Fe-Mn-Ni-Cu-C Filler Metal Ductile Cast Iron for Welding

With proper control copper can be substituted for Mn and Ni in austenitic weld metal

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ABSTRACT. A practical limit of solubility is established for copper in austenitic Fe-Mn-Ni-Cu-C weld metal, using an equation based upon existing liquid miscibility diagrams and experimental weld cracking behavior. Thermal expansion behavior of the weld metal is also evaluated.

Introduction

Manganese, copper and carbon have been used as alloying substitutes to reduce the nickel content in austenitic welding consumables used in the joining of cast irons, dissimilar metals and other problem welding applications. The substitution of manganese for specific amounts of nickel in Fe-Ni cast iron welding consumables (*i.e.,* Fe-55Ni) has been examined by Davila and Olson (Refs. 1, 2), and favorable results have been reported. They found that alloy compositions in the range of Fe-20Mn-20Ni were very satisfactory in welding ductile irons. Carbon contents had to be adjusted in the consumable for multiple pass welding. A commercial Fe-Ni-Mn welding composition has been introduced and its properties have been recently discussed by Kelly, et al. (Ref. 3). The present study examines the feasibility of further substitution of copper for nickel in austenitic Fe-Mn-Ni-C weld metal. The solubility of copper in austenite and the liquid miscibility of copper in iron are of primary importance in achieving this type of alloy modification.

Experimental Procedure

A series of submerged arc bead-on-plate welds was produced on 32 mm (1¼ in.) thick pearlitic ductile cast iron plates of composition given in Table 1. The weld metal compositions were systematically varied, by powdered metal additions to the flux, to produce a broad matrix of compositions for study. The powdered metal additions of manganese, nickel and copper were introduced into a commercial flux, in the manner of Self, Matlock and Olson (Ref. 4), using a mild steel welding wire (ER70-S3). Fifty-one welds were produced, with resultant compositions listed in Table 2. The silicon content, which was not analytically determined, is estimated to be approximately 0.8 weight percent, based on dilution calculations. Heat input was held constant at approximately 4 kJ/mm (100 kJ/in.).

The welds were sectioned to provide transverse metallographic specimens of all the welds and longitudinal dilatometric specimens of selected welds for thermal expansion determination of the weld metal. The optical metallographic specimens were etched with ten weight percent ammonium persulfate solution to reveal copper-rich phase (light-etching) and iron-rich phase (dark-etching). Average thermal expansion coefficients of weld metal were determined from 20°-550°C (68°-1022°F) using a quartz pushrod type dilatometer, standardized with NBS Standard Reference Material No. 737. Chemical analysis of the weld metal was performed by x-ray spectrometry and combustion carbon analysis.

Results and Discussion

Copper is normally considered (Refs. 5-7) to be deleterious in weld metal when its concentration exceeds approximately one weight percent. However, this limit is for low-alloy steels which are ferritic rather than austenitic. Thorneycroft (Ref. 8) reported the range of hot cracking susceptibility for Fe-Ni-Cu alloys, as seen in Fig. 1. The austenitic weld metals of this study showed tolerances for considerably higher levels of copper, as might be expected of mutual FCC structures.

Typical microstructures for the weld metals of this study are shown for various compositions in Figs. 2-4. Note that the

Table 1—Composition of Ductile Iron Parent Plate (weight percent)

C	Si	Mn	Mg	Cr	Mo	Cu	P	Ni
3.80	2.64	0.60	0.05	0.09	0.09	0.07	0.16	0.08

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light etching copper-rich phase is found in isolated globules within grains and in veins between dendrite boundaries. In several of the welds, the copper veins were observed to be the sites of fissures or hot-cracks (Fig. 3), but the presence of the veins was not always accompanied by the fissures—Fig. 4. Therefore, it appeared that the mere presence of copper in the weld compositions, and the associated segregation of copper phase to the grain boundaries, was not necessarily deleterious at the experimental weld restraint condition used in this investigation.

