DEPARTMENT OF MINES AND RESOURCES

BUREAU OF MINES

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Ottawa, April 26, 1946.

REPORT

of the

ORE DRESSING AND METALLURGICAL LABORATORIES.

Investigation No. 2031.

Metallurgical Examination of Pressure-Welded Reinforcing Steel Bars.

(Copy No. 8.)

Bureau of Mines
Division of Metallic
Minerals

Physical Metallurgy
Research Laboratories

CANADA
DEPARTMENT
OF
MINES AND RESOURCES
Mines and Geology Branch

O T T A W A April 16, 1946.

R E P O R T

of the

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Introduction:

On February 10, 1946, Mr. R. J. Anderson, Manager, Unionmelt Service, Dominion Oxygen Company Limited, Toronto, Ontario, requested the assistance of these Laboratories in the problem of pressure welding of reinforcing steel bars. This material is made by re-rolling old rail steel at the Burlington Steel Co., Hamilton, Ontario, and this latter company is interested in the process as applied in the field. Prior to this request the above companies had conducted a series of experiments on 1"-diam. bars and had attempted to evaluate weld quality by means of bend tests. The striking characteristic

(Introduction, cont'd) -

of these tests was the inconsistency of bend test results.

On February 18, 1946, the writer visited the Toronto plant of the Dominion Oxygen. Test welds were made by Mr. J. Ross, engineer of the Dominion Oxygen Co. Ltd., on material supplied by Mr. N. Metcalfe, metallurgist of Burlington Steel, who was present. The material used was 1"-diam. plain bars cut from material rolled from one rail. The test pieces were numbered according to their position in the original bar. The pieces had been machined in a lathe to provide mating surfaces at right angles to the axes of the tests. This operation had left a fairly rough surface. Bend tests made on the welded samples were, with one exception, decidedly unsatisfactory. In these bend tests, as with all previous tests, the samples were prepared for bending by completely grinding off the upset at the area of contact of the former, and partially grinding off the remainder of the upset. Bending was around a 1½"-diam. former. After some discussion Mr. Metcalfe agreed to an acceptance bend test of 180° around a 4"-diam. former after complete removal of the upset down to the original diameter of the bar. Unfortunately, by this time most of the welds had been bend-tested. Those untested were returned to these Laboratories for testing to the above standard. It is interesting to note that normalizing the welds in the welding machine produced no definite trend toward better bend test results.

Details of the experimental welds, and a description of the machine used, are given below.

Object of Investigation:

To determine the cause of inconsistent bend test results on pressure-welded reinforcing steel made from re-rolled rail steel.

PROCEDURE:

(1) Description of Welding Process and Machine:

The material to be welded consisted of 18 sets of two pieces each, each piece being 1"-diam. x 12" long. These are plain bars with no ribs. All pieces came from one long bar rolled from one rail. The ends to be welded were machined square on a lathe which left a fairly rough, torn surface.

The machine is one of the earliest types, with all stages of operation manually controlled. The flame head is of the split ring type with 30 No. 72 drill size holes. The work pieces are side clamped, the ends are pressed together by means of a hand-pumped hydraulic press, and the pressure obtained is registered on a gauge which has 4 small divisions per 500 pounds of pressure. The pieces are positioned so that they are closer to the upper half of the flame head than to the lower. It was stated that the more perfect combustion of the gases from the lower half results in a higher heat input on the bottom of the work pieces, and that the reverse is true of the upper half. The off-centre position is intended to counteract this effect and the optimum position must be determined by trial.

In operation, two men are required. The work pieces are inserted and an initial pressure of approximately 1,000 p.s.i. is applied. This action brings the surfaces to be welded into close contact and tends to exclude atmospheric oxygen. When the initial pressure is applied the flame head is lighted and immediately oscillated by hand over a range of approximately 1½ inches, in which the interface is at the centre. One operator oscillating the flame head continually observes the heating of the steel and when he judges from the appearance of of the steel that the proper welding temperature has been reached, he instructs the second operator to increase the

(Procedure, cont'd) -

pressure to approximately 4,000 p.s.i. of cross-section. It is well to note at this point that since the hydraulic system is not equipped with a by-pass valve the initial pressure is not constant during heating. Since the work is rigidly clamped the metal cannot expand during heating, and as a result the pressure continues to increase until upsetting begins. When the upsetting pressure is called for, the second operator by constant pumping endeavours to obtain the desired pressure and hold it constant. The upsetting pressure, it was noted, cannot be held closer than 100 pounds gauge reading to the desired pressure even with rapid pumping. This condition occurs because the metal rapidly upsets and the pumping capacity is insufficient to maintain the pressure. When the desired amount of total shortening, which is a measure of the amount of upsetting, is reached, the flame head and hydraulic pressure are simultaneously cut off.

The total upset, or shortening, is determined on the basis of experience and is measured as follows. A scale is attached to a fixed collar on the shaft along which the end pressure clamps slide. The collar is so positioned that with zero pressure the clamp and collar are in contact. When upsetting takes place, the distance between the collar and the clamp shortens, and the scale can be read directly to measure the total shortening of the test pieces. The desired upset is that which will produce a maximum diameter of upset of 1-1/3 times that of the original bar. This is a standard derived from experience and adhered to in these experimental welds.

