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Influence of Chromium on the Mechanical Properties and Microstructure of Weld Metal from a High-Strength SMA Electrode

Increasing chromium leads to larger proportions of columnar structure in the weld metal at the expense of a refined microstructure

BY E. SURIAN, J. TROTTI, A. CASSANELLI AND L. A. DE VEDIA

ABSTRACT. In the present work, the influence of Cr on mechanical properties and microstructure of weld metal from a high-strength SMA electrode is analyzed by considering 12 experimental low-alloy low-hydrogen iron powder AWS E10018, E11018, E12018-M type covered electrodes. These electrodes were manufactured to obtain in the weld deposits Cr contents ranging from 0 to 1.8%, with two different Mn levels for each Cr content, maintaining the amount of other elements at a fixed value. All-weld-metal specimens and production-type single V-groove welds were mechanically tested in the as-welded and stress-relieved conditions, and a metallographic study was conducted. Chromium was found to be deleterious to toughness with only a minor influence due to Mn variations. A postweld heat treatment led in all cases to a reduction of toughness. Increasing Cr content in the welds produced a higher proportion of acicular ferrite and a general refinement of the microstructure.

Introduction

The investigation described in this paper is part of a long-term study of the influence of alloying elements on the mechanical properties and microstructure of high-strength SMA electrode weld metal. Previous studies on the influence of Mn and C revealed that optimum toughness was achieved with Mn content between 1.0 to 1.4% and C content at the lowest tested level of 0.04%.

In the present work, the influence of chromium is analyzed. Like many other alloying elements, Cr produces solid solution strengthening (Ref. 3), although the possibility of precipitation hardening should not be ruled out (Ref. 4). Evans (Ref. 5) analyzed the effect of Cr on the microstructure and the mechanical properties of C-Mn all-weld-metal deposits, concluding that increasing the Cr content of the welds led to an increase of the yield and tensile strengths coupled with a reduction in toughness in the as-welded and stress-relieved conditions. Chromium additions to the weld metal also reduced the volume fraction of primary ferrite, and although the proportion of acicular ferrite initially increased, it was finally replaced by ferrite with second-phase particles.

Now, the influence of Cr was studied by considering 12 experimental low-alloy low-hydrogen iron powder AWS E10018, E11018 and E12018-M type covered electrodes, which were designed to obtain weld deposits with Cr in the range of 0 to 1.8%. The electrodes had two different Mn levels: 1.0 and 1.4%, for each Cr content. The amounts of the other elements were maintained at a fixed value. The electrodes were em-

KEY WORDS

E10018, E11018,
E12018-M
SMAW Electrode
Chromium Content
Alloying Element
Chemical Composition
Mechanical Properties
Microstructure
Postweld Heat Treat.
Single V-Groove Weld
Multipass Welds

E. SURIAN and J. TROTTI are with Conarco Alambres y Soldaduras S.A., Buenos Aires, Argentina. A. CASSANELLI is with Intema, Buenos Aires, Argentina. L. A. De VEDIA is with Fundacion Latinoameriacana de Soldadura, Buenos Aires, Argentina.

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Table 1 — Test Welding Procedures

Weld Preparation	Electrode Diam. mm	Pass	Interpass °C	Current A	Voltage V	Heat Input kJ/mm
ISO 2560	4	1-last	107	170	24	2.1
Single-V joint 70 deg	4	Backing	250	160	22	1.2
		Rest	250	170	23	1.2

Table 2 — Base Metal Composition in Production Single V-Groove Weld

Element (%)				
C	Mn	Si	P	S
0.08–0.115	0.34–0.62	0.10	0.010–0.015	0.020–0.028

ployed to produce the weld test coupons, out of which the standard all-weld-metal samples and production-type single V-groove welds necessary to carry out the study were obtained.

Experimental Procedure

Electrodes

Twelve experimental low-alloy low-hydrogen iron powder AWS E10018, E11018 and E12018-M electrodes were designed with varying Cr powder content in the coatings to obtain all-weld-metal variations of 0 to 1.8% Cr, with Mn contents of 1.0% and 1.4%.

The electrode diameter was 4 mm (0.16 in.), and the coating factor (D/d) was 1.65. Before welding, the electrodes were redried at 400°C (752°F) for 90 min.

Weld Preparation

Two sets of all-weld-metal samples according to ISO 2560-73 were made with each electrode in the flat position. The typical welding parameters used are shown in Table 1. One of the mentioned sets was tested in the as-welded condition and the other after a postweld heat treatment of 1 h at 620°C (1148°F).

Mechanical Testing

One subsize all-weld-metal tensile specimen (Ref. 6) was machined and tested for each of the different deposits at room temperature. Also, a cross-section for metallographic studies and enough Charpy V-notch specimens to construct transition curves between –100° to 20°C (–148° to 68°F) were obtained from each weld deposit.

Metallography

A metallographic study and a hardness survey were carried out on the cross-section of each of the all-weld-metal ISO test coupons. The metallographic study was conducted using light microscopy on the top bead, the grain-coarsened and the grain-refined regions of the weld metal, and along a line coincident with the location of the notch of the Charpy V-notch samples.

