The Effect of Stress Relieving on the Microstructure and Properties of C-Mn All-Weld Metal Deposits

Stress relieving benefits the impact toughness of weld deposits with low concentrations of C and Mn

BY G. M. EVANS

ABSTRACT. The effect of stress relieving multi-run SMAW deposits, containing 0.05–0.15% C and 0.6–1.8% Mn, at 580°C (1076°F), has been investigated. It was found that the morphology of the microphases changed after heat treatment, with a concurrent reduction in overall hardness. The tensile properties also decreased but were still described by equations of the form:

$$\sigma = a + b \cdot (C) + c \cdot (Mn) + d \cdot (C \cdot Mn)$$

Stress relieving had a beneficial effect on the Charpy V-notch impact toughness of low-C, low-Mn deposits and a deleterious effect on high-C, high-Mn deposits. At intermediate levels of C and Mn, where optimum toughness was exhibited, no essential shift occurred.

Introduction

This investigation forms part of a continuing program to evaluate the factors affecting the mechanical properties of C-Mn shielded metal arc deposits. Previous work has examined the role of carbon and manganese (Refs. 1, 2), as well as the process variables, such as interpass temperature (Ref. 3), electrode diameter (Ref. 4), heat input (Ref. 5) and welding position (Ref. 6). In the main, only as-welded properties have been determined, and it was hence considered expedient to extend the program to include the effect of stress relief heat treatment. The temperature chosen was 580°C (1076°F), and by repeating the test series carried out to clarify the influence of carbon (Ref. 1), a direct comparison with the as-welded condition has been made possible. Furthermore, the metallographic studies conducted in the past were supplemented by examining replicas in the electron microscope, so as to follow in more detail the changes due to composition and heat treatment.

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Experimental Procedure

Electrodes

Low-hydrogen, iron powder type electrodes — coded A, B, C and D — of the same batches as used previously (Ref. 1) were employed. The manganese content of the coatings had been varied so as to yield deposits containing 0.6, 1.0, 1.4 and 1.8% Mn, respectively. At each distinct manganese level, different amounts of graphite had been added to the coatings so as to produce four nominal levels of carbon in the deposits, namely 0.045, 0.065, 0.095 and 0.145% C. The core wire diameter of the 16 different experimental electrodes was 4 mm (5/32 in.) and the coating factor (D/d) was 1.68.

KEY WORDS

C-Mn Weld Deposits
C-Mn Manual MA Wldng
C-Mn Weld Microphase
C-Mn Weld Charpy V's
C-Mn Weld Heat Treat
C-Mn Weld Properties
Multi-run C-Mn Welds
Stress Relief Effect
Low H_2 Electrodes
ISO 2560 Joint Geom

Weld Preparation

The joint geometry was that specified in ISO 2560. Welding was done in the flat position and three beads per layer were deposited (Refs. 1, 5). The total number of runs required to fill the individual joints was 27. Direct current (electrode positive) was employed, the amperage being 170 A, the voltage 21 V and the heat input was nominally 1 kJ/mm (25 kJ/in.). The interpass temperature was standardized at 200°C (392°F).

Heat Treatment

The all-weld metal deposits were stress relieved at 580°C for 2 h. The effect of long-term heat treatment was investigated by allowing one specific test series, *i.e.*, 0.15% C, 1.8 % Mn, to soak for times up to 100 h.

Mechanical Testing

Two subsize all-weld metal tensile specimens (Minitrac) were machined and tested for each of the different deposits. Also, approximately 35 Charpy V-notch specimens were struck in each case, so as to obtain full transition curves.

Electron Microscopy

Carbon replicas for electron microscopy were prepared at The Welding Institute from cross-sections of deposits laid with Electrode C (1.4% Mn) at the two extremes of carbon, namely 0.045% and 0.145%. The specimens were firstly electropolished in a 6% solution of perchloric acid in methanol and ether, and then etched in 2% nital. The replicas were removed electrolytically in 10% nital, and the areas of interest were initially located under the light microscope. In accordance with previous optical work (Refs.

1-6), attention was directed towards three specific locations, namely the center of the top bead, the adjacent coarse-grained reheated region, and the fine-grained reheated region directly below. Six to eight individual photomicrographs were taken and an example, which showed certain common features, was chosen for representation.

Results

Chemical Composition

The chemical analyses of the 16 all-weld metal deposits studied are given in Table 1. The values are essentially identical to those determined for the as-welded condition (Ref. 1), except that the silicon contents show more conformity than previously.

Table 1—Chemical Compositions (wt-%) and Tensile Data[1]

Average carbon content	Electrode	C	Mn	Si	S	P	σ_E (N/mm^2)	σ_R (N/mm^2)	El. (in percent)	R.A. (in percent)
0.045%	A	0.043	0.69	0.30	0.006	0.007	373	448	34.4	83.0
	B	0.042	0.98	0.31	0.006	0.007	392	476	34.4	80.6
	C	0.045	1.39	0.31	0.005	0.007	414	502	31.0	80.6
	D	0.045	1.83	0.29	0.005	0.008	444	525	29.8	79.9
0.065%	A	0.058	0.63	0.33	0.007	0.007	386	465	33.4	78.8
	B	0.065	0.97	0.34	0.007	0.008	418	500	35.0	80.6
	C	0.066	1.36	0.35	0.007	0.008	455	540	31.2	77.9
	D	0.074	1.80	0.36	0.008	0.008	504	594	26.2	75.0
0.095%	A	0.089	0.68	0.35	0.008	0.008	394	499	34.2	78.8
	B	0.095	1.05	0.36	0.007	0.008	435	546	34.0	77.0
	C	0.088	1.33	0.34	0.008	0.007	461	568	28.6	77.9
	D	0.089	1.69	0.33	0.007	0.008	490	597	30.2	75.0
0.145%	A	0.151	0.63	0.36	0.008	0.008	449	533	30.6	76.0
	B	0.147	1.02	0.36	0.007	0.007	482	576	29.4	76.9
	C	0.147	1.38	0.35	0.007	0.007	513	623	27.4	72.9
	D	0.145	1.76	0.35	0.006	0.007	567	679	24.0	69.8

[1]Effect of carbon (stress relieved).

Metallographic Examination

Low Carbon (0.045% C, 1.4% Mn)

Top bead—Figure 1A shows acicular ferrite occurring in as-deposited weld metal. A certain amount of cementite film is evident, together with retained austenite, which has partly transformed to martensite (M/A). Stress relieving (Fig. 1B) caused precipitation of carbides at the grain boundaries.