Oxygen and acetylene were obtained from a manifold system and controlled by standard regulators. The gases delivered to the machine are controlled by a quick-acting

(Procedure, cont'd) -

valve and an acetylene needle valve which permits flame adjustment from oxidizing to carburizing. The regulators used were standard regulators which cannot operate satisfactorily at low gas pressures. Therefore the gas pressures reported below are probably inaccurate.

The following table lists the operational data of the experimental welds:

TABLE I.

Test No.	Pressures, pounds: Initial	Upsetting	Total Shortening, inches	Times, in minutes: Initial	Upsetting	Total	Gas Pressures, in pounds: Oxygen	Acetylene
1	250	500	9/16	1.5			3	2
3	"	"	1/2	1.33	0.33	1.66	"	"
5	"	"	"	1.50	0.23	1.73	"	"
7	"	"	7/16	1.32	0.26	1.58	"	"
9	"	"	"	1.55	0.23	1.78	2½	3
11	"	"	"	1.68	0.17	1.85	"	"
13	"	"	1/2	1.62	0.20	1.82	"	"
15	"	"	"	1.85	0.17	2.02	"	"
17	500	500	"	1.63	0.24	1.87	"	"
19	"	"	"	1.63	0.19	1.82	"	"
21	300	"	"	1.57	0.20	1.77	2½	2
23	"	"	"	1.54	0.18	1.72	"	"
25	250	"	"	1.57	0.23	1.80	4	3
27	"	"	"	1.55	0.19	1.74	2½	2
29	425	"	"	1.62	0.28	1.90	"	"
31	250	"	"	1.59	0.20	1.79	"	"
33	"	"	"	1.55	0.25	1.80	4	3
35	"	400	"	1.75	0.14	1.89	"	"

Note: (a) Times were measured by stop watch. Initial time is period between lighting of the flame head and application of the upsetting pressure. Upsetting time is period between application of upsetting pressure and cut-off of flame head and pressure.

(b) Pressures of 250 pounds and 500 pounds are respectively 785 and 3,930 pounds per square inch of cross-section.

(2) Bend tests were made on all of the above specimens after various methods of preparation. During the course of welding, surface preparation of the interface was varied to determine its importance. The results of the bend tests and

(Procedure, cont'd) -

and the variations referred to above are shown in the following table:

TABLE II.

Test No.	Interface Prep.	Prep. for Bending	Bend Result	Comments
1	Machined.	Light grind.	Unsatisfactory.	Upset badly ruptured - broke 1/8" from interface - A.W.
3	"	"	"	Uniform upset - broke on interface - N.
5	"	"	"	Upset longitudinal ruptures - interface failure - N.
7	"	"	"	Uniform upset - interface failure - N.
9	"	"	"	" " "
11	"	"	Not tested.	Uniform upset - N.
13	"	Upset removed.	Unsatisfactory.	Uniform upset - interface failure - N.
15	"	Light grind.	"	" " "
17	"	"	"	" " "
19	"	"	Not tested.	Uniform upset - A.W.
21	Fine filed.	Upset removed.	Unsatisfactory.	Uniform upset - interface failure - A.W.
23	"	"	"	" " "
25	Machined.	Light grind.	"	" " "
27	Fine filed.	Upset removed.	"	" " N
29	"	"	"	" " "
31	"	Light grind.	"	Concentrated upset - H.A.Z. failure - A.W.
33	"	"	Satisfactory.	Very smooth upset - no failure in bend - A.W.
35	"	"	Unsatisfactory.	Upset uniform but ruptured - interface failure - A.W.

Legend: A.W. = As welded.
N = Normalized in machine, estimating temper visually.
Light grind = Ground to original diameter at area of contact of bending pin. A light variable grind on remainder of upset.
Machined = Interface prepared in lathe by cutting tool; surface fairly rough.
Fine Filed = Pieces were put in lathe and rough-machined surface filed smooth with a fine file while pieces were rotated.

Note: Where interface failure occurred in bending, nearly all fractures showed signs of the original rough machining marks, indicating no bonding.

(Procedure, cont'd) -

The following test bars were returned to these Laboratories: Nos. 1, 13, 15, 21, 23, 27, 29, 31, 33, and 35. Tests Nos. 13, 21, 23, 27 and 29 were machined to remove the upset and bent here.

(3) Chemical analysis samples were removed from one bar by milling transverse to the longitudinal axis. This provides an average analysis and minimizes the effect of segregation. Only one bar was used, since all the material used in these tests came from the same rail. The table below lists the results of the analysis:

TABLE III.

		Per Cent
Carbon	-	0.79
Phosphorus	-	0.010
Sulphur	-	0.047
Manganese	-	0.87
Silicon	-	0.12
Chromium	-	None.
Nickel	-	None.
Molybdenum	-	None.

(4) Transverse sections from each of the tests received were deep-etched in 50 per cent HCl at 180° for 15 minutes. No evidence of shatter cracks was detected.

(5) Hardness readings were taken along the centre line of a longitudinal section of an 'as welded' and normalized test. A Vickers machine was used with a 20-kilogram load. The readings extended from the fractured edge through the heat-affected and transition zones and into the unaffected metal. The hardnesses ranged from 290 to 330 V.P.N. with both samples, the lowest hardness being in the transition zones.

(6) Transverse sections were machined $1\frac{3}{4}$ in. long from the ends of bars remote from welded areas. Three samples were heated to each temperature of 2,000°, 2050°, 2100°, 2150°, 2200°,

(Procedure, cont'd) -

2250°, 2300°, 2350° and 2400° F. and then compressed to 1" height. This approximates the desired upset of 1-1/3 times the original diameters. In no case was any evidence of hot shortness or surface rupturing detected.

