WELDING RESEARCH

SUPPLEMENT TO THE WELDING JOURNAL, AUGUST, 1983
Sponsored by the American Welding Society and the Welding Research Council

Effect of Stress Relief on Microalloyed Weld Metal Impact Properties

Welds made in base metals containing less than 0.030% Cb are not likely to exhibit a loss of toughness after postweld heat treatment

BY C. H. ENTREKIN, JR.

ABSTRACT. The present study was subdivided into two sections: first, a review of the published literature; and second, the collection and analysis of pertinent data which had been developed at the author's laboratory in the past few years. The objective was to review and resolve seemingly numerous inconsistencies in the available data, and where possible, to develop guidelines for the prudent use of stress relief on weld metals deposited in microalloyed steels. The literature review showed that a relatively small amount of work has been published on the effects of stress relief (i.e., postweld heat treatment) on microalloy-bearing weld metals. Many of the authors studied widely varying chemical compositions and welding variables.

Experimental work was performed on carbon - manganese - columbium steel plates in three heat-treated conditions and at thicknesses from 0.75 to 8.0 in. (19 to 203 mm). In these tests, a reduction of impact properties was usually noted where a high heat input had been used and/or where an additional alloying element such as Mo had been added to the weld pool via the electrode. Welds made in base metals containing less than 0.030% Cb are considered unlikely to exhibit a loss of toughness after postweld heat treatment.

Introduction

Microalloyed steels are usually considered to be low carbon-manganese steels which contain less than 0.10% of such alloying additions as columbium, vanadium, titanium, etc. In recent years, however, the amount of microalloying addition has increased in some steels to 0.15% or more.

Basic research on microalloying began in the late 1950's and continued through the 1960's. Most of the early work in this area was best summarized in a 1967 paper by Irvine, Pickering, and Gladman (Ref. 1) and again in a 1975 paper by Pickering (Ref. 2).

Columbium (or niobium) was one of the first elements investigated as a microalloying addition. Columbium combines with carbon and nitrogen in steel to form a carbonitride. Using the solubility product described by Irvine, *et al.* (Ref. 1), it can be seen that the Cb (C,N) precipitate can remain undissolved in austenite at temperatures in excess of 1800°F (982°C), depending on the relative concentration of the elements involved. It is this relative insolubility of Cb (C,N) that makes Cb desirable as a microalloying element. Depending on the specified heat treatment of the steel, Cb (C,N) precipitates can be utilized in different ways. Of great commercial interest are both heat-treated and as-rolled C-Mn-Cb plate steels.

Effects of Rolling Practice

In heat-treated C-Mn-Cb plate steels, no particular restrictions are placed on the rolling practice. During soaking, most of the Cb is taken into solution in the austenite. As the plate cools during and after rolling, the Cb precipitates from solution as Cb (C,N). During the austenitizing stage of heat treatment, the Cb (C,N) precipitates do not dissolve; instead, they act as grain refiners and restrict the austenite grain size. Upon cooling, a very uniform, fine grained microstructure results. It is well known that grain size refinement has a beneficial effect on both yield strength and impact transition temperature. Precipitation hardening is not a major factor in the heat-treated Cb-bearing steels.

As-rolled Cb-bearing steels rely on a form of controlled rolling to create the desired fine grained microstructure. In these steels, the presence of the Cb (C,N) precipitates formed during cooling prevents the recrystallization of austenite from occurring below approximately 1650°F (899°C). If rolling is continued below this temperature but above the austenite-to-ferrite transformation temperature, the unrecrystallized austenite grains become heavily deformed or "pancaked" and possess a high surface area-to-volume ratio. Upon transformation, numerous ferrite grains are nucleated from these austenite grains, thus creating a very fine-grained structure. Some additional strengthening may also result from precipitation hardening in these as-rolled steels.

Like Cb, other elements may be added to carbon plate steels as microalloying additions. However, base metals containing V, Ti, Zr and other microalloys are not discussed in this paper.

Welding Heat Input

When added to the weld pool, filler metal may carry certain alloying additions such as Ni or Mo to enhance the properties of the finished weld; however, these

Paper presented at the 64th AWS Annual Convention held in Philadelphia, Pennsylvania, during April 24-29, 1983.