Coarse-grained reheated region—Figure 2A reveals a ferrite envelope region with pearlite (P) and extensive cementite film at the grain boundaries. After stress relieving (Fig. 2B), partial breakdown of the pearlite occurred with an associated spheroidization of the films.

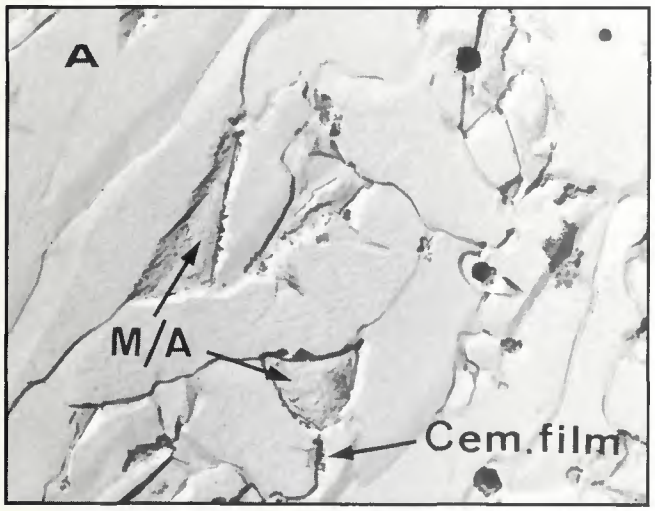
Fine-grained reheated region—Figure 3A shows the second phases which have been previously (Ref. 1) quantified. The featureless light gray areas are similar to those identified by Widgery (Ref. 7) as retained austenite (A). The lower triangular area of this type has partially transformed to martensite (M), as indicated by a roughening of the surface. Cementite films are evident, as also is a degenerate form of pearlite, referred to previously (Ref. 1) as bainite/pearlite (B/P). Stress relieving (Fig. 3B) led once again to breakdown of bainite/pearlite and the precipitation of carbides.

High Carbon (0.15% C, 1.4% Mn)

Top bead—At the higher carbon level, the acicular ferrite (Fig. 4A) was confirmed (Ref. 1) to be associated with a greater amount of martensite/austenite (M/A) phase. Cementite films were also present, and the overall effect was to make the ferrite laths appear more angular. The M/A regions responded to stress relieving (Fig. 4B) by the formation of carbide aggregates.

Coarse-grained region—Figure 5A indicates the presence of cementite films, bainite/pearlite, retained austenite and martensite/austenite. Stress relieving, over the time involved, induced carbide precipitation within the matrix and at the grain boundaries—Fig. 5B.

Fine-grained region—Figure 6A shows cementite films, M/A phase, degenerate pearlite (B/P) and pearlite (P). The M/A phase is particularly distinct in this case, the austenite being almost completely transformed to martensite. Once again, grain boundary carbide precipitation and spheroidization of the pearlite lamellae occurred as a result of stress relieving—Fig. 6B.



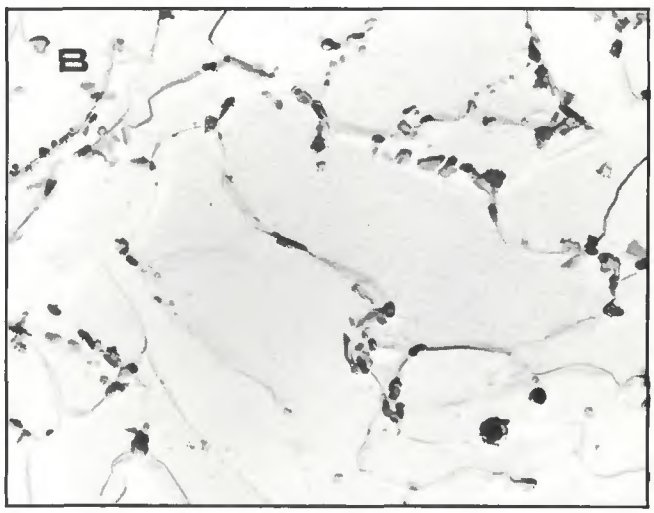


Fig. 1—Top bead, columnar; 0.045 C, 1.4 Mn. A—As-welded; B—Stress relieved

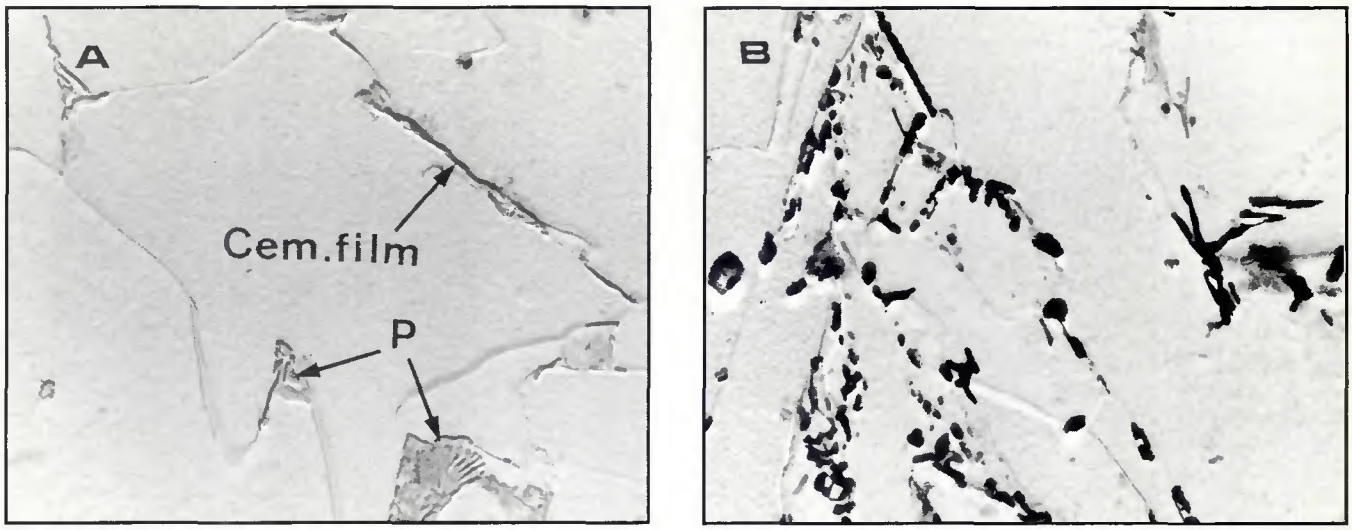


Fig. 2 — Coarse-grained region; 0.045 C, 1.4 Mn. A — As-welded; B — Stress relieved