(7) Typical samples were photographed in the 'as received' condition. Figure 1 shows two 'as welded' samples and No. 33 which showed far greater ductility than the remainder of the tests. Figures 2 and 3 show the fractured ends of Bend Tests Nos. 1 and 35, showing coarse grain and a burnt skin. Figure 4 shows a typical fractured end of an interface failure (No. 15) which shows the original rough machining marks. Figure 5 shows bend tests of which the upset was completely removed by machining.

(8) One end of each of three of the tests shown in Figure 5 was bent between 9-in. centres around a 4"-diam. pin. All test bars bent 90° without failure. Figure 6 shows the condition of these bars after bending. It is apparent that the ductility of the unwelded material is far superior to that of the welded material.

(9) In an attempt to duplicate the brittle condition of the welded material, two samples were heated to 2100° F. and 2200° F. in a furnace, air cooled, and bent as above. Both test bars bent 90° without sign of failure.

(10) Samples were machined longitudinally through the weld from various test bars and subjected to microscopic examination. Figure 7 shows a coarse-grained structure at a fractured edge of a test piece in the 'as welded' condition. Figure 8 shows the smooth fractured edge of a fine-grained, normalized test piece. Figure 9 shows a typical area containing large numbers of manganese sulphide inclusions common to all samples.

(Procedure, cont'd) -

Figure 10 is the structure of the 'as rolled' material remote from a weld. Figure 11 is a typical heat-affected zone structure of an 'as welded' test and Figure 12 a similar area of a normalized test. Figure 13 shows typical intercrystalline cracks below the original diameter of the upset portion in which the upset was severely localized.

(11) Two unwelded bars, previously heated to 2100° and 2200° F. respectively and cooled in still air, were heated at their central portions over a length of 1½ inches. Heating was done with an oxyacetylene torch with a reducing flame. During heating a continuous check was kept on the temperature of the bars, by means of an optical pyrometer. When temperatures of 2150° F. and 2200° F. respectively were attained, the material was allowed to cool in still air. No restraint was applied nor was any upsetting action attempted.

When cold both bars were bent similarly to previous tests. Both bars broke with a brittle fracture after bending approximately 10°.

(12) Since no material remained for additional tests on the original size, 15 bars were machined to 6" x ½"-diam. from the fractured test pieces. After machining, all tests were annealed at 1500° F. to eliminate the effects of previous heat treatments and machining, and also to bring all tests to a common grain size and structure. After annealing, the pieces were split into three groups of 5 and treated as follows:

(a) Bent after annealing.
(b) Heated at centre to 2200° F. with an oxyacetylene torch, using a reducing flame. Temperature checked by means of an optical pyrometer. Tests cooled in still air and bent when cold.
(c) Treated as in (b) but annealed at 1500° F. before bending.

(Continued on next page)

(Procedure, cont'd) -

The following table lists the results of these tests:

TABLE IV.

Condition of Samples	Maximum Applied Load, pounds	Comments
Annealed -		
1	2,500	Broke at approximately 20° permanent deflection.
2	2,900	" " 30° "
3	2,800	" " 20° "
4	2,850	" " 30° "
5	2,750	" " 20° "
	Aver. 2,760	See Figure 14.
Annealed, centre heated 2200° F. -		
1	2,350	Broke at approximately 2° permanent deflection.
2	2,400	" " 5° "
3	2,800	" " 5° "
4	2,300	" " 10° "
5	2,150	" " 0° "
	Aver. 2,400	See Figure 15.
Annealed, centre heated 2200°, re-annealed -		
1	2,300	Broke at approximately 20° permanent deflection.
2	2,800	" " 45° "
3	2,500	" " 20° "
4	2,600	" " 20° "
5	2,700	" " 45° "
	Aver. 2,580	See Figure 16.

Notes: (a) Localized heating times using oxy-acetylene torch averaged 1.25 minutes.

(b) Bend tests were on 5-in. centres using a 2"-diam. former.

(13) One bar, unwelded 1" diam., was heated by means of an induction coil at its centre to a temperature of approximately 2000° F. Temperature attained was uncertain due to oxide film interfering with optical pyrometer reading. This bar, after cooling in still air, bent 90° without failure. See Figure 17.

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DISCUSSION:

Numerous criticisms can be directed at the design and operational technique of the welding machine, most of which would not apply to machines of more recent design. Manually controlled lateral travel of the ring burner may result in too restricted a volume of metal being heated, with the result that upsetting may be concentrated in a small area with consequent surface rupturing. Visual estimation of temperatures at which welding is to be accomplished is subject to personal errors and consequent erratic results. This may be offset by standardization of gas pressures, length of time of heating, etc., where such standardization is first accomplished by means of temperature recording devices. On sensitive steels, such as were used in this work, small variations may produce inconsistent results. Too high an initial pressure, subsequently increased by prevention of thermal expansion, may result in upsetting taking place when the steel is at too low a temperature to be sufficiently ductile to absorb the deformation without damage. In view of the considerable number of variables in these welding experiments, little useful purpose would be served in trying to estimate the importance of these variables by an examination of the data of Table I. It should be noted that of the eighteen welded tests, only one exhibited satisfactory ductility.

