One-Run Versus Multi-Run Welds

For conventional C-Mn steels, embrittlement due to hot straining of the strain-affected zone (SAZ) presents a potential hazard for multipass welds, while no serious damage occurs in single-pass welds

BY WALTER SOETE

ABSTRACT. For conventional C-Mn steel there exists an embrittled area due to hot straining. A technique is described which records the hot strain cycles during welding. The cumulative effect of heating and cooling is aggravated in multipass welds, while it seems innocuous in single-pass welds.

For high strength steels, an area of low ductility may appear in the heat-affected zone near the fusion line. Welding simulation machines and plugs pressed into the surface prepared for welding, combined with light and electron microscopic techniques, are used to investigate the nature of the problem. Wide plate tests indicate that the use of low heat input reduces this type of embrittlement of the heat affected zone.

A practical wide plate test is proposed and used to check both the embrittlement due to aging away from the weld and the metallurgical embrittlement near the fusion line.

Introduction

To an outsider, it must seem unlikely that, after 50 years of welding technology, there still does not exist a clear prescription for "how a weld joint must be filled." The specialist realizes that this simple problem goes straight to the crux of welding science, and entails such fundamental aspects as behavior, distortion, and costs of the joint.

The answer to the question "What is the most economical way to fill a weld joint?" is rather simple. The fastest technique is probably also the cheapest. This solution can be obtained either by a one-run weld or by a high speed multipass technique. Since the welding speed of a one-run technique is nearly independent of plate thickness, the economical advantages of the one-run technique will be greater the thicker the plate. On the other hand the setup time for a one run weld is practically the same for a long or short weld. Therefore the economical advantages of the one-run technique increase with weld length. This brings us to the conclusion that for long butt welds in thick plates, a one-run technique is by far the most economical welding procedure.

Japanese researchers[1] have established welding sequences for butt welds in order to reduce distortion to a minimum. But here again if a one-run weld can be used, distortion will be minimized; this is especially important if the one-run technique uses a square groove joint which eliminates all angular distortion. From this short introduction one may conclude that both economics and avoidance of distortion plead in favor of the one-run technique.

The final question is whether a one-run technique is able to produce joints complying with service conditions.

The answer to this question is complicated and, at first glance, it quickly appears that there is no single and simple answer; it all depends (as will be shown) on the nature of the base metal and the welding procedure.

It is clear that the problem of the number of weld runs arises only with thick plates, where a multi-run technique may be applied.

The single-run techniques for the vertical position which are actually at our disposal are:

1. Electroslag welding.
2. Electrogas welding.
3. Consumable nozzle electroslag welding.

For the downhand position we have granular-metal filler metal* and the Russian technique of using a movable copper backing.

Typical multi-run techniques are manual, semi-automatic and automatic welding using a stringer bead technique.

Situated between the single and multipass procedures are submerged arc and manual and semi-automatic welding using a weave bead technique. In general the higher the heat input, the less the number of passes, and the more the base metal (in the vicinity of the weld) will have properties similar to those of the single pass technique.

As will be recognized, the difference in influence of one or more runs will depend largely on the nature of the base metal. The problems raised by welding the so-called conventional C-Mn steels are different from those which appear on welding high strength steels. For the former, the weldability* problem is practically solved and only the possibility of brittle fracture still exists, which finds its origins in a higher susceptibility to aging of these steels. For the latter, the weldability problem is in many cases not yet solved and, although these steels may also be prone to aging, the most urgent problem to be solved is their response to rapid thermal treatment.

Conventional C-Mn Steels

Wells was the first to reproduce systematically low load brittle fractures in welded wide plates of conventional steels. The essential conditions leading to a low load brittle fracture in a wide plate test are:

1. A notch in the base metal affected by welding, oriented perpendicular to the weld and present before welding;
2. "Sufficiently wide plate";
3. A final tensile stress parallel to the weld at low temperature.

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*Arcmetal® (a registered trademark of Arcos Corp.)

**Weldability* here means the possibility of welding without cracking during or after operation, while *brittle fracture* is the appearance of a brittle failure starting at a locus of strain concentration when an external load (even a small one) is applied.

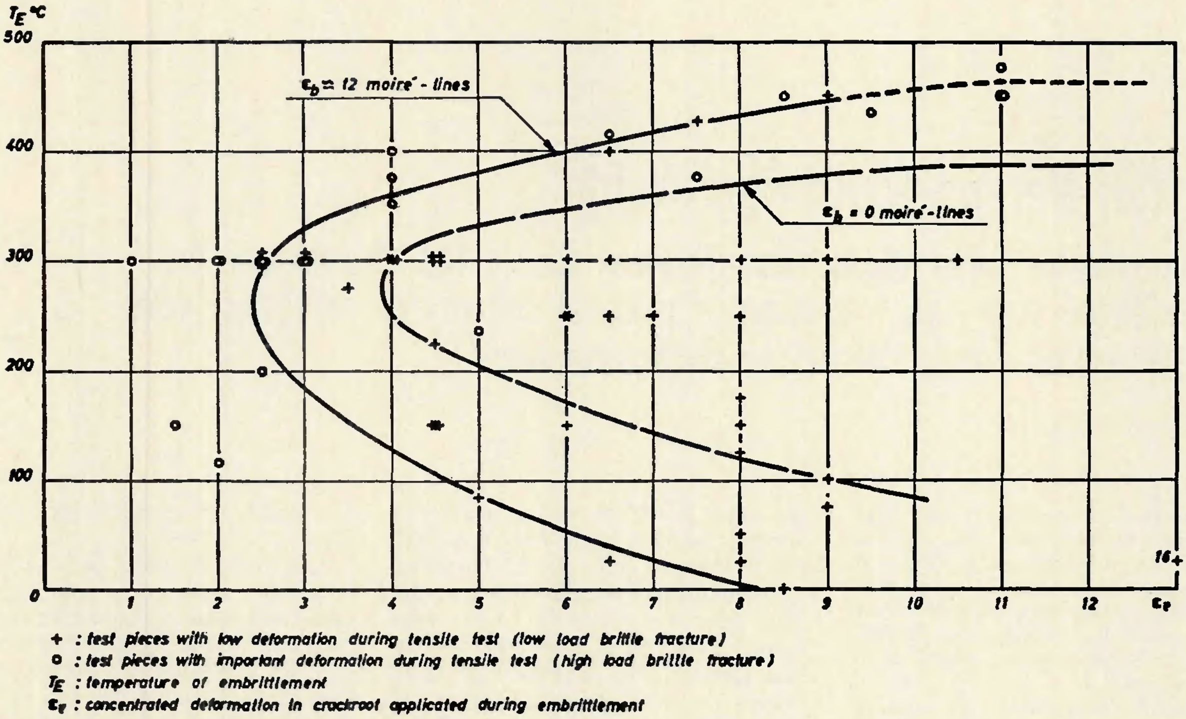

Fig. 1—Ductility of strain-affected metal

The cause of low load brittle fractures in such specimens has been the subject of many discussions. It is generally accepted that the main reason for the unstable crack is the embrittled condition of the material at the root of the notch. During welding, the base metal near the weld is subjected to thermal and plastic strain cycles. When a wide plate is welded the base metal near the weld is compressed during heating; when cooling starts this area is stretched. The magnitude of these plastic strains, first in compression and then in tension, is small and practically without any deleterious effect on the base metal, provided however that this straining occurs uniformly along the weld.

