As-Rolled Plate Product With Improved Yield Strength, Toughness, and Weldability for Pressurized Railroad Tank Cars

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Keywords: HSLA, Thermo-mechanical Controlled Processing (TMCP), Tank Car Steel, Weldability, Submerged Arc Welding, Normalizing, Stress Relieving

Abstract

Normalized AAR TC128-Grade B steel plate is used in pressurized railroad tank cars. This paper describes an alternative low-carbon steel plate product that conforms to ASTM A841-Grade F-Class 6 and has been produced via TMCP. As a result of its low-carbon content and carbon equivalent, the TMCP product offers superior levels of yield strength and impact toughness, as well as better weldability. The strength of the A841 steel decreases somewhat, but remains within specification, and the toughness of the steel does not change significantly as a result of stress relieving at 1200°F. In addition, optimal consumables and welding practices that provide excellent toughness in the HAZ and weld metal from submerged arc welds have been identified. However, the CVN toughness of the weld metal deteriorates significantly after stress relieving, falling below current TC128-B weld metal toughness levels. As a result, it is recommended that the welds of A841 not be stress relieved. Such a practice of using non-stress-relieved welds in service without detriment is employed in the production of oil and gas transmission linepipe.

Introduction

It has been long recognized that there is a need to improve the puncture resistance and toughness of steel plates used in the fabrication of pressurized railroad tank cars, which are sometimes employed to carry hazardous chemicals and gases. This need has been spurred in recent years by a number of tank car punctures occurring in derailments which have led to the release of hazardous chemicals and gases, e.g., Minot, ND (anhydrous ammonia) – 2002 [1], Graniteville, SC (chlorine) – 2005, Brooks, KY (cyclohexane) – 2007, and Castleberry, AL (phenol) - 2007.

The current plate product utilized for pressurized tank cars is Association of American Railroads (AAR) TC128-Grade B. TC128-B is an Al/Si killed 0.20% C steel that is normalized for such applications. The physical metallurgy of normalized plate steels can be found in a paper by Bodnar, et al. [2]. For pressurized cars for low-temperature service, for example cars carrying liquid CO_2, the plates and weld joints must have a Charpy V-notch (CVN) energy of at least 15 ft-lbs at –50°F. Over the years, the toughness of TC128-B plates has been enhanced, mainly by utilizing clean steelmaking practices, minimizing plate mid-thickness chemical segregation by employing sound casting practices, and since 1989, applying a normalizing heat treatment for new cars. With these improvements, the achievable toughness of TC128-B plates has reached its metallurgical limit.

Lower-carbon microalloyed, control rolled or thermo-mechanically processed (TMCP) steel plates offer improved toughness over TC128-B plates. In the severely controlled rolled condition such steels derive their strength from a combination of ferrite grain refinement, Nb,V(C,N) precipitation strengthening, and dislocation strengthening from warm-worked ferrite. Over the past twenty years, there have been a number of studies of as-rolled steels, mostly American Petroleum Institute (API) 5L X-70 linepipe type, as alternatives to TC128-B. For example, Philips [3] studied an X-70 steel with 0.07% C, 1.36% Mn, 0.034% Nb, 0.066% V, and 0.012% N. Although base metal and heat-affected-zone (HAZ) toughness were good, weld metal toughness was poor (< 15 ft-lbs at –30 and –50°F), which was attributed to the use of incorrect welding consumables (LS3 wire/Lincoln 880M flux).

Hukle, et al. [4] studied a control rolled 0.07% C, 1.31% Mn, 0.029% Nb, 0.047% V, 0.015% Ti, and 0.0070% N steel, which is employed for both X-70 linepipe and API 2MT1 offshore platforms. Base metal and HAZ toughness were good in both the as-welded and stress-relieved conditions, and weld-metal toughness was somewhat improved using SD-3 wire and OP121TT flux, viz., 42 and 6 ft-lbs at 0 and –50°F, respectively, in the 1150°F stress-relieved condition.

Sims [5] studied a control rolled ASTM A841-Grade C-Class 2 plate with 0.08% C, 1.42% Mn, 0.035% Nb, 0.069% V, 0.015% Ti, and 0.0090% N. The poor toughness of this steel after the cold and warm forming of heads was attributed to severe plate mid-thickness chemical segregation, which led to microcracking of martensite streaks. As might be expected, stress relieving did not improve the toughness of this material.

Bai, et al. [6] studied a control rolled + accelerated cooled plate with 0.045% C - 1.65% Mn – Mo – Nb - Ti. Excellent properties were achieved in both the base metal and HAZ in both the as-welded and stress relieved at 1175°F conditions. The weld-metal toughness in the stress-relieved condition of 25 ft-lbs at –50°F is the best achieved to date. In this case, the weld wire was Lincoln LA85, the flux was Lincoln 8500, and the plate edges single "V" beveled.

The present study focuses on a comparison of normalized TC128-B plate, processed through IPSCO-Mobile's new state-of-the-art normalizing furnace, and a more cost-effective low-carbon X-70 (with Nb-V-Ti microalloying) plate than that employed by Bai, et al. [6] for pressurized tank car applications. Data from several weldments of both plates are presented in both the as-welded and stress-relieved conditions.

Experimental Procedure

As-Produced Plates

Coupons measuring approximately 10" wide x 20" long were procured from 0.51" thick normalized (N) TC128-B and 0.54" thick as-rolled (AR) X-70 production plates made at the IPSCO-Mobile plant. Product compositions for the two plates investigated are compared with some of the requirements for AAR TC128-B and ASTM A841-F in Table 1. The TC128-B plate meets the requirements of AAR TC128-Grade B and the X-70 plate meets the requirements of ASTM A841-Grade F. Note that the X-70 plate has the lower carbon equivalent (CE_{IIW}), suggesting improved weldability.

Table 1 Comparison of steel product compositions, wt. %

Element	AAR TC128-B	TC128-B	ASTM A841-F	X-70
C	≤ 0.24	0.20	≤ 0.10	0.055
Mn	1.00/1.65	1.40	1.10/1.70	1.55
P	≤ 0.025	0.013	≤ 0.020	0.010
S	≤ 0.015	0.003	≤ 0.008	0.003
Si	0.15/0.40	0.32	0.10/0.45	0.30
Cu+Ni+Cr+Mo	Not Specified Except Cu ≤ 0.35	0.50	≤ 2.05	0.38
Nb+V+Ti	≤ 0.12	0.05	≤ 0.22	0.13
Al	0.015/0.060	0.025	≥ 0.020	0.022
CE_{IIW}	≤ 0.53	0.50	Not Specified	0.36

An electric arc furnace was used to make the steels, which were continuously cast into 6" thick slabs. Slabs representing both compositions were reheated to approximately 2280°F. Solubility calculations [7] for Nb,V(C,N) after accounting for TiN formation show that all of the Nb and V are in solution at the reheat temperature. The TC128-B slab was hot rolled to a 0.51" thick plate and normalized (N) using an austenitizing temperature of 1650°F. The X-70 slab was severely control rolled, with the finish rolling temperature well below the Ar_3 temperature of 1397°F [8], to a plate thickness of 0.54". Plate processing for both steels is compared schematically in Figure 1.