In order to obtain a relationship to describe the compositional effects upon the hot cracking tendency of Fe-Mn-Ni-Cu-C weld metal, published phase diagrams were consulted. The Fe-Cu-C phase diagram (Ref. 9), as seen in Fig. 5, showed an extensive region of liquid immiscibility bounded by a nearly hyperbolic phase boundary, such that increasing copper or carbon causes the alloy composition to enter into the two-liquid region, and the effect of both elements was greater than equivalent amounts of either. The copper equivalent or tendency for cracking due to copper-rich phase separation was therefore postulated, based on Fig. 5, to be of the form:

$$\mathrm{Cu(eq)} = \mathrm{Cu}\ (\mathrm{C} + \mathrm{constant}), \qquad (1)$$

rather than a simple linear form.

Parravano (Ref. 10) collected extensive data on the solid-liquid equilibria of the Fe-Ni-Mn-Cu system. Through analysis of this data, the influence of nickel to reduce the mushy (liquid plus solid) zone at 10 weight percent manganese (Fig. 6) and at 30 weight percent manganese (Fig. 7) can be seen. It is apparent that below five weight percent copper the solidification range is not very sensitive to variation in nickel and manganese contents. Above ten weight percent copper the nickel and manganese contents must be adjusted to prevent a large solidification range and thus an increased susceptibility to hot cracking.

Ostermann (Ref. 11) reported the liquid miscibility diagram seen in Fig. 8. Manganese is seen to promote miscibility of the liquid state, but only at very high concentration (>30 wt%). In lower manganese concentrations, which are of concern in the current study, Fig. 8 shows manganese, when substituted for iron, to be a mild promoter of liquid immiscibility, for carbon >0.80 weight percent. For compositional ranges of this study, a possible copper equivalent was therefore assumed to be of the form:

$$\mathrm{Cu(eq)} = \mathrm{Cu}\ (\mathrm{C} + k_1) + k_2\ \mathrm{Mn} \qquad (2)$$

where k_1 and k_2 are constants to be determined. The cracking results were plotted using the copper equivalent in Fig. 9. Over 80 percent of the observed cracking behavior was explained with the cracking threshold defined by:

$$\mathrm{Cu(eq)} = [\mathrm{Cu}\ (\mathrm{C} + 1) + 0.5\mathrm{Mn}] > 16 \qquad (3)$$

There is a steelmaker's rule-of-thumb (Ref. 5), which holds that surface cracking from hot-working (a related phenomenon) can be reduced by the addition of approximately one-half as much nickel as copper. Various forms of empirical expressions were evaluated to test this rule with the results from the austenitic weld metal of this investigation. The best empirical fit using the concept that nickel reduces the influence of copper on promoting hot cracking is seen in Fig. 10. Cracking susceptibility was plotted for the weld compositions investigated on a plot of weld metal manganese content versus a copper equivalent expression of the following form:

$$\mathrm{Cu_{eq}} = (\mathrm{C}-0.2)\ (\mathrm{Cu}-0.5\mathrm{Ni}-2) \qquad (4)$$

The degree of fit of the experimental data is equivalent to that found in Fig. 9. Since both Figs. 9 and 10 represent different functional variations for their expression to predict cracking susceptibility, equations 3 and 4 were added together and normalized to give copper a coefficient of one. This result is an equation of

