Effect of Oxygen Content on Charpy V-Notch Toughness in 3%Ni Steel SMA Weld Metal

Controlled levels of magnesium in the electrode covering may be an effective means of reducing oxygen content in the weld metal

BY E. S. SURIAN, J. L. TROTTI AND T. BONISZEWSKI

Introduction

Numerous studies of carbon-manganese (C-Mn) and low-alloy steel weld metals, published in the 1980s, indicate that the major factors important in controlling the Charpy V-notch toughness of the weld metal are as follows:

1) *The microstructure of the metal matrix.* Increasing the volume fraction of acicular ferrite in the as-deposited regions is beneficial to toughness.

2) *The nitrogen content.* Increasing nitrogen content is detrimental to toughness.

3) *The oxygen content and the associated size and number of nonmetallic inclusions.* An increase beyond a certain optimum level of 200 to 250 ppm oxygen is detrimental to toughness.

4) *The yield and/or tensile strength.* With the other factors being equal, an increase in strength is detrimental to toughness.

In some cases, the separation of the effects of those individual factors is not easy, and even impossible. For instance, when the Mn content is increased in C-Mn weld metal, factors 1, 3 and 4 change simultaneously (Refs. 1–4). The changes that occur are the volume fraction of acicular ferrite increases, the oxygen content decreases by about 100 ppm as the Mn-content rises between 0.6 to 1.8%Mn, because the Mn is a deoxidant in addition to being an alloying element, and the yield and tensile strengths increase.

With C-Mn and C-Mn-1%Ni weld metals, the nitrogen content is altered either by the type of current (Refs. 3, 5), or the current type and arc voltage (Ref. 6). An increase in the nitrogen content in usually accompanied by: 1) an increase in strength when a change is made from electrode positive DC to AC operation (Ref. 3), and 2) an increase in the weld metal oxygen content as the arc voltage is increased (Ref. 6).

Therefore, it is impossible to separate factor 2 from factors 3 and 4 in their effects on weld metal toughness.

Concurrently, with the studies of the weld metal toughness, there has been great interest in the role of nonmetallic inclusions (oxides) as promoters of acicular ferrite nucleation (Refs. 7–10). However, it is textbook knowledge (Ref. 11) that nonmetallic inclusions, which easily debond from the metal matrix and/or crack under the plastic strain of dislocation pileups, are detrimental to toughness. For fibrous (ductile) fracture, the increasing oxygen/oxide inclusion content has been shown (Ref. 12) to lower the upper energy shelf in the Charpy-V notch transition curve of the weld metal. For cleavage (brittle) fracture, nonmetallic inclusions lying within the plastic zone ahead of the crack tip were found to be active as cleavage initiation sites (Refs. 13, 14). However, the effect of the oxygen/oxide inclusion content on the toughness in the cleavage range has not been demonstrated so far in isolation from factors 1, 2 and 4, listed above.

This demonstration has been attempted in the present work. For this purpose, low-alloy steel weld metal with 3%Ni was used to achieve sufficient hardenability, which would be insensitive to the effect of the inclusion content on the formation of acicular ferrite and grain refinement in general, unlike in the case of C-Mn weld metal. The weld metal was deposited using standard E7016-C2L electrode, but because of the small modification required to change the oxygen content, the weld metal carbon content rose to 0.07%, *i.e.*, above the AWS requirement of 0.05% max.

KEY WORDS

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Inclusions

E. S. SURIAN is Head, Development Department; and J. L. TROTTI is Head, Laboratory of Physical Testings, Conarco S.A., Buenos Aires, Argentina. T. BONISZEWSKI s a private consultant, Kent, U.K.

Experimental Conditions

Electrodes and All-Weld-Metal Deposits

A standard electrode to AWS Classification E7016-C2L, depositing nominally 3½%Ni low-alloy steel weld metal, was used as a vehicle for two experimental variants. The flux covering of this electrode was based on the following major mineral ingredients: 47%$CaCO_3$-17%CaF_2-7%TiO_2-3%K_2TiO_3

Because of the absence of iron-powder in the covering, the electrode was thinly coated, with the linear coating factor (D/d) being 1.58 for the 4-mm (0.16-in.) diameter core wire.