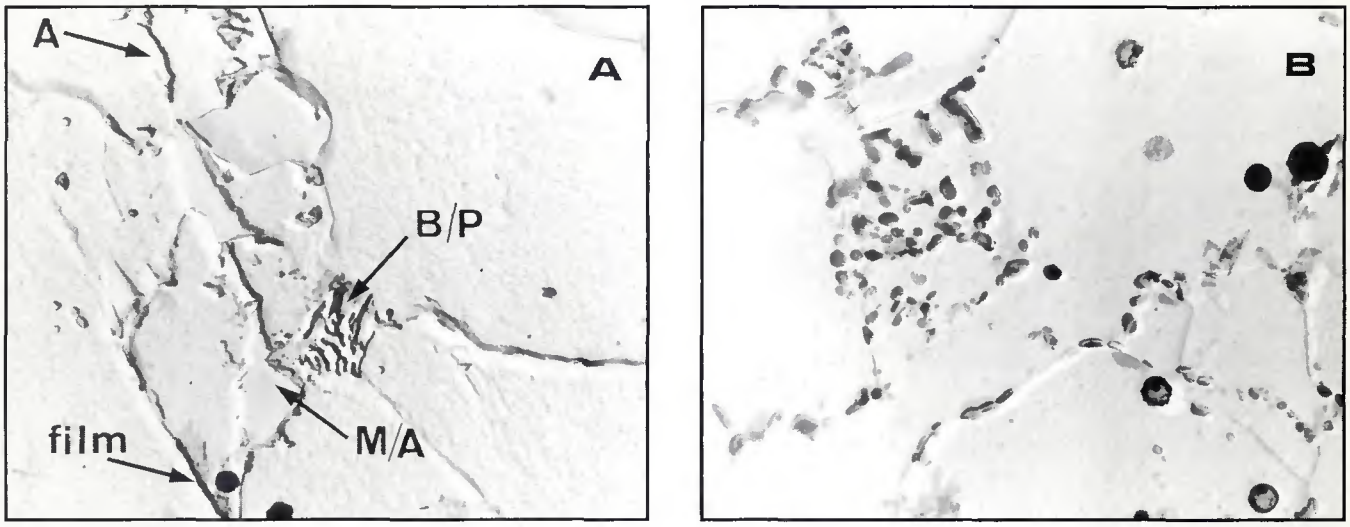


Fig. 3 — Fine-grained region; 0.045 C, 1.4 Mn. A — As-welded; B — Stress relieved