CTOD Testing

To take into account any possible effect of dilution and/or dynamic strain aging at the root region on fracture toughness of the weld deposits (Ref. 7), production type single V-groove multipass welds were made on a 19-mm (0.75-in.) thick plate with each electrode. Typical welding parameters used in this case are shown in Table 1, and the chemical composition of the base plate is shown in Table 2. Welding was done in the flat position, and the sequence was such that a backing pass was deposited first, and after grinding to sound weld metal from the other.side, the weld was completed. The test panels were clamped to prevent angular distortion during welding. Fracture toughness of the as-welded and stress-relieved production-type single V-groove welds were assessed by means of CTOD testing. For this purpose, full-thickness single-edge-notched three-point bend specimens were ex-

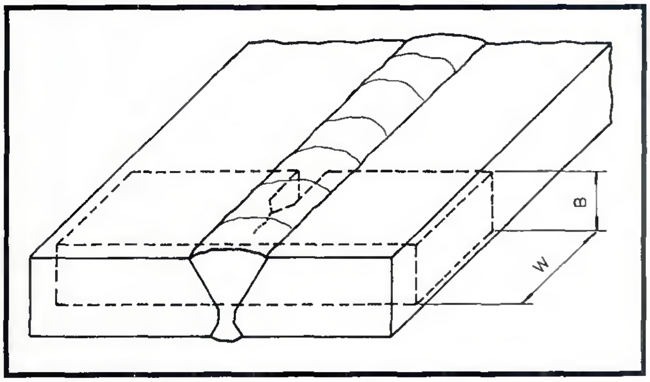

Fig. 1 — Way to obtain CTOD test specimens.

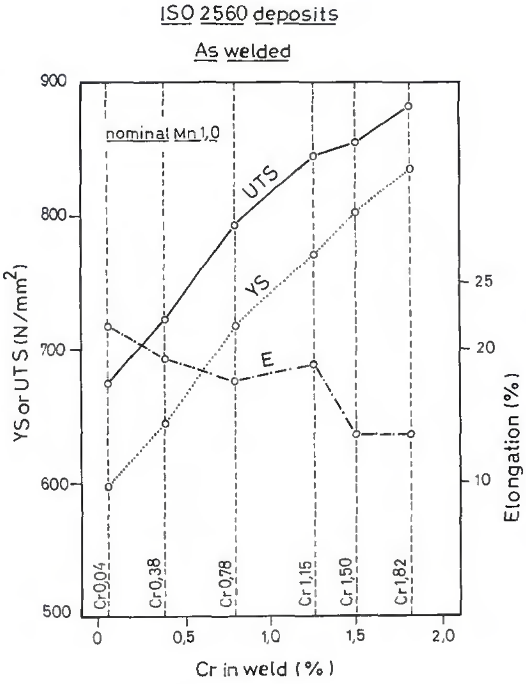

Fig. 2 — Effect of chromium on all-weld-metal tensile tests, nominal Mn 1.0%. As welded.

Table 3 — All-Weld-Metal Chemical Composition, Nominal Mn 1.0

Chromium in Weld (%)	Element (%)										
	P	S	C	Si	Cu	Ni	Cr	Mo	Mn	V	N (ppm)	O (ppm)
0.04	0.014	0.010	0.038	0.36	0.07	2.00	0.04	0.37	1.03	0.01	98	476
0.38	0.014	0.011	0.040	0.35	0.07	1.96	0.38	0.35	1.00	0.01	79	474
0.78	0.014	0.010	0.041	0.35	0.07	1.96	0.78	0.37	1.03	0.01	84	487
1.15	0.015	0.011	0.042	0.38	0.07	1.95	1.15	0.37	1.06	0.01	90	489
1.50	0.014	0.011	0.042	0.40	0.07	1.98	1.50	0.35	1.07	0.01	105	525
1.82	0.014	0.011	0.042	0.38	0.07	1.92	1.82	0.34	1.06	0.01	101	517

Sn, As, Co, Nb, Ti and Al 0.01 maximum.

Table 4 — All-Weld-Metal Chemical Composition, Nominal Mn 1.4

Chromium in weld (%)	Element (%)											
	P	S	C	Si	Cu	Ni	Cr	Mo	Mn	V	N (ppm)	O (ppm)
0.04	0.013	0.010	0.042	0.33	0.065	1.98	0.04	0.37	1.46	0.01	94	472
0.41	0.013	0.010	0.040	0.35	0.065	1.94	0.41	0.36	1.43	0.01	104	459
0.75	0.013	0.010	0.048	0.34	0.065	1.86	0.75	0.34	1.37	0.01	103	470
1.15	0.013	0.010	0.043	0.34	0.065	1.98	1.15	0.38	1.45	0.01	120	462
1.43	0.014	0.011	0.044	0.33	0.065	1.88	1.43	0.36	1.39	0.01	92	486
1.89	0.014	0.011	0.040	0.36	0.065	1.99	1.89	0.38	1.49	0.01	103	472

Sn, As, Co, Nb, Ti and Al 0.01 maximum.

tracted from each weld, with the notch in the through-thickness direction as indicated in Fig. 1. An initiating fatigue precrack, with initial crack depth-to-width ratio of a/w = 0.5, was used in all cases. In order to promote plane strain conditions at the crack tip, 25% side grooving of the specimens was adopted (Ref. 8). Testing was conducted at −10°C (14°F) according to BS 5762:79 (Ref. 9).