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Table 1—Literature Survey of Stress-Relieved (Postweld Heat Treated) Columbium-Bearing Weld Metals

Literature ref. no.	Base metal components, % C	Mn	Nb	Gauge in.[a]	Heat input kJ/in.[b]	Electrode type	Flux	Nb dilution %	PWHT temperature °F[c]	Toughness reduction after PWHT
7	.17	1.35	.03	1.00	84	C-Mn	Neutral	50	1112	No
	.17	1.35	.03	1.00	193	C-Mn	Neutral	66	1112	No
	.17	1.35	.03	1.00	84	C-Mn	Basic	40	1112	No
	.17	1.35	.03	1.00	193	C-Mn	Basic	66	1112	No
9	.03	1.90	.06	0.6	208	C-Mn	Basic	50	1020-1185	Yes
12	.14	1.43	.03	1.26	108	C-Mn	Basic	51	1112	No
13	.05	2.0	.03	0.59	unk.	C-Mn	unk.	70	1076	Yes
	.05	2.0	.07	0.59	unk.	C-Mn	unk.	69	1076	Yes
14	.08	0.97	.02	1.0	99	C-Mn	Carbonate	66	1157	No
15	.12	1.15	–	unk.	64	C-Mn	Nb-bearing	unk.	932-1292	No
16	.12	1.01	.09	0.5	56	C-Mn	Neutral	59	1100	Yes

(a) 1 in. = 25.4 mm.
(b) 1 kJ/in. = 2.54 kJ/cm.
(c) °F = (9/5)°C + 32.

rarely contain microalloying additions such as Cb or V. Since the applied thermal energy of the welding process causes a portion of the base material to melt, a percentage of any microalloying elements present in the base metal will enter the molten weld pool. This mixing or dilution process is a function of several factors, including the starting chemical composition of the base metal and the thermal energy applied through welding.

The final chemical composition of the weld rarely matches that of the starting base metal. This is because the filler metal deposit is designed to provide the desired mechanical properties with an as-cast microstructure, while the base metal is a wrought structure. Because microalloying additions such as Cb and V were designed to provide grain refinement and possibly precipitation strengthening in a wrought structure, their presence in the as-cast weld metal may not necessarily be desirable.

In some cases, particularly low heat input welding such as manual shielded metal arc welding (SMAW), the amount of microalloying element diluted into the weld pool is minimal and insignificant. In higher heat input processes such as submerged arc welding (SAW) and electroslag welding (ESW), a higher concentration of microalloying element may be diluted into the weld pool. In higher concentrations, these elements can have an effect on the microstructure and properties of the weld, and this effect must be considered when selecting welding consumables (Ref. 3).

Postweld Heat Treatment

The properties of many weldments can be improved through postweld heat treatment (PWHT). The most common form of PWHT usually consists of heating the weldment to an elevated temperature below the transformation temperature and holding it long enough to relax residual stresses. A typical PWHT for a carbon plate steel weld might consist of heating to the range of 1100–1250°F (593–677°C) and holding for 1 hour (h) per inch of thickness. In addition to the removal of residual stresses, PWHT can provide other benefits (Ref. 4, 5); these include:

1. Tempering of lower temperature transformation products.
2. Minimization of potential strain-age embrittlement near heat-affected zones.
3. The development of improved fracture toughness and increased resistance to brittle fracture.
4. The removal of residual hydrogen.
5. The development of dimensional stability.

For fabricated structures intended for service in boilers, pressure vessels, nuclear and other critical applications, a postweld heat treatment is required by various code-writing bodies.

PWHT after welding may not be beneficial in all cases. One factor that must be considered is the susceptibility of the weldment to precipitation-hardening reactions that could lead to a possible reduction in toughness. Such reactions are possible in both the heat-affected zone of the base metal and the as-solidified weld metal. The balance of this report will discuss the potential for a reduction in toughness of the weld metal in microalloyed steels after PWHT.

Review of Literature

Numerous technical papers have been published by authors discussing the effects of stress relief or postweld heat treatment (PWHT) on weld metals in microalloyed steels. One of the first papers to address this subject was published by Garland and Kirkwood in 1975 (Ref. 3). They state that, in common welding processes such as submerged arc welding, the cooling rates in the as-deposited weld bead are normally so rapid that actual precipitation of microalloy carbonitrides is not likely to occur in the as-welded weld metal, despite dilution from the base metal. However, during stress relief the operation of pre-precipitation clustering and epitaxial precipitation can reduce the impact properties of the weld metal.

A similar conclusion was reached by Bernard who states that the precipitation of microalloying elements during the weld-cooling is incomplete due to sluggish precipitation kinetics (Ref. 6). Garland and Kirkwood maintain that, only when the precipitation mechanisms are accompanied by both a significant decomposition of martensite and other beneficial changes, will a large reduction of impact properties be avoided. The balance between the tempering of undesirable martensite and the occurrence of precipitation hardening is also discussed in a second Garland and Kirkwood paper (Ref. 7).

Not all authors agree with Garland and Kirkwood's contention that no precipitation occurs during the cooling of an as-deposited weld bead. Billy, *et al.* have stated that both coarse continuous precipitation and precipitation at prior austenite grain boundaries can be observed in as-welded weld metals (Ref. 8). These authors go on to state that the amount and types of precipitates increase significantly on reheating (stress relieving) and that the most marked effect of precipitation during reheating appears to occur in conjunction with cell, or small-angle grain boundaries. Both Billy, *et al.*, and Bosansky, *et al.*, agree that stress relieving will also cause precipitation to occur on dislocations in certain microalloy systems (Ref. 8, 9).

