

# Weld Cracking and Mechanical Properties of 17% Chromium Steel Weldment

Welding materials containing "Nb-N" or "Nb-Ti-Al" produce crack-free weldments and suitable postweld heat treatment improves the ductility of 17% chromium weldments

BY Y. NISHIO, T. OHMAE, Y. YOSHIDA AND Y. MIURA

**ABSTRACT.** A study was carried out on the cause for the weld cracking and embrittlement of the heat-affected zone of 17% chromium steel and led to the following conclusions:

1. By means of promoting the ferritizing and refining of the weld metal structure by adding of Nb, Ti and Al to 17% chromium weldment, crack sensitivity is reduced, enabling the production of sound weld metal without preheating.

2. Compared with structural low alloy steels, the 17% chromium weldment is apt to cause delayed cracking with a long incubation period.

3. The embrittlement of the heat-affected zone is due to the formation of retained austenite and martensite structure; however, ductility can be recovered by decomposing these structures by applying postweld heat treatment.

4. At a postweld heat temperature of 150-250° C, there is a peculiar phenomenon in which the retained austenite is transformed to martensite, resulting in a decrease of ductility at the heat-affected zone.

## Introduction

In chemical apparatus, austenitic stainless steels have been used mainly for corrosion and heat resisting applications. However, since austenitic stainless steel is liable to stress corrosion cracking due to chlorine or sulfides, there has been a recent trend to use 17% chromium ferritic stainless steel in such environments. In relation to the welding of this stainless steel, the following can be cited as the main problem:

Y. NISHIO, T. OHMAE, Y. YOSHIDA and Y. MIURA are associated with Hiroshima Technical Institute, Mitsubishi Heavy Industries, Ltd., Japan.

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1. The weld metal and the heat-affected zone are liable to weld crackings.

2. The heat-affected zone becomes embrittled, which makes it difficult to obtain satisfactory results of bending test.

To solve those problems, the following research has been carried out. The 17% chromium weld metal forms partially the martensite, and this is liable to cold cracking. On the other hand, 17% Cr-Nb weld metal becomes coarse ferrite grains and this induces hot cracking. Therefore, with regard to the 17% Cr-Nb-Ti-Al electrode recently developed from the standpoint that a sound weld metal can be obtained, providing the weld metal is ferritized and refined, its practicality was confirmed by conducting a modified finger-type cracking test.

Cracking at the heat-affected zone is largely influenced by diffusible hydrogen. For this reason, it is considered effective for the prevention of the cracking to reduce diffusible hydrogen by preheating and drying of electrodes. Based on this viewpoint, the above effect was examined by Y-groove restraint cracking test. On the other hand, from the standpoint that the 17% chromium steel has a

low diffusion rate of hydrogen and is liable to delayed cracking with a long incubation period, the incubation period was investigated by the circular ring cracking test.

As for the embrittlement of the heat-affected zone, it is considered that the above is due to the fact that the Ar<sub>1</sub> transformation is suppressed by the increase of chromium content, with resultant formation of the retained austenite and martensite.

Based on this thinking, an investigation was carried out on the relation between these structures and mechanical properties and also on the recovery conditions of mechanical properties by postweld heat treatment. This was done by comparing results of the synthetic test for weld thermal cycle with the results of welded joint bending tests. The cause for the weld cracking and the embrittlement of the heat-affected zone as well as their prevention methods have been clarified through these researches carried out in a series.

## Weld Metal Cracking

### Preliminary Study on Welding Materials

Since the 17% chromium weld metal partially forms martensite, it has a high sensitivity for cold crack-

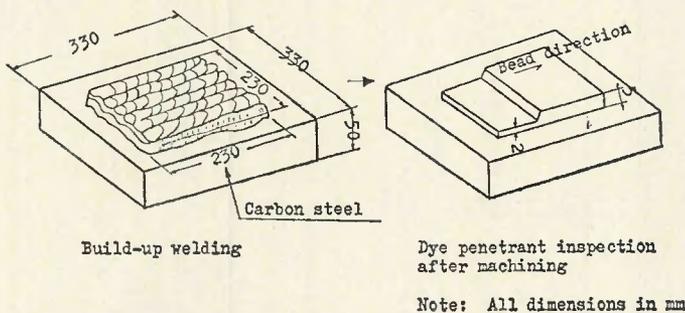
Table 1—Chemical Composition of Materials used in Preliminary Test, wt-%

Material	Thickness or diameter, mm	Composition, %						
		C	Si	Mn	P	S	Cr	Nb
Carbon steel base metal	50	0.17	0.03	0.73	0.017	0.028	—	—
ER430 filler metal <sup>a</sup>	1.6 <sup>b</sup>	0.04	0.27	0.25	0.022	0.011	17.36	0.66
	2.4 <sup>c</sup>	0.04	0.29	0.25	0.023	0.011	16.67	0.63

<sup>a</sup> Oscillating gas metal-arc filler metal.

<sup>b</sup> Hot wire for oscillating gas metal-arc filler metal.

<sup>c</sup> Cold wire for oscillating gas metal-arc filler metal.



Welding conditions			
Current:	300 - 340 A	Layer:	2
Voltage:	30 - 35 V	Oscillating cycle:	1.3-1.6 sec/cycle
Welding speed:	110-130 mm/min	Argon flow rate:	20 L/min

Fig. 1—Test procedure of build-up welding by oscillating gas metal-arc welding

ing. However, it is considered that this weak point can be improved by making the refined structure of single phase ferrite through the addition of alloy elements to the weld metal. In order to examine the effect of the ferritizing, a 17% Cr-Nb filler metal as shown on Table I was manufactured for trial. With this filler metal, two-layer build-up welding was conducted for a carbon steel plate by using oscillation with the gas metal-

arc process. The welded part was then inspected for crack sensitivity by dye penetrant inspection. The test procedure is shown in Fig. 1.

From Fig. 2, it can be seen that 17% Cr-Nb weld metal causes numerous cracks regardless of whether preheating is applied or not. This weld metal is remarkably coarsened, although it is of a single phase ferrite structure as shown on Fig. 3. Moreover, as these cracks were detected at the grain boundary, it is presumed that these were caused by hot cracking ascribable to low melting point impurities. Next, in case nitrogen was added by shielding gas for the refining of ferrite, a sound weld metal free from cracks could be obtained as shown on Fig. 4.

As mentioned above, ferritizing and refining are considered to be inevitable conditions for preventing the cracking of 17% chromium weld metal. Therefore, 17% Cr-Nb was adopted in the experiments mentioned hereunder, since these elements have the same action and effect as nitrogen. As for the reason why titanium, aluminium or nitrogen is effective for the prevention of weld cracking, details are explained under "Discussion."

#### Materials

From the results of the foregoing item, a 17% Cr-Nb-Ti-Al electrode was employed for shielded metal-arc welding since it shows a fine grain, ferrite structure. On the other hand, two different fluxes—*A* and *B*—were used for submerged arc welding; these were adopted in combination with a ER 430 (17% chromium) electrode. *A* is a bonded flux containing niobium, titanium and aluminium, and *B* is a flux containing no alloy elements other than chromium. The latter is the one being employed for general austenitic stainless steels and was used for comparison with *A*.

Tables 2 and Table 3 show their respective chemical compositions.

