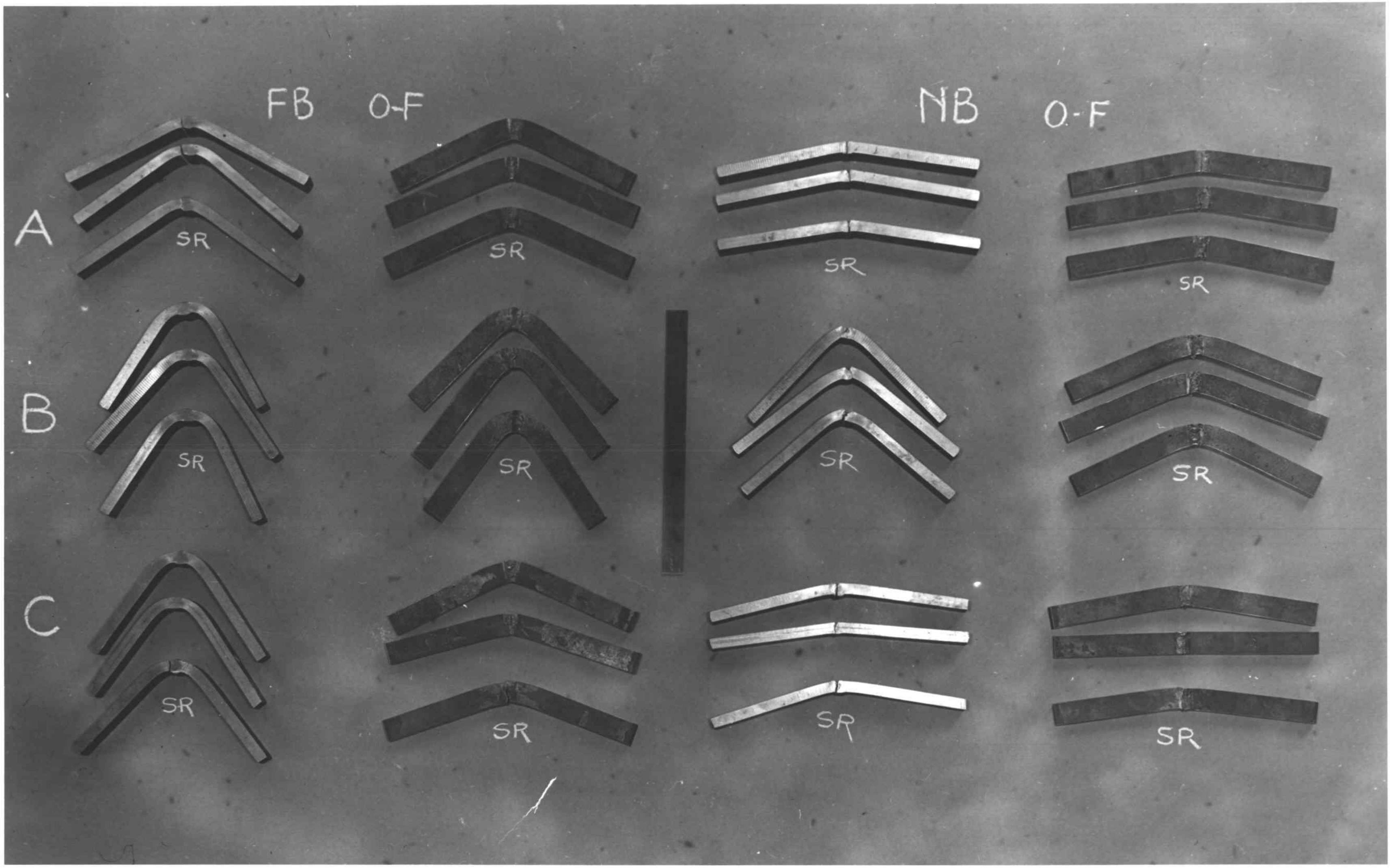


Figure 16. Notched and Free Bend Specimens After Fracture at 0 F

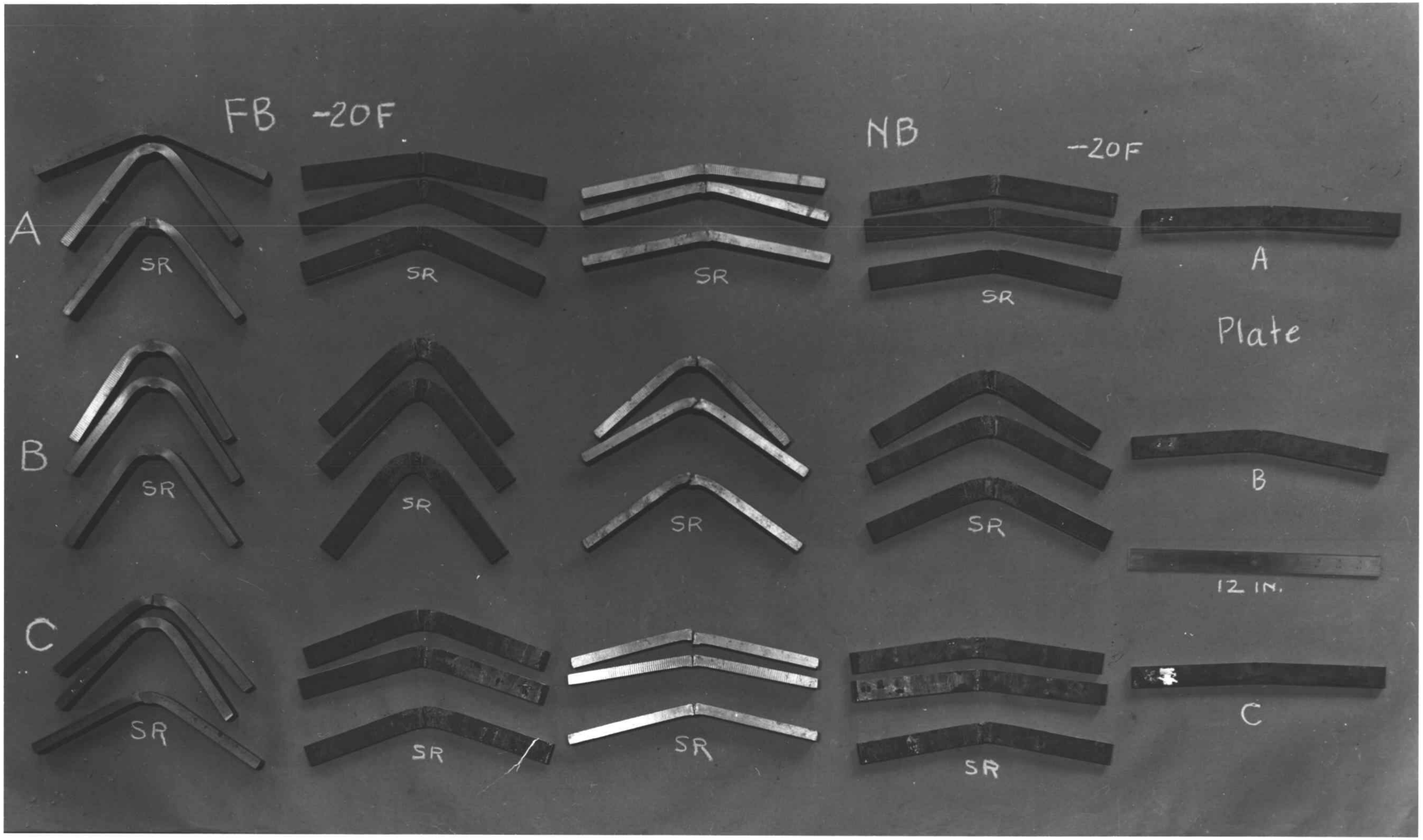


Figure 17. Notched and Free Bend Specimens After Fracture at -20 F

TABLE III
NOTCHED BEND TESTS (70 F, 0 F, -20 F)

"A" Specimens - Mayari-R 0.10% C Steel
"B" Specimens - 0.11% Plain Carbon Steel
"C" Specimens - 0.33% Plain Carbon Steel

TESTED ON FLAT

		70 F		0 F		-20 F	
Specimen		Bend Angle	Fracture	Bend Angle	Fracture	Bend Angle	Fracture
As rolled	A	31.5°	F.Gr., duct. in W	22°	Med.Gr., R., Br. thru weld	22°	Med.Gr., Br. thru W
	B	73°	F.Gr., ductile, tearing in weld	74°	Sl.duct., R. tearing thru weld	73°	Sl.duct., F.Gr. thru W
	C	45° 24°	F.Gr., ductile Rather brittle	22.5°	Br., rough gr.	24°	Br., mod.Gr., R.
Stress relieved	A	36°	F.Gr., duct. in W	21°	F.Gr., Br. thru W	19°	Med.Gr., Br. thru W
	B	64°	Fine, duct.tearing	78°	R., Sl.duct. laminat	66°	Sl.duct., F.Gr. thru weld
	C	41°	F.Gr., ductile	24°	Med.Gr., rough	22°	Br. Fine Gr.

TABLE III (Cont'd)

TESTED ON EDGE

Specimen		70 F		0 F		- 20 F	
		Bend Angle	Fracture	Bend Angle	Fracture	Bend Angle	Fracture
As rolled	A	27°	F.,duct. at junct. pl.and weld	20°	Med.Gr., Br. thru weld	15°	Br., med.Gr., R., thru weld
	B	46°	F., duct. junct. of pl. and weld	47°	Sl. duct.	55°	Sl.duct., R. thru weld to HAZ
	C	21°	F. ductile	22° 3°	Br., F.Gr. F.Gr., failed first in high C	12°	R., Br.
Stress relieved	A	35°	F., duct. thru W	25°	Sl.duct., R., F.Gr.	26°	R., Br., Med. Gr., thru weld
	B	59°	F., duct. thru W	54°	R.,Sl.duct. along edge of W into HAZ	49°	R., tearing break into HAZ
	C	27°	F., ductile	22°	R., Br.	23°	R., Br.