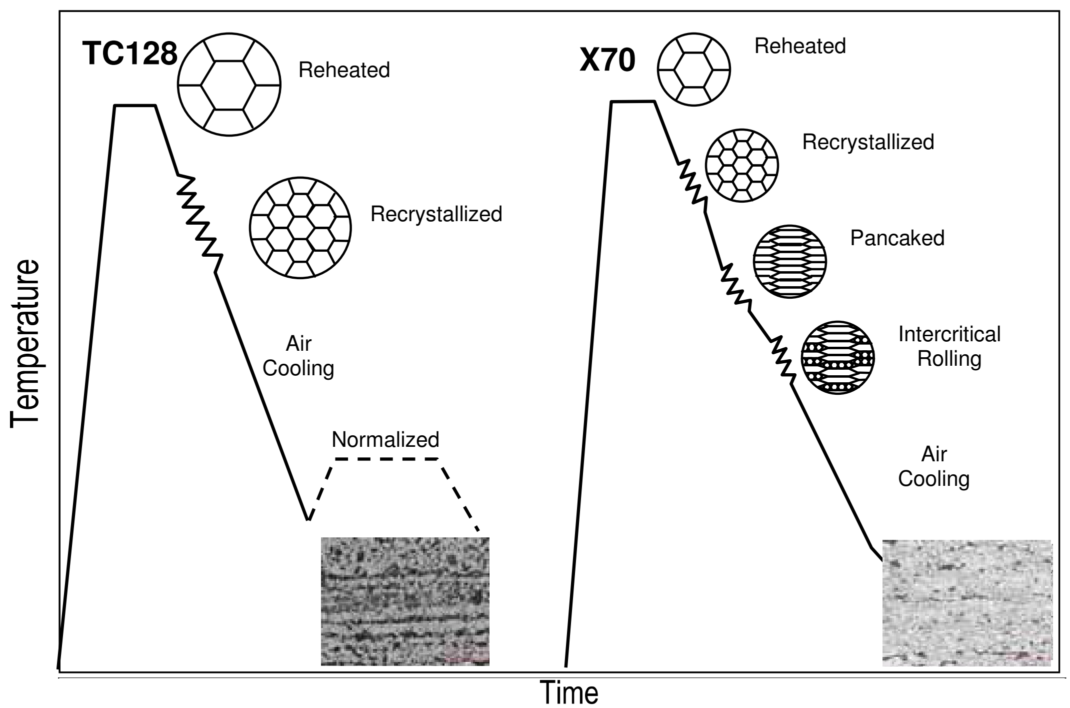


Figure 1 Schematic diagram comparing hot rolling + normalizing vs. severe control rolling into the ferrite-austenite region

Weldments

In the initial phase of the program, six wire/flux combinations were used to double-submerged arc weld (SAW) the two grades of plates (TC128-B and X-70) to themselves. These wire/flux combinations are described as combinations A, B, C, D, E and F. The AWS class and general wires chemistries and flux characteristics are as follows:

A. AWS-ENi5 wire and agglomerated flux of basicity index 1.6.
B. AWS-ENi5 wire and agglomerated flux of basicity index 3.1.
C. AWS-EG (C-Mn-Mo) wire and agglomerated flux of basicity index 1.3.
D. AWS-EG (2.5% Ni, 0.5% Cr & 0.5% Mo) wire and agglomerated flux of basicity index 2.6.
E. AWS-EM14K wire and agglomerated flux of basicity index 2.9.
F. AWS-ENi5 wire and agglomerated flux of basicity index 2.9.

Consistent with tank car production, the double "V" plate edge preparation shown in Figure 2 was employed for the welds.

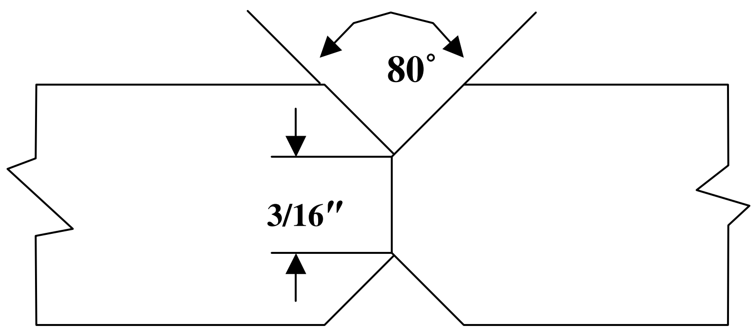


Figure 2 Double "V" plate edge preparation for the welds

As an initial screening study, triplicate CVN testing was conducted at -50°F to determine the weld-metal toughness of these various wire/flux combinations. Based on these tests, wire/flux combinations A and C provided the best weld metal toughness. Interestingly, consumable combination F that had shown good results in the study by Bai, et al. [6] produced poor weld-metal toughness in these two grades. The two best consumable combinations were used to make subsequent weldments at low (32 inches/minute) and high (62 inches/minute) welding speeds. Welding parameters employed at the different speeds are shown in Tables 2 and 3.

Table 2 Welding parameters at low welding speed

Material Thickness	Pass #	Polarity	Wire Diameter	Amperage	Voltage	Travel Speed	Heat Input (KJ/in)
0.510” 0.540"	1	DC+	5/32"	400-425	28	32 ipm	21.0-22.3
		AC	5/32"	550-650	32	32 ipm	33.0-39.0
0.510” 0.540"	2	DC+	5/32"	500-625	28	32 ipm	26.3-32.8
		AC	5/32"	600-650	32-34	32 ipm	36.0-41.4

Table 3 Welding parameters at high welding speed

Material Thickness	Pass #	Remarks	Wire Diameter	Amperage	Voltage	Travel Speed	Heat Input (KJ/in)
0.510” 0.540"	1	DC+	5/32"	400-425	28-31	62 ipm	10.8-12.8
		AC	5/32"	775-910	34-39	62 ipm	25.5-34.3
0.510” 0.540"	2	DC+	5/32"	800-875	32	62 ipm	24.8-27.1
		AC	5/32"	900	39-40	62 ipm	34.0-34.8

Stress Relieving

The welded plates were stress relieved (SR) in accordance with ASME Section VIII [9] requirements for post-weld heat treatment. Specifically, samples were placed in a furnace at 800°F and heated at a rate of 400°F/hr to 1200°F. Samples were held at this temperature for one hour per inch of thickness and allowed to furnace cool at a rate of 500°F/hr to a temperature of 800°F. The samples were then allowed to air cool to ambient temperature. Tank car steels are typically stress relieved in the 1100 to 1200°F range, and 1200°F was chosen to determine if TC128-B properties can be maintained in the weldments for the most severe stress-relief cycle.