Despite some disagreement on when the microalloy precipitates first form, most authors writing on this subject agree that they do form and that they can be a cause for concern. Thomas has written that B, Cb, Mo, Ti and V in weld deposits may precipitate in fine dispersions of complex carbides, nitrides, or intermetallic compounds upon reheating to temperatures in the range of 900–1300°F (482–704°C) and that these precipitates can reduce notch toughness (Ref. 10). Rothwell quotes Hannerz as

Table 2—Literature Survey of Stress-Relieved (Postweld Heat Treated) Columbium-Molybdenum-Bearing Weld Metals

Literature ref. no.	Base metal components, % C	Mn	Nb	Gauge in.(a)	Heat input kJ/in.(b)	Electrode type	Flux	Cb dilution (%)	PWHT temperature °F(c)	Toughness reduction after PWHT
3	.17	1.35	.03	1.00	84	C-Mn-Mo	Neutral	47	1112	Yes
	.17	1.35	.03	1.00	84	C-Mn-Mo	Basic	33	1112	No
9	.03	2.00	.19	0.6	208	C-Mn-Mo	Basic	42	1020-1185	Yes
12	.14	1.43	.03	1.26	108	C-Mn-Mo	Basic	57	1112	No
13	.05	2.00	.03	0.59	unk.	C-Mn-Mo	unk.	59	1076	Yes
	.05	2.00	.08	0.59	unk.	C-Mn-Mo	unk.	65	1076	Yes
15	.12	1.15	—	unk.	64	C-Mn-Ni-Mo	Nb-bearing	unk.	1112	Yes
16	.12	1.01	.09	0.5	56	C-Mn-Ni-Mo	Neutral	49	1100	Yes

(a)1 in. = 25.4 mm.
(b)1 kJ/in. = 2.54 kJ/cm.
(c)°F = (9/5)°C + 32.

stating that stress relief of low-carbon, higher alloy weld metals "may lead to severe embrittlement and great care must be exercised" (Ref. 11).

Only one study was found that disputed the claim that stress relief caused a toughness reduction in microalloyed steel weld metals. Fick and Rogerson wrote that their work with Nb and Mo containing SAW weld metals showed no evidence of stress relief toughness reduction (Ref. 12). In this study, the starting base metal contained 0.028% Cb and the deposited weld metal contained 0.017% Cb.

After studying the literature, it becomes apparent that many of the conclusions reached by various authors are the result of relatively limited investigations, often involving one or two base metal chemistries and one or two sets of welding conditions. Some of the more specific cases are examined below.

Seven articles selected from the literature are summarized in Table 1. It is important to note that both the base metal and the deposited weld metal were microalloyed with Cb only, *i.e.*, Mo, V, Ti or other similar elements were not present. In the eleven individual cases cited, PWHT toughness reduction was noted in four. In three of the examples where a reduction of toughness after PWHT was noted, the columbium concentration in the base metal was 0.06% or greater. It is difficult to draw conclusions from the fourth example due to the limited details in the original paper.

Seven papers selected from the literature dealing with Cb-Mo-bearing weld metals are summarized in Table 2. In these examples, Mo was not present in the base metal. In all cases but two, stress relief toughness reduction was reported by the authors. Mo is most commonly added to the weld pool via the SAW electrode for the purpose of increasing the hardenability of the weld, thereby improving its microstructure and notch toughness. During stress relief, however, carbides such as Mo_2C precipitate in addition to the Cb (C,N) precipitation and contribute to the possible reduction in notch toughness (Ref. 3).

Two cases are shown in Table 2 where a reduction in notch toughness was not reported. Here, it is suspected that the final weld metal deposit was too lean in alloy content and/or the precipitation kinetics experienced during testing were not favorable for precipitation to occur.

Experimental Procedure

Several experiments were conducted in the author's laboratory involving the postweld heat treatment (PWHT) of submerged arc welds made in both as-rolled and heat-treated commercial C-Mn-Cb steels. All steel plates had been produced in electric arc furnaces, and some had also been calcium treated in the ladle to reduce sulfur concentrations and provide inclusion shape control. After hot rolling, most of the plates were mill heat-treated by either normalizing or quenching and tempering. One plate was hot rolled, utilizing controlled rolling practices; this was left in the as-rolled condition. The finished plates ranged in gauge from 0.75