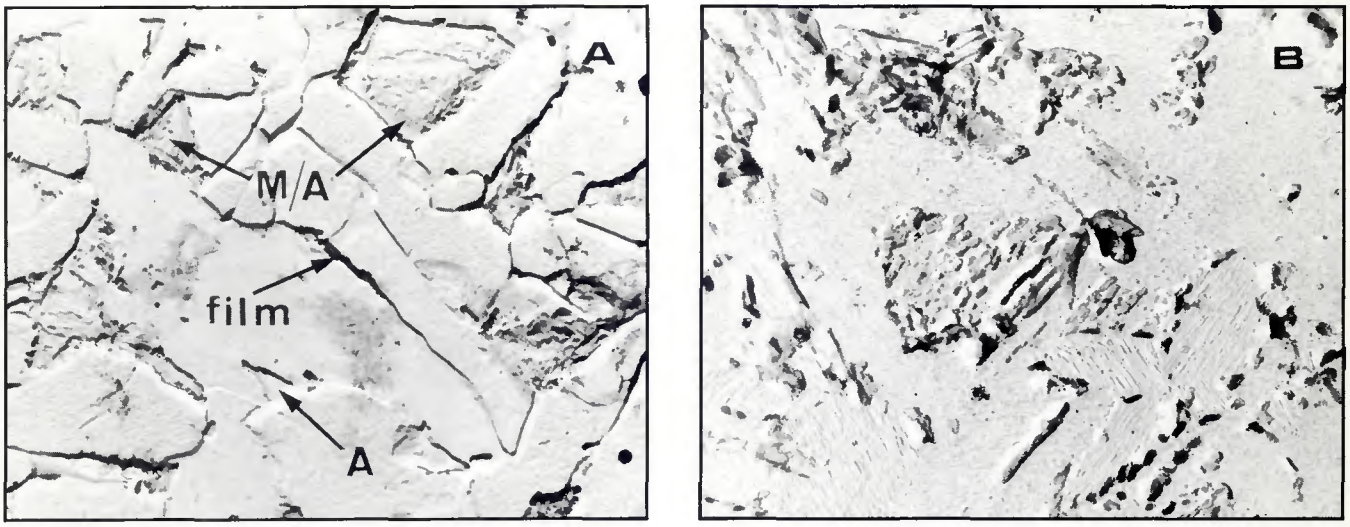


Fig. 4 — Top bead, columnar; 0.145 C, 1.4 Mn. A — As-welded; B — Stress relieved

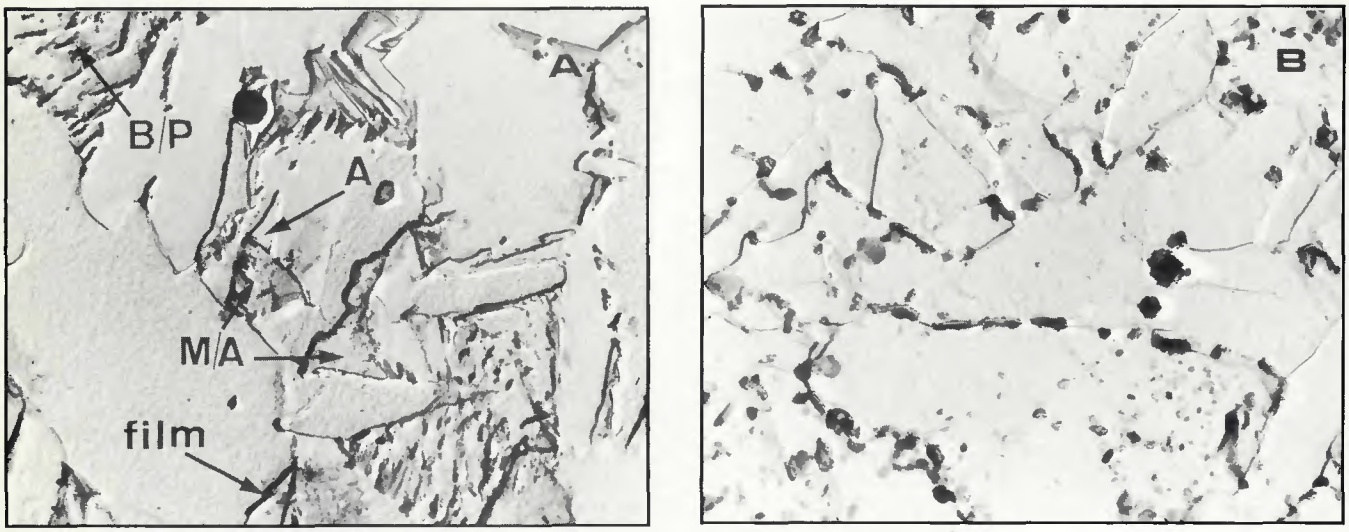


Fig. 5 — Coarse-grained region; 0.145 C, 1.4 Mn. A — As-welded; B — Stress relieved

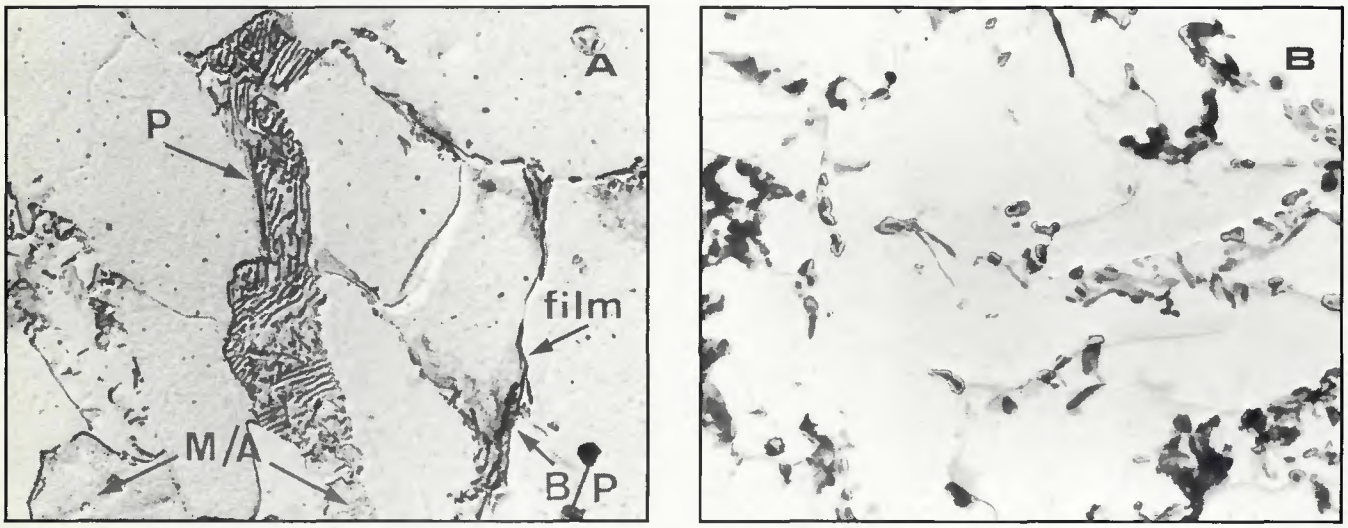


Fig. 6 — Fine-grained region; 0.145 C, 1.4 Mn. A — As-welded; B — Stress relieved

Hardness Testing

Average hardness values, obtained for the last bead to be deposited in each case, are plotted in Fig. 7. The hardnesses were lower than those obtained for the as-welded condition (Ref. 1) and, in contrast, varied non-linearly with respect to carbon content.

Hardness traverses along the centerline of multi-run welds deposited from electrodes at the two analytical extremes, *i.e.*, lowest and highest levels of C and Mn, are plotted in Fig. 8. It is seen that, in general, stress relieving resulted in a reduction of hardness throughout the bulk of the deposits.

Mechanical Properties

Tensile results — Tensile test data for stress relieved weldments are presented in Table 1. The yield strengths and the ultimate tensile strengths are plotted against carbon content in Figs. 9 and 10, respectively.

On assuming the tensile properties to be linearly related to both carbon and manganese, the following regressions were obtained:

For yield strength (in N/mm^2)

$$\sigma_E = 310 + 391\ C + 50\ Mn + 429\ (C \cdot Mn) \quad (R^2 = 0.973) \qquad (1)$$

For ultimate tensile strength (in N/mm^2)

$$\sigma_R = 396 + 330\ C + 42\ Mn + 643\ (C \cdot Mn) \quad (R^2 = 0.982) \qquad (2)$$

Similar relationships were derived for the as-welded condition (Ref. 1), an interaction occurring between the two principal elements.

Stress relieving resulted in a lowering of strength throughout the system, the average decrease being 33 and 12 N/mm^2 (4.8 and 1.7 ksi) for yield and tensile strength, respectively.

Impact results — The Charpy V-notch impact curves for stress relieved weldments are plotted in Fig. 11. On considering the absorbed energy as a function of manganese (Fig. 12), the optimum composition for the transition range was once again (Refs. 1-6) found to occur at approximately 1.4% Mn.

The lateral shift derived by comparison with as-welded data (Ref. 1) is plotted in Figs. 13 and 14, for the 100 J and 28 J levels, respectively. A clear trend is indicated — stress relieving is beneficial at the low end of the compositional range and deleterious at the other extreme. At intermediate levels of carbon and manganese, a balance was achieved, the displacement due to heat treatment being negligible.