Abbreviations:
F.Gr. - Fine Grain
R. - Rough
Sl. - Slightly
duct. - ductile
Br. - Brittle
W - Weld
pl. - plate
HAZ - Heat-Affected Zone

TABLE III (Cont'd)

TESTED ON EDGE

		70 F		-20 F
Specimen	Bend Angle	Fracture	Bend Angle	Fracture
Original un-welded plate A	10°	Sudden, Fine Gr., Br.	8°	Br., F.Gr., Med. R. fracture
B	31°		16°	
C	11°	Sl.duct., F.Gr.	3°	Very brittle

NOTCHED BEND TESTS

Mayari-R - 0.10% C "A" Specimens

Span 6" - 1.20" Pin Amsler Machine

Length of Specimen Transverse to Direction of Rolling

Specimen 1 x $\frac{1}{2}$ in. ASTM - 45° V-Notch 2 mm deep

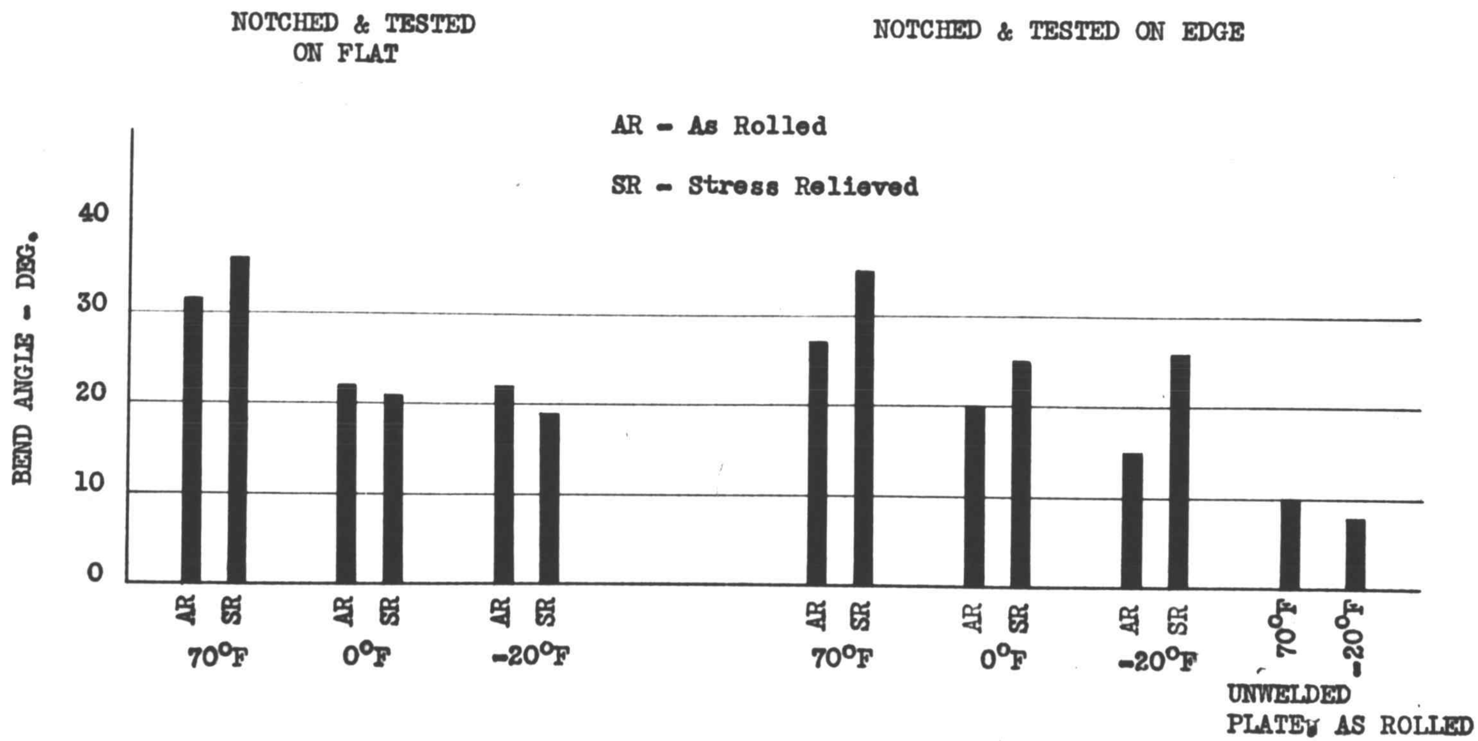


Figure 18.

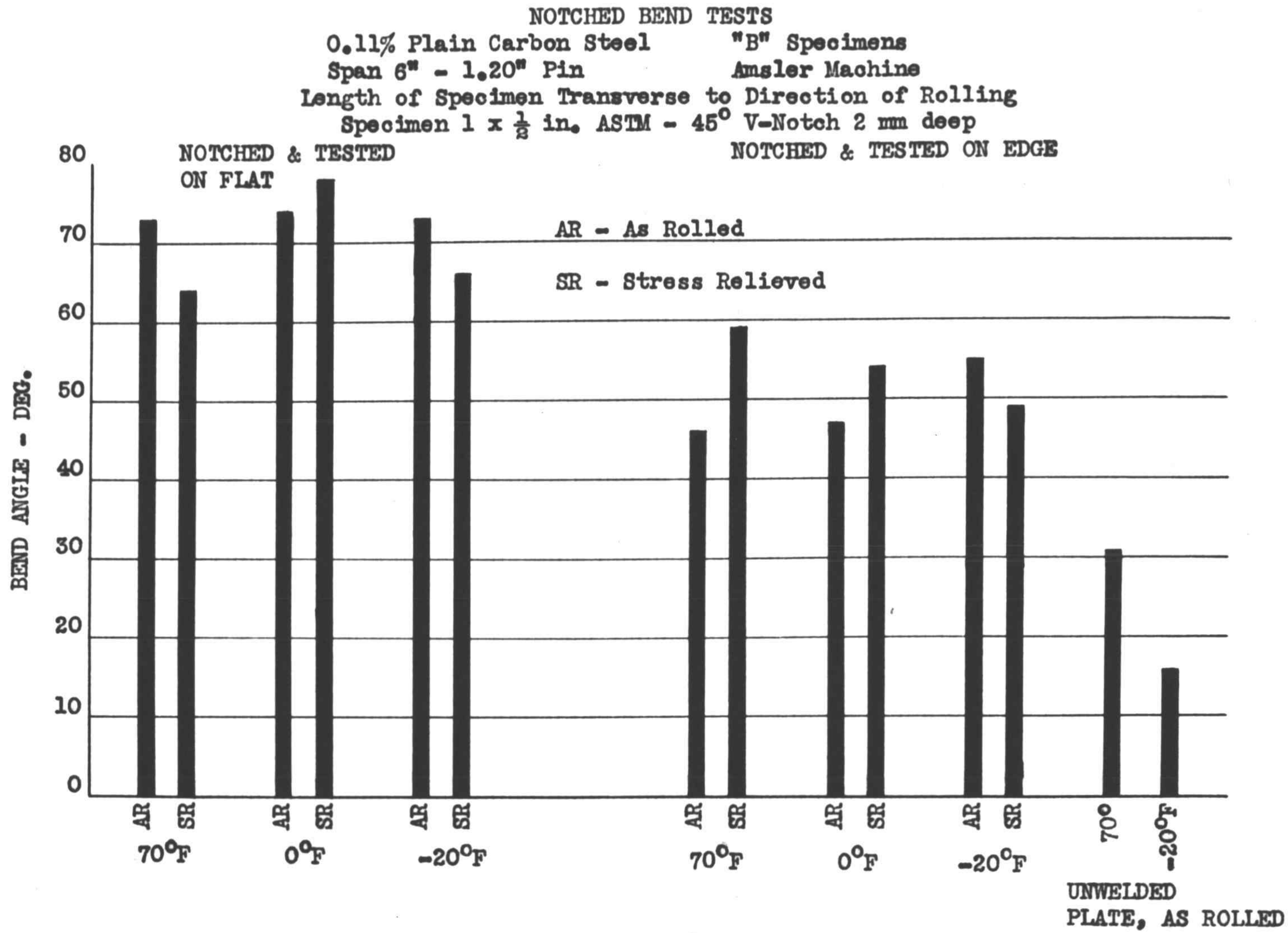

NOTCHED BEND TESTS
0.11% Plain Carbon Steel "B" Specimens
Span 6" - 1.20" Pin Amsler Machine
Length of Specimen Transverse to Direction of Rolling
Specimen 1 x ½ in. ASTM - 45° V-Notch 2 mm deep
NOTCHED & TESTED ON FLAT
NOTCHED & TESTED ON EDGE
AR - As Rolled
SR - Stress Relieved
BEND ANGLE - DEG.
80
70
60
50
40
30
20
10
0
AR
SR
70°F
0°F
-20°F
70°
-20°F
UNWELDED PLATE, AS ROLLED

Figure 19.

NOTCHED BEND TESTS

0.33% Plain Carbon Steel "C" Specimens

Span 6" - 1.20" Pin Amsler Machine

Length of Specimen Transverse to Direction of Rolling

Specimen 1 x ½ in. ASTM - 45° V-Notch 2 mm deep

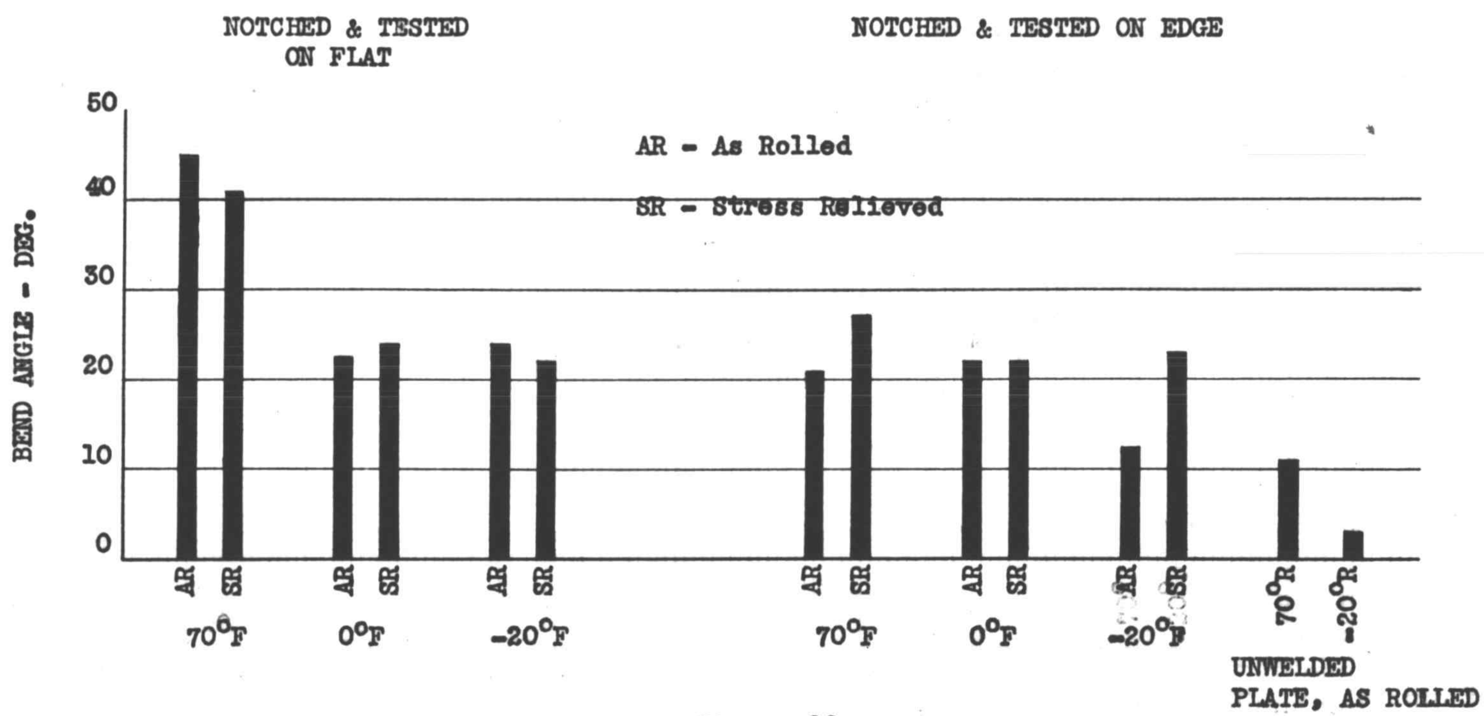


Figure 20.