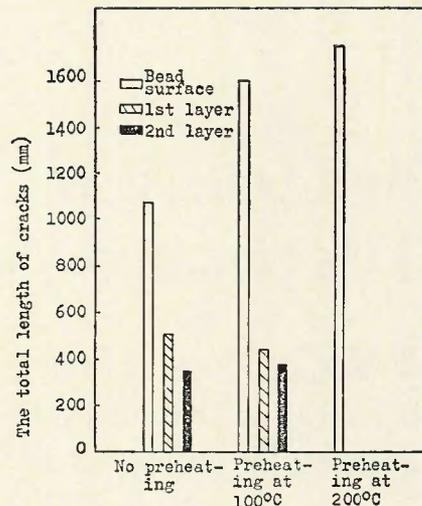


Fig. 2—Cracking test results of build-up welding. Welding process—oscillating gas metal-arc welding; filler metal—17% Cr containing Nb; shielding gas—100% argon

#### Test Procedure

By conducting cold cracking test with modified finger-type cracking test

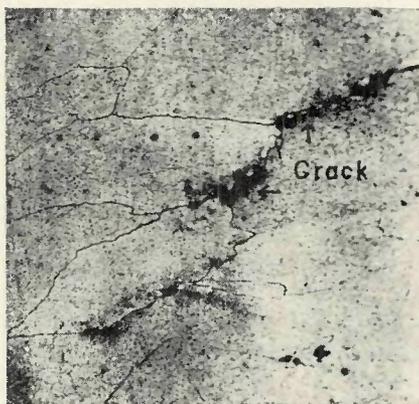
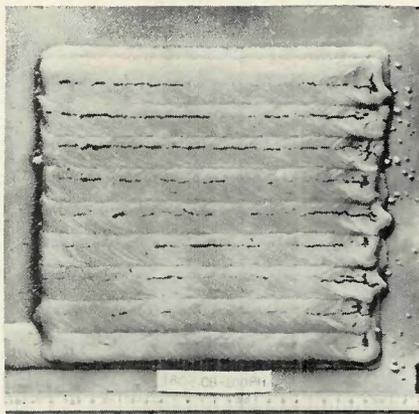


Fig. 3—Cracking of 17% Cr-Nb weld metal. A (top)—appearance of bead surface showing many cracks; B (bottom)—microstructure of the second layer showing initiating cracks in boundary between coarse ferrite grains (chromic acid etchant, X100)

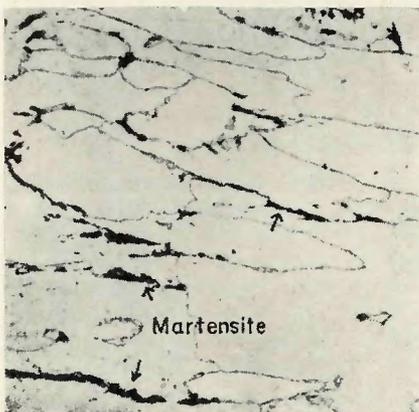
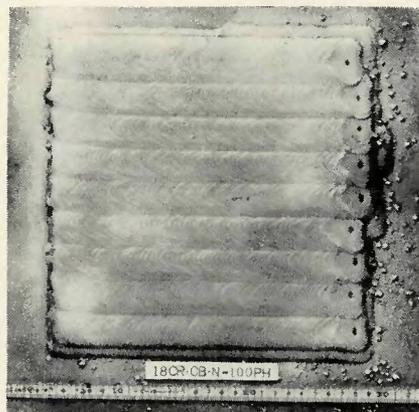


Fig. 4—Appearance of 17% Cr-Nb weld metal to which nitrogen was added by shielding gas (shielding gas: 99% argon + 1% nitrogen). A (top)—bead surface showing free from cracks; B (bottom)—microstructure of the second layer showing martensite at ferrite grain boundary and free from crack (chromic acid etchant), X100 (reduced 8% on reproduction)

specimens, crack sensitivity was examined for the welding materials shown on Table 2. The shape and dimensions of these specimens are shown in Fig. 5.

In this test, one bead welding was conducted for each specimen after its side surfaces had been restrained by tack welding. The number of cracks was then detected by conducting dye penetrant inspection after more than 120 hr had passed from the completion of test bead welding.

## Results

Test results are shown in Table 4. In the case of 17% Cr-NbTiAl weld metals prepared by submerged arc welding (using A flux) and by shielded metal-arc welding (modified E 430 electrode), no crack was recognized without preheating. On the other hand, the 17% chromium weld metal made with B flux had a high crack sensitivity and it needed to be preheated at a temperature over 150° C. The difference in crack sensitivity is due to existence of the martensite in the weld metal. Table 5 shows the respective chemical compositions and Fig. 6 shows their respective structures.

Of the above two kinds of weld metal, the former showed a fine single phase ferrite structure because of ferritizing action by niobium and refining action by titanium and aluminium. Since the latter does not contain these alloy elements, the martensite is formed at its ferrite grain boundary. Therefore, it requires preheating for the prevention of delayed cracking.

It can also be seen from Table 4 that, even in the case of the 17% Cr-NbTiAl weld metal (modified E430 and ER 430 + A), cracking is caused if the base metal is a carbon steel. Accordingly, preheating is necessary at a temperature exceeding 100° C. This is to say that if build-up welding is applied to a carbon steel with a 17% Cr-NbTiAl electrode, most of the weld metal becomes a single phase ferrite structure. However, the interface of a weld joint is diluted by carbon steel and results in the formation of a thin martensite structure as shown in Fig. 7.

## Discussion

From the above, it is clear that the cracking of 17% chromium weld metal can be prevented effectively when it is ferritized and refined by adding "niobium and nitrogen" or "niobium, titanium and aluminium." In this respect, the authors' comments are described hereunder. The martensite formed in the 17% chromium weld metal has a high sensitivity for hydrogen embrittlement as suggested by

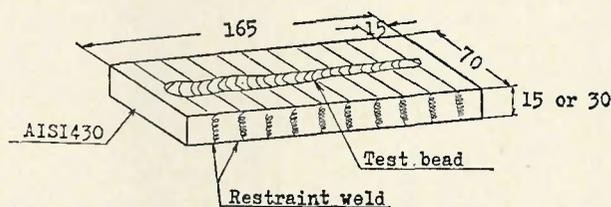
Table 2—Chemical Composition of Materials Tested, wt-%

Material	Thick-ness or diameter, mm	Composition, %									
		C	Si	Mn	P	S	Cr	Ni	Al	Ti	Nb
AISI430 base metal	15	0.06	0.55	0.40	0.032	0.005	17.04	0.19	—	—	—
ER430 filler metal <sup>a</sup>	4.0	0.07	0.10	0.41	0.026	0.014	19.25	0.21	—	—	—
Modified E430 electrode <sup>b</sup>	4.0	0.09	0.35	0.32	0.008	0.009	17.15	0.23	0.06	0.07	0.78

<sup>a</sup> Filler metal for submerged arc welding.  
<sup>b</sup> Electrode for shielded metal-arc welding.