Table 3—Experimental SAW Parameters

Weld code	Base metal characteristics: Chemistry, % C	Mn	Cb	Gauge in.(a)	Heat treatment	Consumables: Electrode	Flux	Heat input kJ/in.(b)	No. of passes	Grow precipitation	Preheat °F(c)
A	.12	1.43	.04	8.0	Norm.	0.5% Mo	Neutral	56	96	24° dbl. V.	70
B	.12	1.43	.04	8.0	Norm.	0.5% Mo	Acidic	96	55	24° dbl. V	70
C	.13	1.47	.03	1.5	Norm.	1.7% Ni	Acidic	50-60	15	60° incl. bev.	200
D	.13	1.47	.03	1.5	Norm.	1.7% Ni	Acidic	100-120	9	60° incl. bev.	200
E	.13	1.47	.03	1.5	Q & T	3.5% Ni	Neutral	50-60	16	60° incl. bev.	250
F	.13	1.47	.03	1.5	Q & T	3.5% Ni	Neutral	100-120	7	60° incl. bev.	250
G	.13	1.47	.03	1.5	Q & T	Mo-Ti-B	Basic	75	11	60° incl. bev.	250
H	.11	1.35	.03	0.75	Norm.	Mo-Ti-B	Basic	75	3	60° dbl. V	70
J	.11	1.35	.03	0.75	Norm.	1.7% Ni	Acidic	75	3	60° dbl. V	70
K	.05	1.36	.05	0.75	A.R.	Mo-Ti-B	Basic	75	3	60° dbl. V	70
L	.05	1.36	.05	0.75	A.R.	1.7% Ni	Acidic	75	3	60° dbl. V	70
M	.10	1.48	.03	0.75	Q & T	Mo-Ti-B	Basic	75	3	60° dbl. V	70
N	.10	1.48	.03	0.75	Q & T	1.7% Ni	Acidic	75	3	60° dbl. V	70
P	.19	1.25	—	0.75	Norm.	Mo-Ti-B	Basic	75	3	60° dbl. V	70
Q	.19	1.25	—	0.75	Norm.	1.7% Ni	Acidic	75	3	60° dbl. V	70

(a)1 in. = 25.4 mm.
(b)1 kJ/in. = 2.54 kJ/cm.
(c)°F = (9/5)°C + 32.

Table 4—Chemical Analyses of Weld Deposits, Wt-%[a]

Weld	C	Mn	P	S	Cu	Ni	Cr	Mo	Si	Ti	Al	B	Cb
A	.08	1.41	.011	.017	.16	.02	.05	.46	.27	ND	.004	ND	.004
B	.03	2.00	.020	.020	.15	.03	.05	.45	.34	ND	.014	ND	.003
C	.075	1.12	.009	.005	.22	1.35	.05	.12	.30	.01	.035	ND	.008
D	.068	1.19	.010	.008	.25	1.03	.07	.09	.29	ND	.028	ND	.008
E	.02	1.01	.004	.004	.29	3.41	.07	.05	.31	.005	.003	.0002	NA
F	.05	1.15	.006	.005	.30	2.62	.09	.05	.30	.006	.009	ND	.004
G	.02	1.09	.011	.004	.17	0.13	.09	.26	.12	.005	.010	.0010	ND
H	.07	1.36	.017	.009	.21	.11	.14	.19	.16	.005	.012	.0015	.012
J	.06	1.25	.018	.015	.26	1.28	.09	.12	.33	.006	.019	.0004	.009
K	.05	1.33	.010	.008	.20	.07	.09	.17	.16	.005	.010	.0015	.019
L	.05	1.22	.010	.014	.26	1.18	.05	.09	.33	.006	.020	ND	.015
M	.06	1.44	.011	.006	.16	.10	.12	.25	.17	.007	.012	.0006	.009
N	.06	1.28	.013	.009	.22	1.17	.08	.16	.35	.008	.021	.0001	.008
P	.10	1.25	.008	.009	.21	.18	.13	.18	.17	.006	.016	.0015	ND
Q	.08	1.20	.010	.014	.28	1.21	.09	.11	.35	.006	.020	.0002	ND

[a]ND = not detectable; NA = not analyzed.

Table 5—Partial Chemical Analyses of Weld Deposits, Wt-%[a]

Weld	Mn	Ni	Mo	Ti	B	Cb
A	1.41	.02	.46	ND	ND	.004
B	2.00	.03	.45	ND	ND	.003
C	1.12	1.35	.12	.010	ND	.008
D	1.19	1.03	.09	ND	ND	.008
E	1.01	3.41	.05	.005	.0002	NA
F	1.15	2.62	.05	.006	ND	.004
G	1.09	.13	.26	.005	.0010	ND
H	1.36	.11	.19	.005	.0015	.012
J	1.25	1.28	.12	.006	.0004	.009
K	1.33	.07	.17	.005	.0015	.019
L	1.22	1.18	.09	.006	ND	.015
M	1.44	.10	.25	.007	.0006	.009
N	1.28	1.17	.16	.008	.0001	.008
P	1.25	.18	.18	.006	.0015	ND
Q	1.20	1.21	.11	.006	.0002	ND

[a]ND = not detectable; NA = not analyzed.

in. (19 mm) to 8.0 in. (203 mm).