An examination of the data in Table II reveals that normalizing in the welding machine produces no pronounced beneficial effect on ductility in bend tests. Neither uniformity or non-uniformity of upset, nor light or heavy grinding of upset prior to bending, has any pronounced effect on ductility. Face preparation prior to welding apparently has no definite effect on ductility. It is interesting to note, however, that all interface failures exhibited discernible traces of machining marks remaining from the face preparation

(Discussion, cont'd) -

in a lathe. In those cases where this preparation was improved by fine filing some failures in bending occurred away from the interface but within the heat-affected zone. Preparation of the welded test for bending, either light grind or complete removal of upset, had no strong effect on ductility as measured by the bend test. It would appear that all of the above factors may be important but their effects are being masked by one or more factors with major effects.

The chemical analyses of the samples returned to these Laboratories show higher sulphur content than is usual with steels of this composition. In view of the fact that this is re-rolled rail steel, the possibility exists that this is a dephosphorized Bessemer steel, that is, a steel originally made in a Bessemer furnace and subsequently transferred to an open-hearth furnace for reduction of the phosphorus content. This latter step is not possible in a Bessemer furnace. If this steel were made in this manner it might be heavily charged with nitrogen in the blowing operation in the Bessemer furnace. Should the steel be high in nitrogen, brittleness after treatment at high temperatures may be expected.

Deep-etched cross-sections removed from the ends of samples received show no evidence of shatter cracks as a result of too rapid cooling after re-rolling. Had such cracks been present they would have been a fertile source of rapid failure in bend tests. Similarly, hot compression or upsetting tests indicate that the material is not 'hot-short' in the temperature range of 2000 - 2400° F. in compression. Consequently this is not a factor in the low ductility detected. This was also confirmed by microscopic examinations.

Bend tests on short (8 inch) samples of unwelded material showed a permanent deflection of 90°, after bending

(Discussion, cont'd) -

around a 4"-diam. former without failure. Similar bars heated to 2100° F. and 2200° F. in a furnace and air-cooled, showed equally good ductility. Therefore, the material with very coarse grain size showed ductility far superior to that of 'as welded' bend tests in which the grain size would be equally as great. Hardness readings on 'as welded' and welded-and-normalized transverse sections of welds, revealed that there were only minor differences in maximum hardness and that therefore hardening due to rapid cooling after welding was not the reason for low ductility in 'as welded' bend tests.

Microscopic examination revealed the anticipated coarse-grained heat-affected zone of 'as welded' tests and showed that this coarse grain had been satisfactorily refined by machine normalizing. This confirms the effectiveness of machine normalizing for grain refinement but gives no clue as to the lack of ductility of tests given this treatment. Where fracture took place remote from the interface, no harmful oxidation at the interface was detectable. On these samples complete grain coalescence across the interface was noted, giving a microscopically perfect weld. The steel was found to be quite dirty, as might be expected from the high sulphur content. The manganese sulphide inclusions would have no detrimental effect on ductility unless the steel were heated to the melting point of this constituent, and these on cooling were rejected to the grain boundaries. No evidence of this was found in any sample. On those tests in which the upsetting action was severely localized, intercrystalline rupturing had occurred all through the upset material and below the original diameter of the bar. This is the result of too severe hot working when the metal is of low strength, and points to the necessity of uniformity of heating to ensure smooth changes of section when upsetting occurs.

(Discussion, cont'd) -

of section when upsetting occurs.

Bars previously heated to 2100° F. and 2200° F. and air-cooled have been shown to possess good ductility even though coarse-grained. Bars similarly treated, after heating at their central portions by means of a reducing flame of an oxyacetylene welding torch, showed low ductility very reminiscent of welded tests. Those tests were subsequently repeated on $\frac{1}{2}$"-diam. bars and revealed that the effect of heating to a welding temperature with an oxyacetylene flame with an excess of acetylene is to reduce drastically the ductility, and that this ductility can be almost completely restored by an annealing treatment. Annealing all tests together ensured that all were in the same condition with respect to grain size and hardness. Therefore, the differences after various treatments can be attributed only to effects of these treatments.

Unfortunately, insufficient material was available to repeat this series of tests using induction heating at the central portions of the bars rather than an oxyacetylene flame. However, one bar, 1" diam., after induction heating at the centre and air cooling, when bent showed unimpaired ductility. This cannot be regarded as complete confirmation but does give some support to the theory of damaging the material when a reducing oxyacetylene flame is used as a means of localized heating. These, of course, are the conditions which prevail in the oxyacetylene pressure-welding process.

While definite proof cannot be advanced, every indication points to hydrogen embrittlement being responsible for the greatly reduced ductility of welded test pieces. It is well known that all steels at high temperatures can readily absorb into solution appreciable volumes of hydrogen.(1) In this welding process the hydrogen is available in acetylene gas used

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(1) A.S.M. Handbook, 1939 Edition, p. 356.