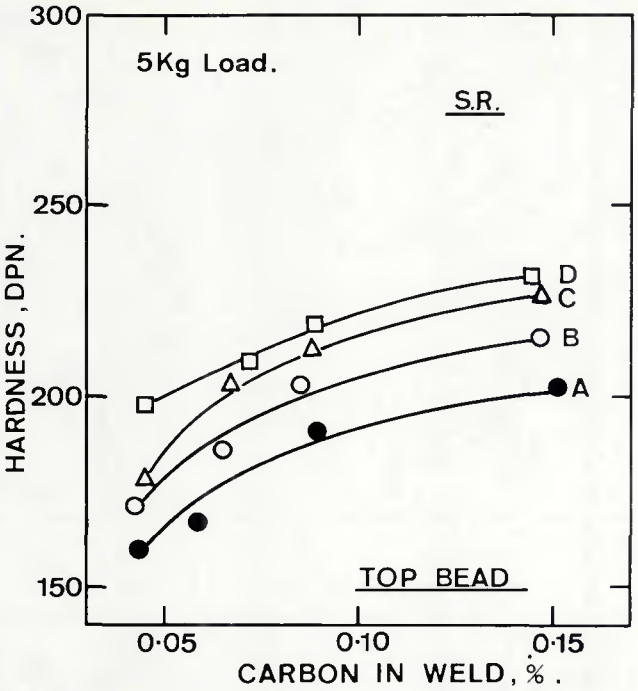


Fig. 7—Hardness of the top bead after stress relieving (different C and Mn levels)

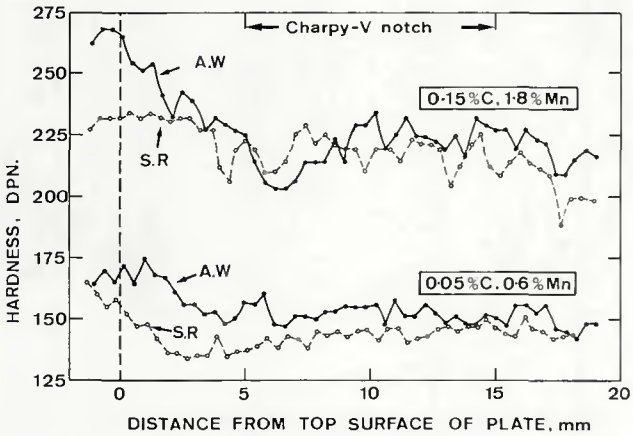


Fig. 8—Hardness variations along the vertical centerline (as-welded and stress relieved)

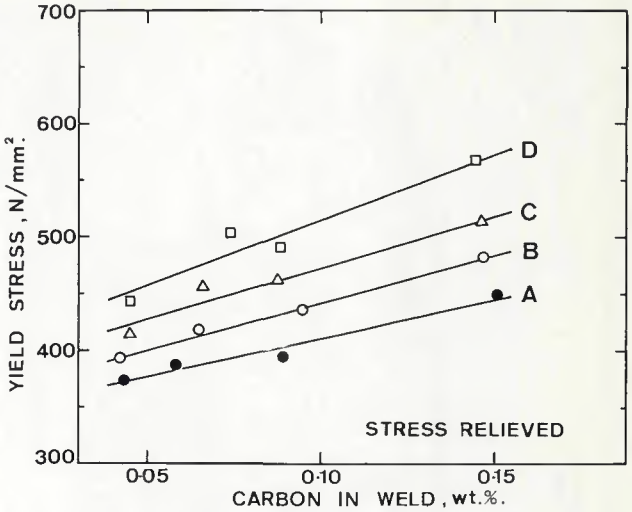


Fig. 9—Effect of carbon on yield strength (different Mn levels)

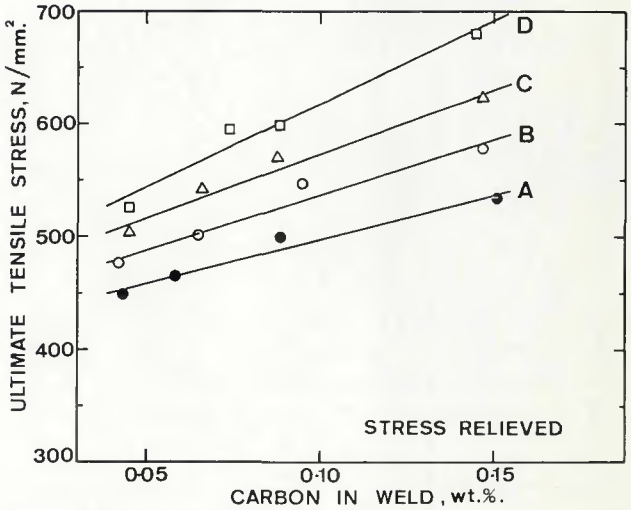


Fig. 10—Effect of carbon on ultimate tensile strength (different Mn levels)

Discussion

A previous investigation (Ref. 1) revealed that carbon promoted acicular ferrite, at the expense of grain boundary polygonal ferrite, and caused grain refinement of the reheated regions. Also, it was observed that the aspect ratio of the acicular ferrite changed and that increased amounts of carbide and other second phases formed between the laths and in the fine-grained zones. The present study serves to extend these findings by examining in more detail the nature of the different microphases. The most significant observation was the existence of martensite/austenite (M/A) phases in both the as-deposited and the reheated regions. The presence of retained austenite has been noted earlier (Ref. 2), but only at the highest level of manganese was a sufficient amount present to be detected by x-ray diffraction. The statement made at that time, namely, that the martensite was too fine to be resolved, has since been invalidated, in part due to the fact that the carbon range has been extended up to 0.15%. Another feature has been the existence of cementite films in the as-deposited weld metal. Grain boundary cementite films have previously (Ref. 1) been quantified in the fine-grained reheated region and coexist with pearlitic type constituents.

The metallographic studies have confirmed that stress relieving has a pronounced effect on the microstructure, causing precipitation and spheroidization of second phase particles. The phenomenon has been documented by Cochrane (Ref. 8), for plate steel, and by Farrar, *et al.* (Ref. 9), for submerged arc weld metal. The latter authors state that two significant microstructural changes occur, namely: (1) a coarsening and/or spheroidization of pearlites and carbides, and (2) a development of carbides at grain boundaries and as a fine matrix dispersion.