Table 2—Weld Metal Composition and Cracking Behavior

No.	Chemical Analysis Cu	Ni	Mn	C	Copper Equiv. (Eq.6)	Cracking Observed	Coeff. of Thermal Expansion (μm/m°C)
1	0.93	10.60	1.55	1.83	−6.74	#	
2	1.56	8.75	0.76	1.66	−2.63	#	19.96
3	2.49	7.66	1.70	1.68	2.04		20.51
4	1.09	7.42	1.37	2.07	−4.43		
5	6.97	5.21	19.40	0.56	19.52	#	
6	3.78	5.41	21.60	0.53	14.13		
7	0.76	13.00	10.50	1.50	−3.59		
8	1.89	10.90	2.68	1.94	−2.93		
9	1.00	9.59	3.61	1.59	−3.86		20.71
10	4.71	9.38	0.99	1.49	8.57		20.36
11	4.78	13.50	2.57	1.66	7.02		
12	2.83	11.80	3.22	1.43	1.52		20.12
13	1.52	9.96	3.65	1.67	−2.44		
14	0.72	9.98	4.63	1.56	−4.58		
15	5.62	9.34	1.03	1.58	12.15		
16	4.31	9.96	1.90	1.49	7.19		20.97
17	2.87	7.66	2.60	1.72	3.87		
18	2.20	8.14	3.33	1.52	1.50	#	20.52
19	1.64	9.92	5.25	1.46	−0.64		
20	0.53	8.75	5.55	1.59	−4.21		21.23
21	4.96	7.00	0.87	1.46	10.78		20.00
22	5.22	8.08	1.93	1.62	12.05		20.36
23	4.91	9.63	3.24	1.41	9.86		
24	2.98	6.74	3.41	1.57	5.22		
25	3.91	12.70	7.80	1.43	6.58	#	20.77
26	2.02	9.83	7.82	1.33	2.12		
27	0.63	11.10	10.10	1.25	−1.71		
28	10.60	9.11	1.11	0.73	20.06	#	20.36
29	12.20	14.80	3.04	0.40	18.52	#	
30	5.64	6.31	3.10	1.31	13.71		
31	6.45	8.41	5.08	1.34	16.15	#	
32	4.48	4.91	5.47	1.52	12.56		
33	3.68	5.43	8.06	1.27	9.91		21.39
34	1.81	5.93	6.42	1.39	2.96		
35	0.56	9.71	10.10	1.05	−0.24		21.59
36	8.82	4.67	0.90	1.30	23.75	#	
37	10.70	4.93	1.99	1.15	27.92	#	
38	5.51	3.00	2.18	1.39	15.23	#	
39	9.26	6.95	5.50	0.80	20.35	#	
40	8.59	8.37	8.42	0.50	16.75	#	
41	9.21	9.67	13.20	0.30	17.68	#	
42	3.83	5.19	10.10	0.56	9.52	#	
43	2.98	7.57	15.00	0.86	9.42		
44	1.00	5.30	11.10	0.33	4.93		
45	1.03	5.10	23.50	0.73	9.39	#	21.72
46	26.50	7.08	3.97	0.17	34.95	#	
47	10.70	3.11	3.36	0.22	15.41	#	
48	22.00	6.27	8.95	0.44	40.13	#	
49	20.20	6.93	13.70	0.38	37.11	#	
50	13.30	5.02	13.20	0.56	29.25		
51	5.11	3.20	8.99	1.31	16.20	#	