(Discussion, cont'd) -

as a fuel, particularly since a reducing (excess acetylene) flame is used to reduce the danger of burning (oxidizing) the steel. The sensitivity of this steel to hydrogen embrittlement is well known, and is counteracted in rail-producing procedures by very slow cooling from 600° F. to normal temperatures. This treatment gives time for the hydrogen to diffuse out of the steel and eliminates "shatter cracks" which are the result of hydrogen occlusion. Since the oxy-acetylene pressure welding process is widely used to weld rails together, with very satisfactory results, the question naturally arises as to why the same process used on the same steels should not be equally satisfactory. It is believed that the answer lies in the vast differences in section between a standard rail and a 1"-diam. bar. In the case of the rail a much larger volume of metal is raised to the welding temperature and consequently the cooling rate is slower. The slower cooling gives an opportunity for any dissolved hydrogen to diffuse away; the same opportunity is not available in the 1"-diam. bar. It must be borne in mind that as the temperature of the steel decreases from the welding temperature, the solubility of the hydrogen in the steel also decreases. If the cooling rate is such that diffusion prevents the precipitated gas from building up dangerous pressures, no damage is done to the steel. If the reverse is true, internal rupturing may occur ("shatter cracks") in the steel or, in less severe cases, severe external stresses may be set up.

It has been demonstrated that the embrittling effect cannot be eliminated by normalizing in the welding machine, since the cooling rate is too rapid on the small section. Slower cooling, as in annealing, almost completely restores ductility. However, since it is impossible to anneal the reinforcing bars on the job, an alternative treatment somewhere

(Discussion, cont'd) -

between annealing and normalizing must be employed. Essentially the process of welding should be: weld and cool, reheat to the austenitizing temperature to refine the grain, and slow cool. It is believed that further experimental work must be done to establish the critical cooling rate after grain refinement. Cooling rates faster than the critical cooling rate will result in poor ductility and slower cooling rates will produce satisfactory ductility.

Conclusions:

1. Manual operation of the welding machine permits too great latitude for errors of judgment. This may result in too localized upsetting, too high or too low welding temperature, etc.

2. It is impossible to estimate the importance of uniformity of upset, face preparation, etc., since their effects are masked by other factors with a major effect. There is some reason to believe that smoothing of the interface increases weld quality.

3. Chemical analysis shows a higher than normal sulphur content. This steel may be dephosphorized Bessemer steel.

4. No evidence of "shatter cracks" found as a result of re-rolling.

5. Unwelded bars bend 90° around a 4"-diam. former without difficulty or failure.

6. Unwelded bars heated uniformly to the normal pressure welding temperatures and air-cooled show no reduction in ductility. Therefore, coarse grain is not responsible for lack of ductility.

7. Microscopic examination reveals no reason for lack of ductility in 'as welded' or machine-normalized bend

(Conclusions, cont'd) -

tests. No evidence of burning was found other than the outer layers of the upset portion on Tests Nos. 1 and 35.

8. When too localized upsetting occurs, internal rupturing results to a depth well below the original diameter of the bar.

9. Machine normalizing is effective in refining the grain of the heat-affected zones.

10. Where fracture took place remote from the interface, no harmful oxidation at the interface was detectable. On these samples complete grain coalescence across the interface was noted, giving a microscopically perfect weld.

11. Bend tests showing interface failures with original machining marks visible on the interface are considered to be welded at too low a temperature.

12. Brittleness can be induced in unwelded bars by heating their centres with an oxyacetylene torch, using a reducing flame.

13. This brittleness can be eliminated by slow cooling from the austenitizing temperature.

14. It is believed that brittleness is the result of hydrogen adsorption when the metal is above the austenitizing temperature.

15. The material is not hot short in compression in the temperature range of 2000° to 2400° F. This range is well above and below normal oxyacetylene pressure welding temperature.

Recommendations:

From the experimental work reported above it is apparent that the cooling rate from the last austenitizing is the factor of greatest importance governing the ductility of the welded joint, assuming that the proper welding temperature was attained. It is also apparent that the cooling rate

(Recommendations, cont'd) -

necessary for maximum ductility lies somewhere between that of normalizing and annealing.

It is recommended that further experimental work be undertaken to establish the critical cooling rate which if exceeded will result in unsatisfactory ductility and vice versa. The Speedomax machine of these Laboratories would be suitable for this work. The machine could be shipped to Toronto and the work done there if 60-cycle, 110-volt current is available. Alternatively, the work could be done in these Laboratories on material supplied by Burlington Steel, if the welding machine were brought here. The welding machine and the Speedomax must be in operation together in order that heating and cooling rates characteristic of the welding machine may be determined. The determination of critical cooling rates by furnace or torch heating in these Laboratories would not be applicable directly to the welding equipment without prior knowledge of the characteristics of the welding machine.

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HJN:LB.

(Figures 1 to 17 follow,)
(on Pages 19 to 27.)

Figure 1.

AS RECEIVED SAMPLES (TOP TO BOTTOM)
NOS. 29, 21 AND 33.

As-welded samples showing uniform upset and no rupturing. Sample No. 33 is typical of preparation for bending by light grind on upset. No. 33 is only sample exhibiting satisfactory ductility as compared with other tests.

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Figure 2.

FRACTURED END OF SAMPLE NO. 1.

Note coarse grain and burning of metal around complete periphery. This is a sample in which burning was detected and which also exhibited severely localized upsetting.

-

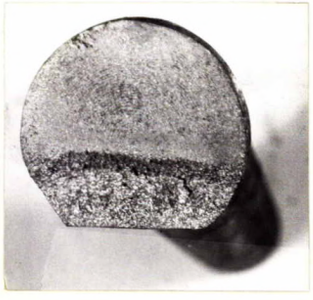
Figure 3.

FRACTURED END OF SAMPLE NO. 35.

Note coarse grain and burning around complete periphery. This sample and No. 1 are the only ones in which burning was detected, and both samples show severely localized upsetting.

-

Figure 4.



FRACTURED END OF SAMPLE NO. 15.