Table 3—Composition of Fluxes Used in Study, wt-%

Code	SiO <sub>2</sub>	MnO	CaF <sub>2</sub>	CaO	TiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	MgO	Cr	Nb	Ti	Al
A	18.52	0.66	16.84	8.84	8.84	17.80	1.27	4.88	1.88	2.22	1.10
B	35.1	1.8	11.55	31.7	—	3.2	3.7	2.7	—	—	—



Note: All dimensions in mm

### Welding conditions

	Submerged arc welding	Shielded metal-arc welding
Current:	4.0φ 550 A	4.0φ 140 A
Voltage:	32 V	24 V
Welding speed:	300 mm/min	200 mm/min

Fig. 5—Modified finger type cracking test

Bastien.<sup>4</sup> For this reason, cracking is apt to be caused when preheating is omitted. On the other hand, if niobium is added to the 17% chromium, a stable carbide is produced by combining with carbon in steel; the carbon content in matrix is thereby decreased and a single phase ferrite structure is formed.

Since this weld metal has no martensite structure, it does not easily

cause the hydrogen embrittlement and accordingly has no apprehensions of the delayed cracking. However, it causes many hot cracks as shown in Figs. 2 and 3. This would be due to the reason that, since the weld metal is of a single phase, its structure is remarkably coarsened, and low melting point impurities gather at the grain boundary. In the preliminary study of welding materials, it was

Table 4—Results of Modified Finger Type Cracking Tests

Base metal	Welding process	Welding material	No preheat	Crack test results			Diffusible hydrogen in JIS hydrogen test specimen, cc/100 g <sup>a</sup>
				Pre-heating at 100° C	Pre-heating at 150° C	Pre-heating at 200° C	
AISI430	Submerged arc	ER430+A	None	None	None	None	0.32
		ER430+B	Crack	Crack	None	None	0.02
Carbon steel	Shielded metal-arc	Modified E430	None	None	None	None	0.89
		ER430+A	Crack	None	None	None	0.32
Carbon steel	Shielded metal-arc	Modified E430	Crack	None	None	None	0.95

<sup>a</sup> Determination of hydrogen content is in accordance with JIS Z3113.

**Table 5—Chemical Composition of Deposited Metal, wt-%<sup>a</sup>**

Welding material	Composition, %									
	C	Si	Mn	P	S	Ni	Cr	Al	Ti	Nb
ER430 + A <sup>b</sup>	0.06	0.55	0.39	0.032	0.005	0.18	18.56	0.20	0.20	0.92
ER430 + B <sup>b</sup>	0.08	0.43	0.83	0.027	0.006	0.20	18.98	—	—	—
Modified E430 <sup>c</sup>	0.09	0.36	0.32	0.008	0.009	0.23	17.15	0.06	0.07	0.78

<sup>a</sup> Composition determined from deposited metal free from base metal.  
<sup>b</sup> Submerged arc welding process.  
<sup>c</sup> Shielded metal-arc welding process.

explained that nitrogen addition is effective for the prevention of hot cracking. This is to say that if nitrogen is added to 17% Cr-Nb, nitrogen in the molten metal reacts with niobium and forms NbN of a high melting point (2323° K). Many crystal nucleuses are thereby grown, enabling a fine grain structure to be obtained. The finer the crystal grains, the more the low melting point impurities are distributed uniformly without gathering at the grain boundary; this acts effectively on the prevention of hot cracking.

Welding materials for testing (modified E430 and A flux) were added with titanium and aluminium which perform the same action as nitrogen—namely, as titanium and aluminium have respectively a large affinity with nitrogen or oxygen, these easily form TiO, TiN, Al<sub>2</sub>O<sub>3</sub>, AlN, etc., in the molten metal. All of them are of a high melting point and show the same action as the above-mentioned NbN. Accordingly, these become fine grain ferrite structures, and this enables the obtaining of a sound weld metal.

As stated above, the 17% chromium weld metal has a weak point that it is liable to the hot cracking and also to the delayed cracking due to diffusible hydrogen. However, provided that the weld metal is made to be a fine grain ferrite structure by adding niobium, titanium, aluminium, etc., a sound welding can be carried out without preheating.

## Cracking at the Heat-Affected Zone

### Testing Procedure

The crack sensitivity at the heat-affected zone of 17% chromium steel was examined by Y-groove restraint cracking test specimens shown in Fig. 8. After the both ends of the test plate was restrained by welding as shown in Fig. 8, the Y slit part was welded one layer.

After more than 120 hr had passed after completion of welding, the bead surface was subjected to dye penetrant inspection. A micro-structure test was carried out for 3 sections of the Y slit part to investigate the existence and length of cracks. The kind of testing materials used is as shown on Table 2.

### Results

Table 6 shows the results of the Y-groove restraint cracking test. The content of diffusible hydrogen in the weld metal shows a value for a 100 g weld metal measured by the glycerin replacing process. In the case of an electrode (0.89 cc/100 g H<sub>2</sub>) dried at 350°C for 1 hr, cracks do not occur even without preheating. However, in the case of an electrode (4.6 cc/100 g H<sub>2</sub>) which has absorbed humidity in saturated steam, delayed cracking is caused if preheating is omitted. For this reason, it is necessary to dispel diffusible hydrogen by preheating at a temperature over 50° C.

As the delayed cracking due to

diffusible hydrogen is caused at the heat-affected zone even in the 17% chromium steel, it has been confirmed that preheating and drying of electrodes are essential for the prevention of delayed cracking.

## Incubation Period of Delayed Cracking

### Test Procedure

Circular ring cracking test specimens devised by the authors for testing the 13% chromium weld metal were employed for investigating the incubation period of delayed cracking. Figure 9 shows the shape of these specimens.

After the build-up welding of 5–8 beads by modified E430 on the inside surface of a carbon steel plate ring, the welded parts was inspected by dye penetrant inspection to detect cracks, and the incubation period of delayed cracking was examined. The results of modified E410 (13% chromium) were also examined in comparison with the above.

### Results

The test results are shown on Table 7. In the case where preheating was omitted, one transverse crack occurred in several hours after welding and, after passing a few days (after 70 hr), one more crack was further detected. However, if preheating is applied at 50° C, cracking can be prevented perfectly.

Modified E410 showed a similar result, i.e., it caused many cracks even after 120 hr from welding. From the above, it is clear that delayed cracking with a long incubation period occurs in the weldment of high chromium steels like the 17% chromium steel.

### Discussion

As shown in Table 7, the 17% chromium weldment has a very long incubation period of cracking, i.e., it presents a remarkably different



Fig. 6—Microstructure of weld metal. A (left)—submerged arc welded metal containing Nb, Ti, Al (using ER430 + A) showing fine ferrite grain; B (center)—shielded metal-arc welded metal containing Nb, Ti, Al (using modified 1430) showing finer ferrite grain than (A); C (right)—submerged arc welded metal not containing Nb, Ti, Al (using ER430 + B) showing martensite at ferrite grain boundary. Chromic acid etchant. X100 (reduced 25% on reproduction)

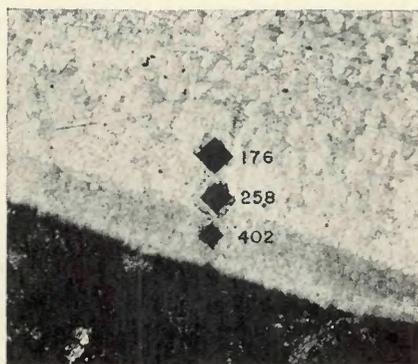
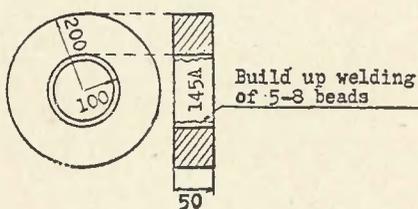


Fig. 7—Vickers microhardness determination across hardened transition zone between 17% Cr-Nb, Ti, Al welded metal and carbon steel. Chromic acid etchant. X100 (reduced 35% on reproduction)

phenomenon, as compared with structural low alloy steels such as high tension steels in which delayed cracking is caused within about 24 hr. An apparent reason for the above is that the diffusion rate of hydrogen at a normal temperature (30° C) differs remarkably between the 17% chromium steel and the carbon steel.