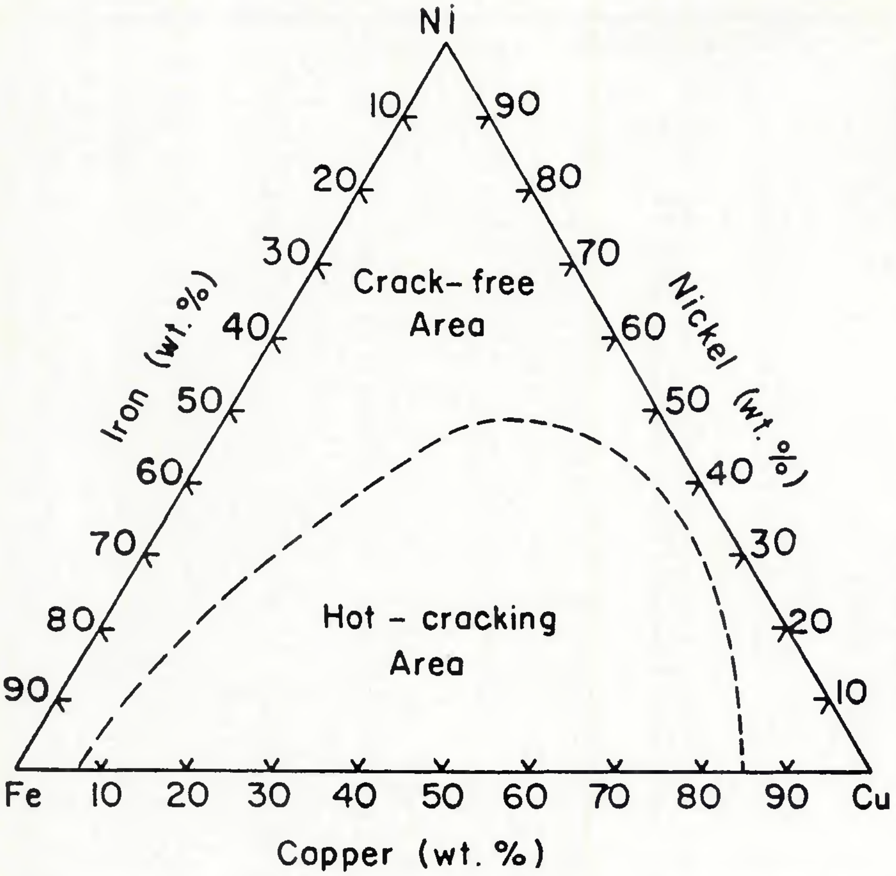

Fig. 1 — The compositional region of hot cracking susceptibility is shown for the Fe-Ni-Cu alloy system

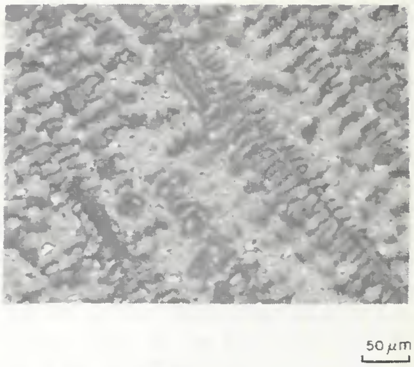

Fig. 2 — The microstructure of Fe-8Mn-5Ni-4Cu-1.3C weld metal. Dark phase is iron-rich austenite and the light regions are copper-rich FCC phase. No cracking observed

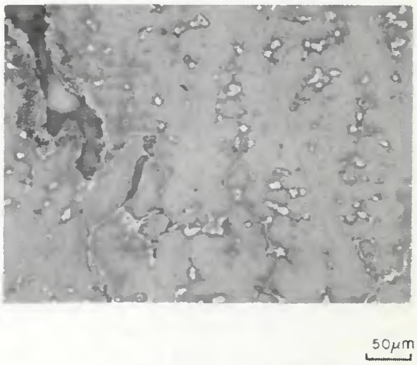

Fig. 3 — The microstructure of Fe-2Mn-5Ni-11Cu-1.2C weld metal. Cracking was observed in the copper-rich dendrite boundary film (light veins)

the following form:

$$Cu + C\,[1.67Cu - 0.42Ni] + 0.42Mn - 1.67C = -0.083Ni + 13 \quad (5)$$

where the copper equivalent can now be defined as:

$$Cu_{eq} = Cu + 0.42C\,[4Cu - Ni] + 0.42Mn - 1.67C \quad (6)$$

This copper equivalent expression is more sensitive to the influence of carbon, nickel and manganese in determining the effect of copper on the cracking susceptibility. Figure 11 illustrates the cracking susceptibility relative to this new copper equivalent. These results suggest that to prevent cracking from the stress state promoted by the welding conditions in the investigation, the copper equivalent must satisfy the following condition:

$$Cu_{eq} = Cu + 0.42C\,[4Cu - Ni] + 0.42Mn - 1.67C \leq 13 \quad (7)$$

In practice, since equation 7 shows strong promotion of cracking by copper

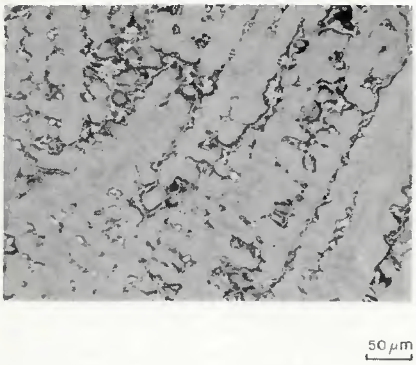

Fig. 4 — The microstructure of Fe-3Mn-8Ni-3Cu-1.7C weld metal. No cracking was observed, despite presence of copper-rich dendrite boundary film