Two variants designated as Batch 3935 and Batch 3939 were produced with identical additions of Ni, Mn and FeSi powders to the flux, but to vary the oxygen content in the weld metal, each variant had a different Mg powder addition, as follows: Batch 3935: 4% Mg; Batch 3939: 6% Mg.

The small difference of 2% in the flux formulation was accommodated by changes in the contents of the two largest ingredients: $CaCO_3$ and CaF_2.

Using 4-mm-diameter electrodes, two separate all-weld-metal assemblies with the joint preparation shown in Fig. 1 were deposited in the flat position ac-

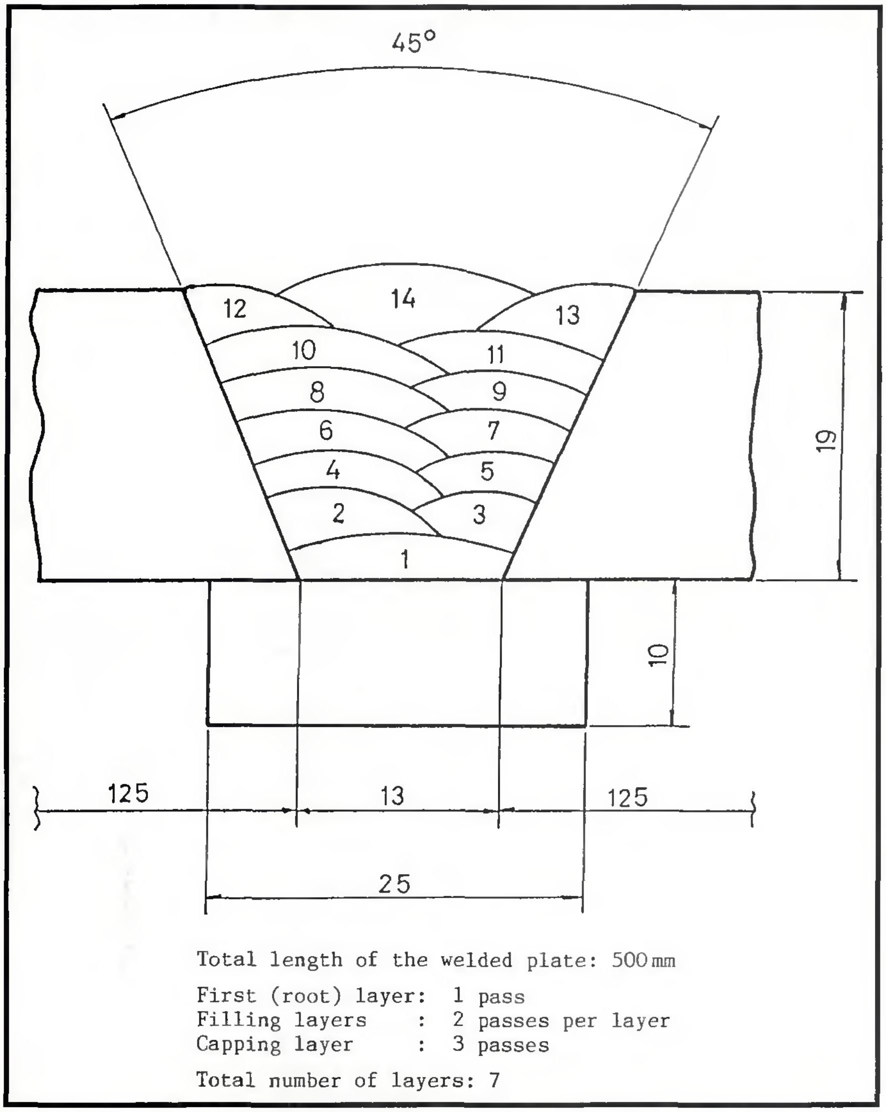

Fig. 1 — Geometry, dimensions (mm) and sequence of weld pass deposition in the all-weld metal assembly according to AWS Specification A5.5-81.