Results and Discussion

Chemical Composition

The chemical compositions of the all-weld-metal specimens are presented in Tables 3 and 4. It can be seen that the values for each element are fairly uniform, except for the two levels of Mn (1.0 and 1.4%) and the Cr, which varied systematically from 0.04% to a maximum of about 1.8%. Nitrogen and oxygen contents are within the normal values for these types of electrodes (Refs. 10–11). The observed variations in the values among the different specimens are within the range accepted for this determination (Ref. 12). In general, it can be observed that a "very clean" alloy base is achieved with these electrodes, with residual ele-

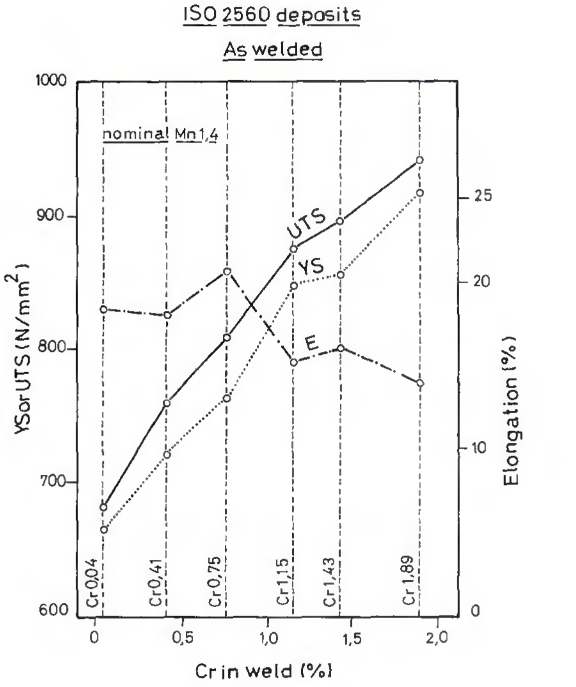

Fig. 3 — Effect of chromium on all-weld-metal tensile tests, nominal Mn 1.4%. As-welded.

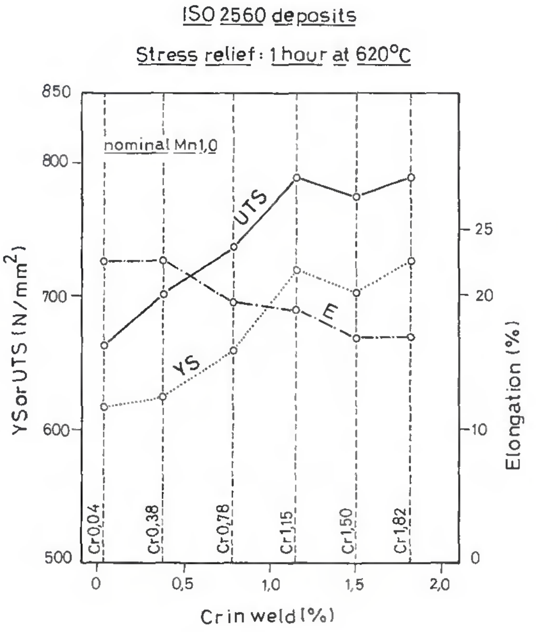

Fig. 4 — Effect of chromium on all-weld-metal tensile tests, nominal Mn 1.0%. Stress relief: 1 h at 620°C.

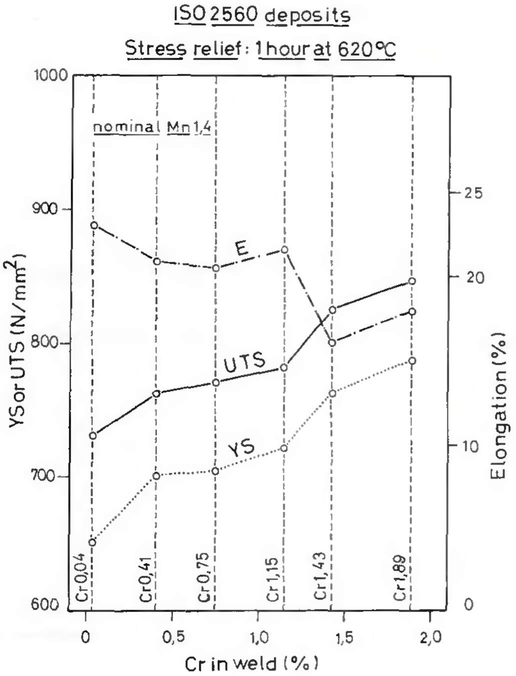

Fig. 5 — Effect of chromium on all-weld-metal tensile tests, nominal Mn 1.4%. Stress relief: 1 h at 620°C.

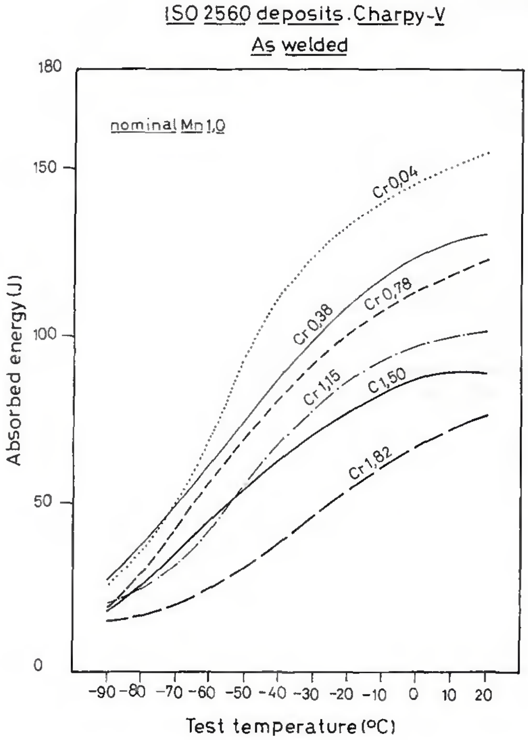

Fig. 6 — All weld metal Charpy V-notch impact test results, nominal Mn 1.0%. As-welded.