Mechanical Property Testing

Mechanical testing of the plate base metal, weld and HAZ was done in accordance with ASTM standard A370 [10]. The material conditions were as-produced and as-welded (AW) for weld and HAZ regions, as well as the base metal, weld and HAZ in the stress-relieved condition. Duplicate longitudinal (L) and transverse (T) tensile tests were conducted in the base metal at room temperature; triplicate LCVN and TCVN testing was conducted in the base metal. In addition, triplicate CVN tests were conducted in weld and HAZ regions. CVN test temperatures were 72, 32, 0, -30, -50, and –76°F.

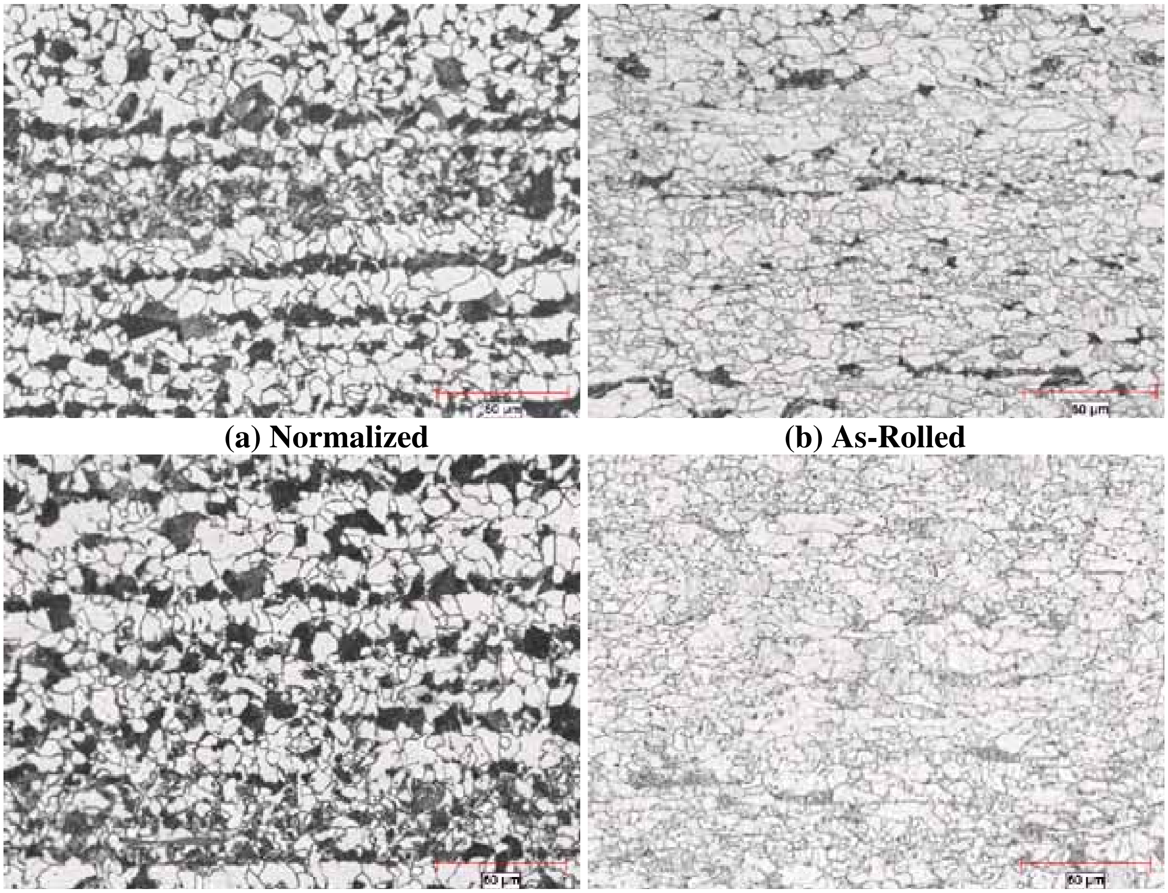
Metallography

The base metal and weld samples were polished using standard techniques, etched with nital, and viewed in both light and scanning electron microscopes (SEM). CVN fractures were also examined in the SEM. Limited transmission electron microscopy (TEM) of carbon extraction replicas was conducted on selected weld metal samples.

Results and Discussion

Base Plate Properties and Microstructure

Microstructures of both plates in the as-produced (N and AR) and stress-relieved conditions are compared in Figure 3. As expected, the normalized plate (Fig. 3a) consists of a ferrite-pearlite microstructure. As is typical for such structures, there is some banding of the pearlite. As shown in Figure 3b, the X-70 steel also consists of a ferrite-pearlite microstructure, with less pearlite due to its lower carbon content. Stress relieving has little noticeable effect on the microstructures shown by light microscopy, with the exception of the pearlite beginning to show signs of spheroidization (Figs. 3c & d).



(a) Normalized **(b) As-Rolled**

(c) N + SR **(d) AR + SR**

Figure 3 Comparison of TC128-B(left side) and X-70 (right side) microstructures in the as-produced and stress-relieved conditions.

The average tensile properties of plates in the as-produced and stress-relieved conditions are summarized in Table 4. In all cases, the plates meet the corresponding requirements of TC128-B and A841-Grade F-Class 6. Note that the tensile properties are very similar in the longitudinal and transverse orientations in both the as-produced and stress relieved conditions, i.e., there is minimal anisotropy in tensile properties. The near isotropic tensile properties of the IPSCO TC128-B plate product is reassuring, considering the significant anisotropy of tensile properties experienced in competitive product studied by Hicho and Harne [11]. Stress relieving of both steels leads to a 3 to 7 ksi drop in both yield and tensile strength and a 2 to 3% increase in elongation. The loss in strength for TC128-B is attributed to partial spheroidization of pearlite. In contrast, the loss in the strength of the X-70 steel is possibly due to recovery of the deformed ferrite and/or coarsening of the Nb,V(C,N) particles. In both conditions, the X-70 product is at least 10 ksi higher in yield strength compared to TC128-B.

CVN absorbed energies in the various conditions are summarized in Table 5 and graphed as a function of test temperature in Figure 4. Figure 4a compares the CVN energy transition curves in the as-produced condition. As expected, for both steels, the L orientation provides a small increment in toughness over the T orientation. Consistent with prior work [3-6], the X-70 steel

Table 4 Comparison of average base plate tensile properties

Grade	Condition	Orientation	0.2% YS, ksi	UTS, ksi	%Elong. in 2"
TC128-B	N	L	67.8	91.0	32.5
	N	T	66.5	90.9	30.8
	N + SR	L	63.0	84.2	35.0
	N + SR	T	62.2	84.0	34.0
AAR TC128-B			50 min.	81/101	22 min.
X-70	AR	L	77.8	87.2	33.5
	AR	T	78.7	87.9	32.0
	AR + SR	L	72.9	83.0	35.8
	AR + SR	T	75.7	84.3	33.8
ASTM A841-F-Cl. 6			70 min.	82/102	20 min.