The picture changes drastically if a notch is present, because straining is then concentrated at the tip of this notch. Under these circumstances the amount of straining may reach values as high as 20 times the strain obtained in a specimen without a notch and aging occurs.

All conventional steels are indeed prone to aging and show a marked increase in Charpy transition temperature—for instance, when prestrained 10% and aged 1 hr at 480° F (250° C). This shift in transition temperature is about 26° F (70° C) for rimmed steel, and 117° F (65° C) for killed fine grained steel. It is obvious that when the tip of the notch is located in a zone where the temperature reaches values between 390 and 750° F (200 and 400° C), serious embrittlement due to aging will occur at the apex of the notch. Even the so-called non-aging steels, obtained by adding Al to form Al-nitrides, and elements such as Ti, V, Zr, Nb to form carbonitrides, show an increase in transition temperature of about 54 to 90° F (30 to 50° C).

Although the shift of the transition temperature obtained on Charpy specimens as a measure of aging is criticized,[2] it remains an indication of a serious loss in ductility. Therefore, it may be concluded that the explanation of the low load brittle fractures obtained in the Wells test is essentially associated with strain aging and not as sometimes claimed only by residual stresses.

If the welding procedure has any effect on the aging process of the strain affected zone (SAZ), a procedure must be chosen to reduce

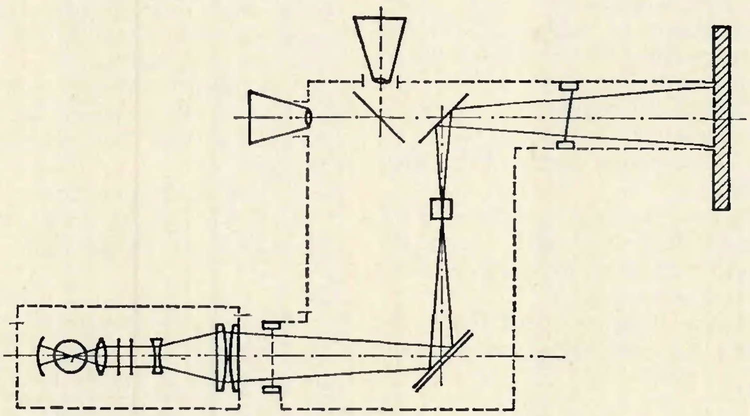
Fig. 2—Schematic drawing of apparatus for projection of reference grid

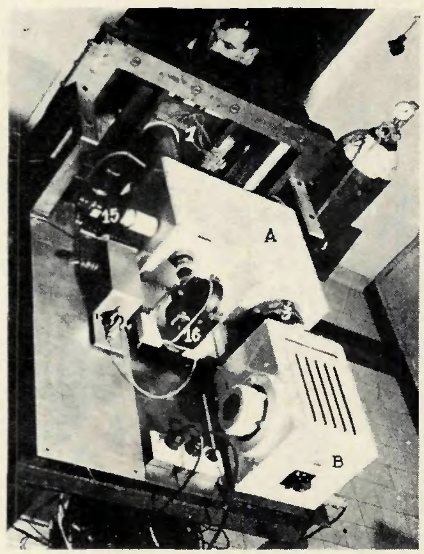

Fig. 3—Equipment used to obtain moiré fringe pattern on weldment

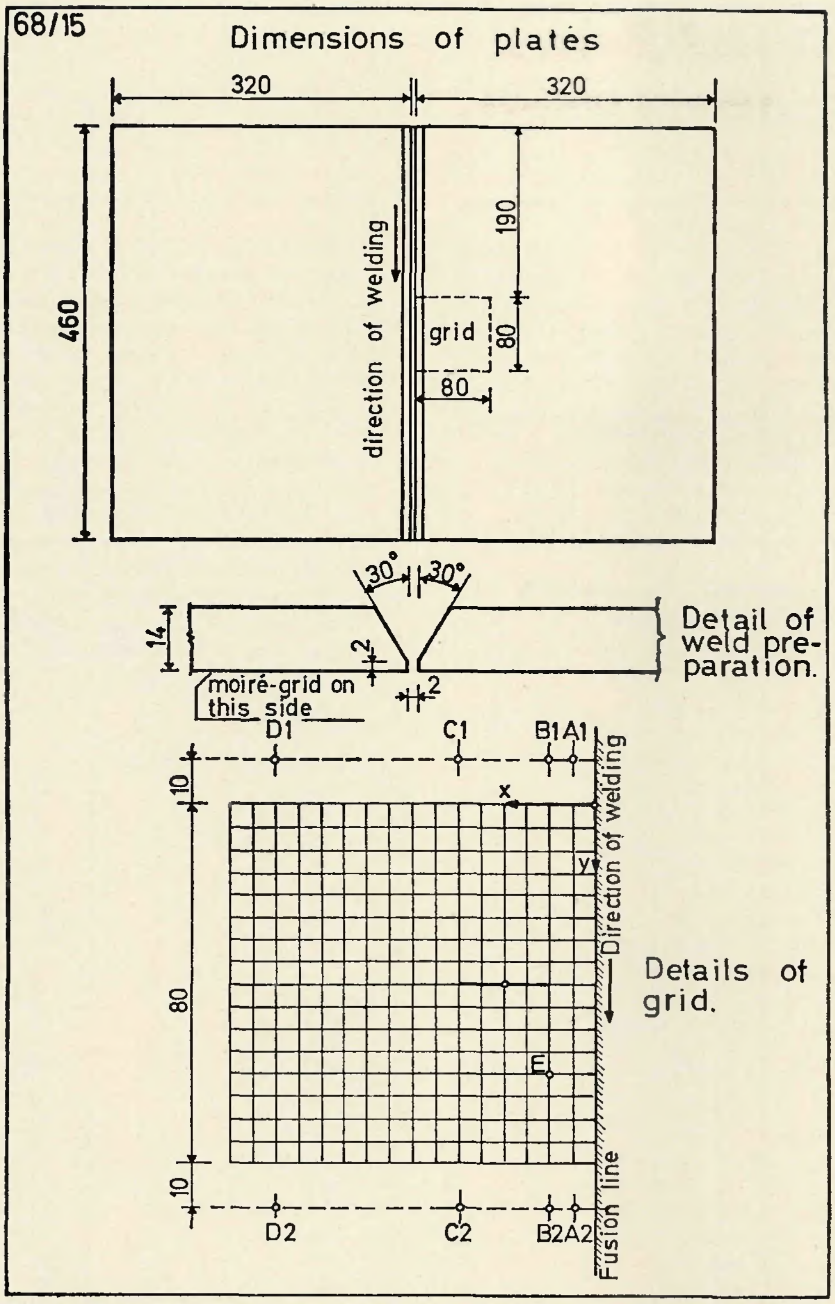

Fig. 4—Weld preparation for moiré study. Dimensions in millimeters

this embrittlement as much as possible. When comparing multipass to single pass welds it is obvious that repetition of the thermal and mechanical cycle will cause a cumulative aging embrittlement at the notch root. Hence the damage done by strain aging will be more important when the multipass technique is used.