Fracture typical of those showing original interface machine marks.

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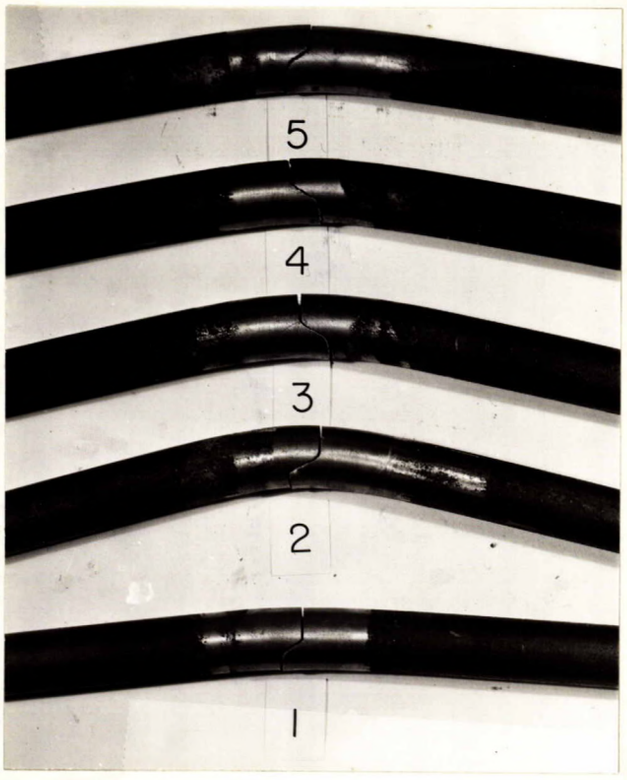
Figure 5.



BEND TESTS MADE IN THESE LABORATORIES.

In these tests the upset portion was completely removed in an effort to assess the importance of the upset as a stress raiser. Removal of upset in no way improved ductility.

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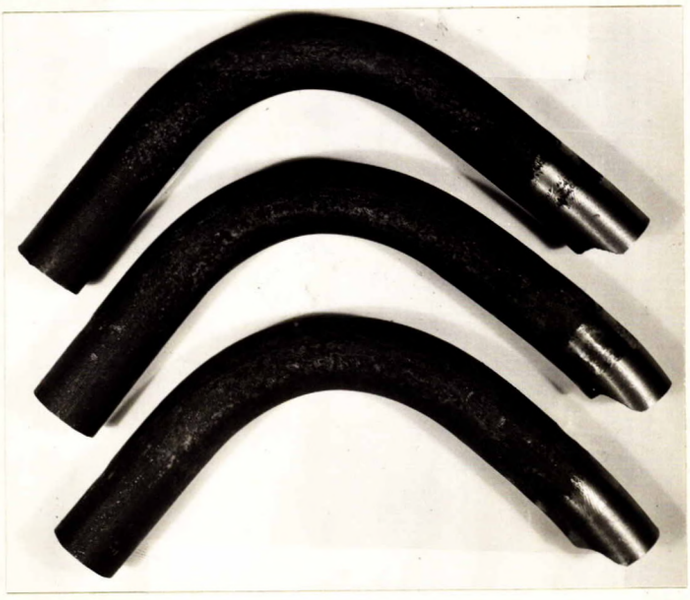
Figure 6.



BEND TESTS ON UNWELDED BARS.

These tests were made on ends of bars shown in Figure 5. Unheated material has far greater ductility than welded tests.

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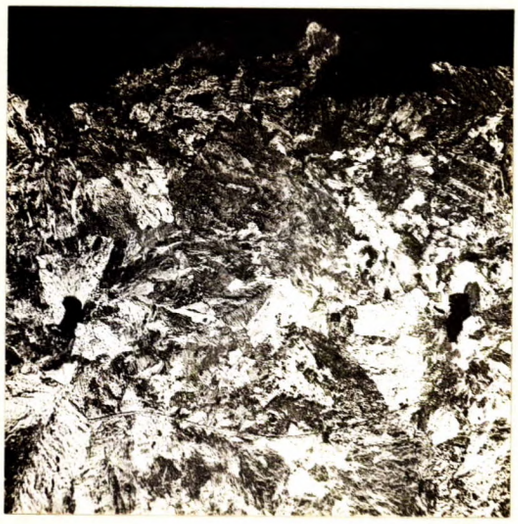
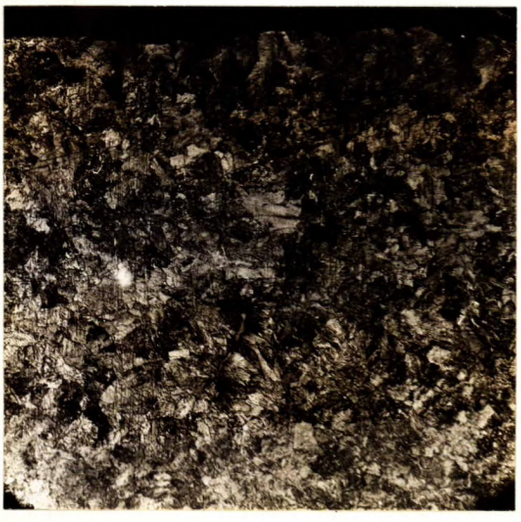
Figure 7.



X100, etched in 4
per cent picral.

COARSE-GRAINED STRUCTURE AT FRACTURED EDGE OF
'AS WELDED' BEND TEST.