Table 5 Comparison of average base plate CVN energies, ft-lbs

Grade	Orientation	Condition	CVN Test Temperature, °F					
			72	32	0	-30	-50	-76
TC128-B	T	N	88	74	55	41	32	34
TC128-B	T	N + SR	120	106	69	63	47	35
TC128-B	L	N	117	108	76	52	53	36
TC128-B	L	N + SR	146	139	105	84	58	40
X70	T	AR	183	188	170	132	122	105
X70	T	AR + SR	186	184	173	138	100	77
X70	L	AR	214	251	214	199	170	121
X70	L	AR + SR	154	178	151	119	86	52

exhibits substantially higher toughness than TC128-B. As shown in Figure 4b, similar trends are evident for the stress-relieved condition, with the exception that the transverse X-70 orientation now exhibits slightly better toughness than in the longitudinal orientation.

Figure 5 displays the effect of stress relieving on the transverse CVN toughness of the two steels. Stress relieving has essentially no effect on the toughness of the X-70 plate. In contrast, stress relieving slightly enhances the toughness of the normalized TC128-B plate. The improved toughness of the TC128-B is attributed to the partial spheroidization of the pearlite during stress relieving. This result is consistent with that of Hicho and Harne [11], but differs from that observed by Bodnar, et al. [2]. The cause for this discrepancy is unclear.

Weld HAZ Properties and Microstructure

Typical weld profiles are shown in Figure 6 and average CVN energies in the weld HAZ are compared in Table 6. Note that the welds for the TC128-B weldments run transverse to the

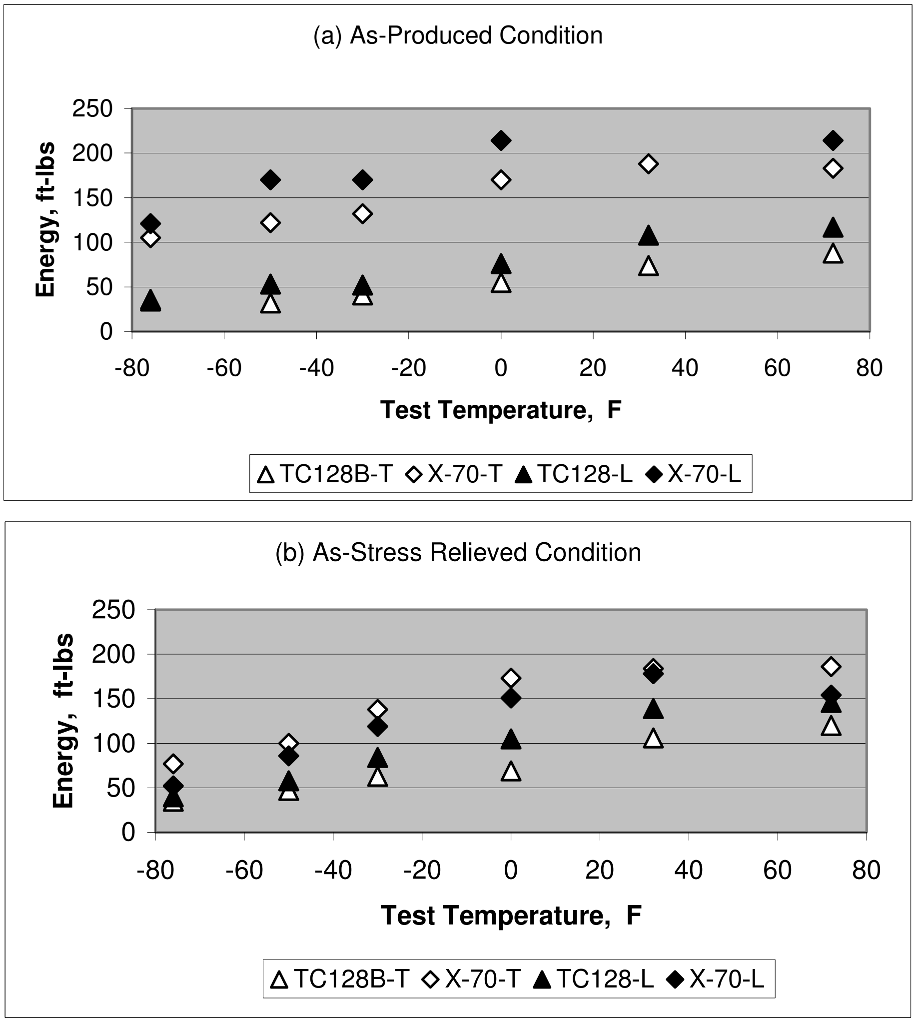


Figure 4 CVN transition curves showing the effect of test specimen orientation in the (a) as-produced and (b) stress relieved conditions

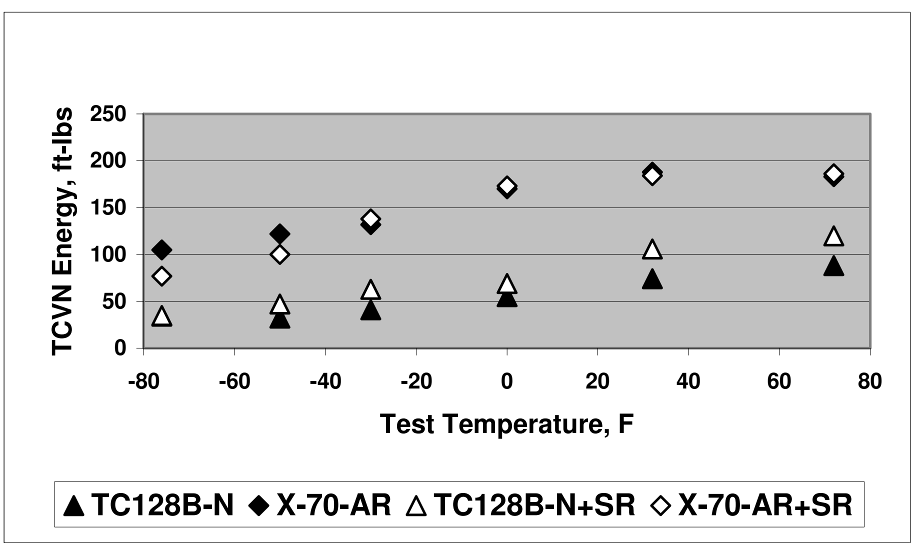
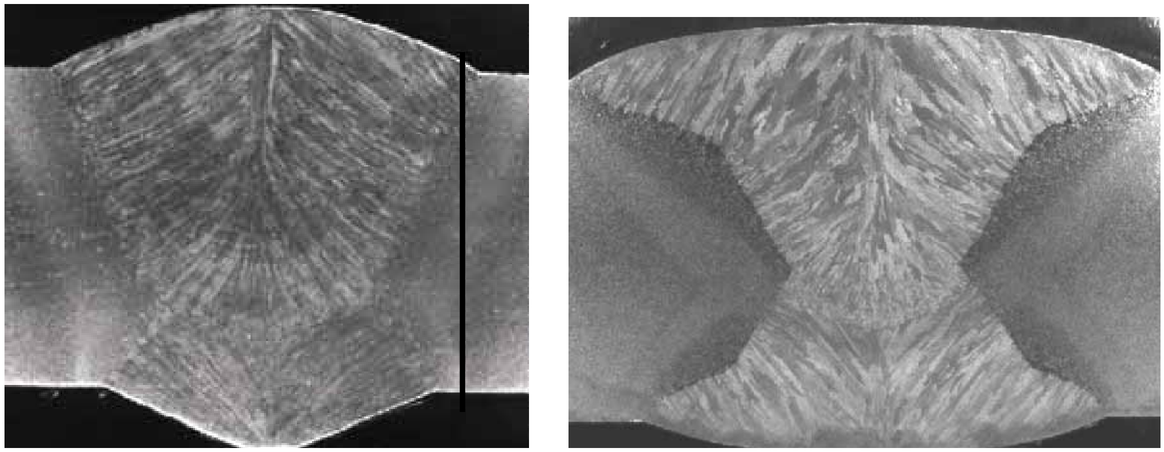