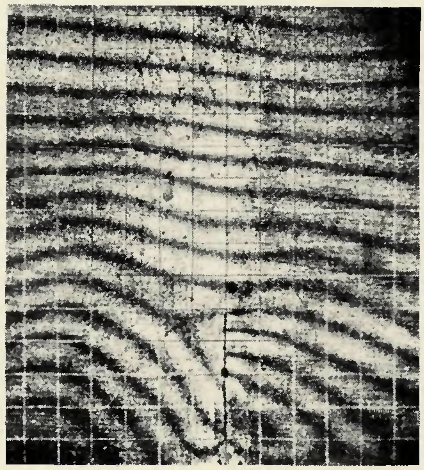

Fig. 5—Moiré pattern for weldment of Fig. 4

On the other hand, the most probable strain concentrations are weld defects, and it is unlikely that such a defect will extend into the SAZ of a weld with high heat imput and remain undetected during inspection. This is not the case when a welding procedure has been used with a steep temperature gradient and where consequently the SAZ is in the immediate vicinity of the weld. This is another reason why strain aging is less dangerous in a single-run weld than in multirun welds.

For both these reasons as far as hot straining is concerned the single pass weld is to be preferred to the multipass weld.

If quantitative information is desired on the risk of brittle failure in a structure similar to a Wells wide plate test, it is necessary to have full information on the available ductility of the strain aged base metal as well as on the plasticity required by the welding procedure used. Techniques to de-

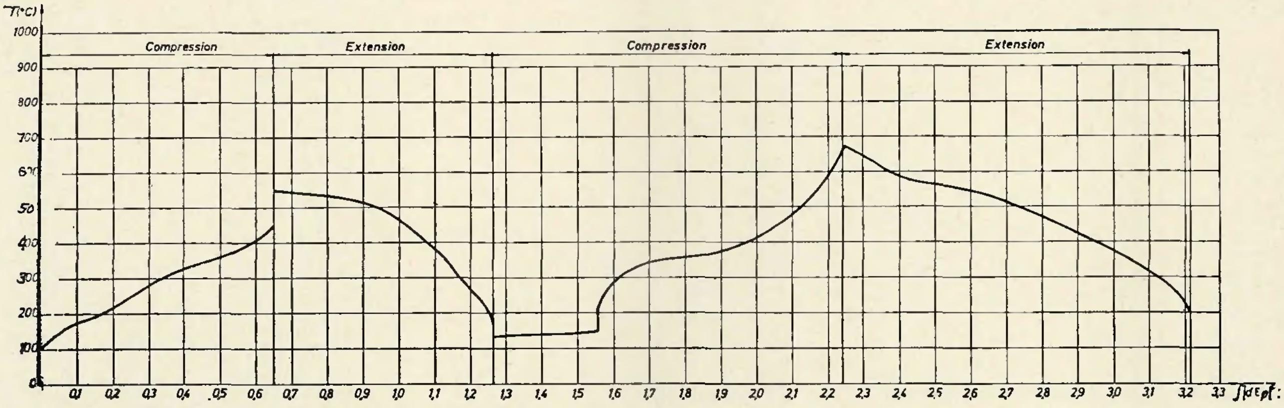

Fig. 6—Cumulative strain history of Point E in weldment of Fig. 4. T(°C) in 100° increments from 0 to 1000°C vs. $\int|dEp|$ in 0.1 increments from 0 to 3.3

Table 1—Welding Conditions

Manual arc welding—flat position
Low hydrogen electrodes, ⅛ in. (3.25 mm) diameter
3 runs
Voltage—24 v; intensity—100 amp
Welding speed:
- 1st run—37.5 cm/min (14.8 ipm)
- 2nd run—26.5 cm/min (10.4 ipm)
- 3rd run—25.1 cm/min (9.9 ipm)

termine both quantities are described below.

Determination of the Available Ductility After Aging[3]

The sensitivity to strain aging can be determined as follows: Notched specimens of the steel are hot strained in different amounts and at different temperatures between 32 and 930° F (0 and 500° C). The amount of local hot straining at the notch tip can be expressed by COD units or moiré lines converging in the notch apex. These embrittled specimens are then broken in tension at the lowest temperature at which the behaviour of the embrittled steel is to be examined. The remaining ductility for fracture is recorded by the same technique used for recording the hot straining.

If we plot points with the same remaining ductility, in a diagram of temperature vs. amount of hot straining, we see that they are located on C-shaped curves with the tip of the nose situated at about 570° F (300° C). Figure 1 is an example of such curves. From Fig. 1 it appears that some combinations of temperature and straining make the steel completely brittle and incapable of sustaining further plastic deformation at low temperature. If such a diagram of the base metal is available, the next step is to see how much ductility is required by the welding procedure, to be sure that after welding the SAZ has still enough ductility left to ensure a safe behavior when loaded in service.

Determination of the Required Ductility for Welding[4,5]

As already mentioned, during each welding cycle the SAZ is submitted to plastic compression while heating and to plastic stretching while cooling. This means that strain determination based on measurements before and after welding are irrevelant. This is because they give no information about the amount of hot straining in compression and the amount of hot straining in tension, but only the algebraic sum of both. But embrittlement occurs as well in compression as in tension, so it is dependent on the sum of all strains regardless of their sign. To be informed about the cumulative damage due to this cycling, it is neces-

Table 2—Test Results

Specimen	Total notch length, mm	Testing temperature °F	Testing temperature °C	Yield stress kg/mm²	Yield stress ksi	Ultimate stress kg/mm²	Ultimate stress ksi
I	2 × 5 = 10	−31	−35	29	41	>42.4	61
II	2 × 15 = 30	−31	−35	—	—	11.2	16

Table 3—Chemical Analysis and Mechanical Properties

Composition, % C	Mn	Si	S	P
0.21	0.6–1.4	0.35	0.05	0.05

Charpy at 0° C: 4.85 kgm/cm² or 28 ft-lb
Tensile strength: 41–50 kg/mm² or 59–71 ksi
Elongation (1 = 5.65A): 22%

Table 4—One-Run Welding Conditions

Welding procedure[a]	Intensity, amp	Voltage, v	Speed cm/min	Speed ipm
EG 1, 2, 3	500	30	9	3.5
CE 1, 2, 3	600	32	5	2
AM 1	1100	37–38	25	10
AM 2	1100	38	25	10
AM 3	1100	36–37	25	10
SA 1, 2:				
1st run	650	32	30	12
2nd run	800	33	40	16
SA 3:				
1st run	660	32	40	16
2nd run	820	32	35	14

[a] EG—electrogas; CE—consumable electrode; AM—granular-metal filler metal (i.e., Arcmetal®); SA—submerged arc.