The values obtained from the welded specimens when compared with those of the unwelded plate indicate two possibilities:

(a) The superiority of the weld metal analysis with respect to low temperature characteristics

(b) The specimens were not notched and tested in the zone of lowest ductility.

The first indicates the possibility that the tests were more on the weld metal and quality of the weld than on the plate and effect of welding on the plate. It is believed that both these factors are responsible for the higher values obtained from welded specimens. Obviously, this material is unsatisfactory for use in structures where temperatures as low as 0 F to -20 F might be encountered without suitable heat treatments.

The bar graphs of Figure 19, 0.11 percent carbon steel, indicate especially good behavior at low temperatures. The transition temperature of the welded plate (considering that the test involved mainly the weld) was not encountered at the temperatures used. The transition temperature of the unwelded plate material might lie in the vicinity of 0 F. However, an acceptable bend angle of 15 degrees was obtained on the unwelded plate at -20 F.

Bend angles obtained in tests on welded specimens of the 0.33 percent carbon steel (Figure 20) compared almost identically with those obtained on the Mayari-R. The 0.33 percent steel specimens gave slightly higher bend angles when tested on the flat at 70 F. However, the difference was not significant. Tests on the unwelded 0.33 percent carbon plate, however, gave bend angles similar at 70 F, but considerably lower at -20 F. In fact, a bend angle of three degrees was observed at -20 F in the "C" specimens, while a bend angle of eight degrees was obtained in the "A" specimens.

Fine-grained ductile fractures in the weld were observed in the Mayari-R specimens at 70 F, with fine to medium grained brittle fractures observed in the specimens at 0 F, indicating a transition temperature between 0 F and 70 F. The original material indicated brittle fractures at 70 F, placing the transition temperature of the plate metal above 70 F.

"B" specimens, 0.11 percent carbon, indicated slightly ductile fractures in the welds at -20 F. The unwelded plate material also showed ductile fractures at 70 F and -20 F. The "C" specimens, 0.33 percent carbon steel, exhibited ductile fractures at 70 F, with one exception. A specimen as rolled tested on flat showed a rather brittle fracture. At 0 F and -20 F all specimens including the unwelded plate showed brittle fractures.

Due to the limited number of specimens available, it was impossible to determine the transition temperature of these specimens. Tests could not be made on the material notched in the heat-affected zone and the junction between the weld and plate metal, nor could specimens be tested at temperatures other than those used. However, sufficient data were obtained to reject the Mayari-R and the 0.33 percent carbon steel for use in all welded structures exposed to temperatures approaching 0 F to -20 F.

9. Charpy Impact Tests

Un-notched Charpy impact specimens of each material were tested on the edge and flat at 70 F, 0 F, and -20 F. Only one specimen fractured. A "C" specimen with the high carbon center fractured when tested on the edge with an energy absorption of 127 foot pounds. The fracture was fine-grained and brittle with some necking.

Notched plate specimens of each material were tested on the flat and edge at all three temperatures. Two specimens of each welded material were tested on both the edge and flat at each of the three testing temperatures. One notched specimen of each of the welded materials stress-relieved was tested at each of the three temperatures. In addition, one notched specimen of each plate was tested on the flat and on the edge at 120 F. The notches in all the welded specimens were placed so as to coincide as closely as possible with the center of the weld.

The Charpy impact machine and setup for low temperatures impact tests are shown in Figure 21. This photograph also shows the cooling unit and potentiometer used in producing and measuring the low temperatures. Impact specimens tested during this investigation are shown in Figure 22.

Bar graphs indicating the energy absorbed by these specimens in fracture are shown in Figures, 23, 24, 25, and 26. Impact tests on the Mayari-R steels indicate that 70 F, and possibly 120 F, lie inside the transition zone for this material under the

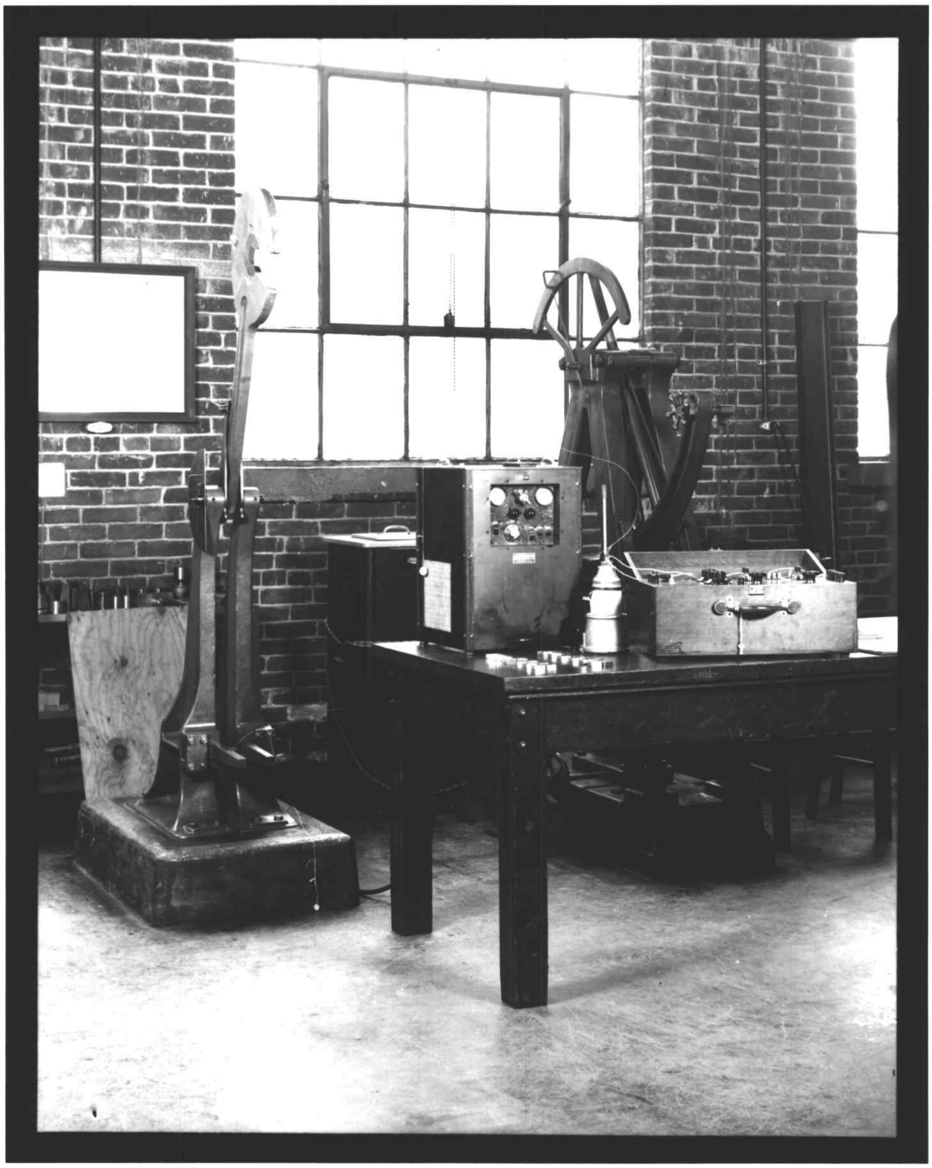


Figure 21. Charpy Impact Machine and Setup For Low Temperature Impact Tests, Including Cooling Unit and Potentiometer

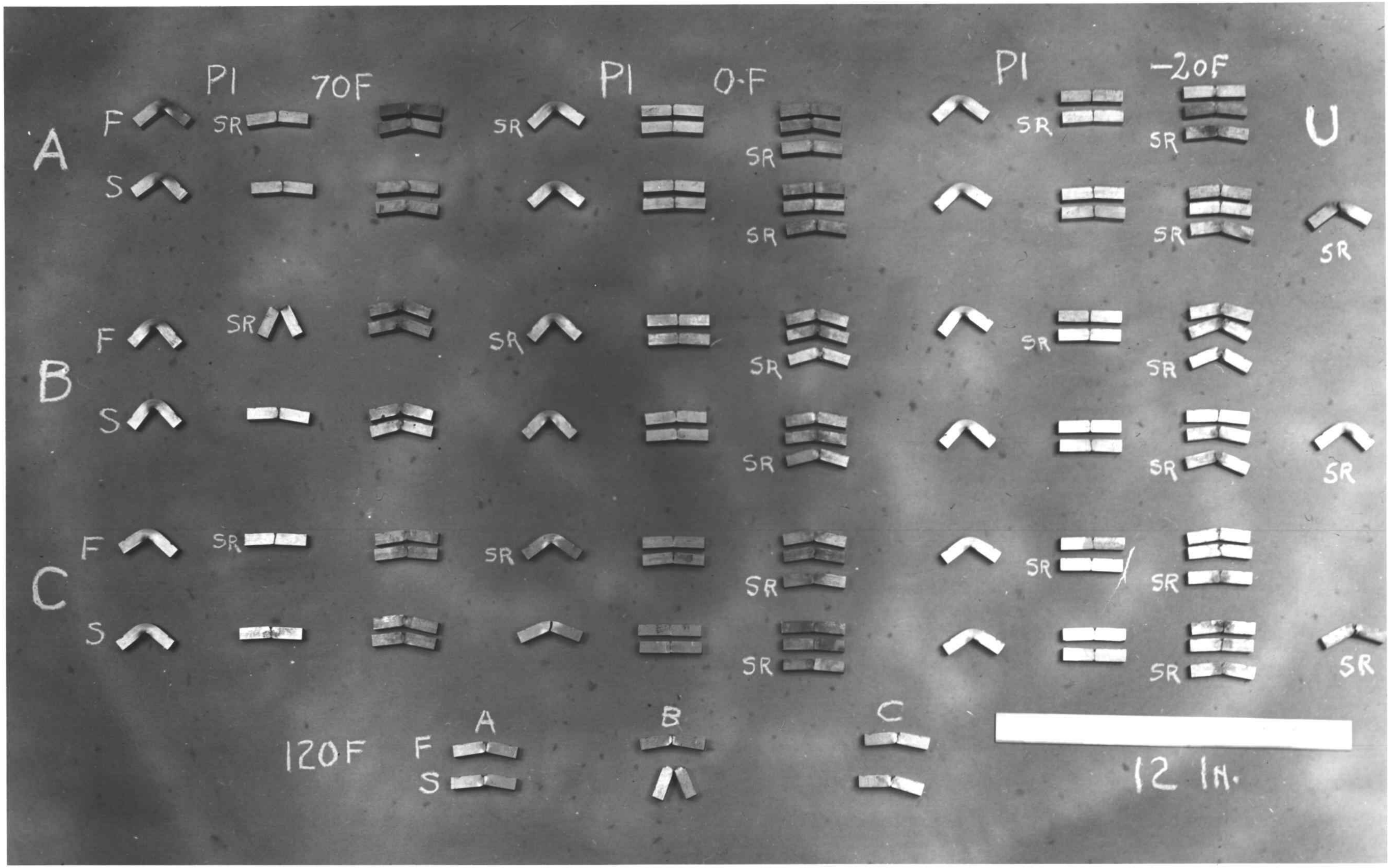
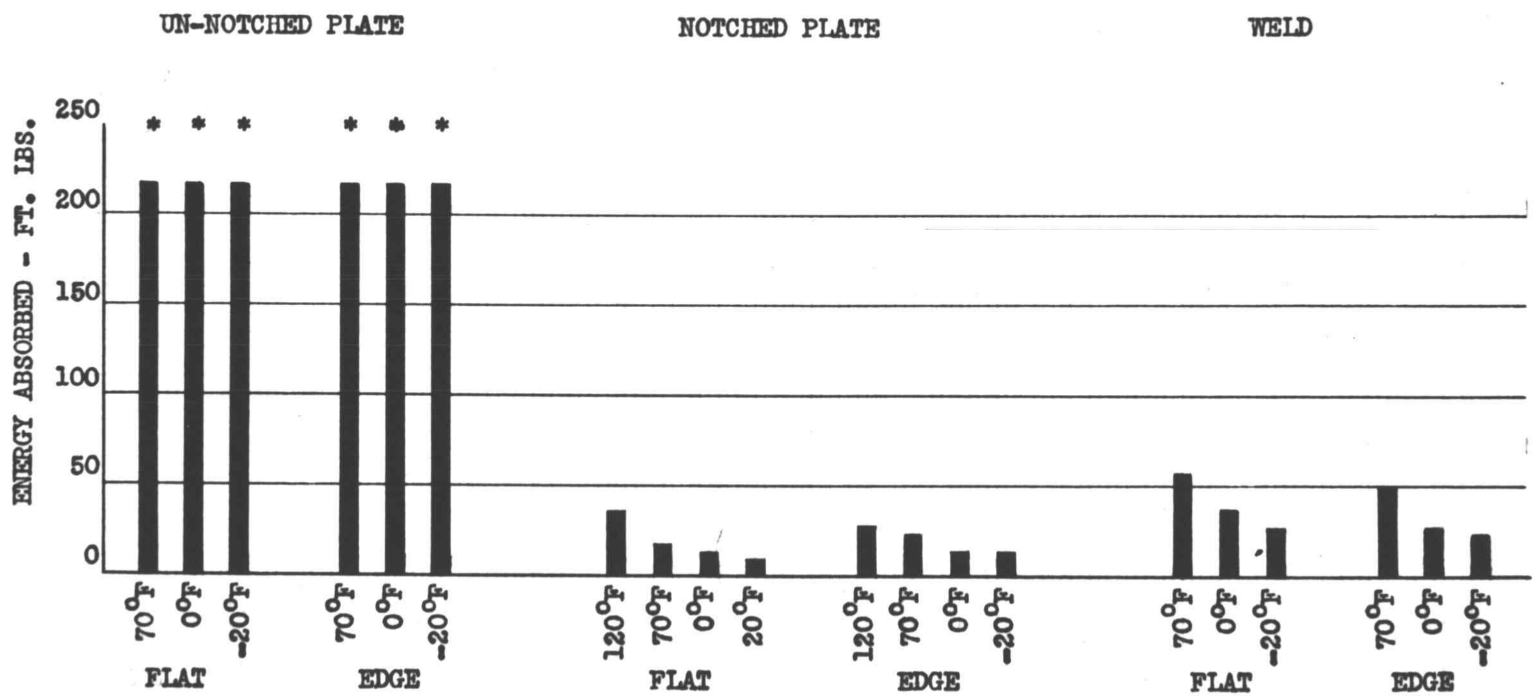