Figure 5 Transverse CVN transition curves showing the effect of stress relieving



(a) TC128-B, Wire/Flux Combination A, 62 ipm *(b) X-70, Wire/Flux Combination C, 32 ipm*

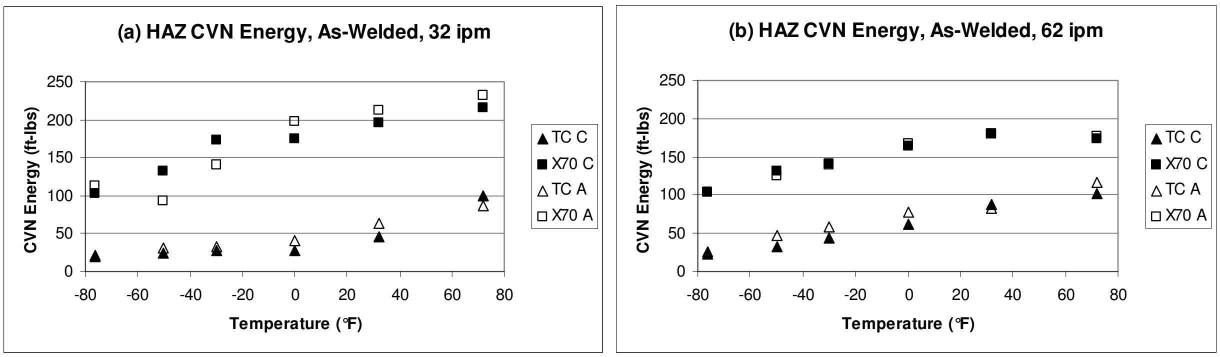
Figure 6 Typical (a) TC128-B and (b) X-70 weld profiles.
Line in (a) shows location of Charpy V-notch for HAZ samples.

Table 6 Comparison of average HAZ CVN energies, ft-lbs

Grade	Wire	Flux	Travel Speed (ipm)	Condition	Test Temperature, °F 72	32	0	-30	-50	-76
X70	LA85	882	32	AW	232	212	197	141	93	113
X70	LA85	882	32	AW + SR	164	169	143	130	95	44
X70	LA85	882	62	AW	177	180	168	140	125	103
X70	LA85	882	62	AW + SR	140	146	111	111	93	63
TC128	LA85	882	32	AW	87	64	42	32	31	21
TC128	LA85	882	32	AW + SR	146	148	106	93	76	83
TC128	LA85	882	62	AW	116	83	78	58	47	25
TC128	LA85	882	62	AW + SR	144	135	86	72	52	48
X70	LA81	995N	32	AW	216	197	175	174	133	102
X70	LA81	995N	32	AW + SR	189	180	107	146	52	86
X70	LA81	995N	62	AW	173	179	165	141	131	104
X70	LA81	995N	62	AW + SR	168	150	164	119	121	77
TC128	LA81	995N	32	AW	100	46	28	28	24	19
TC128	LA81	995N	32	AW + SR	147	147	111	94	80	76
TC128	LA81	995N	62	AW	103	88	61	43	33	23
TC128	LA81	995N	62	AW + SR	144	136	123	81	74	44

rolling direction, and the welds for the X-70 weldments run parallel to the rolling direction. Hence, the HAZ CVN orientations for the TC128-B and X-70 weldments are longitudinal and transverse, respectively. Because both steels are close to isotropic in properties, the difference in weld orientation is not expected to alter the trends in results when comparing conditions. The line in Figure 6a locates the position of the Charpy V-notch. By inspection of Table 6 in comparison with Table 5, the HAZ toughness levels before stress relieving are very similar to those of the as-produced plates. Figure 7 shows for a given grade and travel speed that weld wire/flux combinations A and C provide similar levels of HAZ toughness. Figure 8 shows that for a given weld wire, a higher travel speed (lower heat input) slightly reduces the HAZ toughness of the X-70 steel (presumably due to less recovery of warm-worked ferrite), but slightly increases the toughness of the TC128-B steel (presumably due to less ferrite grain coarsening).

Figure 9 shows that for the wire/flux combination C and a given travel speed, stress relieving results in a slight loss in HAZ toughness for the X-70 steel (presumably due to ferrite grain coarsening), but a significant improvement in toughness for the TC128-B steel (presumably due to partial spheroidization of pearlite). Similar results are obtained with wire/flux combination A.



Figures 7 Effects of grade and weld wire on HAZ toughness for (a) 32 and (b) 62 ipm travel speeds