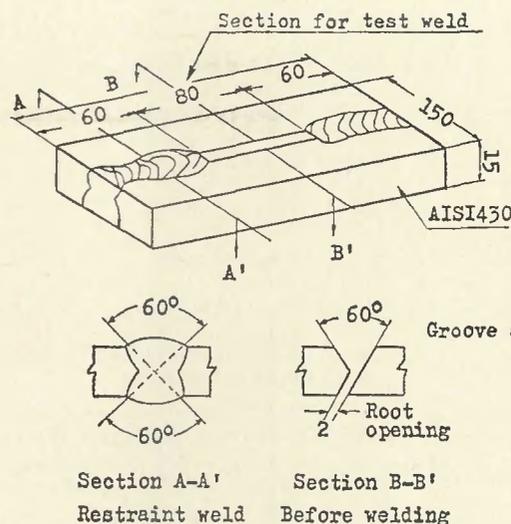
The diffusion rate of hydrogen is in proportion to the gradient of concentration and diffusion coefficient by Fick's Law, but the gradient of concentration is presumed as constant here. The diffusion coefficient has a correlation with the hydrogen permeability. As the hydrogen permeability depends on temperature, its value at a normal temperature can be calculated from the measurement value at a high temperature.

From the hydrogen permeability at a high temperature measured by David<sup>5</sup> for the 17% chromium steel, the hydrogen permeability at a normal temperature can be calculated as  $3.8 \times 10^{-6}$  cc/hr.mm/cm.kg<sup>-1/2</sup>. Likewise, from the measurement values by Otohira<sup>6</sup> and Flint<sup>7</sup>, the hydrogen permeability of carbon steel at a normal temperature can be calculated as  $3.14 \times 10^{-5}$  cc/hr.mm/cm.kg<sup>-1/2</sup> and  $9.7 \times 10^{-5}$  cc/hr.mm/cm.kg<sup>-1/2</sup> respectively. From the above results, it can be seen that the permeability of diffusible hydrogen for the 17% chromium steel is about  $1/9-1/25$ th of that for the carbon steel. Consequently, it can be known that the diffusion



Note: All dimensions in mm.

Fig. 9—Circular ring cracking test



Note: All dimensions in mm

Welding conditions

Electrode: Modified E430 4.0p  
 Current: 130A  
 Welding speed: 250 mm/min

Fig. 8—Y-groove restraint cracking test

rate of hydrogen at the same gradient of concentration is very slow as compared with the carbon steel.

The phenomenon of the delayed cracking due to hydrogen embrittlement is very complicated and differs, depending on the chemical composition, structure, degree of restraint, etc. It cannot be said that the incubation period of cracking is not always related to the diffusion rate of hydrogen only. However, because the diffusion rate of hydrogen is very low in the 17% chromium weldment as mentioned above, it can be said that the 17% chromium weld metal has a delayed cracking with a very long incubation period as compared with the carbon steel. Therefore particular-

ly prudent consideration must be given to the selection of the time of inspection to be conducted after welding.

### Embrittlement of the Heat-Affected Zone and its Prevention Testing Procedure

When a welded joint is subjected to a bending test, cracking is caused at the bonded part. Therefore, examination was made by comparing the results of synthetic test for weld thermal cycle for the heat-affected zone with those of bending test for the welded joint. The procedure of the synthetic test for weld thermal cycle for the heat-affected zone was as shown be-

Table 6—Results of Y-Groove Restraint Cracking Test—AISI 430 Base Metal and Modified E430 Electrode

Contents of diffusible hydrogen, cc/100 g <sup>a</sup>	Cracking test results				
	No preheat	Preheating at 50° C	Preheating at 100° C	Preheating at 150° C	Preheating at 200° C
0.89 <sup>b</sup>	None	None	None	None	None
4.60 <sup>c</sup>	Crack	None	None	None	None

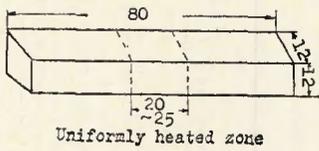
<sup>a</sup> Determination of hydrogen content is in accordance with JIS Z3223.

<sup>b</sup> Electrode dried at 350° C for 1 hr.

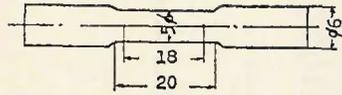
<sup>c</sup> Electrode has absorbed humidity by leaving 3 hr in saturated steam.

Table 7—Relation between the Number of Cracks and Lapse of Leaving Time in Circular Ring Cracking Test

Electrode	Preheat temperature	Immediately after welding	Total number of cracks				
			After 24 hr	After 48 hr	After 70 hr	After 120 hr	After 340 hr
Modified E430	No preheating	0	1	1	2	2	2
	50° C	0	0	0	0	0	0
Modified E410	No preheating	4	17	19	—	Many	—



(a) Synthetic test piece for weld thermal cycle



(b) Tensile test piece

Note: All dimensions in mm

Fig. 10—Test specimen of synthetic test for weld thermal cycle

low. A single bead was deposited on a carbon steel of 15 mm thickness by shielded metal-arc welding (4 mm electrode diameter; 140 amp current; 24 v voltage; 200 mm/min welding speed; 150° C preheating) and on another plate of the same thickness by submerged arc welding (4 mm electrode diameter; 500–600 amp current; 32–35 v voltage; 300–380 mm/min welding speed; 150° C preheat). Then, by measuring the thermal cycle at the respective positions of the bonded part, the results were reproduced on test specimens of the shape and dimension shown in Fig. 10, using a synthetic apparatus for weld thermal cycle. Thereafter, tensile test and microstructural investigation were conducted with these test specimens.

#### Results of Investigation on the Bending Property of Welded Joint

Table 8 shows the results of bending test for the welded joint. In each test, cracking occurred at a small angle in as-welded condition and no test piece could be bent soundly to 180 deg.

Investigation on crack initiating positions proved that, cracking being caused at the bonded part, this part had become remarkably embrittled. Also in the above bonded part, a coarse ferrite grain and a martensite were recognized as shown on Fig. 11. The influence of such structures upon the embrittlement of the weld heat



Fig. 11—Microstructure of the heat-affected zone showing coarse ferrite grains and martensite at ferrite grain boundary. Chromic acid etchant. X100 (reduced 33% on reproduction)

affected zone was then examined.