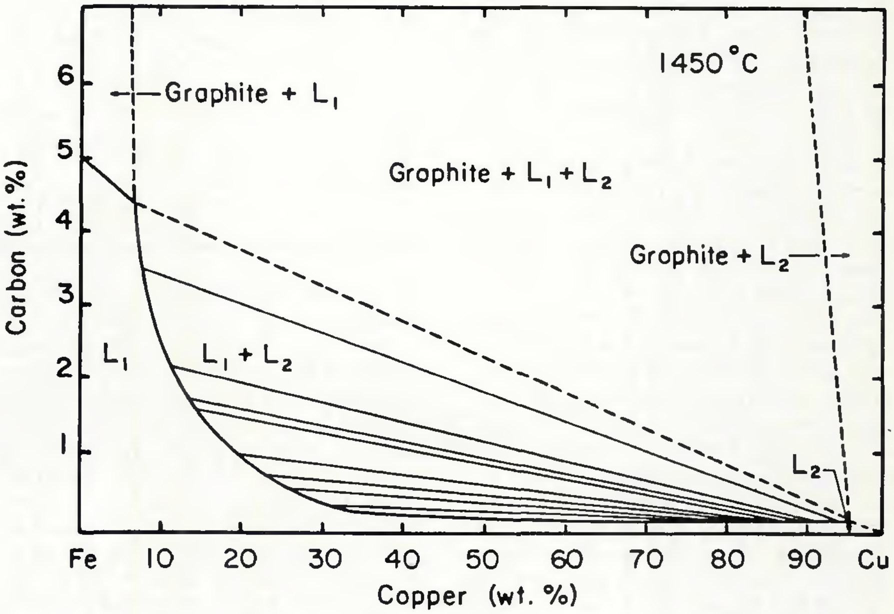

Fig. 5 — Phase equilibrium diagram for the iron-rich alloys of the Fe-Cu-C system at 1450°C

and carbon, and since carbon is present in this investigation only as a product of dilution, it would be prudent to use Fe-Mn-Ni-Cu-C filler metals with a minimum-dilution welding practice (*i.e.*, using a "butter-pass" of a low-carbon filler). The minimization of carbon content by these measures should lower the copper equivalent of the weld metal and reduce cracking.

It must be emphasized that the observed cracking was for simple bead-on-plate welds. Actual weld joints may produce more severe stresses on cooling under different conditions of restraint, but it should be expected that these variations would simply lower the threshold value of copper equivalent for

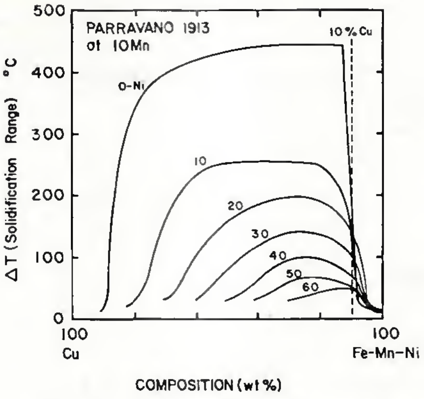

Fig. 6 — The solidification temperature range for Fe-10Mn-Ni-Cu alloys

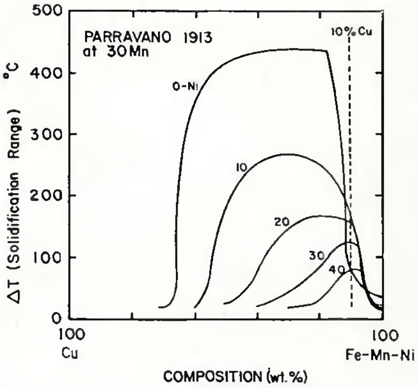

Fig. 7 — The solidification temperature range for Fe-30Mn-Ni-Cu alloys. Notice that nickel decreases the mushy zone temperature range