The two mechanisms are considered

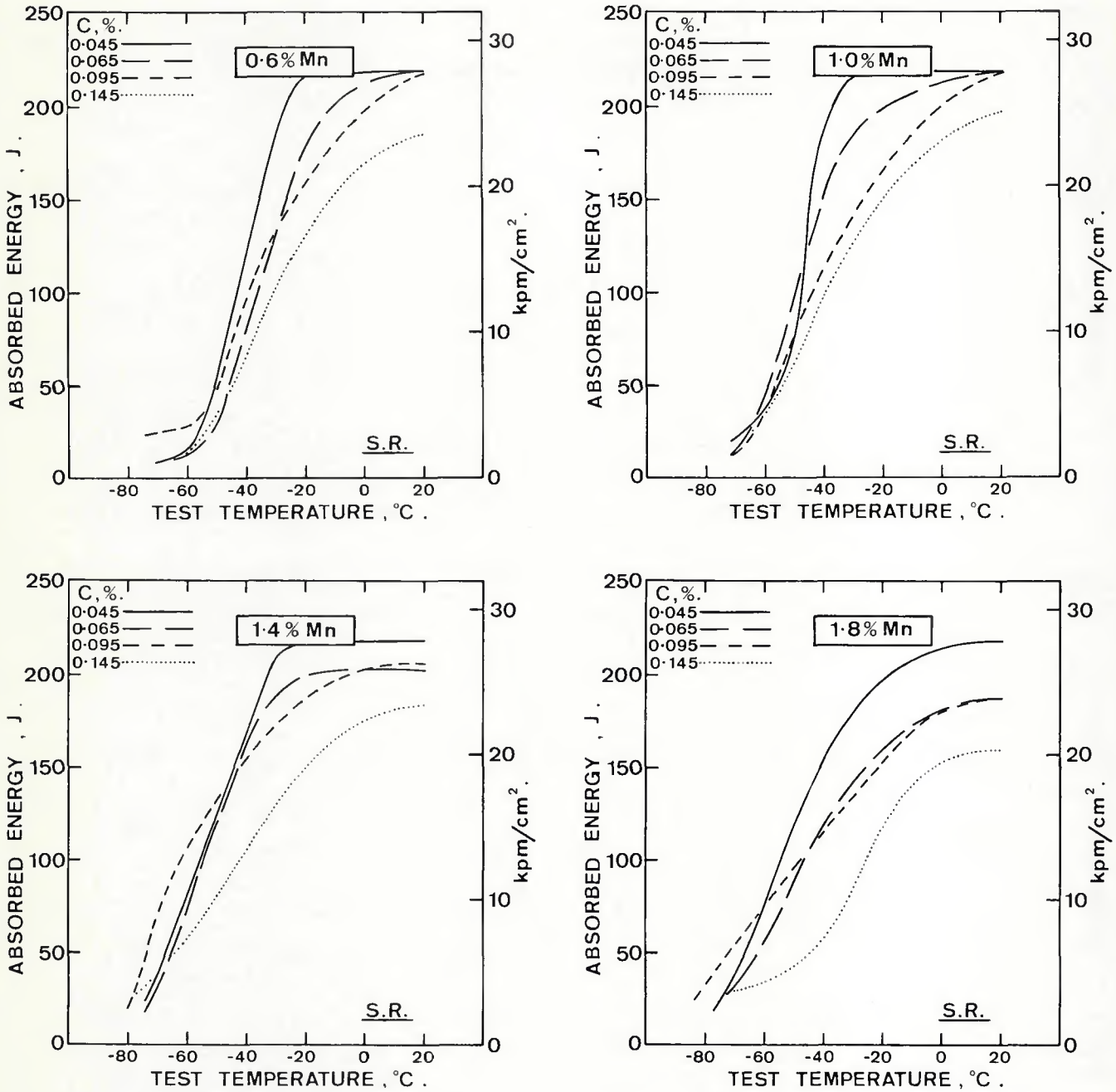


Fig. 11—Charpy V-notch impact test results (stress relieved)

to be opposed with respect to their effect on fracture toughness. Firstly, when coarsening or spheroidization of the carbides, especially pearlites, takes place, the fracture process becomes more difficult. Secondly, as time proceeds, embrittlement develops due to grain boundary cementite acting as a crack initiator. According to Cochrane (Ref. 8), a correlation exists between the cementite particle size, particularly thickness, and the rise in impact transition temperature.

The tensile properties achieved in the present instance varied linearly with respect to both carbon and manganese, the regression equations being in the form:

$$\sigma = a + b \cdot C + c \cdot Mn + d \cdot (C \cdot Mn) \quad (3)$$

The relationships were similar to those for the as-welded condition, except for the specific constants. A decrease occurred as a result of stress relieving, the drop being a complex function of composition, and was greater for yield strength than for tensile strength. The proportionally greater decrease in yield was such that the yield to ultimate ratio was reduced to less than 0.85. As would be expected, a general softening was encountered for the complete plain C-Mn system.

The influence of carbon on the form of the Charpy V-notch curves was essentially the same as for the as-welded condition (Ref. 1). Thus, it was noted that the upper shelf values decreased and that the transition between the ductile and the brittle mode of fracture became more gradual, with a concurrent reduction in the extent of scattering. In addition, the optimal toughness with regard to manganese was retained at approximately 1.4%, independent of the carbon content.