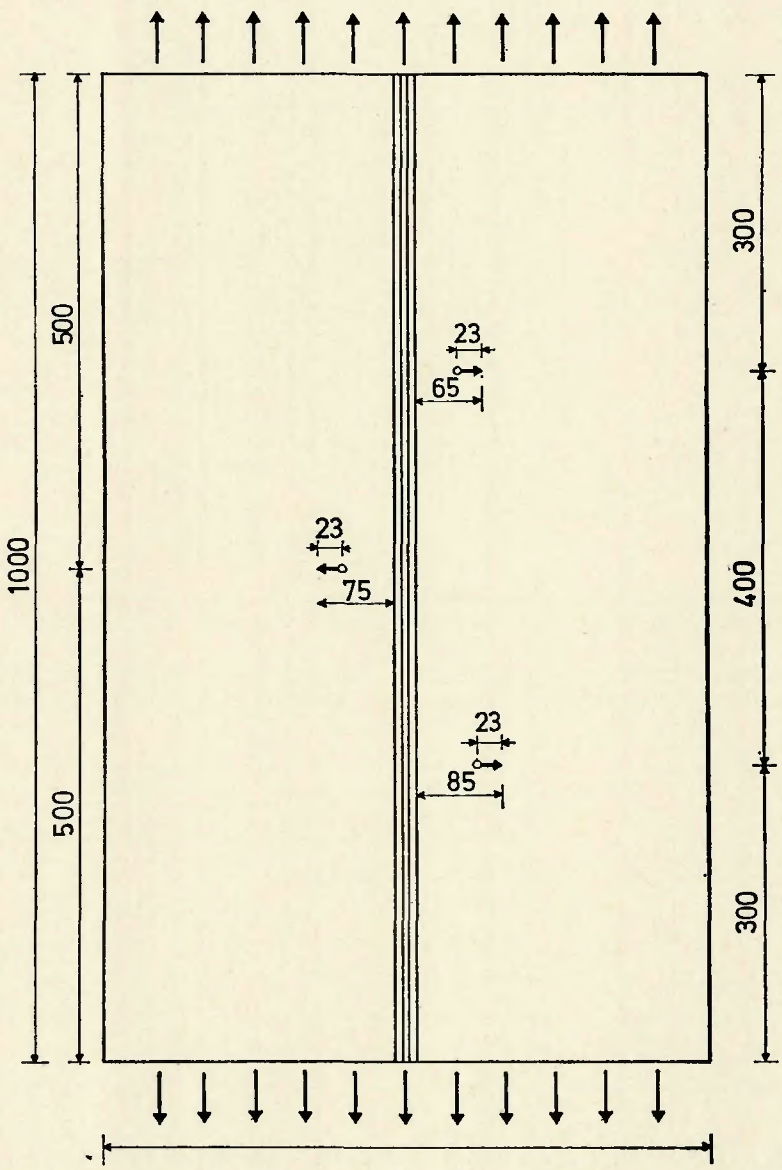

Fig. 7—Notch locations in one-run weld plates. Dimensions in mm

Table 5—Automatic Welding Test Results (Notch Length = 23 mm)

Welding procedure specimen[a]	Notch apex — Maximum temperature °F (°C) at distances "d" shown[b] 2.55 in.	(65 mm)	2.95 in.	(75 mm)	3.34 in.	(85 mm)	Test temperature °F	°C	Elongation, %	Fracture kg/mm²	ksi	Fracture
EG 1	464	(240) (F)	433	(223)	394	(201)	—67	—55	2.43	34.1	48.1	Total
EG 2	450	(232)	424	(218)	370	(188) (F)	—49	—45	2.45	35.3	50.4	Partial
EG 3	491	(255) (F)	437	(225)	394	(201)	—58	—50	2.2	33.1	47.3	Partial
CE 1	541	(283) (F)	518	(270) (F)	491	(227)	—67	—55	1.5	30.4	43.4	Total for (F) at 491 °F; partial for (F) at 541 °F
CE 2	576	(302) (F)	549	(287)	466	(241)	—49	—45	2.7	33.4	47.7	Total
CE 3	513	(267)	453	(234)	405	(207)	—58	—50	2.85	37.1	53.0	None
AM 1	563	(295) (F)	509	(265)	466	(241)	—67	—55	1.7	32.2	46.0	Total
AM 2	538	(281) (F)	486	(252)	450	(252)	—49	—45	2.65	37.4	53.4	Total
AM 3	563	(295)	502	(261) (F)	464	(240) (F)	—58	—50	2.20	35.6	50.9	Partial for (F) at 502 °F; total for (F) at 464 °F
SA 1 (1st run)	343	(173)	318	(159)	284	(140)	—72	—30	4.0	—	—	None
(2nd run)	367	(175)	322	(167)	288	(142)						
SA 2 (1st run)	352	(178)	318	(159)	284	(140)	—67	—55	1.14	28.6	40.9	Total
(2nd run)	338	(170) (F)	302	(150)	271	(133)						
SA 3 (1st run)	370	(188)	318	(159)	189	(143)	—40	—40	3.0	36.7	52.4	None
(2nd run)	370	(188)	336	(189)	313	(156)						

[a] EG—electrogas; CE—consumable electrode; AM—granular-metal filler metal (i.e., Arcmetal®); SA—submerged arc.
[b] (F)—denotes notch in which fracture was initiated.

sary to know the strain-temperature history of the SAZ. For this purpose a special apparatus has been conceived and built at Ghent University.

The strains during the welding cycle are recorded by use of the moiré technique. A temperature resisting grid is photo engraved on the surface and follows its deformations during welding while a reference grid is projected with an optical system onto it. The moiré fringe patterns created by the interference of both grids is recorded with a moiré camera during welding. The principle is illustrated by Fig. 2; a photograph of the equipment is shown in Fig. 3. To illustrate the results obtained by this technique, the strain history is given of point E of Fig. 4, situated $^3/_8$ in. (10 mm) from the weld. The plates were manually welded in the downhand position in two runs.

From the moiré patterns taken at various intervals one of which is shown in Fig. 5, it was possible to draw Fig. 6, which gives the cumulative strain at point E during the two weld runs. The total hot straining reached for the considered point E is of the amount of 3.2%, which is high taking into account that E is not located in the direct vicinity of the notch.

Determination of the Remaining Ductility After Welding

Once the sensitivity to strain aging of the base metal and the required ductility for a welding technique are known, the possibility of using this particular welding procedure with the considered steel can be checked. It suffices to plot on a single diagram the curves of Figs. 1 and 6. The C curve (Fig. 1) going through the end point of the welding curve (Fig. 6) gives the remaining ductility at the tip of the notch when the specimen is loaded at the lowest temperature at which the hot strained specimens have been broken. If this end point approaches the C curve with $E_l = 0$, it can be expected that a low load fracture will occur.