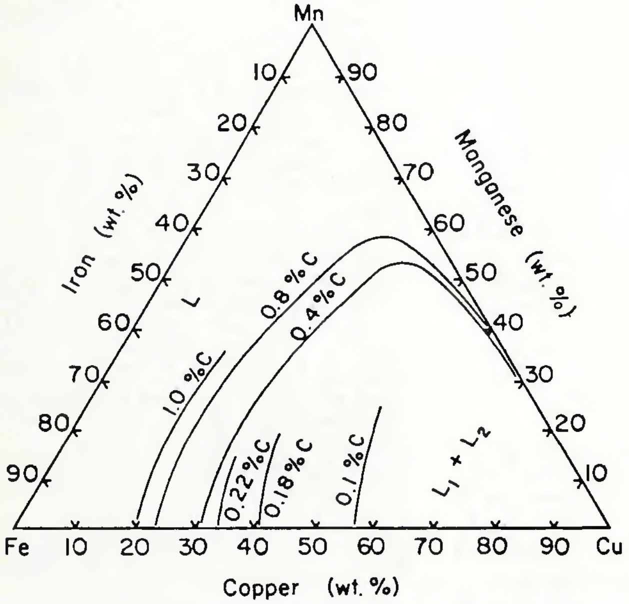

Fig. 8 — The Fe-Mn-Cu-C equilibrium phase diagram indicating the limits of miscibility in the liquid phase as a function of the carbon content

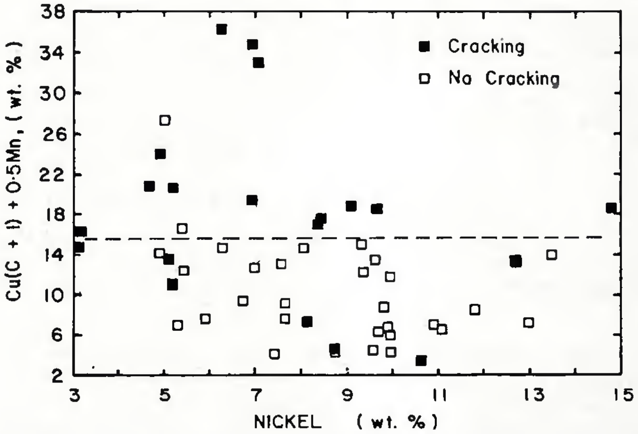

Fig. 9 — Cracking susceptibility as function of a copper equivalent expression, Cu (C + 1) + 0.5Mn, and nickel. This copper equivalent expression is based on the copper-carbon relationship suggested in Fig. 5 and the influence of manganese suggested in Fig. 8

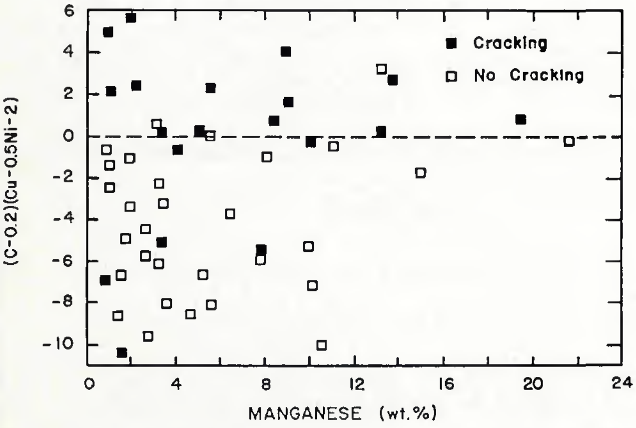

Fig. 10 — Cracking susceptibility as a function of copper equivalent expression (C−0.2) (Cu−0.5Ni−2), and manganese. This copper equivalent expression is based on the suggestions of the steelmakers' rule that nickel additions reduce the detrimental effects of copper

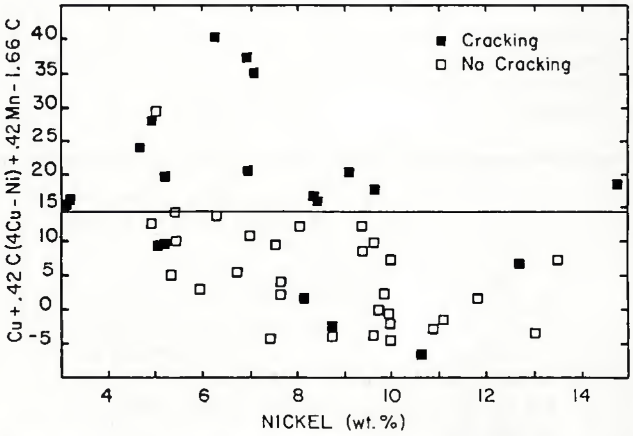

Fig. 11 — Cracking susceptibility as a function of copper equivalent expression, Cu + 0.42C (4Cu−Ni) + 0.42Mn−1.67C, and nickel. This copper expression considers the assumptions used in both Figs. 9 and 10