The main consequence of stress reliev-

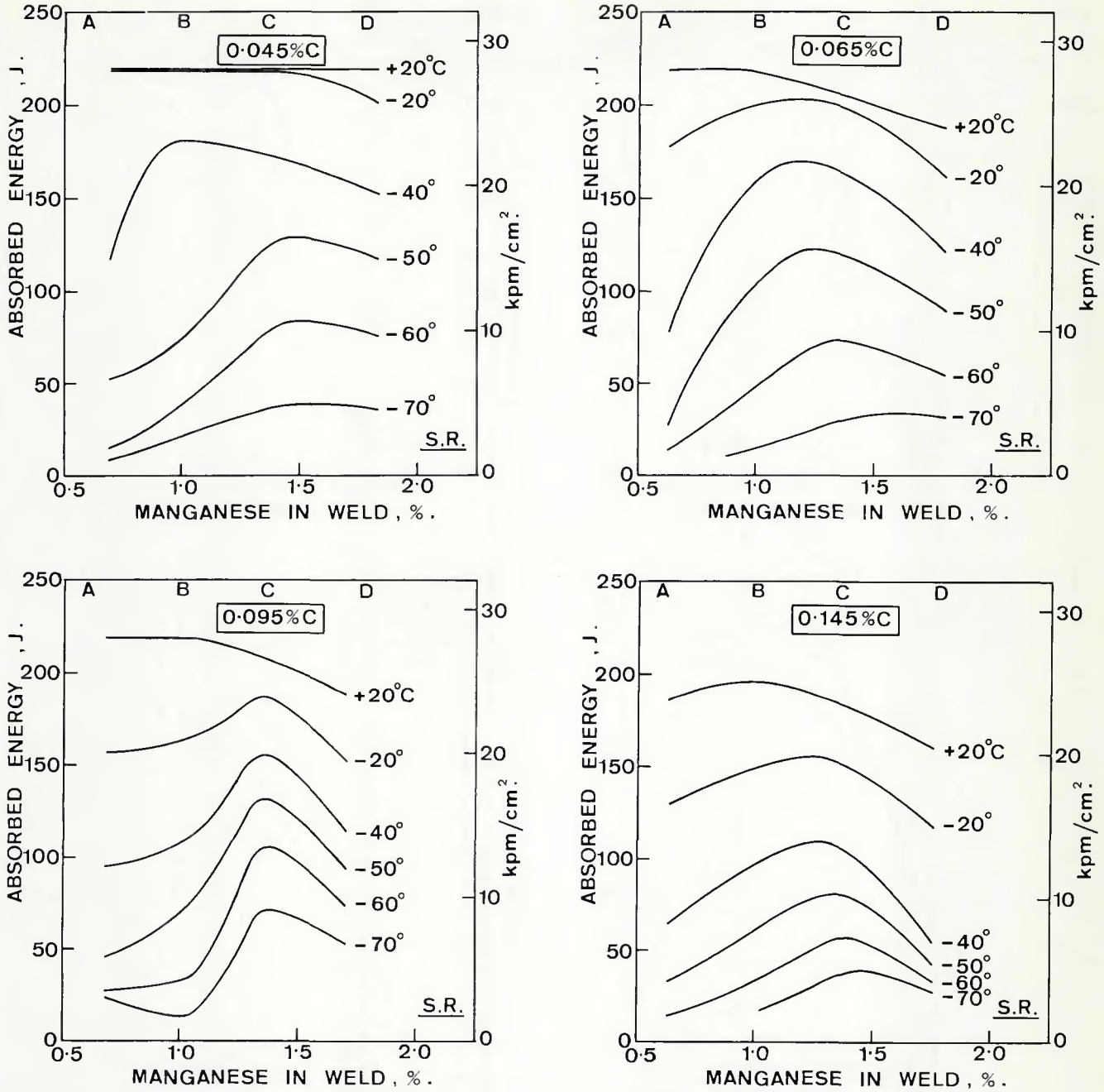


Fig. 12—Effect of manganese on energy absorbed at different temperatures (stress relieved)

ing was to affect the shift in the transition range, depending on the interrelated carbon and manganese levels. At low concentrations, stress relieving had a beneficial effect on notch toughness, whereas at high concentrations, the converse occurred. A balance is thus indicated where relaxation, solute precipitation and carbide spheroidization are counteracted by both elements, due to the increased development of grain boundary cementite particles. The loss in toughness is time dependent, as illustrated by the Charpy V-notch curves (Fig. 15) obtained after stress relieving the extreme composition (0.15% C, 1.8% Mn) for times up to 100 h. On plotting the 100 J and 28 J values (Fig. 16), it is seen that deterioration occurred up to 20 h, and thereafter the situation improved. The effect of a change in the Holloman-Jaffe parameter is indicated by the replicas shown in Fig. 17. The carbides coarsened in the period between 2 and 100 h, and also possibly became more spheroidal.

Optimal toughness for the as-welded condition was achieved (Ref. 1) at a manganese content of 1.4%, when the carbon content was in the intermediate range, *i.e.*, between 0.07 and 0.09%. After stress relieving, the idealized composition remained optimized and no essential shift occurred. The insensitivity of the system to heat treatment is clearly a positive feature, especially considering that the process variables (Refs. 3–6) have no effect on the position of the manganese peak.

Conclusions

For ISO 2560 type joints, welded with low-hydrogen, iron powder electrodes of a specific basic slag type, the following occurred as a result of stress relieving:

1. The morphology of second-phase particles changed, with breakdown occurring to ferrite and carbide.

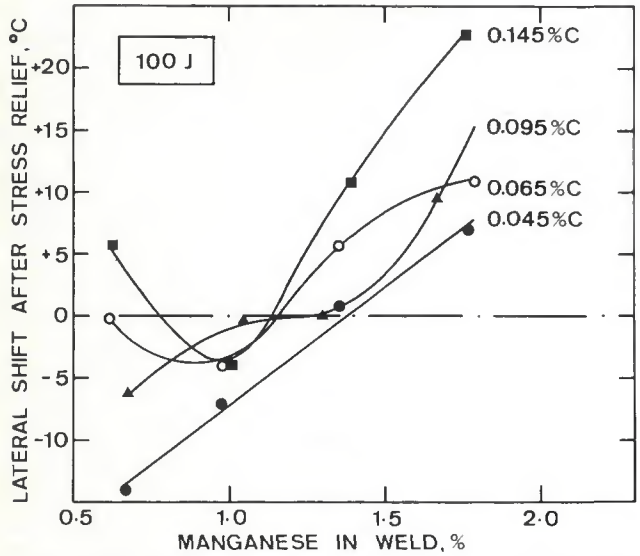


Fig. 13 — Effect of manganese on the lateral shift at 100 J (different carbon contents)

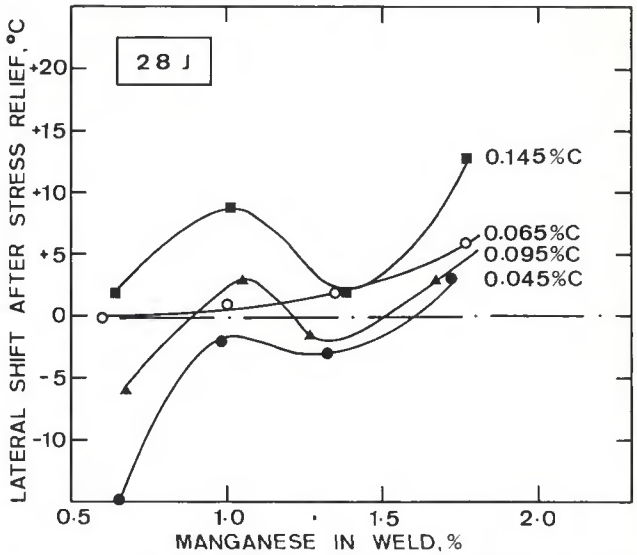


Fig. 14 — Effect of manganese on the lateral shift at 28 J (different carbon contents)