To check this situation test specimens similar to Wells wide plates are instructive. The question may arise, where must the apex of the notch be located? British authors claim[6, 7] that an open notch 0.20 in. wide in the leveled edges is adequate for weldments involving heat inputs of the range of 35–45 kilojoules/in. This may be open to criticism. Since the most harmful damage is done at about 570° F (300°C), it seems logical to place the notch apex at such a distance from the weld that this temperature range is reached. However, for welding procedures with a flat temperature distribution, this requires long notches with the apex far from the weld. In this case an open side notch is no longer realistic, and the use of closed through-cracks becomes mandatory.

Wide Plate Tests

To illustrate the importance of the location of the notch apex, two wide plates specimens were welded, one with a notch length of $^1/_4$ in. (5 mm), the other with a notch length of $^5/_8$ in. (15 mm). Both specimens were hand welded under similar conditions (Table 1).

The maximum temperature recorded during welding was 1463° F (795° C) at the area of the short notch and 797° F (425° C) at the apex of the long notch. Tensile tests at —31° F (—35° C) parallel to the weld gave the results summarized in Table 2.

Specimen I did not fail at a net stress of 61 ksi (42 kg/mm²), but specimen II failed at a very low stress of 16 ksi (11.2 kg/mm²), or about 40% of the yield strength. The behavior is explained by the C curves of Fig. 1: heating at high temperatures wiped out the detrimental influence of hot straining at the aging temperature.

Fig. 8—Notched weldment showing partial fracture at notch apex 85 mm from weld

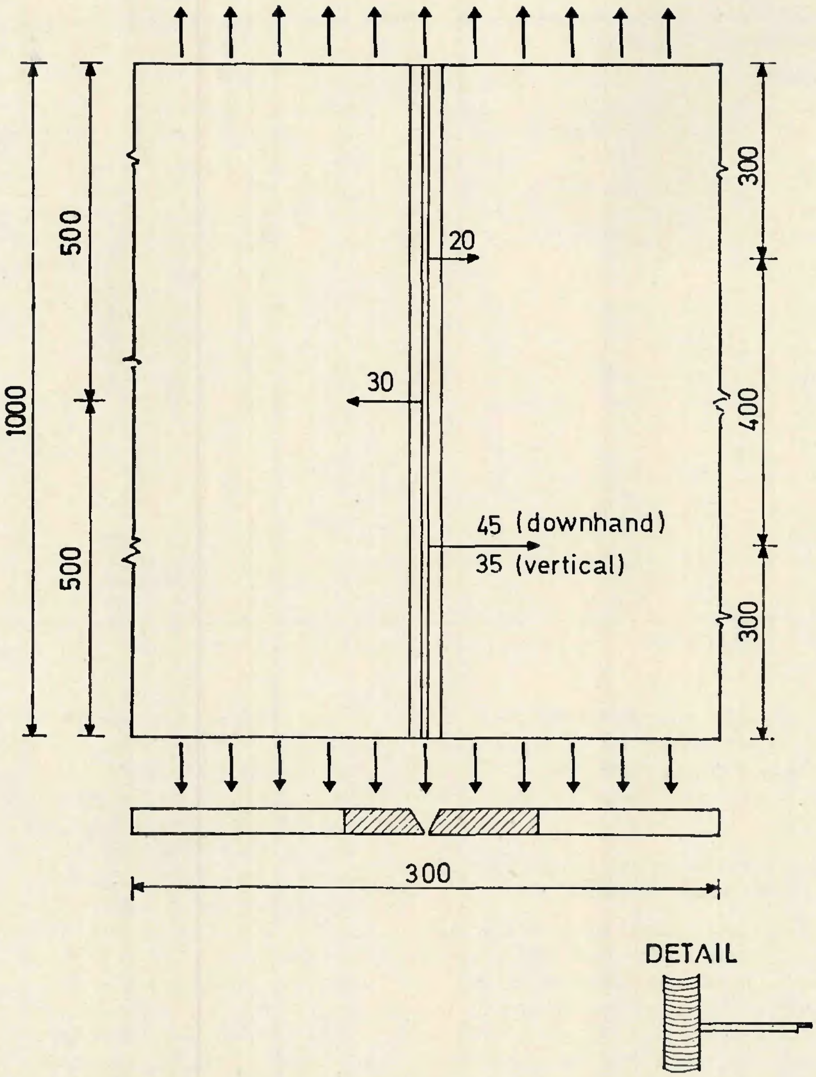

Fig. 9—Plate and notch dimensions (in mm) for tests of multipass welds

Taking this into account, a series of wide plate tests has been done with the apex of the notch located in the 390–750° F (200–400° C) range.

The plate material used was an L D conventional C-Mn steel (grade B, according Lloyds). The material was in the form of hot rolled 23 mm thick plate with the chemical analysis and properties summarized in Table 3.

One-Run Welds. One-run welds were made using the following automatic welding procedures:

1. Submerged arc (in 2 runs) in downhand position.
2. Alloyed metal, one-run, downhand position.
3. Electrogas, one-run vertical position.
4. Consumable electrode, one-run vertical position.

From each of these procedures three specimens were welded and tested. In each specimen 3 notches were machined by drilling a hole and extending it to one side with a saw cut and finishing the apex with a jewelers saw cut. The total length of the notch was about equal to the plate thickness. The notches were located as indicated on Fig. 7.

As already mentioned the apex of the notch was located as accurately as possible in the 570° F (300° C) temperature range obtained during welding. For this, temperature measurements were carried out to determine the temperature distribution for each welding procedure. The notches were oriented with the hole towards the weld and with the apex pointing away from the weld, since preliminary tests had indicated that that orientation gave the most reliable results.

At each notch apex a thermocouple

Table 6—Welding Conditions for Manual Welding

Position	Run	Electrode diameter, mm	Electrode diameter, in.	Intensity, amp
Downhand	1	3.25	1/8	100
	2	4	5/32	180
	3		3/16	230
	4		3/16	230
Vertical	1	3.25	1/8	100
	2	4	5/32	150
	3	4	5/32	180
	4	4	5/32	180

Table 7—Manual Welding—Four Runs

Position	Notch temperature for runs shown, °F, 1	2	3	4	°C, 1	2	3	4	Notch length[a], mm	in.	Testing temperature, °C	°F	Fracture stress, kg/mm²	ksi	Fracture
Horizontal 1	476	470	584	660	247	243	307	349							
	608	692	756	777	320	367	402	414			+51	+124			
	—	925	1030	905	—	496	555	485	12	0.47			14.3	20.4	Total
Horizontal 2	302	452	436	436	150	233	225	225	43	1.68			2.79	4.0	Partial
	374	572	500	500	190	300	260	260			−50	−58			
	457	797	662	572	236	425	350	300	16	0.63			10	14.3	Total
Horizontal 3	298	452	428	400	148	233	220	205	41	1.61			3.5	5.0	Partial
	385	545	508	508	156	285	265	265			−50	−58			
	464	796	652	562	240	425	345	295	15	0.59			8.2	11.7	Total
Vertical 1	382	428	482	446	195	220	250	230	28	1.10			3.0	4.3	Partial
	472	490	545	472	245	255	285	245	24	0.94	−50	−58	18.0	25.7	Total
	562	572	626	599	295	300	330	315	14	0.55			5.8	8.3	Partial
Vertical 2	419	446	482	464	215	230	250	240							
	446	453	518	518	230	234	270	270	25	0.98	−50	−58	7.9	11.3	Total
	536	508	662	617	280	265	350	325							

[a] The difference between the notch length "a" and the length of the saw cut is due to the weld penetration.

was spot-welded. Recordings of temperature against a time base were synchronized with the welding and continued after completion of the weld. The welding conditions are listed in Table 4.