Welding conditions selected were considered to be representative of those used in the fabrication of heavy plates. More details on the base metal chemical composition and the welding conditions used are found in Table 3. After welding, the plates were given PWHT for 1 hour (h) per inch of thickness at a temperature in the range of 1125-1150°F (607-621°C). Impact properties of the PWHT weldments were determined using full-size Charpy V-notch specimens. Complete chemical analyses of the deposited weld metals were obtained and are included here in Table 4. An abbreviated version of these analyses is found in Table 5.

Results and Discussion

Test welds A and B were conducted on an 8.0 in. (203 mm) thick plate of normalized C-Mn-Cb steel (0.12 C, 1.40 Mn, 0.009 S, 0.046 Cb). Weld A involved the use of a low heat input, *i.e.*, 56 kJ/in. (22 kJ/cm), while weld B involved a moderate heat input, *i.e.*, 96 kJ/in. (38 kJ/cm). Both welds were made with a Mn-Mo electrode (0.15C − 2.0 Mn − 0.5 Mo). CVN impact results from these welds are presented in Fig. 1. Data for the base metal in the normalized and the normalized plus PWHT conditions are also presented.

Figure 1 indicates that the transition behavior of the base metal was affected by the 1125°F (607°C) PWHT, but that the behavior of the two welds was virtually unaffected at either heat input. There is no known metallurgical reason for the apparent reduction of the base metal notch toughness properties; consequently, this result is discounted as experimental scatter, test error, etc.

In multipass welds such as those studied here, the heat from subsequent passes causes a tempering or PWHT effect on earlier passes. This fact, com-