Figure 22. Impact Specimens Tested at 70 F, 0 F, and -20 F

CHARPY IMPACT TESTS
Mayari-R - 0.10% C "A" Specimens

Standard Charpy 10x10x55 mm Specimen
ASTM 45° V-Notch 2 mm Deep

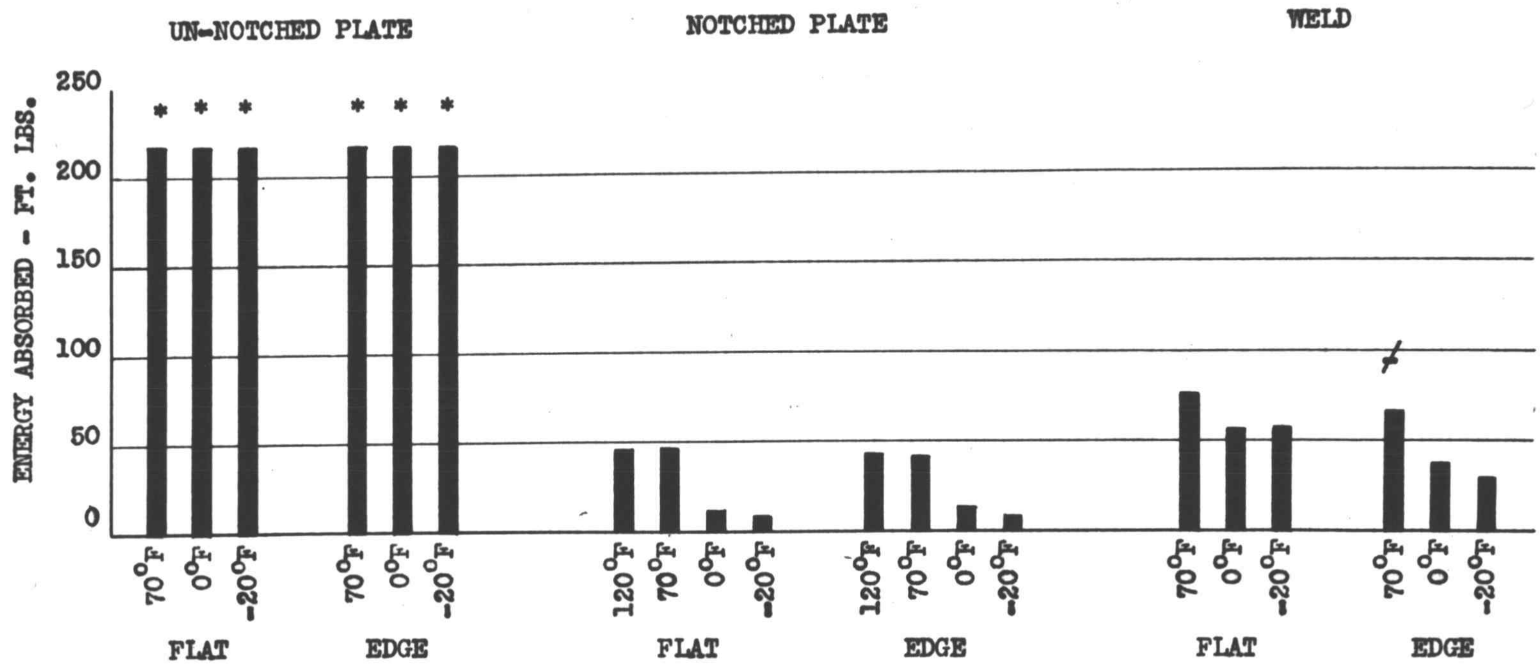


* These specimens not fractured

Figure 23.

CHARPY IMPACT TESTS

0.11% Plain Carbon Steel "B" Specimens
Standard Charpy 10x10x55 mm Specimen
ASTM 45° V-Notch 2 mm Deep

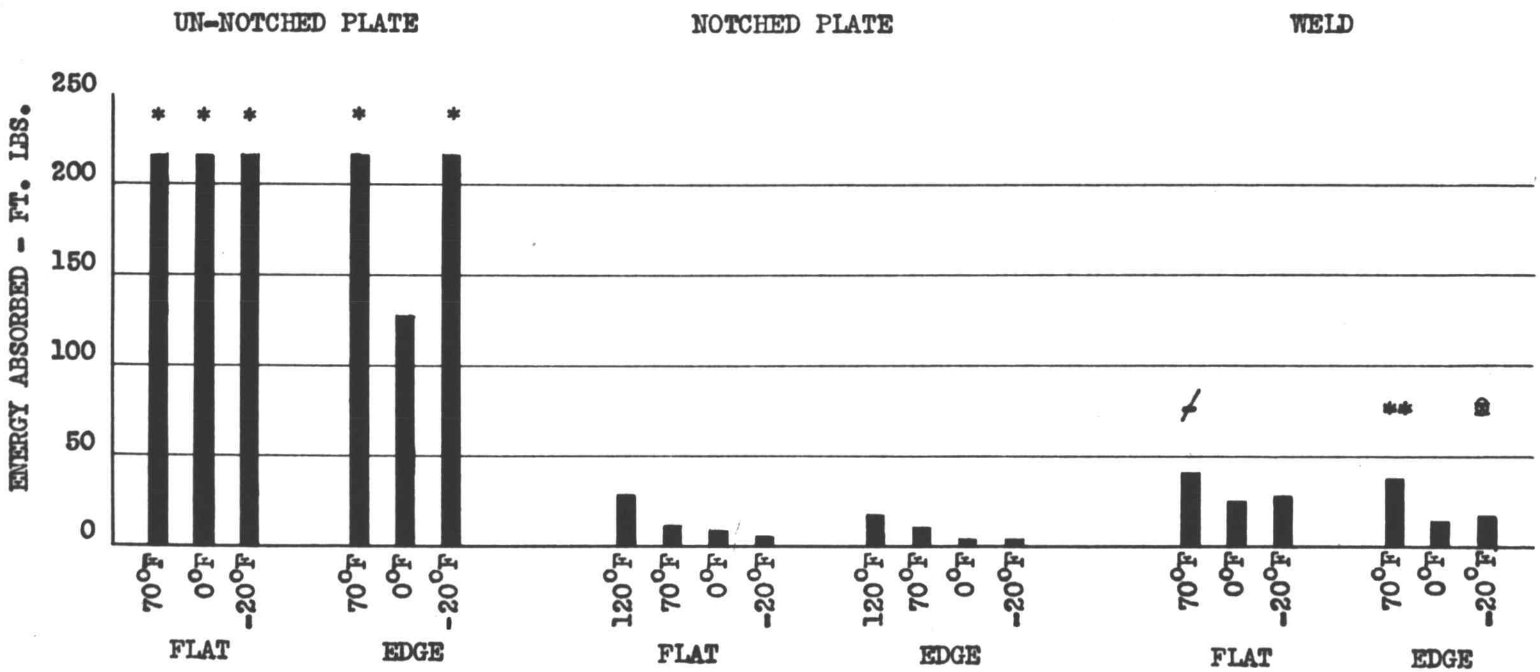


*These specimens not fractured
⌿ Individual values 83 & 52

Figure 24.

CHARPY IMPACT TESTS

0.33% Plain Carbon Steel "C" Specimens
Standard Charpy 10x10x55 mm Specimen
ASTM 45° V-Notch 2 mm Deep



* These specimens not fractured
/ Individual values 54 & 27
** " " 54 & 22
@ " " 27 & 55

Figure 25.