Test Results of One-Run Welds. Table 5 gives the results of the wide plate tensile tests. In Table 5, (F) denotes the notch in which fracture was initiated, and the highest notch temperature corresponds to the notch with its apex being the nearest to the weld. Also in the same table, "d" denotes the distance in mm from the notch apex to the groove of the plate before welding, and elongation is the overall elongation measured over the length of the specimen. The fracture stress is based on the net section of the specimen.

In Table 5, the indication "total fracture" means that the specimen was completely broken, while the indication "partial fracture" refers to those cases where fracture only propagated at the side of the notch apex and did not initiate at the side of the drilled hole (Fig. 8). It may be interesting to note that, in the case of a partial or total fracture, both fractures occurred at the same moment. These fractures are not two-stage fractures, as have been observed to occur in other instances.

From these tests we may conclude that all the investigated welding procedures give satisfactory results, for an elongation of 1% for a specimen with a through crack can be considered quite satisfactory. From the tests results obtained at −55° C we can classify the different welding procedures as follows:

Procedure	Elongation, %	Fracture stress kg/mm²	ksi
Electrogas	2.43	34.1	48.9
Granular filler metal	1.70	32.2	46.0
Consumable electrode	1.50	30.4	42.9
Submerged arc (2 runs)	1.14	28.6	40.9

The behaviour of the submerged arc technique may be explained by the 2-run technique used in this procedure.

Multipass Welds. Multipass welds were obtained by manual welding. These welds were carried out either in the downhand or the vertical position.

In order to increase the strain aging effect the welds were allowed to cool to room temperature after each weld run. Three specimens were welded for each position.

Since the temperature gradient in the SAZ is now very steep, it is impossible to notch the specimen in the same way as the automatically welded specimens. The dimensions of the notch are given in Fig. 9; the saw cut was finished with a jeweler's saw. In order to have the notch apex in the temperature range of 390—750° F (200—400° C), three notches with different lengths were sawed in one specimen (Fig. 9).

The same temperature measurement technique was used as for the automatic welds.

Welding was carried out with low hydrogen electrodes; the welding conditions are listed in Table 6.

Test Results of Multipass Welds. Table 7 gives the results obtained on wide plate tests. The most remarkable observation is certainly the low stresses at which all fractures occurred. Here the SAZ has been plastically strained four times in compression and in tension, which must have seriously damaged the metal at the apex of the notch.

In contrast to the automatic welds, partial cracks occurred in different stages. Specimen "vertical 1" is a typical example in which three separate fractures initiated at three different stress levels. In the first two instances the cracks were abruptly arrested, presumably because the net average stress was below the critical stress level required for propagation.

Conclusions for C-Mn Steels

Comparison of the automatic and manual welds clearly indicates that for conventional C-Mn steels the embrittlement due to hot straining of the SAZ is a serious danger in multipass welds, while no serious damage occurs in single-pass welds.

These tests show clearly that local straining is far more severe when the number of weld passes is increased. Seen from the viewpoint of aging, the single run technique is less harmful than the multi-run weld. Simular conclusions were found by other authors. [6, 7] It is, however, difficult to give quantitative information because the aging damage depends on the amount of hot straining and on the temperature distribution; during welding these quantities depend not only on the welding procedure but also on such factors as heat input, stiffness of the plates, position of the weld, use of tack welds. For conventional C-Mn steels the hot straining produced by welding will in general be insufficient to initiate a brittle fracture, but if strain concentrators are located in the SAZ real danger may exist.

Heat Treatment

A look at Fig. 1 shows that no strain aging occurs at temperatures higher than 930° F (500° C). There is further experimental evidence that strain aged specimens recover when heated above this temperature. This means that the so-called stress relieving treatment not only relieves residual stresses but—and this is perhaps more important—it metallurgically restores conventional steels which have been embrittled by hot straining. For these steels a stress relief treatment is always beneficial.

Further Research

An investigation is currently running to see if simular damages may occur in weld metal. The results of this research work will be reported at the Kyoto meeting of the I.I.W.

To study the behavior of weld metal, wide plate tests are used involving two welds (Fig. 10); weld no. 1 is the test weld in which a notch is introduced after welding; weld no. 2 is the so called embrittling weld, because it

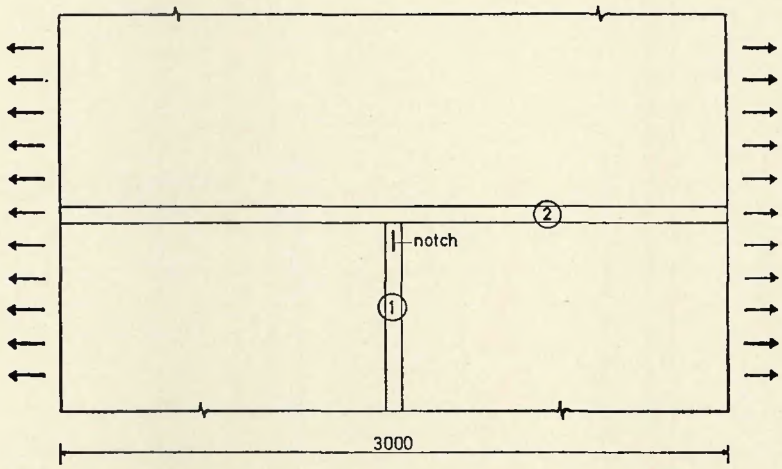

Fig. 10—Wide-plate weldment. Test weld 1, notched after welding, becomes embrittled by hot straining provoked by deposition of weld 2

will provoke hot straining in the weld metal of weld no. 1.

High Strength Steels

Conscious of the deleterious influence of aging on the properties of welds, the metallurgist turns to the so-called "non-aging steels". The effects of aging may be restricted by lowering the C and N concentrations. In modern steel manufacturing processes the nitrogen concentration has already been reduced, but a further reduction in the susceptibility to strain aging is obtained by adding such elements as Nb, Ta, V, Ti, which form stable carbonitrides, or Mo-forming carbides. By binding the C and N the steel is made not only less sensitive to aging but grain refining occurs; this results in an increase in both yield and ultimate strength.

A further increase in the strength properties may be obtained by special heat treatments. By combining alloying elements and heat treatments, the following high strength steels are manufactured:

1. Low alloyed Nb or V steels: precipitation of Nb-X or V-X particles occurs during cooling.
2. Low alloyed Nb or V steels normalized: the heat treatment gives a further grain refining.
3. Low alloyed V and Mo steels normalized and tempered: by tempering, a secondary hardening takes place by precipitating particles of the type Mo-X and V-X.
4. Low alloyed Mo and B steels with a bainitic structure.
5. Quenched and tempered steels: (a) unalloyed C-Mn steels; (b) alloyed steels.
6. Maraging steels.
7. Ultra high strength steels.