#### Mechanical Properties and Structure of the Heat-Affected Zone

Figure 12 shows the results of tensile test at each position of the heat-affected zone based on synthetic test pieces for weld thermal cycle. As a matter of course, embrittlement was recognized at the zone heated over  $A_{c1}$  transformation point and the most remarkable embrittlement was shown at the highest heating temperature of 1,350° C in both shielded

Table 8—Results of Face Bend Test for Welded Joints<sup>a</sup>

Welding material	Bending angle, deg	
ER430 + A	26	30
ER430 + B	12	40
Modified E430	38	180 <sup>b</sup>

<sup>a</sup> As-welded condition.

<sup>b</sup> Cracking occurred at the bonded part.

metal-arc welding and submerged arc welding. The elongation percentage of these test pieces was decreased from 33% to 8% or 4–5%, respectively, which was considered to be the cause for cracking at the bonded part. The particularly large decrease of elongation percentage in submerged arc welding is attributed to a remarkably grain coarsened ferrite structure compared with the structure shown in the case of shielded-metal arc welding.

As shown in Fig. 13, the part heated to 1,350° C becomes once an  $\gamma$

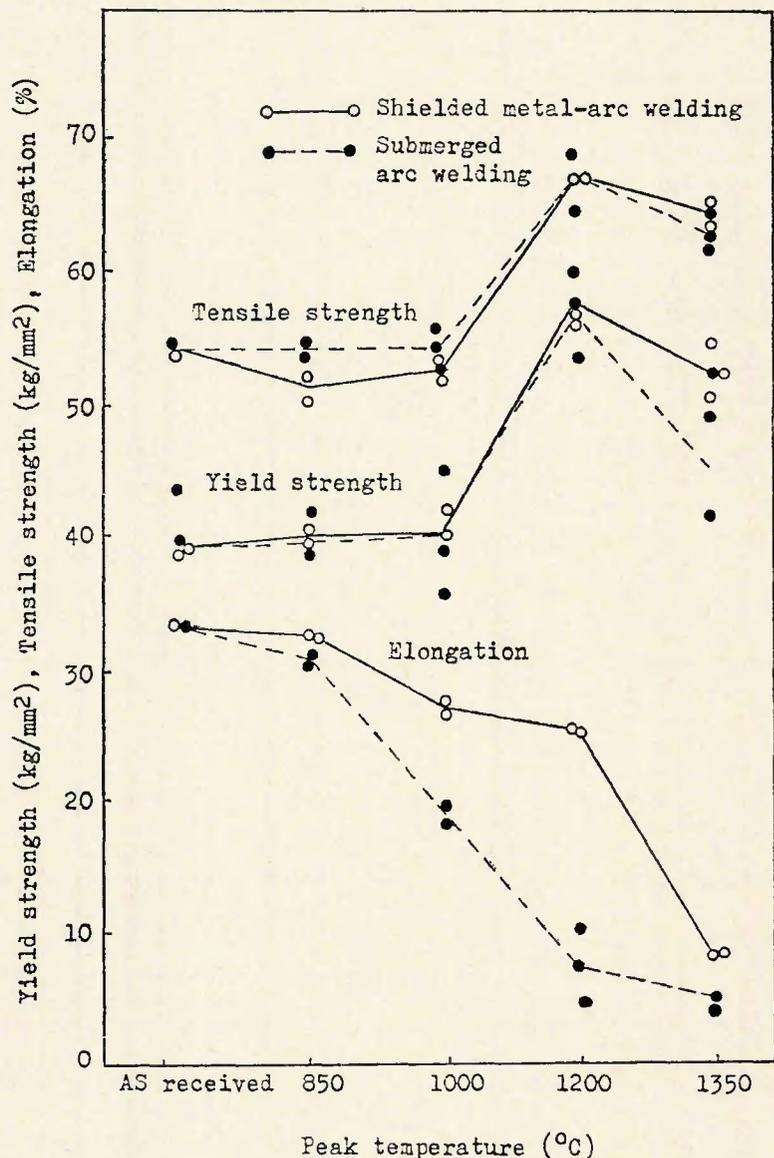


Fig. 12—Effect of peak temperature of weld thermal cycle on mechanical properties

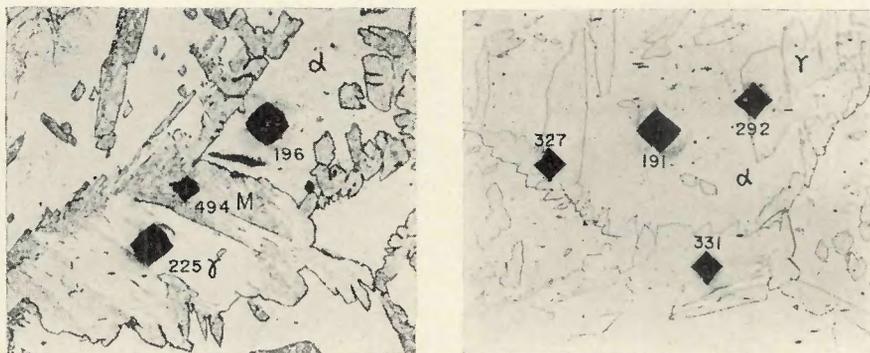


Fig. 13—Microstructure of weld thermal cycled specimen with a peak temperature of 1350° C. A (left)—in the case of submerged arc welding; B (right)—in the case of shielded metal-arc welding. Etchant: hydrochloric and picric acids. X200 (reduced 37% on reproduction)

single phase structure and then becomes a condition that a  $\delta$  phase is precipitated. Thus, retained austenite (light grey part: 225–331 Hv) and martensite (grey part: 494 Hv) coexist at the coarse ferrite grain boundary.

As can be seen from Fig. 13, the shielded metal-arc weld which had a high cooling rate has a lot of retained austenite. On the other hand, the submerged arc welding has little retained austenite and, for the most part, is martensite.

#### Improvement of Mechanical Properties by Postweld Heating

Table 9 shows the measurement results of the transformation temperatures of retained austenite and martensite. In addition, Fig. 14 shows the change in their respective mechanical properties at each bonded part due to heat treatment at a temperature over each transformation temperature. In the case of submerged arc welding, a slight recovery of ductility was recognized by low temperature postheating at 150–250° C. However, in the case

Table 9—Transformation Temperature of Retained Austenite and Martensite—1350° C Peak Temperature

Change in length	Temperature, °C
Contraction ( $M\alpha \rightarrow M\beta$ )	130–150
Expansion ( $R\gamma \rightarrow M\alpha \rightarrow M\beta$ )	200–250
Contraction ( $M\beta \rightarrow \alpha + K$ )	520–550

of shielded-metal arc welding, ductility was further decreased by such low temperature postheating—that is, the latter showed a phenomenon peculiar to the 17% chromium steel, which is not seen in the 13% chromium steel or structural low alloy steels.