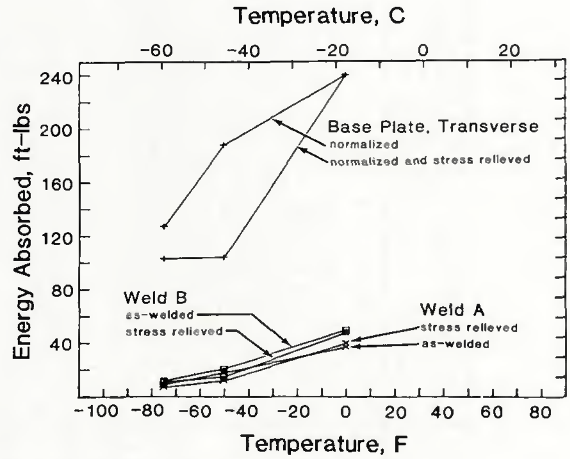

Fig. 1—CVN impact data for welds A and B

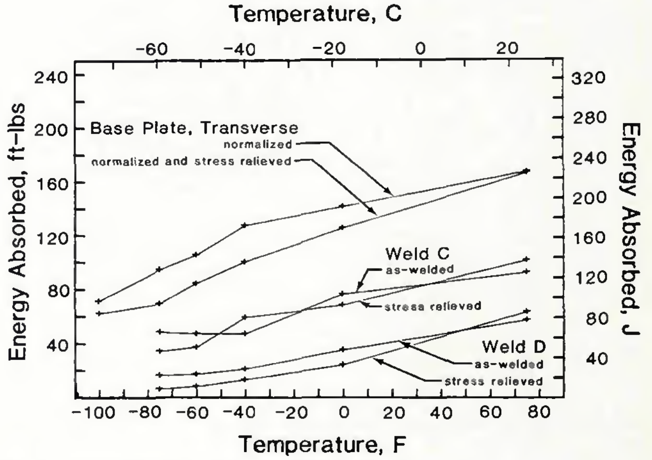

Fig. 2—CVN impact data for welds C and D

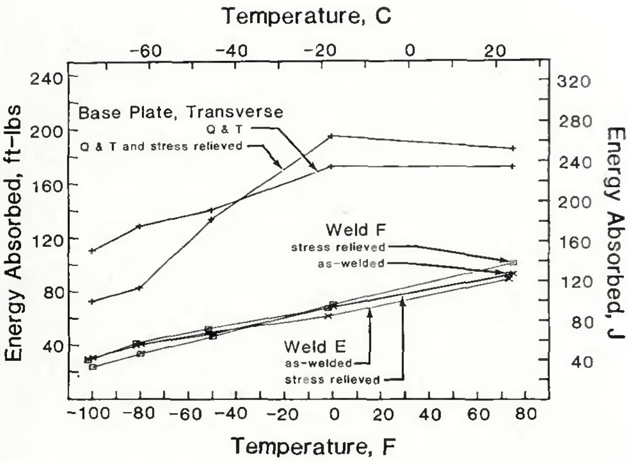

Fig. 3 — CVN impact data for welds E and F

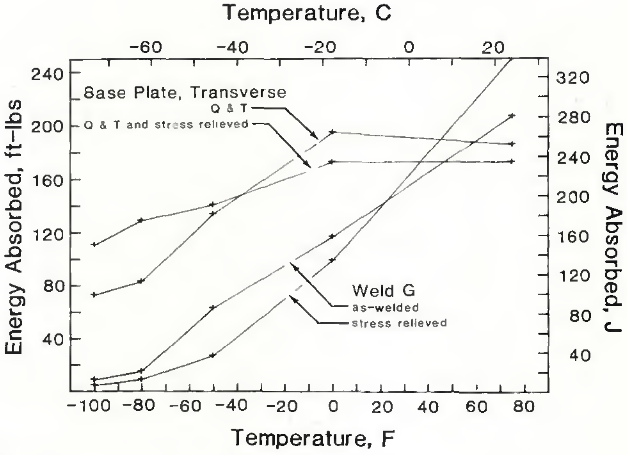

Fig. 4 — CVN impact data for weld G

bined with the added postweld heat treatment, allows precipitates to grow and coalesce and thus minimizes their effect. Table 5 shows that chemical analyses of the deposited weld metal detected less than 0.01% Cb, a result attributed to the relatively low heat inputs used. The absence of significant amounts of Cb in the deposit, combined with the averaging provided by the multiple passes prevented a reduction in notch toughness despite the presence of the Mo in the weld.

A similar set of results caused by the stress relieving can be observed from welds C and D which are graphed in Fig. 2. These tests involved the welding of a 1½ in. (38 mm) C-Mn-Cb plate (0.13 C, 1.38 Mn, 0.006 S, 0.027 Cb), using two different sets of heat inputs with a C-Mn-Ni electrode. At 50–60 kJ/in. (20–24 kJ/cm), no PWHT effects were noted. At 100–120 kJ/in. (39–47 kJ/cm), a minor reduction in toughness can be seen, although it is probably within the range of experimental scatter. Table 5 shows that the Cb content of these welds was below 0.01%. It should be noted for welds C and D as well as welds A and B that the impact toughness of the weld metal falls below that of the base metal.

Figure 3 shows the results of another set of welding trials performed on a quenched and tempered C-Mn-Cb plate. These tests utilized a plate of the same chemical composition as used in tests C and D. The tests shown in Fig. 3 also involved a C-Mn-Ni electrode and two different levels of heat input. Once again, no PWHT effect was observed at either heat input. The notch toughness of the weld metal is below that of the base metal and would not meet a specified toughness criterion of 50 ft-lb at −80°F (68 J at −62°C) which would be typical for this grade of steel.

Test weld G was performed on the same base metal as used for welds E and F. Weld G utilized a moderate heat input, *i.e.*, 75 kJ/in. (30 kJ/cm), and a Mo-Ti-B bearing electrode with a fully basic flux. This electrode/flux combination had been designed specifically for use with microalloyed steels (Ref. 3). Figure 4 shows that the low temperature toughness of the weld metal again would not meet a specified toughness requirement of 50 ft-lb at −80°F (68 J at −62°C), as required for the base metal.

Some reduction in notch toughness can be observed in the transition range as shown in Fig. 4. This result would be expected based on the previously discussed literature reviews involving Mo-bearing welding electrodes. In weld G a number of elements were available for precipitation due to the presence of Mo, Ti, and B in the starting electrode, despite the absence of detectable Cb in the weld deposit — Table 5.

Another series of experiments was conducted on lighter plates of thickness 0.75 in. (19 mm). These experiments were labeled H through Q in Table 3. Tests H and J were performed on a conventional-sulfur level C-Mn-Cb plate (0.11 C, 1.35 Mn, 0.025 S, 0.03 Cb) in the normalized condition. Figure 5 shows portions of the impact transition curves for the base metal and welds H and J.

Weld H was made with a Mo-Ti-B electrode and a fully basic flux. In this case PWHT resulted in reduced weld metal impact properties. As with weld G the effects of stress relief were magnified by the use of a Mo-Ti-B electrode. Table 4 shows that significant amounts of Mo,