CHARPY IMPACT TESTS

Weld Specimens - Stress Relieved
Standard Charpy 10x10x55 mm Specimen
ASTM 45° V-Notch 2 mm Deep

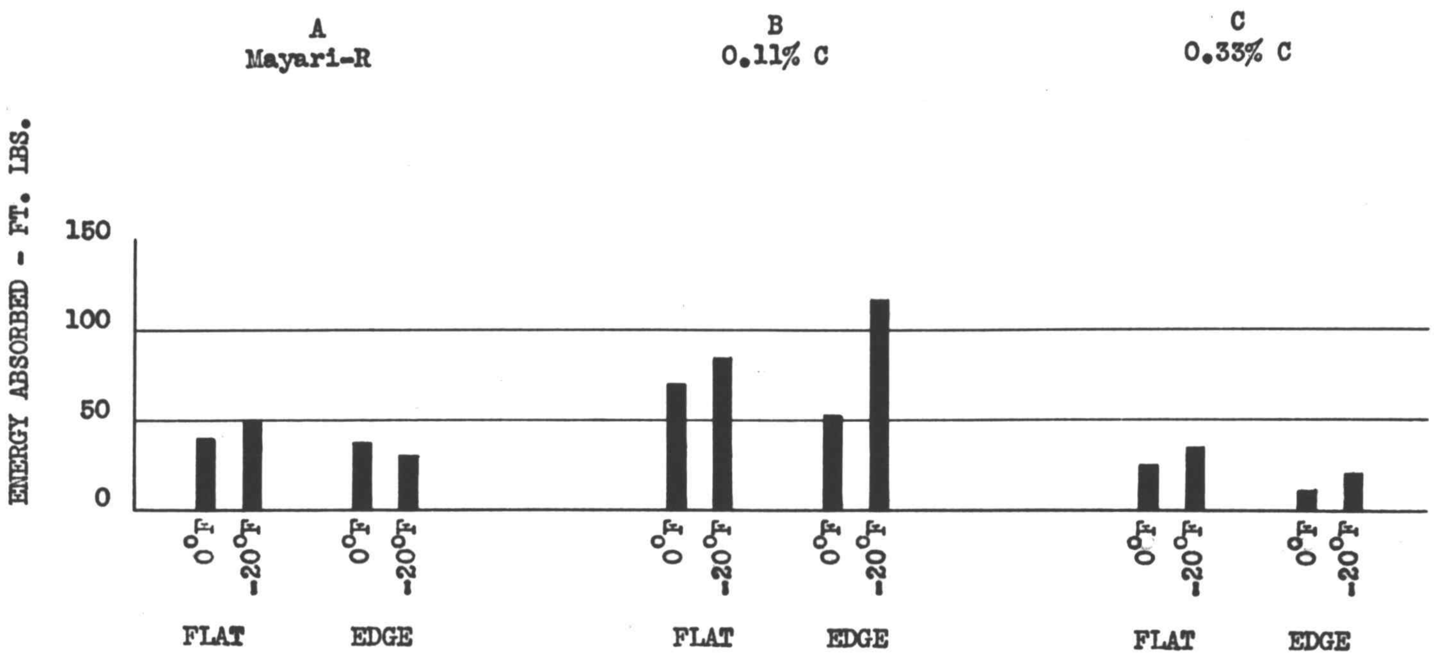


Figure 26.

conditions imposed. The welded specimens gave fairly good values of energy absorption at all three testing temperatures. However, it must be remembered that the conditions imposed made the test one of the weld and quality of welding rather than a test of the material as welded.

Impact values obtained from tests on the 0.11 percent carbon steel ("B" specimens) place the transition zone somewhere between 0 F and 40 F. Again, tests on the welded specimens gave quite satisfactory values at all temperatures.

The 0.33 percent carbon steel ("C" specimens) definitely place 70 F inside the transition zone and probably also 120 F. Welded specimens tested on the flat gave satisfactory values of energy absorption at all temperatures. However, welded specimens tested on edge gave dangerously low values at 0 F and -20 F. Quite probably the high carbon center in some of these specimens had the effect of reducing the energy absorption when tested on edge. As indicated in the data obtained (Table IV) and in the bar graphs of Figures 23, 24, 25, and 26, quite a range of values of energy absorption was obtained on similar specimens tested at the same temperatures. This can be accounted for when it is remembered that previous investigators have found that Charpy impact values do not give an exact transition temperature, but rather a transition temperature zone. When testing specimens at temperatures within this zone, it is possible to obtain energy absorption values ranging from the minimum for a material to the maximum for the material.

TABLE IV
CHARPY IMPACT TESTS

"A" Specimens - Mayari-R 0.10% C Steel
"B" Specimens - 0.11% Plain Carbon Steel
"C" Specimens - 0.33% Plain Carbon Steel

Values are average of two tests, in most cases. Details of test included in original data sheets, Appendix.

UN-NOTCHED PLATE
Energy Absorbed, Ft Lb

	70 F		0 F		-20 F	
Specimen	Flat	Edge	Flat	Edge	Flat	Edge
A	217	217	217	217	217	217
B	217	217	217	217	217	217
C	217	217	217	127+	217	217

+Only specimen broken.

NOTCHED PLATE
Energy Absorbed, Ft Lb

	70 F		0 F		-20 F	
Specimen	Flat	Edge	Flat	Edge	Flat	Edge
A	18	23	12.8	13.2	9.2	12.3
B	48	41	10.3	13.4	8.4	7.1
C	11	9	7.8	3.8	4.7	3.6

NOTCHED WELDED SPECIMENS
Energy Absorbed, Ft Lb

	70 F		0 F		-20 F	
Specimen	Flat	Edge	Flat	Edge	Flat	Edge
A	58	50	35.8	27.8	26.5	22.5
B	76	83 52+	55.7	38.7	58.0	30.0
C	54 27+	54 22+	25.0	14.0	28.4	27.0 5.5+

+Difference in values indicates location in transition zone.

TABLE IV (Cont'd)

NOTCHED WELDED SPECIMENS
STRESS RELIEVED

Energy Absorbed, Ft Lb

	70 F		0 F		-20 F	
Specimen	Flat	Edge	Flat	Edge	Flat	Edge
A			37.7	37.5	28.5	47.0
B			69.5	52.5	119.0	84.0
C			25.5	10.2	19.2	33.5

10. Implication of Test Results

Before any comparison of data obtained is possible, it is necessary to assume that the welds were of equal quality in all specimens. X-ray inspection of the welds and observations made during machining and testing have indicated that this was true in general.

Upon consideration of the results of this test, the 0.11 percent carbon steel will give the most satisfactory service in large all-welded structures when exposed to temperatures in the range of 30 F to -20 F. The Mayari-R and 0.33 percent carbon steel would be doubtful for use in such structures, since definite brittle tendencies were exhibited at temperatures as high as 70 F in the notched bend tests and doubtful tendencies as high as 120 F in the Charpy impact tests.

Since it is practically impossible to insure the absence of all micro-defects in welds, it is necessary to assume the presence of notches. The notched bend tests and the notched impact tests have indicated the behavior of these materials under such conditions. If the low carbon steel is to be used in these structures, the low tensile strength must be considered in the design.

As recommended by Kinzel (11) and Graf (8), it might be possible to improve the qualities of the Mayari-R and the 0.33 percent carbon steel at low temperatures by heat treatment and suitable design. However, such procedure should be the basis for another investigation.

SUMMARY AND CONCLUSIONS

Results obtained in the tension tests followed the expected pattern.

1. Ultimate strength and yield point increased with decrease in temperature. The ductility, as measured by the percentage of elongation in two-inch fractures and the reduction in area, decreased as the temperature decreased.

2. Results of the free bend tests of all three materials indicated the low carbon steel to be the most satisfactory for use at the testing temperatures, and further indicated the presence of a zone of low ductility in some specimens in the plate material near the heat-affected zone. The notched bend tests again indicated the superiority of the low carbon steel for use in temperatures down to -20 F. These tests, however, indicate the desirability of determining the effect of notches placed in the heat-affected zone and at the junction of the parent and weld metal.

The Charpy impact tests indicated that the low carbon steel was the only one of the steels tested that would be satisfactory for service where temperatures as low as 0 F to -20 F might be encountered. If the low carbon steel is to be used for such purposes, it must be remembered that the higher ductility at low temperatures obtained through the use of this steel will be accompanied by a correspondingly lower tensile strength at all temperatures.

The tensile test results place the 0.11 percent carbon steel in either grade B (50,000-60,000 psi) or grade C (55,000-65,000 psi) which would generally be acceptable for structural purposes. These values are from Tentative Specifications, ASTM - 2283-46T. It was interesting to note that this specification does not mention the carbon content of the steels. In view of the effect of carbon on the low temperature characteristics, this is rather surprising. However, it is not considered proper (or practical) to specify both the physical properties required and also the chemical composition.

These tests also indicated the desirability of investigating the effect of notches in the heat-affected zone and at the junction between the parent and weld metal. Location of fractures in the free bend tests was found to correlate fairly well with the location of zones of high hardness in the specimens. These zones of high hardness were also zones of fairly coarse grain size, which might be expected due to the absence of heat treatment.

The effect of stress relief upon the behavior of the material at low temperature was considerably less than might be expected. It must be emphasized that the effect of stress relief on large welded sections should be much greater than on test specimens. In small specimens only, small, locked-up stresses could be present. Therefore, in large sections, the ductility should be increased considerably by stress-relief heat treatments.

In conclusion, the specific purpose of this investigation was accomplished. The relative suitability of the three steels;

the Mayari-R, 0.11 percent carbon steel, and 0.33 percent plain carbon steel, for use in large welded structures to be exposed to minimum temperatures of -20 F was determined. The 0.11 percent carbon steel was found greatly superior to the other two steels, with the Mayari-R and the 0.33 percent carbon steel exhibiting very similar characteristics at the reduced temperatures.

Due to the limited scope of this investigation, it was impossible to accurately locate the brittle transition temperature or zone of these materials. It is felt that, in further investigations of this type, the effects of notches in the heat-affected zone and at the juction between the parent and weld metal should be determined.

The need for standardized test specimens and test procedures for the proper classification of the behavior of structural steels at low temperatures is obvious. Extensive research is under way at the present time at the Battelle Memorial Institute in an attempt to determine the best possible test specimen. Research also is under way at several other laboratories in efforts to correlate test values with various service conditions.