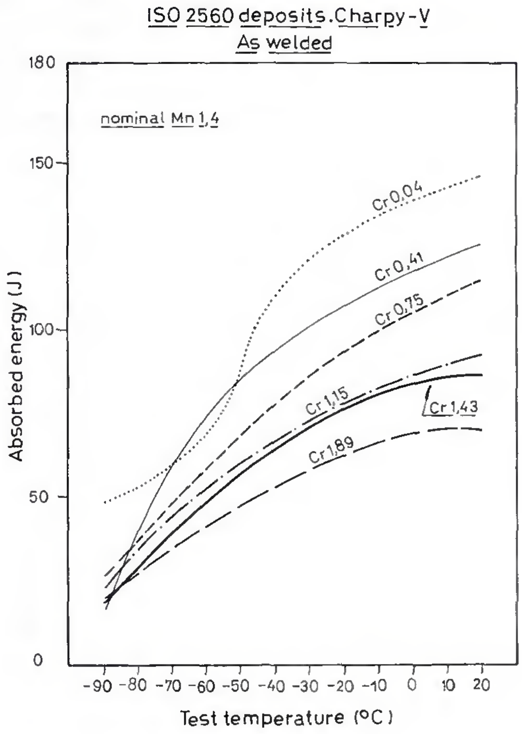

Fig. 7 — All weld metal Charpy V-notch impact test results, nominal Mn 1.4%. As-welded.

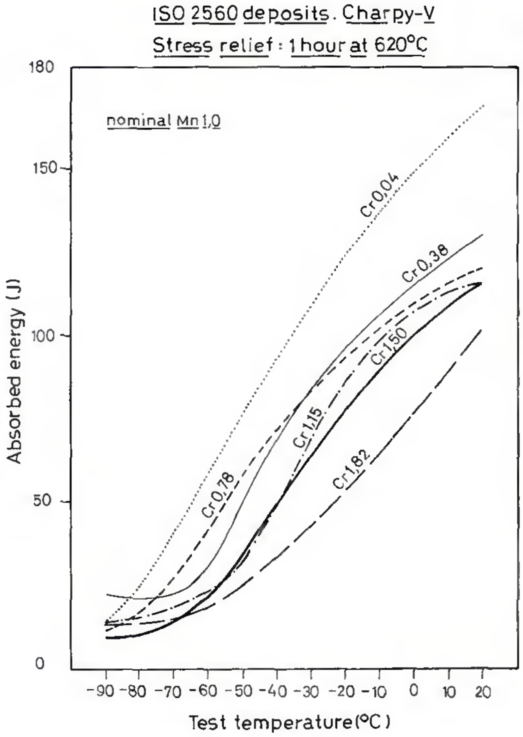

Fig. 8 — All weld metal Charpy V-notch impact test results, nominal Mn 1.0%. Stress relief: 1 h at 620°C.

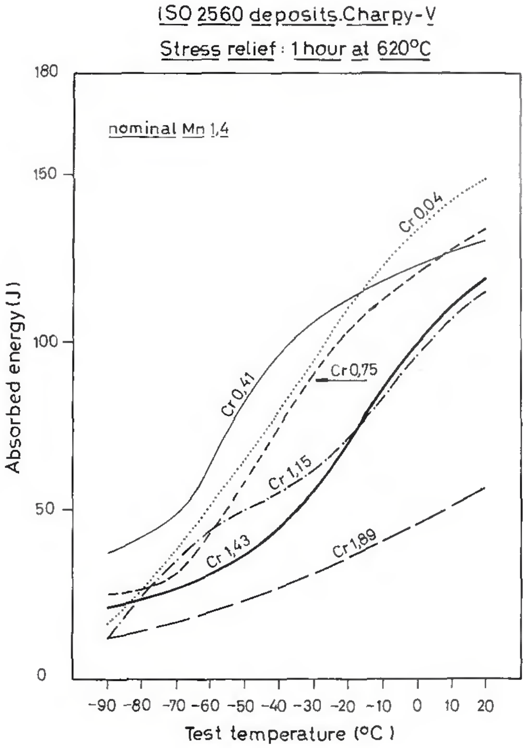

Fig. 9 — *All weld metal Charpy V-notch impact test results, nominal Mn 1.4%. Stress relief: 1 h at 620°C.*

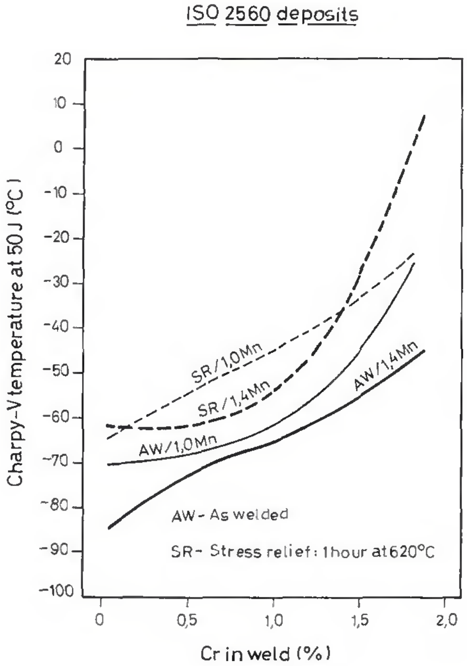

Fig. 10 — *Comparison between the test temperatures corresponding to 50 J of absorbed energy, nominal Mn 1.0 and 1.4%. (As-welded and stress relief: 1 h at 620°C).*

ments being very low. Carbon values are very low too, according to previous results (Ref. 2).