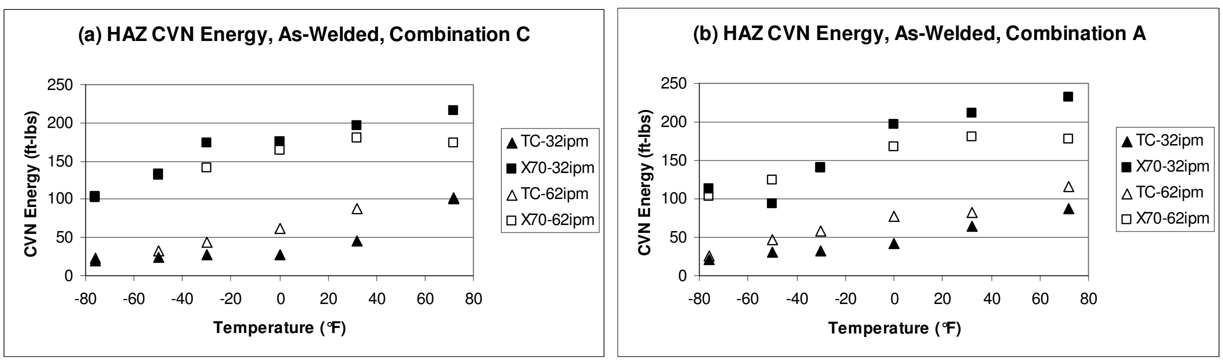
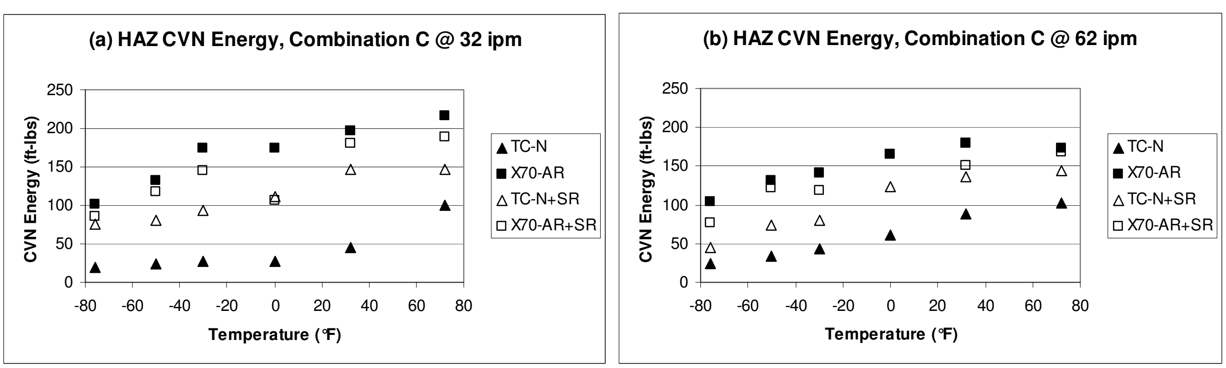


Figure 8 Effects of grade and travel speed on HAZ toughness for (a) Combination C and (b) Combination A



Figures 9 Effects of grade and stress relief on HAZ toughness for Combination C for (a) 32 and (b) 62 ipm travel speeds

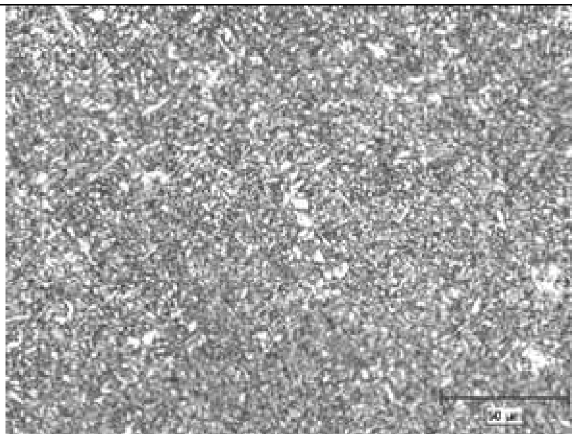
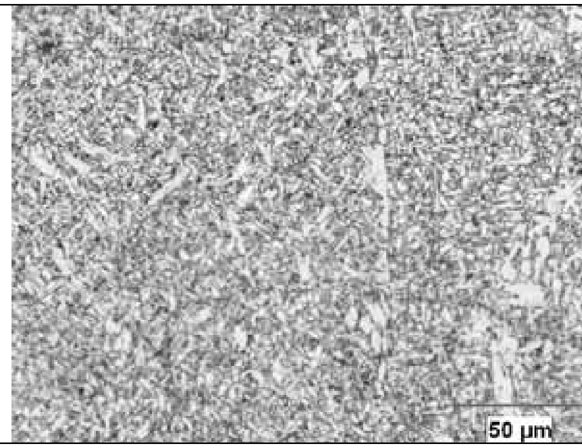
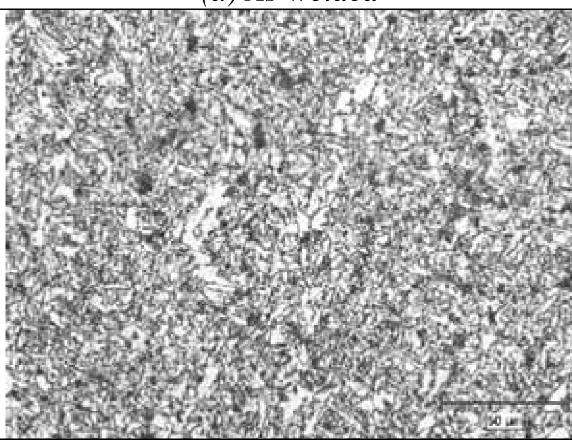
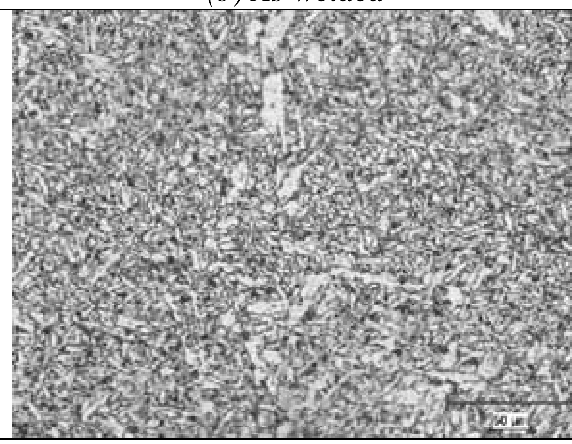
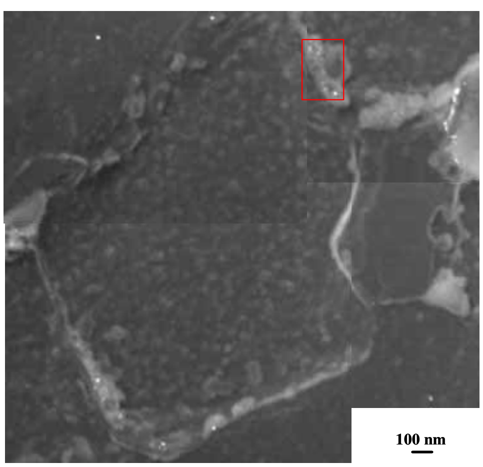
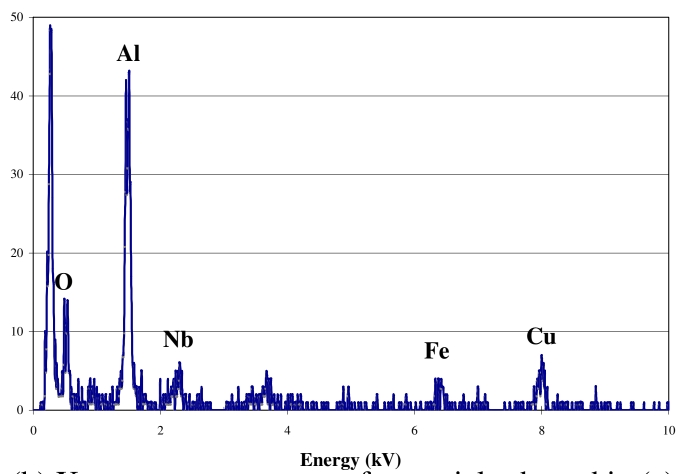
TC128-B	***X-70***
	
(a) As-welded	*(b) As-welded*
	
(c) Stress relieved	*(d) Stress relieved*

Figure 10 Comparison of TC128-B and X-70 microstructures in the (a,b) as-welded and (c,d) stress relieved condition. Combination C and a travel speed of 62 ipm were employed.