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APPENDIX

BRINELL HARDNESS TESTS. AS RECEIVED AND STRESS RELIEVED

300 kg. Load 70 F

Sample No.		Inp. Diam.	BHN	Average
A-1	Edge	4.90	149	
	"	4.90	149	149
As	Side	4.75	159	
rec'd	"	4.75	159	159
B-1	Edge	5.80	103	
	"	5.75	105	104
As	Side	5.60	112	
rec'd	"	5.50	116	114
C-1	Edge	4.20	207	
	"	4.30	196	191
As	Side	4.65	166	
rec'd	"	4.70	163	164
A-5	Edge	4.90	149	
	"	4.90	149	149
As	Side	4.55	174	
rec'd	"	4.65	166	170
B-5	Edge	5.90	99	
	"	5.85	101	100
As	Side	5.60	112	
rec'd	"	5.60	112	112
C-5	Edge	4.75	159	
	"	4.75	159	159
As	Side	4.75	159	
rec'd	"	4.75	159	159
A-3	Edge	4.90	149	
	"	4.95	146	147
SR	Side	4.70	163	
	"	4.80	156	159
B-3	Edge	5.80	103	
	"	5.75	105	104
SR	Side	5.50	116	
	"	5.55	114	115
C-3	Edge	4.75	159	
	"	4.75	159	159
SR	Side	4.80	156	
	"	4.80	156	156

ROOM TEMPERATURE (70) TENSION TESTS
Two Inch Gage Lengths

	Steel Plate as Received			Welds		
Specimen No.	A-1	B-2	C-2	A-1-5	B-1-5	C-1-5
Kind of spec.	May.as rec'd	1011 as rec'd	1033 as rec'd	M welded	1011weld	1033 weld
Width	0.996	0.997	0.998	1.008	0.994	0.993
Thickness	0.493	0.497	0.507	0.495[+]	0.499[+]	0.510[+]
Area	0.491	0.494	0.505	0.498	0.495	0.505
Y.P.	24,300	16,600	24,000	25,100	17,400	23,100
Ultimate	38,500	29,100	43,000	39,550	29,700	42,400
Break	34,900	24,000	37,500	35,000	24,500	37,500
Elong. in 2"	0.63	0.84	0.59	0.21	0.16	0.20
Final width	0.808	0.697	0.773	0.834	0.695	0.774
Final thick.	0.380	0.312	0.373	0.402	0.316	0.371
Final area	0.308	0.218	0.288	0.336	0.220	0.287
Y.P. psi	49,500	33,100	47,600	50,300	35,200	45,800
Ultimate psi	78,670	58,800	85,100	79,300	60,000	84,000
Over weld brk. psi	71,000	48,600	74,300	70,200	49,400	74,200
Ductile %	31.5	42.0	29.5	(10.5)	(8.0)	(10.0)
RA %	37.2	55.9	43.0	32.5	55.6	43.2
Duct. over fr.				24.5	33.0	28.0
Notes of fractures	Normal, fine gran.	Normal, surf. cracks on face of spec.	Normal with slight lamination	In plate above weld. Normal. Elong. in 2" over weld	In plate below weld. Same surf. cracks as in B-2. Otherwise normal.	In plate above weld. Same type of fract. as C-2

[+]Thickness over beads about 0.60 in.

ROOM TEMPERATURE TENSION TESTS (Cont'd)

Specimen No.	A-4-2	B-4-2	C-4-2	A-6-2	B-6-2	C-6-2
Kind of spec.	M welded#	1011 weld#	1033 weld#	M weld with beads	1011 weld with beads	1033 weld with beads
Width	1.000	1.008	0.995	0.998	0.995	0.993
Thickness	0.498	0.492	0.509	0.497+	0.498+	0.506+
Area	0.498	0.497	0.507	0.496	0.496	0.503
Y.P.	25,040	17,410	25,800	25,400	16,200	23,900
Ultimate	38,600	29,800	45,950	38,760	28,550	42,400
Break	36,380	24,550	45,950	34,000	24,400	37,550
Elong. in 2"	0.36	0.31	0.13	0.33	0.25	0.16
Final width	0.844	0.714	0.951	0.905	0.721	0.764
Final thick.	0.413	0.311	0.465	0.372	0.328	0.370
Final area	0.349	0.222	0.442	0.299	0.237	0.283
Y.P. psi	50,300	35,100	50,900	51,200	32,700	47,500
Ultimate psi	77,800	59,900	90,600	78,100	57,600	84,300
Break psi	73,100	49,400	90,600	68,600	49,200	74,600
Elong. over w.	(18.0)	(15.5)	6.5	(16.5)	(12.5)	(8.0)
RA %	29.9	55.3	12.8	39.7	52.2	43.8
Duct. over fr.	18.0	35.0	6.5	25.5	34.5	29.0
Notes on fractures	Fracture normal about 1" above weld. Inside gage length	Normal in in. above gage length. (Outside)	Break in weld. Fine gr. Normal. Few very small inclusions	Normal. Sl. lamination. Fr. just at lower gage point	Break in in. above gage length. Normal. (outside)	Break in in. above gage length. Normal except for slight lamination. (Outside)

+Average thickness over beads about 0.60 in.

These three with beads ground down even with parent plate.

TENSION TESTS (0 F)

Specimen No.	A-2-5	B-2-5	C-2-5	A-4-5	B-4-5	C-4-5
Kind of spec.	May. welded	1011 weld	1033 weld	May. welded	1011 weld	1033 weld
Width	0.997	0.999	1.007	0.993	0.992	0.999
Thickness	0.495	0.498	0.512	0.495	0.499	0.512
Area	0.492	0.496	0.514	0.491	0.495	0.511
Y.P.	26,300	17,250	24,700	27,000	19,500	26,500
Ultimate	39,900	30,300	44,500	39,850	30,900	48,400
Break	35,800	26,000	39,400	37,100	26,000	47,900
Elong. in 2"	0.43	0.71	0.46	0.26	0.71	0.22
Final width	0.797	0.752	0.814	0.832	0.735	0.980
Final thick.	0.370	0.348	0.391	0.399	0.352	0.568
Final area	0.295	0.261	0.318	0.332	0.259	0.557
Y.P. psi	53,400	34,700	48,100	55,000	39,400	51,800
Ultimate psi	81,100	61,000	86,600	81,100	62,400	94,600
Break psi	72,800	52,400	76,700	75,600	52,500	93,600
Duct. %	(21.5)	(35.5)	(23.0)	(13.0)	(35.5)	11.0
R.A. %	40.0	47.4	38.2	32.5	47.7	7.2+
Elong. over w.	10.0	10.0	10.0	13.0	12.0	11.0
Notes on fracture	Normal, about 1/4" above weld. Duct. meas. from center of weld to 2" mark. Fine, gran.	Diag. shear fract. Outside weld, in. 2nd in. above weld. Fine, fibrous appearing	Sl. laminated R. outside W in 2nd in. above W.	Fine, gran. square fract. Little necking. At 1st in. below weld.	Diag. shear fracture in 2nd in. above weld. Sl. laminated, rough	Rough, jagged fr. thru weld. Partly fine & partly coarse

+On basis of t = 0.60 in.

TENSION TESTS (0 F)(Cont'd)

Specimen No.	A-3-5	B-3-5	C-3-5
Kind of spec.	May. anneal. weld	1011 anneal. weld	1033 anneal. weld
Width	1.001	0.996	0.996
Thickness	0.495	0.500	0.511
Area	0.496	0.497	0.508
Y.P.	28,800	16,800	23,200
Ultimate	40,500	30,200	45,900
Break	40,000	27,400	42,600
Elong. in 2"	0.25	0.56	0.40
Final width	0.928	0.810	0.835
Final thick.	0.456	0.382	0.408
Final area	0.423	0.309	0.341
Y.P. psi	58,000	33,800	45,600
Ultimate psi	81,700	60,700	90,500
Break psi	80,600	55,100	84,000
Duct. %	(12.5)	(28.0)	(20.0)
R.A. %	14.8	37.8	32.9
Elong. over w	12.5	13.5	9.5
Notes on fracture	Med. gran. B. fracture about 1/2" below weld	Diagonal shear fracture. Med. rough with laminations. At 1" below weld	Rough diagonal fracture. In 2nd in. above weld

TENSION TESTS (-20 F)
Two Inch Gage Length

Specimen No.	A-5-2	B-5-2	C-5-2	A-5-5	B-5-5	C-5-5
Kind of spec.	May. weld	1011 weld	1033 weld	May. weld	1011 weld	1033 weld
Width	0.995	1.004	0.995	1.004	1.003	0.999
Thickness	0.495	0.500	0.510	0.495	0.501	0.511
Area	0.492	0.502	0.506	0.497	0.502	0.509
Y.P.	25,100	18,800	29,200	27,300	18,600	25,800
Ultimate	40,400	31,000	43,500	41,200	31,400	47,450
Break	34,200	27,200	43,500	38,200	26,000	47,450
Elong. in 2"	0.56	0.57	0.15	0.46	0.69	0.21
Final width	0.794	0.794	0.981	0.859	0.745	0.980
Final thick.	0.371	0.376	0.600	0.396	0.342	0.588
Final area	0.282	0.299	0.589	0.341	0.255	0.577
Y.P. psi	51,000	37,400	57,800	54,900	37,100	50,700
Ultimate psi	82,200	61,800	86,100	82,800	62,600	93,100
Break psi	69,400	54,200	86,100	76,800	51,800	93,100
Duct. %	(28.0)	(28.5)	7.5	(23.0)	(49.2)	10.5
R.A. %	40.8	40.4	2.2	31.6	34.5	3.9
Elong. over w	10.0	10.5	7.5	12.0	12.0	10.5
Notes on fracture	R.B. fract. in 2nd in. above weld. Somewhat laminated	Fine, gran. diag. shear fract. in 2nd in. above weld	R. med. gran. fract. in weld. Br.	Square break Med. gran. in 2nd in. below weld	Normal diag. shear break in 2nd in. below weld Sl. lamin.	Coarse R.B. failed in weld

TENSION TESTS (-20 F)(Cont'd)

Specimen No.	A-6-5	B-6-5	C-6-5
King of spec.	May. anneal. weld	1011 anneal. weld	1033 anneal. weld
Width	0.990	0.993	1.000
Thickness	0.495	0.500	0.506
Area	0.489	0.496	0.506
Y.P.	27,300	18,550	25,500
Ultimate	40,600	30,100	44,500
Break	35,400	24,900	39,100
Elong. in 2"	0.55	0.69	0.48
Final width	0.808	0.741	0.808
Final thick.	0.373	0.346	0.388
Final area	0.301	0.257	0.314
Y.P. psi	55,700	37,400	50,300
Ultimate psi	82,900	60,700	87,900
Break psi	72,300	50,200	77,200
Duct. %	(27.5)	(34.5)	(24.0)
R.A. %	38.4	48.2	38.1
Elong. over w	13.0	11.5	11.5
Notes on fracture	Fine, gran. Sl. laminated Sq. break at 1" below weld	R. Diagonal shearing fract. in 2nd in. below weld	B. Rather fibrous. In 2nd in above weld

FREE BEND TESTS (Flat)
Room Temperature (70 F)

Span - 6 in. 1.20 in. (6 cm) pin. Amsler Machine
Length of specimen transverse to direction of rolling

Sample No.	Height, in.	Width, in.	Load at break lb	Fracture angle, °	Type of fracture
A-1-2	0.493	0.998	4,500	58	3/16" from edge of weld.
B-1-2	0.497	0.995	3,360	180	Cracked at 0.50" rad. at edge of weld.
C-1-2	0.509	1.001	4,810	80	At edge of weld in heat-affected zone.
A-5-9	0.495	0.995	4,400 YP 3,200	180	Cracked at 0.55" rad. at edge of weld.
B-5-9	0.501	0.998	3,440 YP 2,180	180	Cracked just as it was bent flat.
C-5-9	0.508	0.997	4,820 YP 3,000	180	Cracked through edge of weld at 0.45" rad.
SR A-6-7	0.494	0.998	4,400 YP 3,100	93	1/4" from edge of weld.
SR B-6-7	0.501	0.998	3,200 YP 2,100	180	Cracked at edge of weld, 0.37" radius.
SR C-6-7	0.507	0.998	4,540 YP 2,600	180	Cracked at edge of weld, 0.60" radius.