Tensile Properties

The results corresponding to the all-weld-metal tensile tests in the as-welded and stress-relieved conditions are shown in Figs. 2–5. In the as-welded condition there was a consistant increase in yield and tensile strengths with increasing Cr contents. Although the tensile strength did not change significantly when Mn varied from 1.0 to 1.4%, the yield strength showed an increase with Mn for all the Cr values. Elongation was adversely affected by the presence of Cr, particularly when the amount of this element exceeded 1.2%. Stress relief treatment led to a general reduction in tensile and yield strengths, but this reduction was more marked for high Cr levels. On the other hand, elongation was not significantly affected by postweld heat treatment.

Charpy V-Notch Toughness

Charpy V-notch curves corresponding to the all-weld-metal ISO specimens in the as-welded and stress-relieved conditions are shown in Figs. 6–9. It can be observed that increasing Cr content produced in general a systematic reduction in absorbed energy values throughout the entire testing temperature range. The effect of varying Mn content from 1.0 to 1.4% and of stress relieving treatment on the 50-J transition temperatures are presented in Fig. 10, in which it is seen that specimens with 1.4% Mn exhibited marginally lower transition temperatures than specimens with 1.0% Mn. This was true except at the low and high ends of Cr compositions. This is a particularly relevant result from the practical point of view, since Mn acts not only as an alloying element, but also plays a deoxidizing role in the arc environment. This fact, together with the usual variations introduced by electrode manufacturing equipment tolerances, results in Mn content fluctuations in the weld, which are usually larger than those encountered for other elements. The relatively minor influence of Mn variations within the 1.0 –1.4% range on weld metal toughness thus turns out to be beneficial to ensure consistency of mechanical properties.

Stress relief led, in all cases, to an increase of transition temperature. This is in agreement with previous results that showed that Mo is one element that can have a deleterious effect on toughness in welds subjected to a stress relief treatment, due to the precipitation of molybdenum carbides during the heat treatment (Refs. 13, 14).

CTOD Testing

In Figs. 11 and 12, average CTOD test results corresponding to the full thickness specimens extracted from the production-type single V-groove welds are shown, for the as-welded and stress-relieved conditions. In spite of some scatter in the individual results, a general trend toward decreasing CTOD values with increasing Cr content was observed. CTOD testing of stress-relieved specimens was limited for practical reasons to three nominal Cr levels: 0, 0.4 and 1.2%. Critical events corresponded in all cases either to the first attainment of a maximum load plateau (δ_η) or to the onset of unstable crack growth (δ_μ). Postweld heat treatment led in all cases to a reduction in fracture toughness with respect to the corresponding as-welded specimens.

Hardness Results

Figures 13 and 14 present the results of a hardness survey conducted along the central axes of the weld cross-sections before heat treatment. A hardness increase was encountered in the direction of the buildup of the all-weld-metal specimens and as Cr content increases, both in as-welded and stress-relieved conditions.

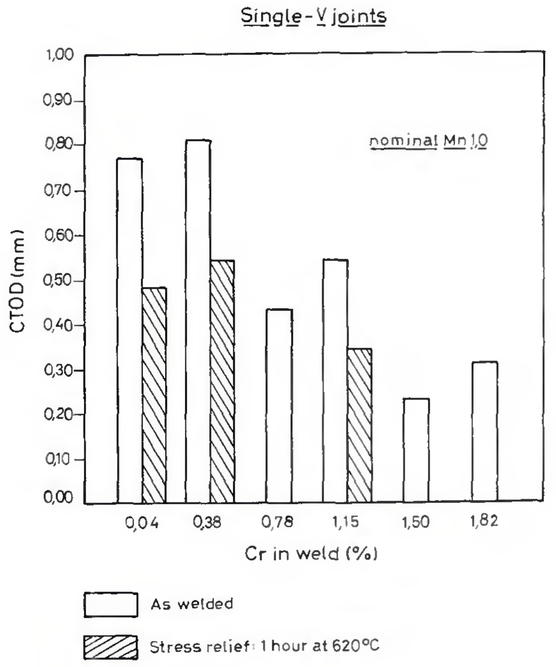

Fig. 11 — Effect of chromium on CTOD values of single V-groove welds, nominal Mn 1.0%. As-welded and stress relief of 1 h at 620°C.

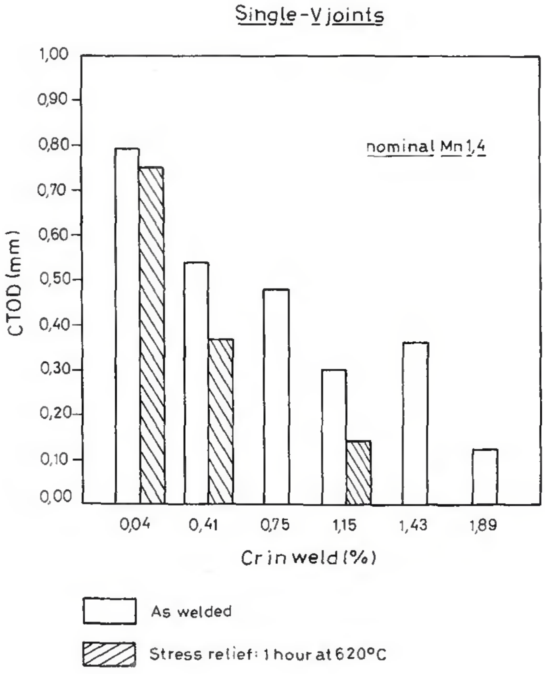

Fig. 12 — Effect of chromium on CTOD values of single V-groove welds, nominal Mn 1.4%. As-welded and stress relief of 1 h at 620°C.