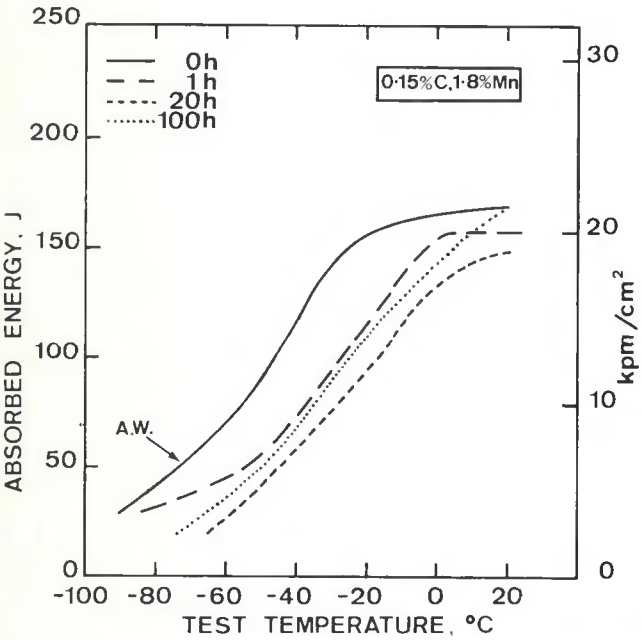


Fig. 15 — Charpy V-notch curves for weldments stress relieved at 580°C (different times)

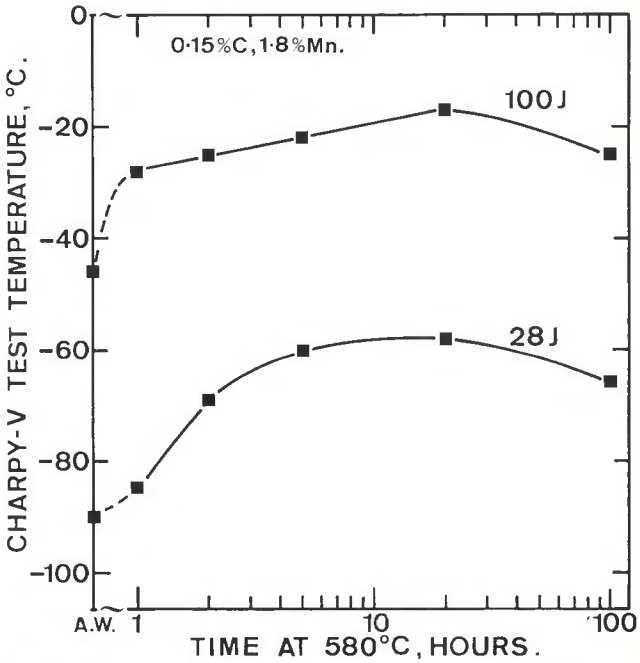


Fig. 16 — Effect of time on Charpy V-notch temperature corresponding to 100 J and 28 J

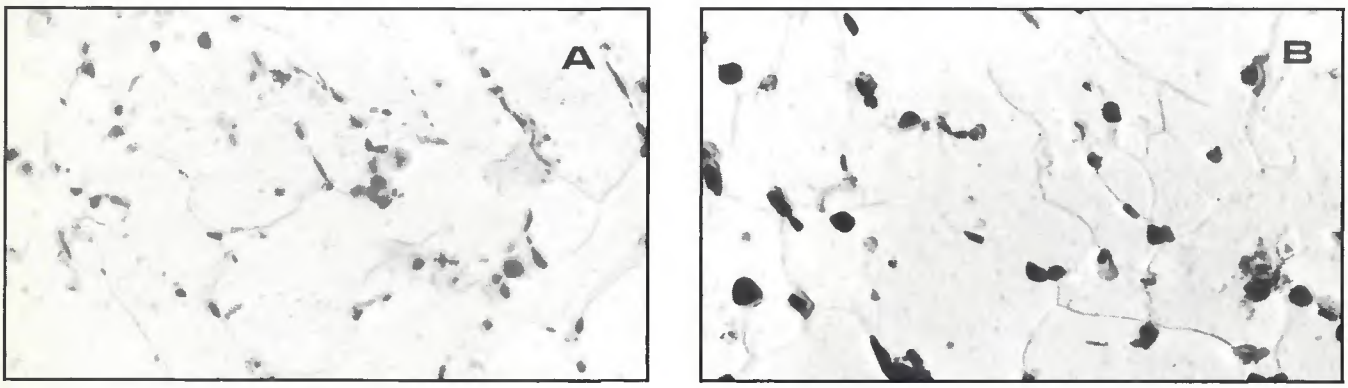


Fig. 17 — Fine-grained region; 0.15 C, 1.8 Mn; stress relieved. A — For 2 h; 8 — For 100 h

2. Pearlite and cementite films were spheroidized.
3. Grain boundary carbides developed and subsequently coarsened.
4. The hardness of deposited and reheated regions decreased.
5. The yield and tensile strength decreased.
6. Notch toughness improved at low C and Mn levels and deteriorated at high C and Mn levels.
7. At intermediate levels, no essential change in toughness occurred, the optimum being retained at 1.4% Mn when the carbon content was between 0.07 and 0.09%.

Acknowledgment

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WRC Bulletin 316
July 1986

Two additional Technical Position Documents that Supplement WRC Bulletin 300, December 1984, have been published under the direction of the Technical Committee on Piping Systems of the Welding Research Council.

Technical Position on Piping System Installation Tolerances
By E. B. Branch, N. Kalyanam, D. F. Landers, E. O. Swain and D. A. Van Duyne

This document, prepared by the Task Group on Industry Practice, provides tolerances on the as-built geometry of light water reactor piping and pipe support locations that are considered acceptable for reconciliation with as-designed geometry.

Technical Position on Damping Values for Insulated Pipe—Summary Report
By J. L. Bitner, S. N. Hou, W. J. Kagay and J. A. O'Brien

This document, prepared by the Task Group on Damping Values, is an extension of the "Technical Position on Damping Values for Piping—Interim Summary Report," appearing in WRC Bulletin 300.

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PVRC Centrifugal Pump-Piping Interaction Experience Survey
By J. R. Payne

Over 100 questionnaires asking about field experience, design standards, and attitudes on the effect of pipe reactions on centrifugal pumps were received from the power and process industries. This survey, which was prompted by industry inquiries, examines the experience and needs of piping and pump system designers, manufacturers, and operators. It was designed to help the Pressure Vessel Research Committee (PVRC) determine whether a significant pump-piping interaction problem exists and to what extent, and also to help set research priorities and provide guidance to code and standards bodies.

The survey and publication of this report was sponsored by the Subcommittee on Piping, Pumps and Valves of the Pressure Vessel Research Committee of the Welding Research Council. The price of WRC Bulletin 317 is $22.00 per copy, plus $5.00 for postage and handling. Orders should be sent with payment to the Welding Research Council, Suite 1301, 345 E. 47th St., New York, NY 10017.