Height, in.: Thickness of plate
Width, in.: About avg. 0.60 over weld beads

FREE BEND TESTS (Edge)
(Conditions same as for flat bend tests)

Sample No.	Height, in.	Width, in.	Load at break lb	Fracture angle, °	Type of Fracture
	Width of specimen	About avg. 0.60 over weld beads			
A-1-6	0.997	0.494	9,300 YP 5,800	42	Cracked diagonally across weld edges.
B-1-6	0.998	0.499	7,450 YP 4,320	119	Cracked along one edge of weld.
C-1-6	0.995	0.510	10,200 YP 5,300	45	Brittle fracture at edge of weld, in HA zone
A-4-3	1.000	0.494	8,550 YP 5,700	23	Cracked diagonally across weld edges.
B-4-3	1.000	0.499	7,620 YP 4120	180	Partial crack at about 0.46" rad.
C-4-3	0.999	0.504	9,630 YP 5,400	22	Brittle crack through weld.

FREE BEND TESTS
(Tested at 0 F)

Span 6 in. 1.20 in. (6 cm) pin. Amsler Machine
Length of specimen transverse to direction of rolling

	Specimen No.	Height, in.	Width, in.	YP & Max. Tested Flatwise	Fracture Angle	Type of Fracture
	A-1-10	0.496	0.998	3500 4900	59	Br., F.Gr. Near edge of weld.+
	B-1-10	0.501	0.997	2300 3650	Not broken	Bent to 120° without breaking.
	C-1-10	0.512	0.998	3200 5150	Not broken	Bent to 120°.
	A-4-7	0.495	0.999	3250 4700	74	Br., F.Gr. At edge of weld+.
	B-4-7	0.498	1.003	2400 3720	Not broken	Bent to 120°
	C-4-7	0.509	1.000	3200 5220	Not broken	Bent to 120°
	A-3-2	0.497	1.001	3100 4500	70	Br., F.Gr. At edge of weld.+
SR	B-3-2	0.501	1.001	2100 3300	Not broken	Bent to 120°
	C-3-2	0.513	0.993	2650 4950	95	Br., F.Gr. Broke at edge of weld.+
				Tested on Edge		
	A-2-2	1.005	0.495	5500 9580	45	B.,V-shaped brk. at edge of W.,R.+
	B-2-2	1.003	0.497	4300 7850	85	B.,R., in heat-affected zone.+
	C-2-2	0.999	0.510	5400 10200	44	B.,Diag.across weld.Ht.af.Z.start
	A-4-9	0.999	0.496	5650 9400	41	B.Diag.across weld Ht.af.zone start.+
	B-4-9	0.999	0.499	4360 7880	Not broken	Bent to about 115°. Ductile.
	C-4-9	0.998	0.510	5600 10400	28	B.R. Partly in weld.
	A-3-6	0.995	0.496	5600 10440	51	B.V-shaped brk. along ht.af.z.R.+
SR	B-3-6	0.999	0.499	3980 7540	Not broken	Ductile.Bent to about 113°.
	C-3-6	0.996	0.510	5300 10520	42	B.V-shaped brk. along edge of w.+

+Fractures in heat-affected zone.

FREE BEND TESTS
(Tested at -20 F)
Tested Flatwise

	Specimen No.	Height, in.	Width, in.	YP & Max. Tested Flatwise	Fracture Angle	Type of Fracture
	A-2-6	0.495	1.000	3100 4560	46	B.F.Gr. At edge of weld
	B-2-6	0.498	1.001	2300 3450	Not broken	Bent to 116° without brk.
	C-2-6	0.510	0.999	2900 4980	91	B.F.Gr. Fract. in HAZ.
	A-5-3	0.495	0.998	3160 4640	Not broken	Bent to 103° without br.Duct.
	B-5-3	0.500	1.000	2290 3500	Not broken	Bent to 111° without br.Duct.
	C-5-3	0.511	0.995	2900 4940	Not broken	Bent to 114° without brk.
	A-6-3	0.496	1.004	3100 4540	101	B.Edge of weld in HAZ.
SR	B-6-3	0.498	0.992	2000 3310	Not broken	Bent to 112° without br.Duct.
	C-6-3	0.506	0.999	2650 4640	65	About 1/4" from edge of weld.B.
				Tested on Edge		
	A-2-10	0.997	0.496	5600 8870	20	B.Edge of weld in HAZ.
	B-2-10	0.999	0.497	4470 7880	99	D.Brk.partly in weld & HAZ.
	C-2-10	0.992	0.511	5350 10580	47	Sl.D. HAZ. Fine granular.
	A-5-7	0.991	0.494	5680 9550	38	Sl.D. At edge of weld.F.Gr.
	B-5-7	1.001	0.499	4540 8120	98	D. HAZ. R. Fine granular.
	C-5-7	0.994	0.510	5800 10260	23	B.R.Starts in HAZ, thru weld.
	A-6-9	1.000	0.497	5750 9440	39	B.R. HAZ, edge of weld.
SR	B-6-9	1.002	0.498	4100 7650	Not broken	D.Bent to 114° without brk.
	C-6-9	0.994	0.506	5200 10100	36	B.Heat-affected zone. F.Gr.

NOTCHED BEND TESTS (Flat)
Room Temperature (70 F)

Span 6 in. 1.20 in. (6 cm) pin. Amsler Machine
Notch - Standard Charpy, milled to 0.079 in.
below plate level
Length of specimen transverse to direction of rolling

Specimen No.	Height, in. (Thickness of plate)	Width, in. (About average 0.60" over welds)	Yield Point lb	Load at Max. lb	Fracture Angle-Deg.	Type of Fracture
A-1-4	0.497	0.998	2700	3440	30	Fine grain, ductile in w.
B-1-4	0.500	0.997	2060	3210	80	Fine,duct., tearing in weld(not broken).
C-1-4	0.511	1.007	2800	4100	45	Fine grain, duct.in w.
A-5-12	0.498	0.997	2660	3440	33	Fine grain, duct. (not broken).
B-5-12	0.498	0.993	1950	3100	66	Fine,duct.,tearing in weld (not broken).
C-5-12	0.509	0.999	2600	4000	24	Rather brittle, but not completely broken.
SR A-3-4	0.494	0.997	2820	3830	36	Fine grained,duct. in weld.(Not broken).
SR B-3-4	0.501	0.999	1820	3040	64	Fine,duct., tearing in weld.(Not broken).
SR C-3-4	0.511	0.997	2560	4120	41	Fine grained. Ductile in weld.(Not broken).

NOTCHED BEND TESTS (Edge)
(Same conditions as for notched bend tests, flat)

Specimen No.	Height, in.	Width, in.	Yield Point lb	Load at Max. lb	Fracture Angle-Deg.	Type of Fracture
A-1-8	1.004	0.495	5800	7900	29	Fine,duct. at junction between weld & pl.
B-1-8	0.998	0.499	4300	7100	48	Fine,duct. at junction between weld & pl.
C-1-8	1.000	0.512	5300	8500	26	Fine, duct.thru weld.
A-4-8	0.999	0.494	5600	7840	25	Fine,duct. at junction between weld & pl.
B-4-8	1.001	0.498	4150	6920	44	Fine,duct.thru weld & at junction of w & pl.
C-4-8	1.001	0.509	5500	8080	17	Fine,duct. at junction of weld and pl.
SR A-6-8	1.003	0.497	5500	7900	35	Fine grain, ductile thru weld.
SR B-6-8	0.994	0.496	3570	8160	59	Fine gr., duct. thru w & at junct. of w & pl.
SR C-6-8	0.998	0.504	4900	7850	27	Fine gr., ductile thru w & at junct. of w & pl.
			Original Plate			
A-2	0.998	0.492	4440	6300	10	Sudden,F.Gr. Brittle (Not broken).
B-1	0.998	0.497	3000	5200	31	F.,duct.(Not broken)
C-1	0.999	0.510	4500	6630	11	Sudden. F.Gr. Sl.duct.

Height: Thickness of plate

Width: About average 0.60" over welds

NOTCH BEND TESTS
(Tested at 0 F)

Tested Flatwise

	Specimen No.	Height in.	Width in.	YP & Max.	Fracture Angle	Type of Fracture
	A-1-11	0.495	1.000	2990 3680	24	Med.Gr.thru w.B.
	B-1-11	0.500	0.994	2160 3270	82	Sl.D.Tearing brk thru weld.R.
	C-1-11	0.512	1.007	2750 4100	24	B.R.Gran. thru weld.
	A-4-10	0.495	1.000	2700 3560	20	B.Med.Gran.,R. thru weld.
	B-4-10	0.499	1.000	2200 3300	68	Sl.D.Tearing brk.in weld.R.
	C-4-10	0.511	0.995	2650 3000	10	B.Fine gran. thru weld.
SR	A-3-11	0.497	1.004	2900 3660	21	B.Med.Gran. thru weld.
SR	B-3-11	0.501	0.999	1920 3010	78	R.Sl.D.Tearing thru weld.Sm. lamination.
SR	C-3-11	0.512	1.002	2620 3920	24	R.thru weld Med.gran.

Tested on Edge

	Specimen No.	Height in.	Width in.	YP & Max.	Fracture Angle	Type of Fracture
	A-2-4	0.998	0.495	5800 8000	17	B.Med.Gran.thru weld.
	B-2-4	0.999	0.498	4200 7550	51	Sl.D.R.Diag. across weld.
	C-2-4	0.998	0.510	5600 8600	22	B.Fine gran.
	A-4-12	0.995	0.494	5550 8060	23	R.Along edges of weld.Med.gran.
	B-4-12	0.998	0.498	4280	43	Sl.D.Along edges of weld.Fine gr.
	C-4-12	1.000	0.509	6500 6500	3	Failed first in high carb.ctr.F.
SR	A-3-10	1.001	0.496	5800 8300	25	Sl.D.Very R. fract.Fine gr.
SR	B-3-10	1.003	0.500	4000 7250	54	R.Sl.D.Along edges ofW.intoHAZ
SR	C-3-10	0.999	0.510	5500 8600	22	B.R.Diag.across on edges of w.