Figure 15 shows a change in hardness at the most embrittled part by postweld heating. The submerged arc weld shows little increase of hardness by low temperature postweld heating at 150–250° C. On the contrary, in shielded metal-arc welding, remarkable hardening is accompanied thereby; for instance, a hardness of Hv max 370 in an “as cycle” condition is changed to Hv max 550 after postheating at 150–250° C. Therefore, it is considered that the decrease of

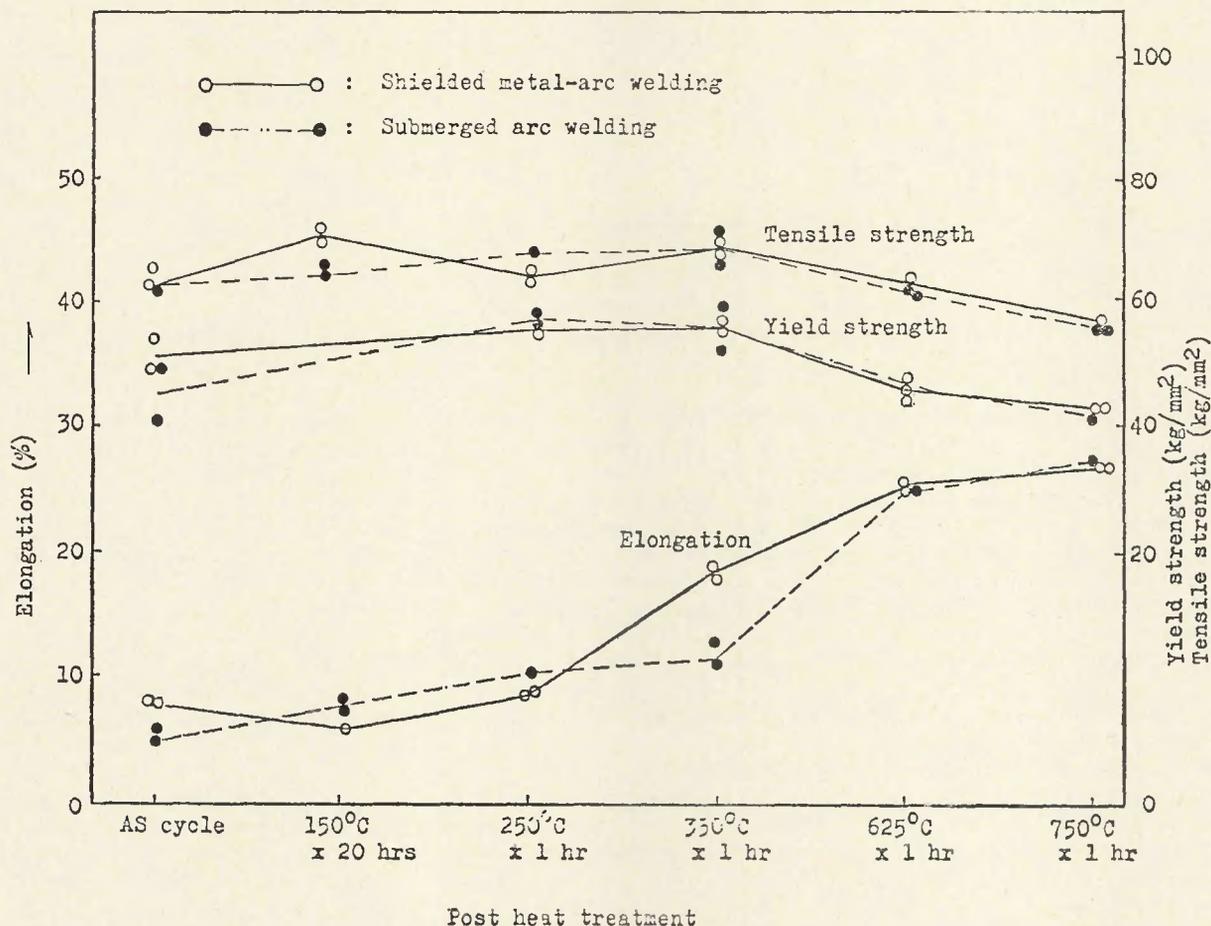


Fig. 14—Effect on mechanical properties by heat treatment applied after weld thermal cycled with a peak temperature of 1350° C

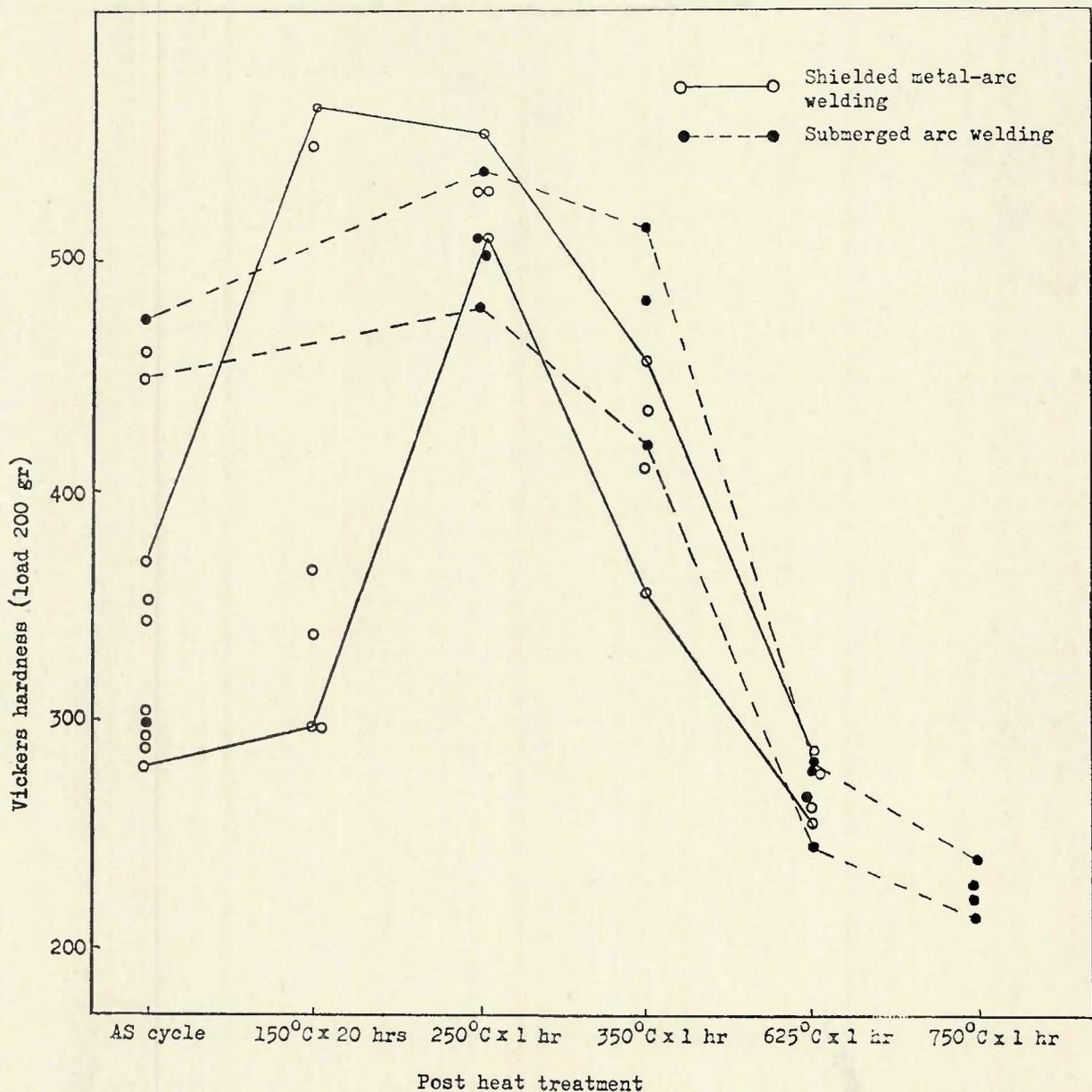


Fig. 15—Effect on Vickers microhardness by heat treatment applied after weld thermal cycled with a peak temperature of 1350° C

ductility at the shielded metal-arc welded part by low temperature post-heating is attributable to the transformation of the retained austenite to the martensite.