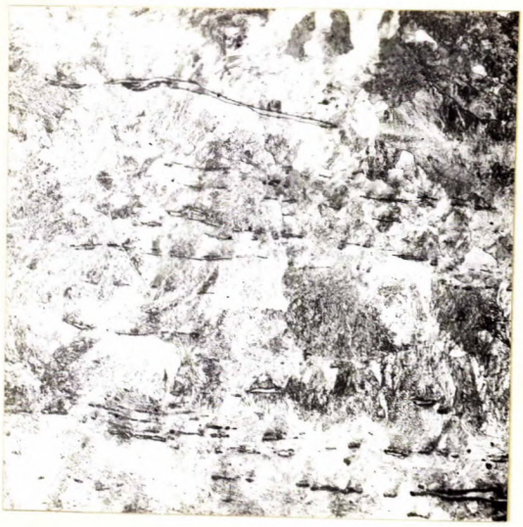
Figure 8.



X100, etched in 4
per cent picral.

FINE-GRAINED STRUCTURE AT FRACTURED EDGE OF
A MACHINE-NORMALIZED SAMPLE.

Figure 9.



X100. light 4 per cent picral etch.

TYPICAL AREA SHOWING NUMEROUS MANGANESE SULPHIDE INCLUSIONS.

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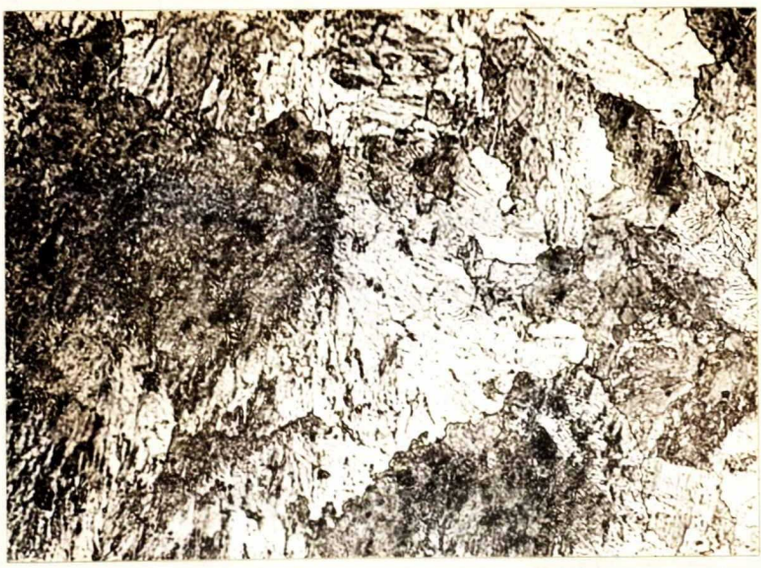
Figure 10.

X500, etched in 4 per cent picral.

FINE AND COARSE PEARLITE STRUCTURE OF 'AS ROLLED' BARS.

-

Figure 11.



X500, etched in 4
per cent picral.

COARSE-GRAINED PEARLITIC STRUCTURE TYPICAL
OF HEAT-AFFECTED ZONES OF 'AS WELDED' MATERIAL.

-

Figure 12.

X500, etched in 4
per cent picral.

FINE-GRAINED, FINE AND COARSE PEARLITIC STRUCTURE
TYPICAL OF HEAT-AFFECTED ZONES OF MACHINE-
NORMALIZED WELDS.

Compare with Figure 10.

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Figure 13.

X500, light 4 per cent picral etch.

INTERNAL RUPTURING FOUND IN TESTS IN WHICH THE UPSETTING IS TOO SEVERELY LOCALIZED.

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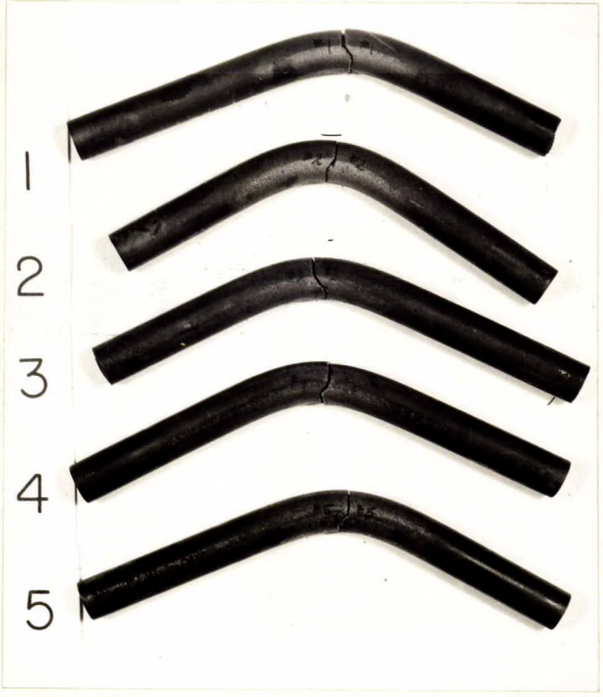
Figure 14.



HALF-INCH-DIAMETER TEST BARS, BENT AFTER ANNEALING.