Although the susceptibility to strain aging of most of these steels is sharply reduced, welding is not easier; it appears indeed, especially for the heat treated steels, that microstructural changes in the heat-affected zone may give rise to serious problems. These problems are essentially of a purely metallurgical nature. The properties of the steel depend on its thermal history, which is defined by the welding procedure and the eventual heat treatment after welding.

There are two ways open to investigate the weldability of these steels:

1. If one is asked to look for the most appropriate thermal cycle for a given steel, the use of a weld simulating machine is indicated: a welding procedure is simulated by an electric current passed through blanks $^3/_8$ in. square $\times$ 4 in. long ($1\times1\times10$ cm); the rate of heating is controlled by adjusting the current, and cooling of the specimens can be accelerated by a flow of argon. After heat treatment the blanks are machined to Charpy specimens. The micro-structures of the specimens are examined with a microscope and replicas of the broken specimens are examined with the electron microscope. The relation between weld cycle fracture toughness and microstructure is presently being investigated in our laboratory. It is hoped to define for a given steel the most appropriate welding procedure giving the highest toughness in each point of the heat-affected zone. A relation between heat input (welding procedure) and C equivalent (steel) is sought which will give a final answer in terms of maximum ductility.

2. If one is asked to look for the most appropriate steel to be welded by a given welding procedure, steel plugs of different steels are pressed into holes drilled in a weldment so that the ends are flush with the weld preparation surface.[8] After welding the plugs are removed, tested, and their structure is examined by conventional or electron microscopy.

The results of such an investigation depend, of course, on the steel. However, some tests have already shown that high heat and slow cooling rates can result in a heat-affected zone with inferior properties. This embrittlement is usually located near the fusion line. It is assumed that during welding the Nb-X and V-X particles are dissolved and their effect lost.

As long as laboratory investigations do not yield clear answers to the question "how to fill in the most economical way a joint between high

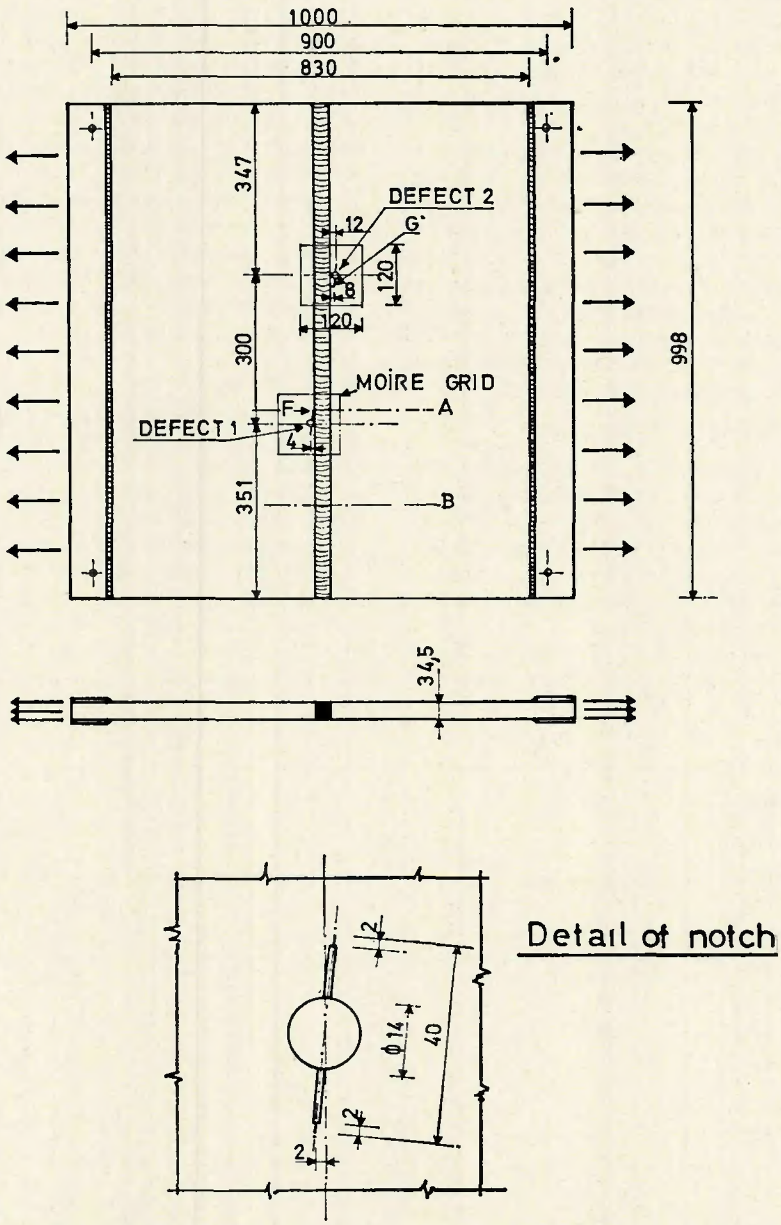

Fig. 11—Industrial wide plate test used at Ghent University, showing detail of notch preparation

Table 8—Wide Plate Tests on High Strength Steel According to Fig. 11[a]

Weld	Notch distance "d" mm	Notch distance "d" in.	Temperature °C	Temperature °F	Stress kg/mm²	Stress ksi	Strain, %	Observations
Electrogas			0	32	24.0	34.3	—	No fracture
(one run)	0	0	—30	—22	27.1	38.7	0	Total fracture
	4	.157						
	8	.314						
	12	.471						
Electrogas			0	32	24.0	34.3		No fracture
(two runs)			— 5	23	24.0	34.3		No fracture
	0	0	—10	14	35.5	50.7	0.17	Total fracture
	4	.157						
Electrogas	0	0	10	50	38.9	55.6	0.50	Partial fracture
(two runs)	4	.157						
Electrogas			—10	14				
(two runs)	0	0			41.7	59.6	0.50	Partial
	4	.157						Fig. 12A, 12B
	8	.314						
	12	.471						
Manual vertical			—10	14				
(10 runs, low	0	0			44.5	63.6	1.92	Partial in weld
hydrogen elec-	4	.157						metal
trode)								

[a] Type steel—Nb 52; yield strength—36 kg/mm² (51.3 ksi); steel ultimate tensile strength—52–62 kg/mm² (74–89 ksi); thickness—34 mm (1.33 in.).

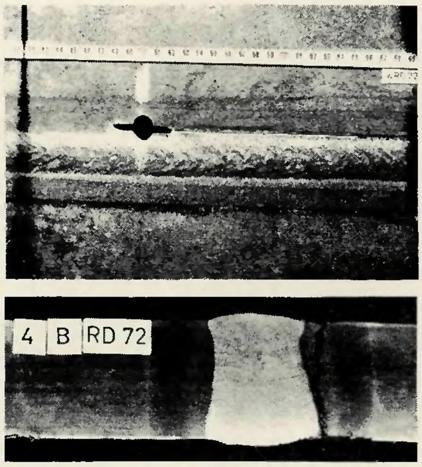

Fig. 12—Two-pass electrogas weldment. A (top)—partial fracture (see Table 8); B (bottom)—cross section through fracture path of A. B—X1 (reduced 52% on reproduction)

strength steels", industrial tests must be done on specimens which are representative of joints of the real structure.