NOTCH BEND TESTS
(Tested at -20 F)

	Specimen No.	Height in.	Width in.	YP & Max.	Fracture Angle	Type of Fracture
	Tested Flatwise					
	A-2-8	0.495	0.996	2920 3560	16	B.Med.gran.,thru weld
	B-2-8	0.497	0.997	2170 3160	84	Sl.D.F.gran.thru weld.
	C-2-8	0.510	0.998	2850 4100	29	B.Med.gran.thru weld.
	A-5-8	0.495	0.998	2900 4160	28	B.Med.gran.thru weld.
	B-5-8	0.497	1.005	2320 3350	63	Sl.D.Fine gran. Thru weld to HAZ.
	C-5-8	0.510	0.998	2800 3720	20	R.Gran. thru weld.
SR	A-6-10	0.495	0.999	2860 3530	19	B.Med.gran. thru weld.
SR	B-6-10	0.499	0.994	2020 3000	66	Sl.D.Fine gran. thru w.to op.edge.
SR	C-6-10	0.506	1.000	2600 3380	22	B.Fine gran.thru weld.
	Tested on Edge					
	A-2-11	1.000	0.494	5800 7860	14	R.Gran.B. thru weld.
	B-2-11	1.000	0.498	4260 7560	59	Sl.D.Gran.thru weld to edge.
	C-2-11	0.998	0.510	5410 8360	14	B.R.Med gran. thru weld.
	A-5-10	0.996	0.494	5700 7700	16	B.Med.R.gran. thru weld.
	B-5-10	0.996	0.498	4510 7650	51	R.D. thru edges of w. into HAZ.
	C-5-10	0.999	0.509	5800 8130	10	R.B.thru weld. Sm.blowhole.
SR	A-6-12	1.000	0.494	5800 7960	26	R.B.thru weld. Med. gran.
SR	B-6-12	1.000	0.496	3950 7160	49	R.tearing brk. into HAZ.
SR	C-6-12	0.997	0.504	5300 8520	23	R.into edges of weld.
Original Material	A-3	0.495	1.001	5100 6550	8	B.Fine gran.Med. R.fracture.
Original Material	B-3	0.500	1.004	3280 5470	16	Very sl.D. Fine gran.fracture.
Original Material	C-3	0.511	1.000	5800 5800	3	Very B.Fine gran. fracture

CHARPY IMPACT TESTS
(120 F)

Standard 10 x 10 x 55 mm specimens with 2 mm ASTM V-notch
Length of specimen transverse to direction of rolling
(B denotes brittle fracture, D ductile Fracture, S slightly, V very, and R rough). (U un-notched, F flat, and E edge).

Specimen No.	Material	Notch Position		Angle	Ft Lb Absorbed	Type of Fracture
A-5-4	Plate		F	130.6	32	Pt.B.Pt.gran. & fibrous.
B-5-4	Plate		F	121.6	46	Pt.gr.& fibrous.
C-5-4	Plate		F	133.0	29	B.Med granular.
A-5-4	Plate		E	133.7	28	Pt.D,Mostly fine fibrous.
B-5-4	Plate		E	124.0	43	Pt.D,Pt.gr. & fibrous.
C-5-4	Plate		E	142.4	17	B.Med.gran.
				(70 F)		
A-1-3	Plate	U	F	0	217	Unbroken.
B-1-3	Plate	U	F	0	217	Unbroken.
C-1-3	Plate	U	F	0	217	Unbroken.
A-2-3	Plate	U	E	0	217	Unbroken.
B-2-3	Plate	U	E	0	217	Unbroken.
C-2-3	Plate	U	E	0	217	Unbroken.
A-3-7	Plate		F	142.0	18	B.Fine gran.
B-3-7	Plate		F	116.5	48	D.R.Fibrous.
C-3-7	Plate		F	147.6	11	B.Med.gran.
A-4-6	Plate		E	138.2	23	B.Fine gran.
B-4-6	Plate		E	125.3	41	FD.Partly gr. & fibrous.
C-4-6	Plate		E	149.4	9	B.Med. gran.
A-1-3	Weld		F	114.0	60	D.Fine gr.thru weld.
B-1-3	Weld		F	110.1	67	D.FR. Fibrous.
C-1-3	Weld		F	117.3	54	D.Fine gr. thru weld.
A-1-7	Weld		E	115.5	57	RD.Fine gr. thru weld.
B-1-7	Weld		E	101.2	83	RD.Fine gr. thru weld.
C-1-7	Weld		E	117.2	54	RD.Fine gr. thru weld.

CHARPY IMPACT TESTS
(70 F)(Cont'd)

Specimen No.	Material	Notch Position	Angle	Ft Lb Absorbed	Type of Fracture
A-5-11	Weld	F	116.8	56	D.Fine gr. thru weld.
B-5-11	Weld	F	100.2	85	RD.Into pl.mat.
C-5-11	Weld	F	134.0	27	Sl.D. Rough, granular.
A-4-4	Weld	E	124.0	43	FDR.Fine gr. thru weld.
B-4-4	Weld	E	118.3	52	RD. Fibrous.
C-4-4	Weld	E	138.6	22	FB.R. partly granular.

CHARPY IMPACT TESTS
(0 F)

(Conditions same as for 70 F)

Specimen No.	Material	Notch Position	Angle	Ft Lb Absorbed	Type of Fracture
A-3-3	Plate	U F	0	217	Unbroken.
B-3-3	Plate	U F	0	217	Unbroken.
C-3-3	Plate	U F	0	217	Unbroken.
A-4-4	Plate	U F	0	217	Unbroken.
B-4-4	Plate	U E	0	217	Unbroken.
C-4-4	Plate	U E	79.0	127	Fine gr.B.With some necking.
A-1-9	Plate	Flat	145.4	13.4	B.Fine, gran.
B-1-9	Plate	Flat	151.0	7.4	B.Med. gran.
C-1-9	Plate	Flat	151.7	6.8	B.Fine,gran.
A-2-9	Plate	Edge	146.1	12.6	B.Fine,gran.
B-2-9	Plate	Edge	144.2	15.3	B.Fine,gran.
C-2-9	Plate	Edge	155.3	3.6	B.Fine, gran.
A-5-6	Plate	Flat	146.3	12.2	B.Fine,gran.
B-5-6	Plate	Flat	145.7	13.2	B.Med.gran.
C-5-6	Plate	Flat	149.6	8.9	B.R.Med.gran.
A-5-6	Plate	Edge	145.0	13.9	B.Fine,gran.
B-5-6	Plate	Edge	147.0	11.6	B.Fine,gran.
C-5-6	Plate	Edge	155.0	3.9	B.Fine,gran.
A-1-9	Weld	Flat	130.3	32.2	SD.R.Fine gran. thru weld.
B-1-9	Weld	Flat	120.3	45.0	D.R.Fine,Ptly. into pl.
C-1-9	Weld	Flat	129.5	34.0	SD,Medgr.thru weld.
A-2-3	Weld	Edge	132.5	29.5	B.Fine gr. thru weld.
B-2-3	Weld	Edge	130.5	32.0	SD.R.Fine gr. thru weld.
C-2-3	Weld	Edge	139.3	21.5	B.Sl.flaw,F.Gr.
A-3-3	Weld	U Spares			
B-3-3	Weld	U Spares			
C-3-3	Weld	U Spares			
A-3-7	Weld	Edge	127.6	37.5	SD.Fine gr.thru weld.
B-3-7	Weld	Edge	118.0	52.5	D.R.Fine gr. into plate.
C-3-7	Weld	Edge	148.2	10.2	B.Fine,gran.
A-3-9	Weld	Flat	127.4	37.7	SD.Fine gr. thru weld
B-3-9	Weld	Flat	109.1	69.5	D.R.Fine gr. into plate
C-3-9	Weld	Flat	136.0	25.5	B.Fine gr.thru w.

CHARPY IMPACT TESTS
(0 F)(Cont'd)

Specimen No.	Material	Notch Position	Angle	Ft Lb Absorbed	Type of Fracture
A-4-6	Weld	Flat	126.5	39.5	B.Fine gr. thru weld.
B-4-6	Weld	Flat	110.1	66.5	D.R.Fine gr. Into plate.
C-4-6	Weld	Flat	143.4	16.0	B.Fine gr. thru weld.
A-4-11	Weld	Edge	135.5	26.2	B.Fine gr. thru weld.
B-4-11	Weld	Edge	122.7	45.5	SD.Fine gr. R. thru weld.
C-4-11	Weld	Edge	152.0	6.5	B.Fine gr. thru weld.

CHARPY IMPACT TESTS
(-20 F)

(Conditions same as for 70 F)

Specimen No.	Material	Notch Position	Angle	Ft Lb Absorbed	Type of Fracture
A-1-7	Plate	U F	0	217	Unbroken.
B-1-7	Plate	U F	0	217	Unbroken.
C-1-7	Plate	U F	0	217	Unbroken.
A-2-7	Plate	U E	0	217	Unbroken.
B-2-7	Plate	U E	0	217	Unbroken.
C-2-7	Plate	U E	0	217	
A-3-9[+]	Plate	Flat	120.7	(48.0)[+]	B.Fine, gran.
B-3-9	Plate	Flat	147.0	11.6	B.Fine, gran.
C-3-9	Plate	Flat	152.5	6.0	B.Fine, gran.
		[+]Not a fair test, hammer struck side of spec. support.			
A-4-11	Plate	Edge	147.0	11.6	B.Med. gran.
B-4-11[+]	Plate	Edge	137.5	(24.0)[+]	B.Fine, gran.
C-4-11	Plate	Edge	154.6	4.1	B.Fine, gran.
		[+]Not a fair test, hammer struck plywood guard.			
A-5-11	Plate	Flat	149.0	9.2	B.R. gran.
B-5-11	Plate	Flat	150.0	8.4	B.Fine, gran.
C-5-11	Plate	Flat	153.9	4.7	B.Fine, gran.
A-5-11	Plate	Edge	145.8	13.0	B.Med.R. gran.
B-5-11	Plate	Edge	151.3	7.1	B.Fine, gran.
C-5-11	Plate	Edge	155.9	3.2	B.Fine, gran.
A-2-7	Weld	Flat	132.2	29.0	Sl.D.Fine gr. thru weld.
B-2-7	Weld	Flat	121.7	47.0	D.R., thru w.
C-2-7	Weld	Flat	133.0	28.4	Sl.D.Med.R.thru weld.
A-2-9	Weld	Edge	137.4	23.5	Sl.D.Fine gr. thru weld.
B-2-9	Weld	Edge	138.4	22.5	Sl.D.Med.R. thru weld.
C-2-9	Weld	Edge	135.0	27.0	Sl.D.Med.R. thru weld.
A-5-4	Weld	Flat	137.1	24.0	Sl.D.Fine gr. thru weld.
B-5-4	Weld	Flat	108.3	70.0	D.R.thru weld.
C-5-4[+]	Weld	Flat	146.4	12.2[+]	B.R.thru weld.
		[+]Small flaw (crack or incl.) in weld.			
A-5-6	Weld	Edge	140.0	21.0	Sl.D.Fine gr. thru weld.
B-5-6	Weld	Edge	127.3	37.5	D.Fine gr.thru weld.
C-5-6	Weld	Edge	153.0	5.5	B.Fine gr.thru weld.

CHARPY IMPACT TESTS
(-20 F)(Cont'd)

Specimen No.	Material	Notch Position	Angle	Ft Lb Absorbed	Type of Fracture
A-6-4	Weld	Edge	132.6	28.5	Sl.D.Med.R. thru weld.
B-6-4	Weld	Edge	82.7	119.0	D.R.thru weld into plate.
C-6-4	Weld	Edge	141.3	19.2	Sl.D.Fine gr. thru weld.
A-6-6	Weld	Flat	121.3	47.0	Sl.D.Fine gr. thru weld.
B-6-6	Weld	Flat	101.0	84.0	D.R.Thru weld.
C-6-6	Weld	Flat	131.0	33.5	Sl.D.Fine gr. thru weld.
A-6-11	Weld	U	31.0		
B-6-11	Weld	U			Not broken.
C-6-11	Weld	U	80.5		