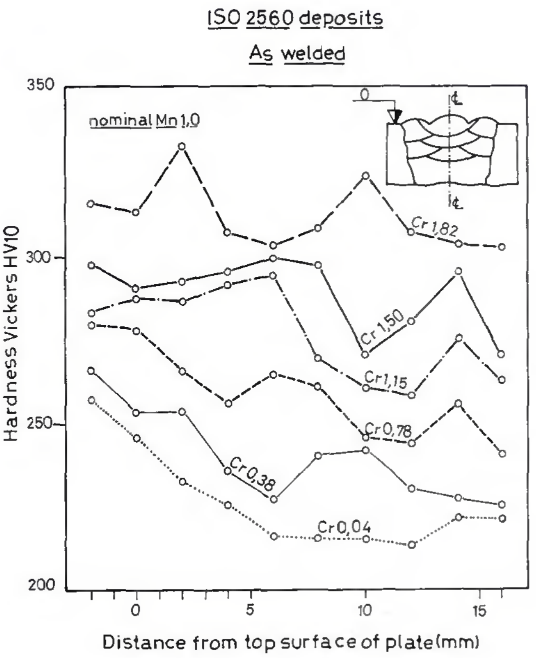

Fig. 13 — Hardness traverses along the vertical centerline, nominal Mn 1.0%. All-weld-metal specimens, as-welded.

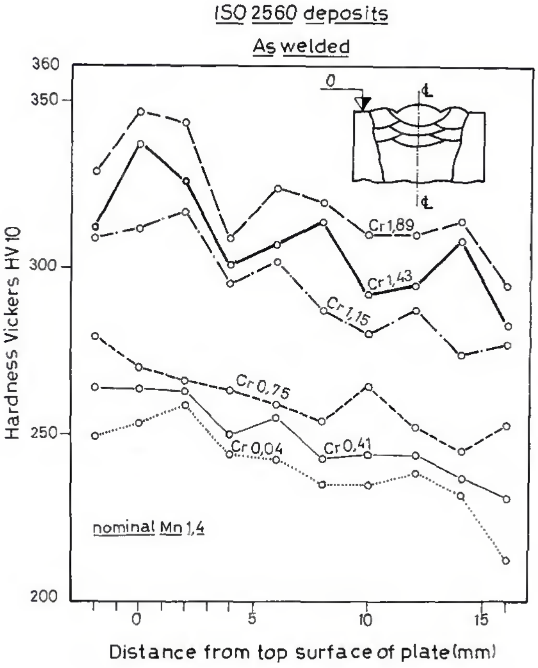

Fig. 14 — Hardness traverses along the vertical centerline, nominal Mn 1.4%. All-weld-metal specimens, as-welded.

Metallographic Study

The influence of Cr on the microstructure of the as-deposited weld metal, for 1.0 and 1.4% Mn levels can be seen in Figs. 15 and 16, which show the results of the quantitative assessment carried out on the top surface of the weld bead of the ISO specimens in the as-welded condition, according to the recommendations of IIW Doc. II-A-389-76 (Ref. 15). In the above-mentioned figures, it is observed that increasing Cr led to a higher proportion of acicular ferrite and to a reduction in grain boundary ferrite. Weld metal containing 1.4% Mn had a larger proportion of acicular ferrite than weld metal with only 1.0% Mn—as could have been expected because Mn is recognized as a promoter of acicular ferrite (Refs. 1, 16). This may account for the somewhat lower transition temperature exhibited by the former. Some small proportion of polygonal ferrite and ferrite with second phase was also present, but the amount of these constituents did not seem to be significantly affected by variations in Mn or in Cr level. Here was found a major departure from the behavior of C-Mn weld deposits as reported by Evans (Ref. 5), who studied the influence of Cr on the microstructure of C-Mn weld metal. He reported that while the proportion of acicular ferrite initially increased with Cr content, it was gradually replaced by ferrite with second-phase particles for higher Cr levels (beyond about 1% Cr). This difference in behavior is due to the presence of Cr in this low-alloy system, along with about 2% Ni and 0.4% Mo. These last two elements depress the transformation temperature range leading to a refinement of the microstructure when sufficient effective ferrite nucleants are present (Ref. 4). However, the presence of Ni alone is not enough to explain the high proportion of acicular ferrite found in the weld metal (Refs. 17, 18), which should thus be ascribed to the combined action of Mo with the other elements (Ref. 14).