At a temperature exceeding 350° C, softening is caused like structural low alloy steels. As shown in Fig. 16 the microstructure is not easily corroded in an "as cycle" condition or by postweld heating at 150° C, but is easily corroded by postweld heating at 250–350° C. At temperatures of 625 and 750° C, the structure (being conspicuously corroded) becomes a structure of ferrite plus carbide. These phenomena show that a stepwise transformation was caused in the microstructure like  $M_a$  ( $\alpha$  martensite)  $\rightarrow M\beta$  ( $\beta$  martensite),  $R\gamma$  (retained austenite)  $\rightarrow M_a$  ( $\alpha$  martensite)  $\rightarrow M\beta$  ( $\beta$  martensite) at a low tempera-

ture and  $M\beta$  ( $\beta$  martensite)  $\rightarrow \gamma$  (ferrite) +  $K$  (carbide) at a high temperature.

Next, Fig. 17 shows the relation between the elongation percentage of synthetic test pieces for weld thermal cycle for the bonded part and the bending angle at bending test for the welded joint. From Fig. 17, it can be recognized that there is a correlation between them, and that the welded metal can be bent soundly up to 180 deg by applying a proper postweld heating (for 1 hr at 625° after submerged arc welding and for 1 hr at 350° C after shielded metal-arc welding) so as to make the elongation percentage over about 18%.

The bending angles of welded joints in Fig. 17 are the ones in as-welded condition. These become largely different between the shielded metal-arc

welding and the submerged arc welding, after postweld heat treatment is applied. This is because the grain coarsening is much more remarkable in the submerged arc welding as compared with the shielded metal-arc welding as shown in Fig. 18.

### Discussion

The 17% chromium steel has a peculiar phenomenon in that its ductility deteriorates with postheating at 150–250° C. This phenomenon is conspicuous at the heat-affected zone with shielded metal-arc welding; the cause is considered to be as follows.

When chromium content in iron is increased, the diffusion of solute atom is suppressed, which hinders the austenite  $\rightarrow$  martensite transformation. Consequently, at the heat-affected zone of 17% chromium steel, retained

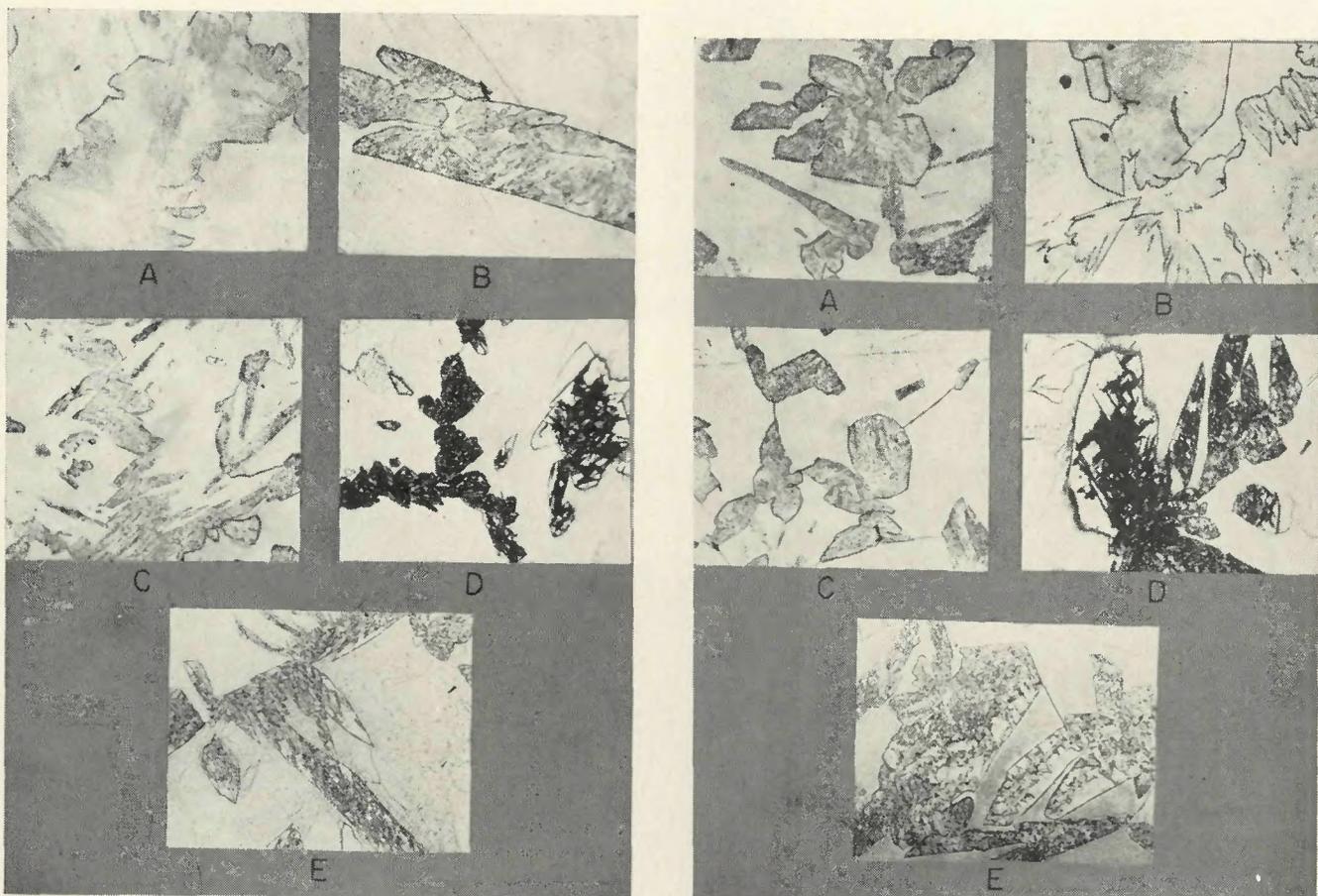


Fig. 16—Effect on microstructure by heat treatment applied after weld thermal cycled with a peak temperature of 1350° C. Left—the case of shielded metal-arc welding: A—after simulated weld cycle; B—same as A plus 250° C for 1 hr; C—same as A plus 350° C for 1 hr; D—same as A plus 625° C for 1 hr; E—same as A plus 750° C for 1 hr. Right—the case of submerged arc welding: A—after simulated weld cycle; B—same as A plus 250° C for 1 hr; C—same as A plus 350° C for 1 hr; D—same as A plus 625° C for 1 hr; E—same as A plus 750° C for 1 hr. Etchant: hydrochloric and picric acids. X400 (reduced 49% on reproduction)

austenite and martensite are formed partially at a normal temperature.