(a) Dark-field electron micrograph



(b) X-ray energy spectrum for particles boxed in (a)

Figure 11 Dark-field electron micrograph of replica (a) and X-ray energy spectrum for particles boxed in (a) for X-70 weld with wire/flux combination C and travel speed of 62 ipm

Weld Properties and Microstructure

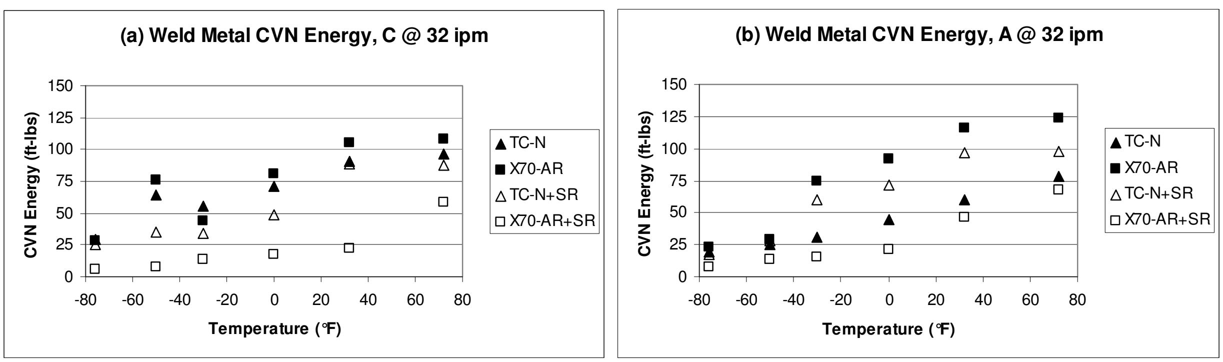
Representative photomicrographs of wire/flux combination C weld metal before and after stress relieving for the two steels welded at 62 ipm are compared in Figure 10. In both cases, the microstructures consist of fine acicular ferrite and veins of grain boundary ferrite. Examination of the microstructures in the SEM at higher magnification confirmed this and revealed no significant differences between the two conditions. Examination of carbon extraction replicas in the TEM in the as-welded condition identified some inclusions containing Mn, Al, Si, Ti, and O, as well as a few relatively large (Ti,Nb)N particles. In the stress-relieved condition, similar particles were observed. Also, fine Nb(C,N) [or possibly Nb,V(C,N)] particles < 50 nm in size were observed after stress relieving (Figure 11); some of these fine particles appear as white specks in the dark-field micrograph in Figure 11a. Based on the x-ray spectrum in Figure 11b, the boxed area in Figure 11a also includes an AlN particle.

Average weld metal CVN properties are compared in Table 7. Figures 12 and 13 show the effect of stress relieving for the various combinations of welding wire and travel speed. In the case of TC128-B weldments with welding wire/flux combination C and travel speeds of either 32 or 62 ipm, stress relieving reduces the toughness (Figs. 12a and 13a). On the other hand, with welding wire/flux combination A and travel speeds of 32 or 62 ipm, stress relieving improves the toughness of TC128-B weldments (Figs 12b and 13b). The reason for this improvement is unclear. In contrast, the toughness of all X-70 weldments, regardless of welding parameters, deteriorates significantly when stress relieved (Figs. 12 and 13). In all cases, weld-metal hardness increases significantly on stress relieving. For example, the maximum hardness of the weld metal with wire/flux combination C increased from 236 to 271 HV and 217 to 250 HV for the X-70 and TC128-B weldments, respectively. These increases in hardness are attributed to precipitation strengthening during the stress-relief cycle, assumed to be a result of some microalloy element pickup from the base metal. In the case of X-70 and TC128-B welds, the particles precipitating are possibly Nb,V(C,N) and V(C,N), respectively. Evidence of the Nb-rich carbonitride particles in the X-70 weld metal has already been provided in Figure 11. Presumably, this precipitation strengthening leads to a deterioration in toughness. SEM examination of broken CVN weld-metal specimens revealed a greater propensity for cleavage fracture after stress relieving, consistent with embrittlement due to precipitation. The greater reduction in weld-metal toughness of the X-70 weldments on stress relieving is attributed to a greater precipitation strengthening increment, i.e., higher maximum hardness.

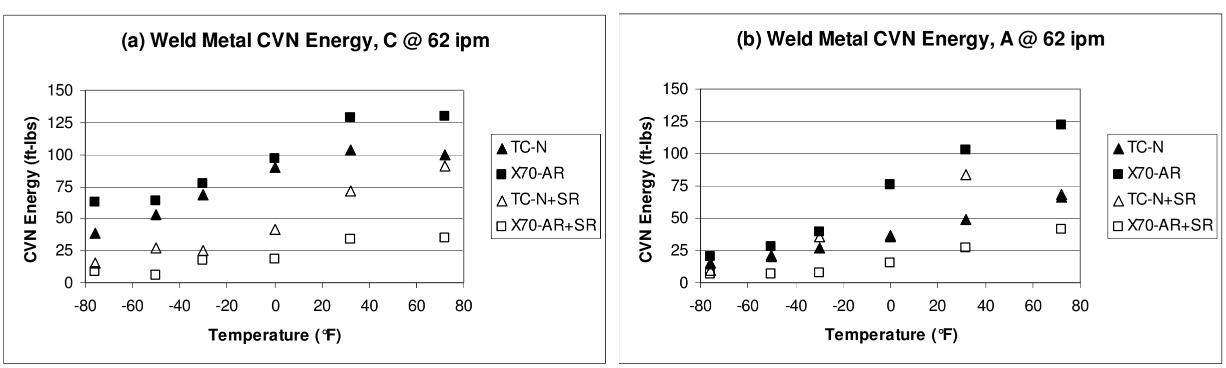
As shown for wire/flux combination C in Figure 14a, weld metal toughness in the as-welded condition is generally similar for all grade and travel speed combinations. In contrast, Figure 14b shows that after stress relieving, the TC128-B weld metal exhibits better toughness than X-70 weld metal at both speeds. Again, this is most likely attributed to embrittlement due to Nb(C,N) or Nb,V(C,N) precipitation strengthening during stress relieving. The weld metal toughness of the stress relieved X-70 steel weldments prepared in the present study is not as good as that achieved by Bai, et al. [6] with a Mo-Nb-Ti X-70 steel. The plate edge preparation employed in the welds of Bai, et al. consisted of a single "V" bevel compared to the double "V" bevel shown in Figure 2. It is possible that this difference in edge preparation may have resulted in less Nb pickup from the base metal, and hence less precipitation strengthening on stress relieving in the study of Bai, et al. [6].