Table 5 — Primary Austenitic Grain Size in the Columnar Region of the Top Bead (All-Weld-Metal Specimens)

Nominal Mn	Chromium in Weld	Average Columnar Grain Width
%	%	μm
	0.04	115
	0.38	109
	0.78	104
1.0	1.15	95
	1.50	92
	1.82	90
	0.04	102
	0.41	98
1.4	0.75	93
	1.15	90
	1.43	88
	1.89	87

Table 6 — Relative Size of the Columnar and Refined Regions Corresponding to the Location of the Notch in the Charpy-V Specimens (All-Weld-Metal Specimens)

Nominal Mn	Chromium in Weld	Columnar Regions	Refined Regions
%	%	%	%
	0.04	34	66
	0.38	40	60
	0.78	45	35
1.0	1.15	55	45
	1.50	56	44
	1.82	57	43
	0.04	37	63
	0.41	41	59
	0.75	47	53
1.4	1.15	51	49
	1.43	57	43
	1.89	59	41

Table 5 shows the variation, with Cr, of primary austenitic grain size in the columnar region of the top bead. It was measured in the columnar zone of a transverse cross-section of the ISO specimen through a linear intercept technique, usually satisfactory for determining the grain dimensions. The straight line intercepting the austenite boundaries was approximately at a right angle (Ref. 19). It was found that the width of the columnar grains decreased as the Cr level went up.

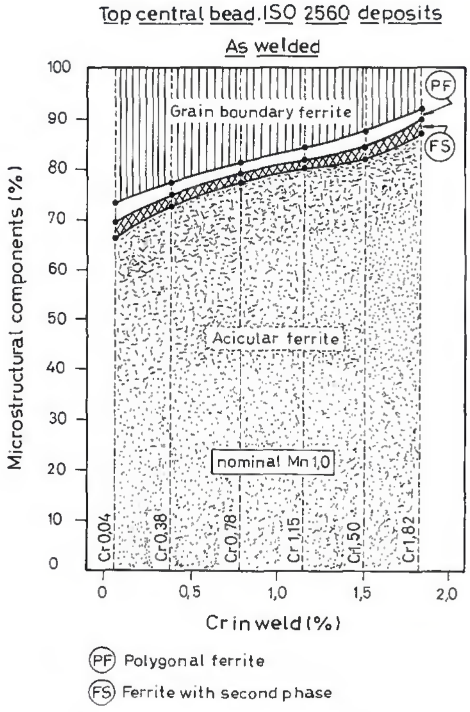

Fig. 15 — Effect of chromium on the microstructure of as-deposited weld metal, nominal Mn 1.0%. As-welded.

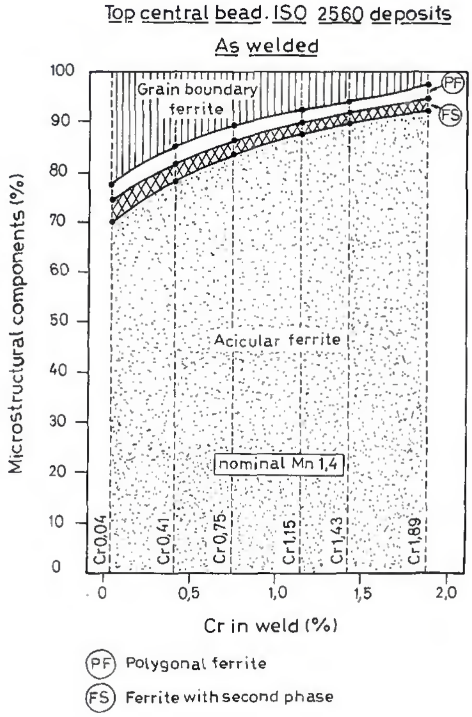

Fig. 16 — Effect of chromium on the microstructure of as-deposited weld metal, nominal Mn 1.4%. As-welded.

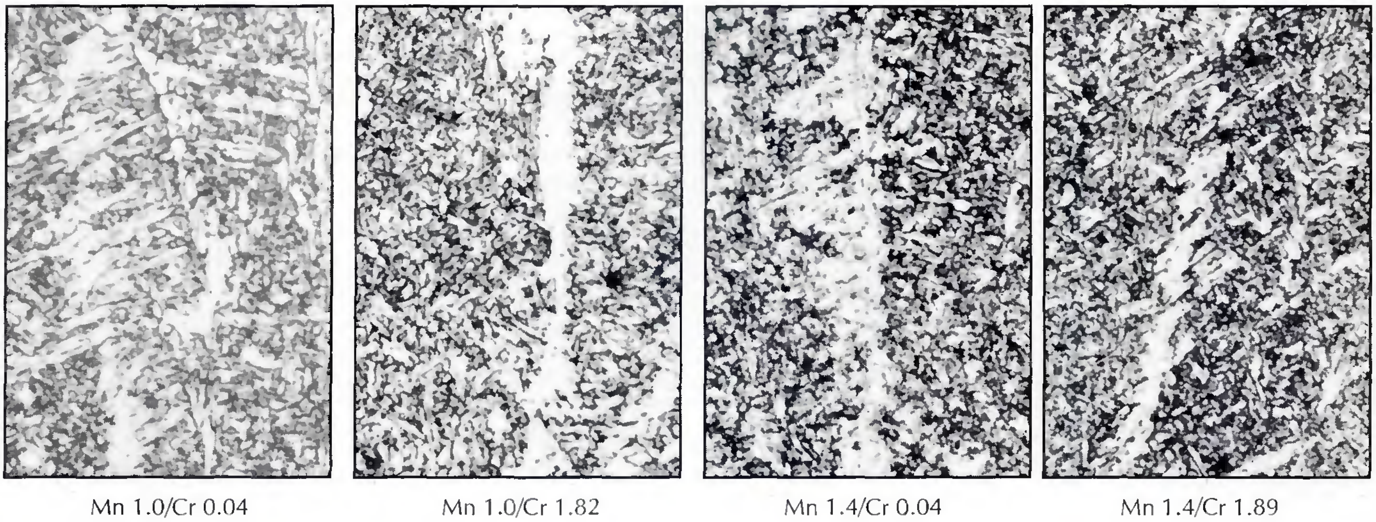

Fig. 17 — All-weld-metal specimen, as-welded. Top central bead, columnar zone. Photomicrographs 500X.