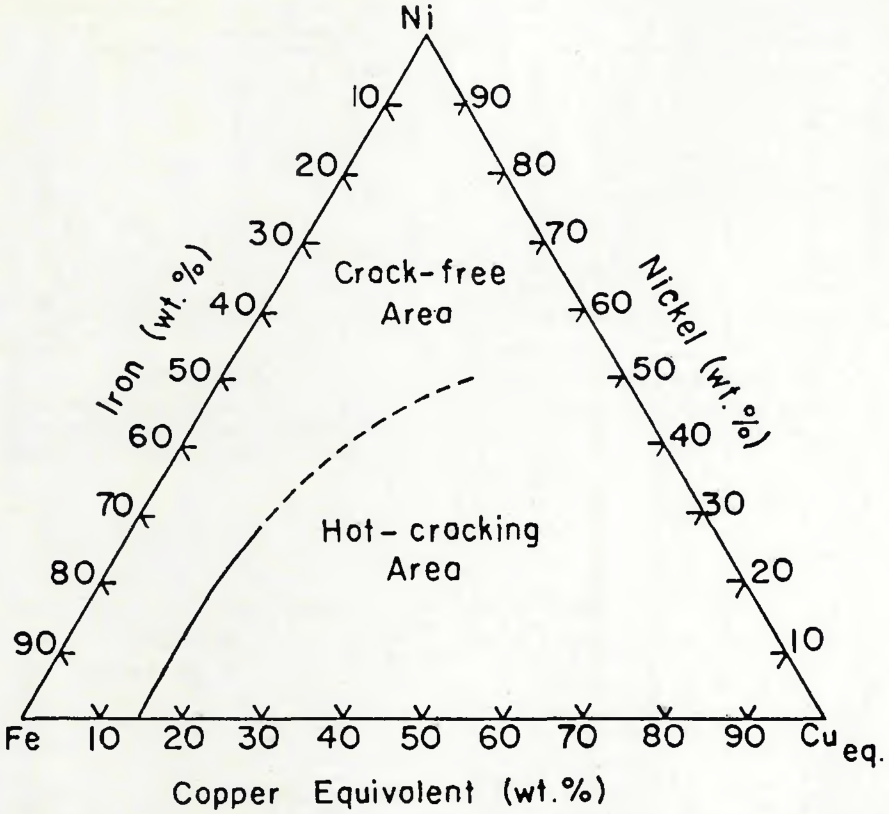

Fig. 12 — A "Thorneycroft type" diagram for cracking susceptibility. Cracking susceptibility is reported as a function of iron, nickel, and the constitutionally more comprehensive form of the copper equivalent, as suggested in equation 6. Compare this figure with Fig. 1

cracking and that the general form of the equation would still hold.

The boundary line between cracking and non-cracking, as seen in Fig. 11 and described by equation 7, can be plotted on a diagram similar to the results of Thorneycroft — Fig. 1. Figure 12 illustrates such a diagram using the new copper equivalent expression for copper. The copper equivalent expression introduces a quantitative approach to describe the influence of carbon and manganese on crack susceptibility. The influence of nickel at higher concentration is suggested by the broken trend line in Fig. 10. The addition of carbon and manganese to this "Thorneycroft type" diagram is important since nearly all ferrous weldments, in particular cast iron, will introduce these elements to the weld pool.

Dilatometric measurements of selected weld compositions showed minor variations in the 20°-550°C (68°-1022°F) average coefficients of thermal expansion (Table 2), but no large deviations from the high (20 μm/m°C) expansion coefficients of most austenitic metals were observed.

Conclusions

1. Copper may be substituted for manganese and nickel in austenitic weld metal if the copper equivalent (equation 6) is sufficiently minimized.
2. Carbon pick-up from dilution of the cast iron base metal should be minimized by welding procedure because of its influence on the copper equivalent.
3. High thermal expansion of the Fe-Mn-Ni-Cu-C weld metal may necessitate thermal or mechanical (hot-peening) stress relief to avoid cracking in restrained joints.

Acknowledgment

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The AWS Railroad Welding Committee has announced that the Third Railroad Welding Conference will be held at the Hilton Hotel, Chicago, Ill., on September 25-26, 1986.

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