At Ghent University wide plate tests are used but, contrary to the tests done on conventional steels, the tensile load is applied perpendicular to the direction of the weld. A notch which simulates a lack of fusion is machined in the heat-affected zone; in a one meter plate several such notches can be machined with their ends at different distances from the fusion line in order to locate at least one notch root in the critically embrittled zone (Fig. 11). The test is done at the lowest temperature imposed by the service conditions. The test result is given by the strain at rupture. An overall strain of 1% is normally required; local strain measurements at the root of the notch may be recorded by photographing a moiré pattern. Test results are given in Table 8.

From these test results it appears that welding procedures using a high heat input have in general a far more severe embrittling effect than low heat input techniques. The results obtained plead in favour of using more runs with a lower heat input.

Although no final conclusion can yet be taken, welding procedures using one run (such as the electroslag and electrogas techniques) should be used with caution when welding high strength steels. The need for an adequate postweld heat treatment may be real.

Restoration of the microstructure may be obtained with a postweld treatment, but the conditions under which such heat treatment must be applied should be seriously investigated. The simple stress relieving treatment required in some specifications may do more harm than good. Several structures in high strength steel have demonstrated cracks after applying the prescribed stress relief treatment at 1110–1200° F (600–650° C). This behavior is fundamentally different from the behavior of conventional steels, where as already mentioned the stress relieving heat treatment when properly applied is always beneficial.

Industrial Test

As mentioned before, the most brit-

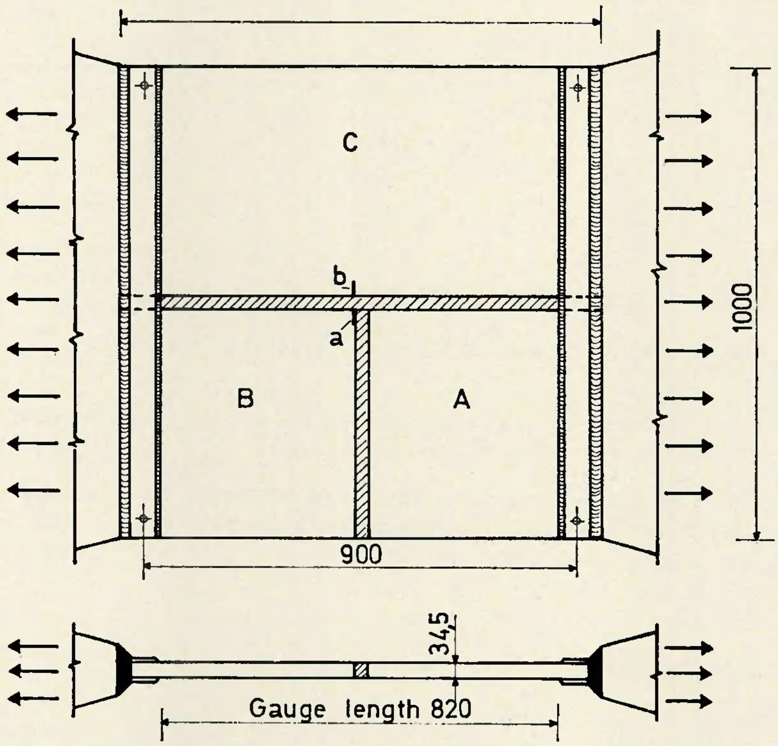

Fig. 13—Special wide plate specimen, which reveals area with lowest ductility. Dimensions in mm. Saw cut "a" is made in HAZ of plate B after welding to A; saw cut "b" is made in plate C before welding to AB

Table 9—Wide Plate Tests of High Strength Steels According to Fig. 13[a]

Steel[b]	Weld Horizontal	Weld Vertical	Temperature °C	Temperature °F	Stress kg/mm²	Stress ksi	Strain, %	Observations
(1)	Manual low hydrogen	Manual low hydrogen	−10	14	52.1	74.4	3.0	No fracture
(1)	Manual	Electrogas (5 runs)	−10	14	49.0	70.0	2.9	Total fracture
(2)	Manual low hydrogen	Manual low hydrogen	−10	14	47.2	67.4	3.0	No fracture
			−20	−4	51.9	74.1	3.0	No fracture
(3)	Manual low hydrogen	Electrogas (10 runs)	−10	14	52.0	60.0	2.41	Partial fracture
							3.19	Total fracture

[a] Yield strength—36 kg/mm² (51.3 ksi); ultimate tensile strength for steel (3) only—52–62 kg/mm² (74–89 ksi); thickness—52.5 mm or 2.06 in. (50.0 mm and 1.96 in. for steel (3)).
[b] Chemical analyses (%) as follows:
(1)—0.17 C; 0.28 Si; 1.42 Mn; 0.020 P; 0.027 S; 0.09 V; 0.032 Al
(2)—0.16 C; 0.26 Si; 1.37 Mn; 0.014 P; 0.09 Cr; 0.14 Cu; 0.05 Mo; 0.57 Ni; 0.02 V; after welding heat treatment at 600 °C (1110 °F).
(3)—0.17 C; 0.34 Si; 1.19 Mn; 0.018 P; 0.027 S; 0.085 Cr; 0.46 Ni; after welding heat treatment at 600 °C (1110 °F).

tle zone in C-Mn steels usually occurs in the thermally strained area (SAZ) outside the transformed heat-affected zone, but even in these steels it is possible to obtain an area of low toughness in the heat-affected zone. In high strength steels the situation is similar, although the most serious embrittlement now occurs in the heat-affected zone. In the strain affected zone (SAZ) some loss of ductility due to aging may occur depending on the susceptibility to strain aging of the steels.

To check with one test both the embrittlement of the strain aged zone and the embrittlement of the heat-affected zone, a special wide plate specimen is used at Ghent University to locate the area with the lowest ductility. Details of the wide plate test are given in Fig. 13: two plates A and B are butt welded; when this weld is completed, a saw cut is made in the fusion line of the weld heat-affected zone. The welded specimen AB is then welded to a plate C in which a saw cut "b" is made before welding. After welding, the plate is cooled to the test temperature and tensioned in a direction perpendicular to the notches.

With this preparation fracture may initiated either at the root of notch "a" or at the root of notch "b"; in the former case embrittlement of the heat-affected zone is the cause of crack initiation; in the latter case aging may be considered as the initiator of fracture. Some test results are listed in Table 9.

This test is actually a classical test used at Ghent University to control the welding procedure as a function of the base metal. Of course, it only answers the question: "Is the technique used acceptable?" It does not elucidate whether the technique used is the best available one.

It is hoped that a complete answer will be obtained by the Laboratory investigations mentioned above.

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