The relative sizes of the columnar and recrystallized regions corresponding to the location of the notch in the Charpy V-notch specimens are presented in Table 6. It was found that Cr additions led to a larger proportion of columnar microstructure at the expense of the refined region, which can be a contributing factor to explain the reduction in toughness observed with increasing Cr.

Figure 17 shows typical microstructures of the columnar region of the weld metal in the as-welded condition, obtained with the light microscope for 0.04 and 1.8% Cr at the two different Mn levels.

Figure 18 shows the corresponding recrystallized weld metal or grain-refined zones. In the columnar grain zone, increasing Cr produced an increase in the proportion of acicular ferrite. In the recrystallized equiaxed zone, it was not possible to distinguish between the grain-coarsened and fine-grained areas. In the grain-refined zones, no significant refinement of the microstructure with increasing Cr was apparent between passes, which may be due to the refining action of Ni and Mo present in the weld metal.

Conclusions

When the Cr content increased in low-alloy low-hydrogen iron powder AWS E10018, E11018 and E12018-M electrode all-weld-metal, the following was found:

1) There was a monotonic increase of yield and tensile strengths for the two levels of Mn studied.

2) Yield strength showed an increase when Mn varied from 1.0 to 1.4%, although tensile strength did not change significantly.

3) Elongation was adversely affected, particularly when Cr exceeded 1.2%.

4) Stress relief led to a reduction in yield and tensile strengths, especially at high Cr levels, but elongation was not affected markedly.

5) Hardness values increased as well with the buildup sequence.

6) A general reduction in the notch toughness of the all-weld-metal samples and in CTOD values of the single V-groove welds was obtained. On the other hand, varying Mn content from 1.0% to 1.4% had a relatively minor influence on weld metal toughness. Stress relief led in all cases to a reduction in Charpy V-notch and CTOD values.

7) There was an increase in the pro-

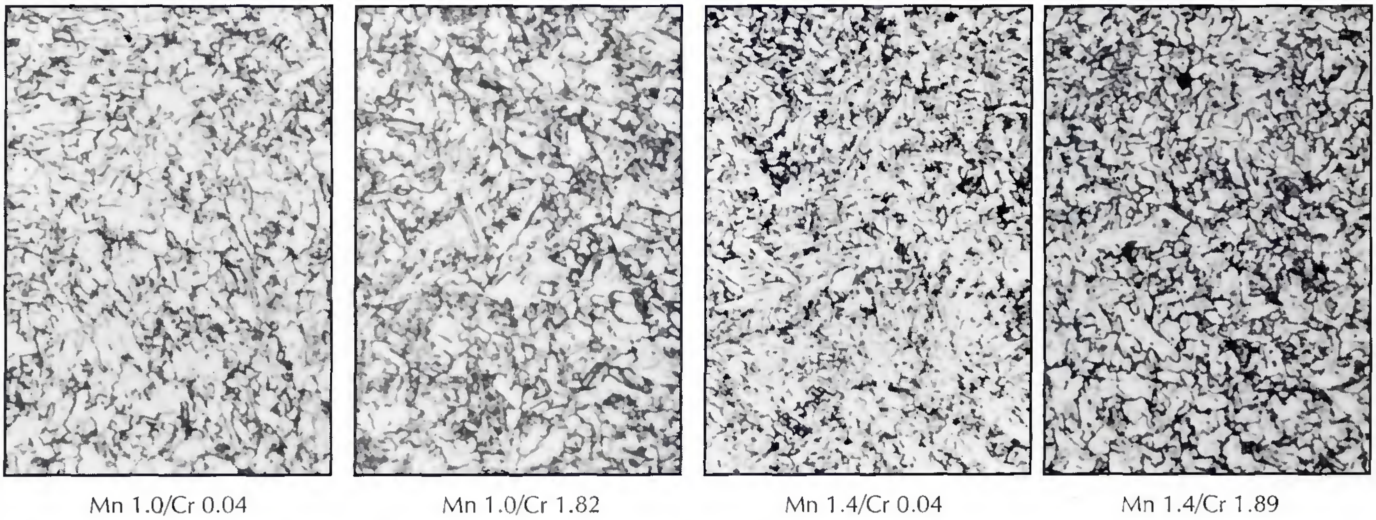

Fig. 18 — All-weld-metal specimen, as-welded. Grain-refined zone. Photomicrographs 500X.

portion of acicular ferrite and a reduction in the amount of grain boundary ferrite in the as-deposited top bead of the ISO specimens. Weld metal with 1.4% Mn had a larger quantity of acicular ferrite than the one with only 1.0% Mn. The amounts of polygonal ferrite and ferrite with second phase did not change significantly. The primary austenitic grain size in the columnar regions of the top bead decreased.

8) There was a larger proportion of columnar region at the expense of the refined zones, in the location of the notch of the Charpy V-notch specimens. This effect could be the cause of the reduction in toughness observed with the increase of Cr, notwithstanding its refining effect on the microstructure.

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