Table 7 Comparison of average weld metal CVN energies, ft-lbs

Grade	Wire	Flux	Travel Speed (ipm)	Condition	Test Temperature, °F					
					72	32	0	-30	-50	-76
X70	LA85	882	32	AW	124	116	92	74	29	23
X70	LA85	882	32	AW + SR	67	47	21	16	14	7
X70	LA85	882	62	AW	122	103	76	39	28	20
X70	LA85	882	62	AW + SR	41	27	15	8	6	7
TC128-B	LA85	882	32	AW	79	60	45	31	25	19
TC128-B	LA85	882	32	AW + SR	98	97	72	60	28	18
TC128-B	LA85	882	62	AW	66	49	35	27	21	15
TC128-B	LA85	882	62	AW + SR	68	83	36	36	20	9
X70	LA81	995N	32	AW	108	105	81	44	76	29
X70	LA81	995N	32	AW + SR	58	23	18	14	8	6
X70	LA81	995N	62	AW	130	129	97	77	64	63
X70	LA81	995N	62	AW + SR	35	34	18	17	6	8
TC128-B	LA81	995N	32	AW	96	90	71	56	65	30
TC128-B	LA81	995N	32	AW + SR	88	88	48	34	35	25
TC128-B	LA81	995N	62	AW	100	104	90	69	53	38
TC128-B	LA81	995N	62	AW + SR	91	71	41	25	27	15



Figures 12 Effects of wire type and stress relief on weld metal CVN energy at low travel speed



Figures 13 Effects of wire type and stress relief on weld metal CVN energy at high travel speed

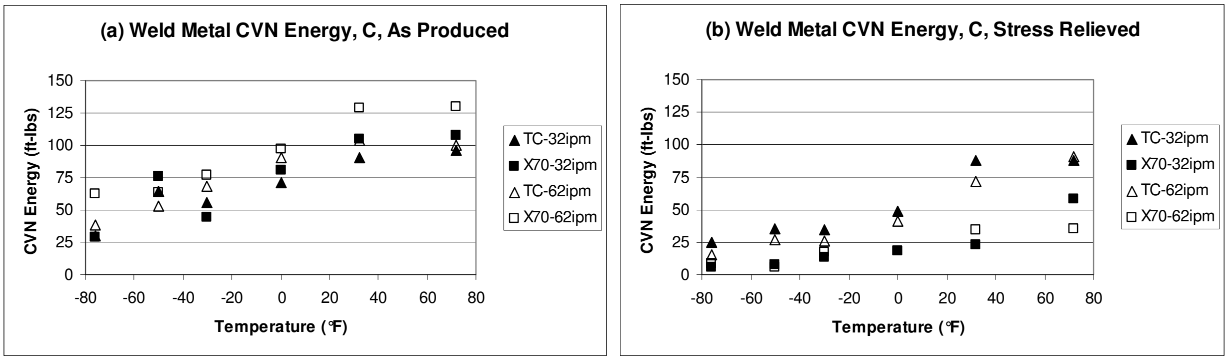


Figure 14 Effect of travel speed using wire/flux combination C in (a) as-produced and (b) stress relieved conditions

Further Discussion of Results

SAW is a common process used in tank car fabrication. It provides the advantages of high deposition rates (high productivity) and process automation. The strength and toughness of the weld depends on the type of microstructure that develops on cooling after welding. Classical studies on the strength and toughness of different microstructural phases have shown that the best combination of properties can be achieved by developing a very fine grain size, without any embrittling second phases [12]. This microstructure can be achieved in weld metals that have high volume fractions of acicular ferrite. The nucleation of fine acicular ferrite, which offers a combination of high strength and toughness, is generally attributed to the presence of finely dispersed oxide inclusions, such as Ti_2O_3, in welds with 0.05% carbon and high hardenability [13-15]. Suppression of the formation of grain boundary ferrite (allotriomorphs) is also important for the production of the desired weld characteristics. Molybdenum has been recognized to suppress allotriomorph formation [16]. In the present study, wires with high manganese and molybdenum contents (1.2 to 1.6% manganese and 0.20 to 0.50% molybdenum) were selected. Consequently, as shown in Figure 10 and confirmed at higher magnification through SEM examination, the resulting weld microstructures were predominantly acicular ferrite.

Stress relieving of the welds made in X-70 plates at 1200°F was found to cause a significant reduction in the weld metal CVN energy, as shown in Table 7, as well as in Figures 12 and 13. Other researchers [4,6] have observed a similar loss of toughness when stress relieving X-70 weld metal, although the toughness loss seen by Bai, et al. [6] for a Mo-Nb-Ti steel was not as severe. The deterioration in weld toughness was not associated with a phase transformation since the stress-relief temperature was below the ferrite-to-austenite start transformation temperature (Ac_1) of 1320°F [17]. The TEM work, shown in Figure 11a for a stress-relieved sample, suggests that the post-weld thermal cycle led to the formation of embrittling Nb-rich carbonitride precipitates. The Nb was presumably picked up by dilution from the base metal. To avoid such embrittlement, it is recommended that X-70 type steel be used in the as-welded condition (without stress relief), similarly to the practice for oil and gas transmission linepipe. IPSCO has been producing X-70 steel and linepipe since 1971. Many hundreds of miles of such pipe have been placed into service in the non-stress-relieved condition and are operating without problems. If the X-70 weldments must be stress relieved, alternative consumables and bevels should be explored to reduce any negative effects related to Nb pickup from the base metal.

Conclusions

- The X-70 type plate, that conforms to ASTM-A841 Grade F-Class 6 and has higher yield strength and CVN toughness compared with TC128-B, maintained its high strength and toughness after stress relieving.

- Both the X-70 and TC128-B plates were remarkably isotropic in mechanical properties.

- Optimal consumables and welding practices have been established for achieving excellent toughness in the HAZ and weld metal from submerged arc welds made from the X-70 steel.

- The CVN toughness of submerged arc welds made with X-70 type steel plates deteriorated significantly after stress relieving.

- While the CVN toughness of submerged arc welds made with TC128-B steel plates using wire/flux combination C deteriorated somewhat with stress relieving, stress relieving improved the CVN toughness of TC128-B welds made with wire/flux combination A.

- The most likely cause for the deterioration in weld-metal toughness on stress relieving is embrittlement attributed to carbonitride precipitation strengthening.

- Unless a suitable wire/flux combination and/or plate edge bevel can be found for welding X-70 type plates, welds of such steel should not be stress relieved for pressurized tank car application. Such a practice of using welds without stress relieving is currently successfully employed in the production of oil and gas transmission linepipe.

Acknowledgments

The contributions of IPSCO employees D. Bai, M. J. Bodnar, L. Collins, J. Dorricott, L. Good, S. Hansen, T. Nelson, J. Russo, and J. Ward were valuable to this study. The TEM work on the weld samples conducted by D. Ivey of the University of Alberta is also gratefully acknowledged.

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