In the case of submerged arc welding because of its low cooling rate (245 sec: from 1,350 to 180° C at 150° C preheating), the austenite → martensite transformation is advanced in its most part during welding, resulting in little retained austenite—Fig. 13. Therefore, a remarkable decrease of ductility is not caused by postheating at 150–250° C.

In the case of shielded metal-arc welding because of its high cooling rate (60 sec: from 1,350 to 180° C at 150° C preheating), the austenite → martensite transformation is scarcely advanced, and a lot of retained austenite remains without being transformed—Fig. 13. Therefore, the retained austenite being transformed to martensite by postweld heating, a secondary hardening is caused, with resultant decrease of ductility—Fig. 15. The decomposing temperature of austenite is 200–250° C as shown on Table 9; however, from the results of investigation on the structure and hardness change due to postweld heating, it appears that austenite is

decomposed in 20 hr at 150° C which is lower than the above temperature.

As to the reason for the above, it is considered that the former requires a short heating time in raising temperature by heating (heating rate: 28° C/hr), but the latter requires holding to temperature for a long time at a constant value (150° C x 20 hr) promoting the transformation of retained austenite to martensite during that period.

In the shielded metal-arc welding, since a ductile joint can be obtained by heat treatment for 1 hr at 350° C, sound bending can be carried out until 180 deg. On the other hand, in submerged arc welding, heat treatment for over 1 hr at 625° C is required to enable sound bending until 180 deg.

This is due to difference in ferrite grain coarsening between the shielded metal-arc welding and the submerged arc welding.

### Conclusions

Weld cracking and embrittlement at the heat-affected zone may present problems in the welding of 17% chromium steel. A study on their causes

and prevention led to the following conclusions:

1. In the welding for 17% chromium steels, sound weld metal can be obtained if welding is carried out using welding materials added with "niobium and nitrogen" or "niobium, titanium and aluminium" to 17% chromium.

2. Because of a low diffusion rate of hydrogen in the 17% chromium steel, the weld metal of 17% chromium steel is liable to delayed cracking with a long incubation period as compared with structural low alloy steels.

3. The heat-affected zone in the as-welded condition becomes embrittled and is lacking in ductility, and this is remarkable at the bonded part. For the improvement of the above, the following postweld heat treatment is required: shielded metal-arc welding—over 1 hr at 350° C; submerged arc welding—over 1 hr at 625° C.

4. When postweld heating is applied at 150–250° C, a peculiar phenomenon deteriorates ductility at the heat-affected zone. This is caused by the transformation of retained austenite to martensite, and this phenom-

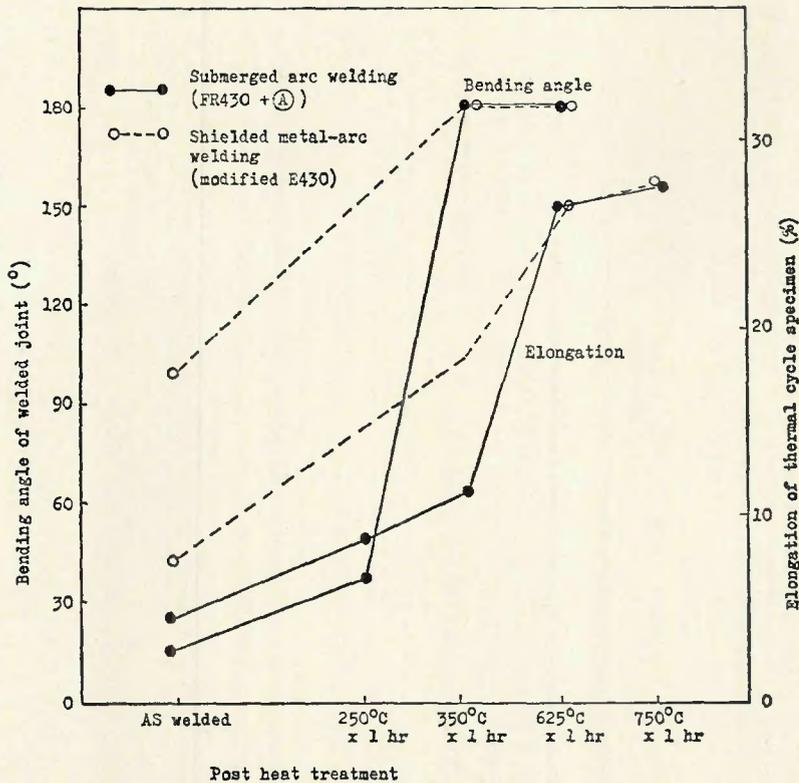


Fig. 17—Effects of heat treatment on bending angle of welded joints and elongation of thermal cycled specimen with a peak temperature of 1350° C

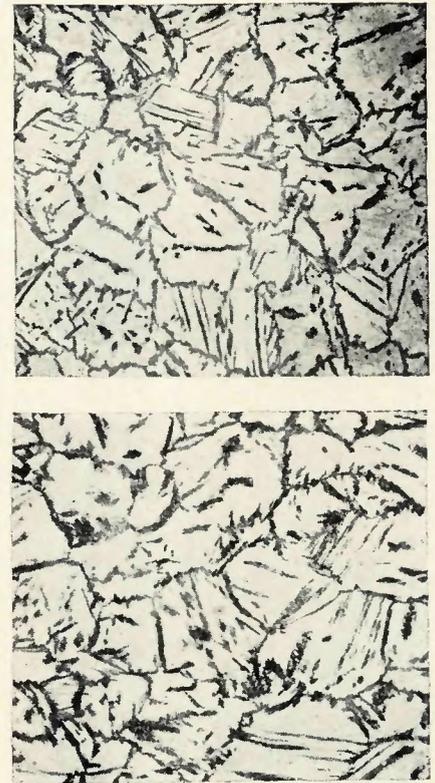


Fig. 18—Ferrite grain size of weld thermal cycled specimen with a peak temperature of 1350° C. A (top)—in the case of shielded metal-arc welding without preheating in which it takes 5 seconds to cool from 1350° C to 900° C;  $N = 1.26$ . B (bottom)—in the case of submerged arc welding with preheating at 250° C in which it takes 15 sec. to cool from 1350 to 900° C;  $N = 0.48$  the ferrite grain size  $N$  is in accordance with ASTM E89-52, Etchant: chromic acid. X50 (reduced 37% on reproduction)

enon is remarkable in the shielded metal-arc welding which has much retained austenite.

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### "Fatigue and Static Tests of Two Welded Plate Girders"

by P. J. Patterson, J. A. Corrado, J. S. Huang and B. T. Yen

This report describes the testing of two full-size slender-web welded plate girders for the purpose of ascertaining the acceptability of proposed design recommendations for bridge girders under repeated loading. The girders were 32 ft. 6 in. and 35 ft. 3 in. long with 1/4 in. thick webs, resulting in web slenderness ratios of 200 and 380. Panel aspect ratios ranged from 1.0 to 1.50. ASTM A36 material was used. These girders were subjected to repeated loading to 2.2 and 4.5 million cycles, respectively, without development of fatigue cracks and were subsequently tested under static loads to determine the adequacy of the stiffeners. It is concluded that the proposed recommendations are sufficiently conservative for ordinary bridge plate girders.

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