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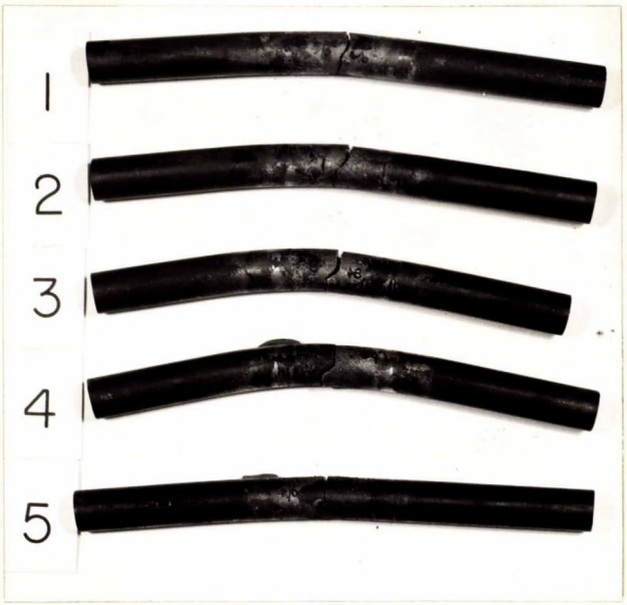
Figure 15.



HALF-INCH-DIAMETER BARS, ANNEALED, HEATED TO 2200° F. AT CENTRE WITH OXYACETYLENE TORCH, COOLED IN AIR, AND BENT.

Compare with Figure 14.

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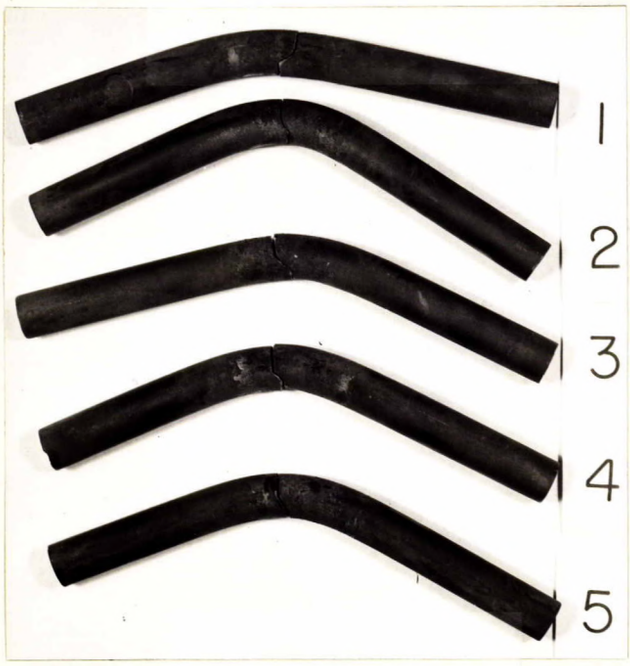
Figure 16.



HALF-INCH-DIAMETER BARS, ANNEALED, HEATED TO 2200° F. AT CENTRE WITH OXYACETYLENE TORCH, COOLED IN AIR, RE-ANNEALED, AND BENT.

Compare with Figures 15 and 14.

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Figure 17.

ONE-INCH-DIAMETER BAR OF UNWELDED METAL,
INDUCTION-HEATED TO APPROXIMATELY
2000° F. AT CENTRE AND AIR-COOLED.

Bent without failure.

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HJN:LB.

(An appendix follows,
(comprising Pages 28 and 29.)

APPENDIX TO REPORT OF INVESTIGATION NO. 2031

Ottawa, April 30, 1946.

Since the above report was written it has been possible to obtain hydrogen analyses of steels in these Laboratories. The samples were prepared as follows:

A sample was cut transversely across a 1"-diam. bar at an area in which the bar had never been heated by an oxy-acetylene flame. This sample was representative of 'as received' material. A second sample of equal weight and volume was cut from a 1"-diam. bar at the centre of an area recently heated to 2200° F. with an oxyacetylene flame and cooled in still air. Both samples were analysed for hydrogen content by the vacuum fusion method, with the following results:

Sample No.	Condition	H_2, per cent
1	As received.	0.0000075
2	Heated locally.	0.000037

It is known that at room temperature iron cannot hold in solution more than 0.00001 per cent hydrogen. The 'as received' sample contains slightly less than this amount, indicating that no reduction in ductility would be expected as a result of hydrogen pick-up in the re-rolling process. On the other hand, the heated sample contains approximately four times as much hydrogen as the 'as received' sample, indicating that hydrogen has been absorbed in the heating process.

Hydrogen embrittlement is considerably facilitated by the presence of non-metallic inclusions. As reported above, this steel contains appreciable quantities of manganese sulphide inclusions. It is generally believed that inclusions

(Appendix to Report of Investigation No. 2031, cont'd)-

act as focal points at which hydorgen may be precipitated, as its solubility in iron decreases with decreasing temperature. In these areas gas pressure may build up to a point which in severe cases may actually rupture the steel and in less severe cases may need only slight additional stress (such as in bending) to bring about premature failure. It is this latter condition that is believed to be the cause of unsatisfactory ductility in these welded tests.

Others (1) have shown that annealing at just under the lower critical temperature (1285° F.) for a period of approximately 15 minutes is sufficient to eliminate hydrogen embrittlement.

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Ottawa, Ont.,
April 30, 1946.
HJN:LB

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(1) "Hydrogen Embrittlement, Internal Stress and Defects in Steel" - C.A. Zapffe and C.E. Sims, METALS TECHNOLOGY, Aug. 31, 1941, pp. 1-37.