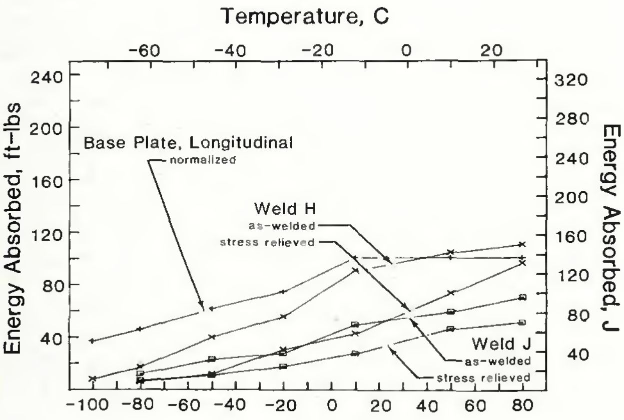

Fig. 5 — CVN impact data for welds H and J

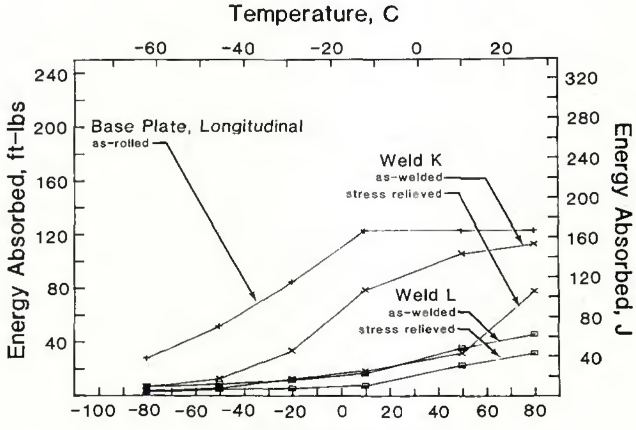

Fig. 6 — CVN impact data for welds K and L

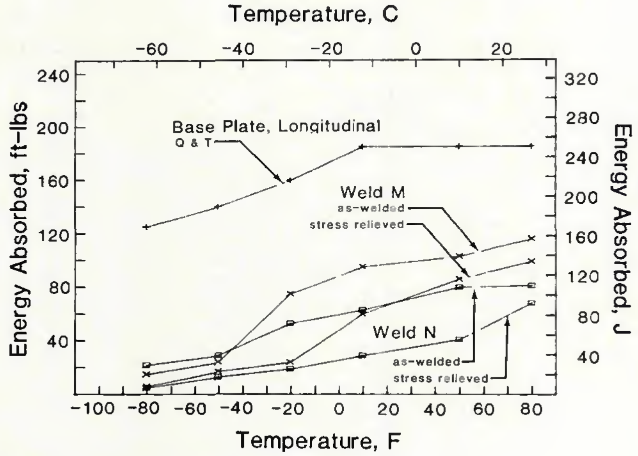

Fig. 7 – CVN impact data for welds M and N

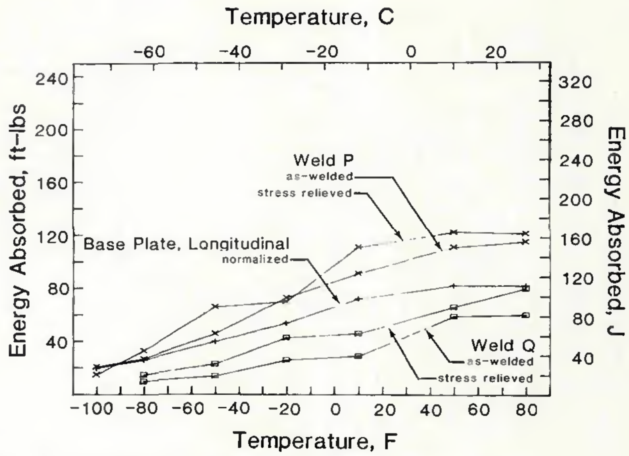

Fig. 8 – CVN impact data for welds P and Q

Ti, and Cb were available for precipitation. The results of test J, using the same base metal as weld H are also graphed in Fig. 5. In this case a C-Mn-Ni electrode and an acidic flux were used. These welds yielded lower overall impact values than their Mo-Ti-B counterparts. Figure 5 shows that stress relief of the C-Mn-Ni weld had a small effect on toughness.

Welds H and J, performed on a heat treated C-Mn-Cb steel plate, were duplicated on an as-rolled C-Mn-Cb plate. Figure 6 shows a portion of the transition curve for conventional quality as-rolled C-Mn-Cb steel (0.05 C, 1.36 Mn, 0.020 S, 0.048 Cb). Figure 6 also shows both as-welded and PWHT data for test weld K, the welds made using a Mo-Ti-B electrode and fully basic flux. Although the as-welded properties of this combination exhibit good notch toughness, a toughness reduction after PWHT can be noted.

This effect is larger than that noted with the heat-treated C-Mn-Cb steel in Fig. 5 and is attributed to the higher starting Cb-level in the as-rolled base metal and the correspondingly rich chemistry of the weld seen in Table 5. Figure 6 further shows the impact properties of weld L, made using a C-Mn-Ni electrode and acidic flux, are lower than those of either the base metal or of the Mo-Ti-B/basic flux combination. Some reduction in weld metal notch toughness after stress relieving was noted in weld L; however, this reduction was nearly within the expected experimental scatter.

One plate of a quenched and tempered Cb-Mo steel (0.10 C, 1.48 Mn, 0.006 S, 0.20 Mo, 0.030 Cb) was welded in the same manner as welds H and J. Figure 7 shows a portion of the transition curve for the quenched and tempered base plate as well as the as-welded and PWHT data for the Mo-Ti-B/fully basic flux consumable combination, weld M. During the study, no consumable combination was found which matched the exceptional toughness of the base metal. The Mo-Ti-B/fully basic flux combination was one of the better combinations tested, however. Some evidence of a reduction in weld metal notch toughness after PWHT can be seen in Fig. 7. This result would be expected not only from the use of a Mo-Ti-B electrode but also from the presence of both Cb and Mo in the base metal. Weld M contained the highest concentration of Mo, as seen in Table 5.

Figure 7 also shows the data obtained from welds made in this C-Mn-Mo-Cb steel, in the case of weld N using the C-Mn-Ni electrode with an acidic flux. As was the case with the C-Mn-Cb steels, the impact properties of this consumable combination were lower than those of the base plate and of the Mo-Ti-B/fully basic flux combination. The effect of PWHT was also more pronounced with this consumable combination in the C-Mn-Mo-Cb steel than in the C-Mn-Cb steels (welds J and L). This was caused by the added presence of Mo in the base metal which then entered the weld pool by dilution. Chemical analysis detected the presence of 0.16% Mo in the weld metal.

One plate of a normalized non-microalloyed carbon steel was included as a control plate and was welded in the manner of welds H and J. The CVN results for welds made in this conventional quality carbon steel plate are graphed in Fig. 8 to allow comparisons with the results obtained for the microalloyed steels. The welds in the non-microalloyed plate have been designated P and Q.

Figure 8 presents a portion of the transition curve for the longitudinal base metal (0.19 C, 1.25 Mn, 0.020 S) and also for as-welded and PWHT welds made with the Mo-Ti-B electrode/fully basic flux consumable combination. In both conditions the weld metal toughness exceeded that of the base metal. PWHT was also seen to have a beneficial effect on weld metal notch toughness.

Similar results are seen in Fig 8 where PWHT also improved the toughness of the C-Mn-Ni electrode/acidic flux combination. These improvements after PWHT are typical of the results normally expected in weld metals not subject to a precipitation-hardening mechanism.

Conclusions

The preceding review has demonstrated that the role of microalloying elements in submerged arc weld deposits is complicated and is dependent upon several factors, most notably chemical composition and welding conditions. At first glance, both the published literature and the experimental work presented here seem to be a mass of conflicting data. Upon more detailed analysis, several trends become apparent, and these trends can be useful in guiding the end user or service engineer in avoiding or minimizing the reduction of weld metal notch toughness through stress relief.

Stress relief, *i.e.*, postweld heat treatment (PWHT), will not necessarily cause a loss of notch toughness in all welds containing microalloying elements. In some cases PWHT can improve the notch toughness of these welds, particularly where any precipitation-hardening effects are offset by the decomposition of both martensite or other lower temperature transformation products and by relaxation of residual stresses.

Several conditions must exist for a reduction of weld metal toughness to occur after PWHT:

1. Certain elements such as B, Cb, Mo, Ti, or V must be present in the as-welded deposit.

2. The concentration of these elements must exceed a critical level and/or they must be present in combination with each other. For example, notch toughness reduction after stress relief is unlikely to occur in plain C-Mn-Cb or C-Mn-Ni-Cb weld deposits where the columbium concentration was less than 0.02%. Similarly, Cb concentrations less than 0.01% in the

presence of 0.10% or less of Mo are unlikely to cause a reduction in impact properties. These results are particularly important for C-Mn base metal containing less than about 0.03% Cb, since at most moderate or low heat inputs (≤60 kJ/in., ≤24 kJ/mm) the Cb content of the weld metal will be less than 0.020%.

3. PWHT toughness reduction will occur if the welding conditions and the PWHT cycle are such that the precipitation kinetics favor the development of finely dispersed coherent precipitates. In cases of multipass welds where the heat from subsequent passes provides a continuing auto-tempering effect or in cases where the stress relieving cycle provides for over-aging of the precipitates, toughness reduction may not be noted due to the growth, loss of coherence, and coalescence of the precipitates.

This review has shown that each application must be considered separately by a knowledgeable engineer. In many instances, postweld heat treatments are not required for a given application, and the welding engineer can enjoy more freedom in the selection of consumables and process. In other cases, a certain amount of toughness reduction can be tolerated and the final structure will still meet specifications.

Acknowledgments

The author gratefully acknowledges the contributions of Messrs. L. K. Keay, R. S. Rote, and D. L. Bracher in the experimental work.

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