Table 1 — Chemical Analysis Results for Two 3% Ni Steel All-Weld Metals Deposited Using E7016-C2L Electrodes

Element %	Batch 3935	Batch 3939	AWS A5.5-81 Requirement for 2(E7016-C2L) Electrode
C	0.07	0.07	0.05 max
Mn	0.70	0.74	1.25 max
Si	0.12	0.16	0.50 max
S	0.005	0.004	0.04 max
P	0.013	0.012	0.03 max
Ni	3.05	3.02	3.00–3.75
Cu	0.015	0.015	
Cr	0.035	0.035	
ppm			
O	460–480	270–317	
N	108–107	80–107	

Other residual elements: Mo, V, W, Co, Nb, Al, Sn and As were less than 0.01% each.

cording to AWS Specification A5.5-81 from each batch of the electrodes. The preheat and interpass temperature was 100°C (212°F). Alternating current (AC) was used at 170 A and the arc voltage was 24 V. The heat inputs calculated for the individual passes were within 1.7 to 2.0 kJ/mm (43 to 51 kJ/in.).

Postweld Heat Treatment (PWHT)

For each batch, one test assembly was heat treated at 620°C (1148°F) for one hour as required by AWS A5.5-81, and the other was treated at 580°C (1076°F) for one hour. In both the cases, the heating rate was 180°C/h (324°F/h) and the cooling was carried out first in the furnace down to 300°C (572°F) at a rate of 50°C/h (90°F/h) and subsequently in still air, down to room temperature.

The reasons for the use of the two different PWHT temperatures were:

Table 2 — Oxygen Analysis for Deposited Weld Metal of Each Electrode Batch

Batch	Mg in Covering	Nominal Oxygen in Weld Metal
3935	4%	470 ppm
3939	6%	300 ppm

1) Previous work (Refs. 15,16) carried out on E8018-C2 electrodes showed that the PWHT at 620°C required by the AWS A5.5-81 Specification may not be the optimum temperature for achieving the maximum impact toughness at −101°C (−150°F) in 3½% Ni weld metal.

2) There was also some collective evidence from IIW (Ref. 17) that the PWHT at 580°C is more conducive to maximum toughness than the one at 620°C.

Mechanical Testing and Metallographic Examination

Each all-weld-metal sample was subjected to standard tensile tests at room temperature, and Charpy V-notch testing was performed at −73°C (−100°F) and −101°C (−150°F).

Metallographic examination of microstructure was carried out in the as-etched condition to quantify the various microstructural constituents.

The nonmetallic inclusions were examined and photographed in the as-polished condition. An attempt was made to quantify the inclusion content using the Omnimet equipment.

Results

Weld Metal Chemical Composition

Table 1 gives the results of chemical analysis. In general, the standard composition of the two weld metals was very close, and it has been influenced very little by the different Mg contents (4 and 6%) in the electrode coverings. The carbon content was above the limit for E7016-C2L, but it would conform to that specified for E8016-C2. The Ni content was close to the bottom limit, but from the viewpoint of impact toughness, this would be advantageous for seeing the behavior with the "lean" metal composition.

As expected and also as found by others (Ref. 4), the different Mg powder additions to the electrode coverings had a strong effect on the oxygen content in the weld metal, without any marked effect on their nitrogen contents. Slightly different oxygen analyses were obtained for each of the two weld metals deposited from each batch of electrodes, but the values were close enough in each case for the nominal oxygen levels given in Table 2 to be ascribed to the two batches.

Mechanical Properties

Table 3 gives the mechanical properties obtained and compares them with the requirements of AWS A5.5-81 for an E7016-C2L electrode after the PWHT at 620°C for one hour.

The tensile strengths of the two batches were very similar as would be expected from the closeness of their weld metal compositions — Table 1. The two experimental batches fulfilled the requirements for the tensile properties specified for E7016-C2L electrode, with a very good margin in each PWHT condition. Perhaps because of the slightly higher Si and Mn contents in Batch 3939, the weld metal from this batch was slightly stronger than that from Batch 3935. Also, slightly higher values for the yield stresses and tensile strengths were obtained for the lower PWHT temperature of 580°C. However, both of those differences were very small, almost in the realm of experimental scatter, and therefore, it is considered that they would not be important in relation to toughness as noted previously.

Taylor and Evans (Ref. 18) found the following equation for the ultimate tensile strength (UTS) of all-weld metal in low-carbon Mn-Ni low-alloy steel system, as a function of alloying:

$$\text{UTS (N/mm}^2\text{)} = 393 + 114\ \text{Mn} + 16\ \text{Ni},$$

after the PWHT at 580°C/2 h. Despite the slight difference in the various PWHTs, it was of interest to test this equation using the data in Table 1.

For Batch 3935: UTS = 393 + 114 X 0.70 + 16 X 3.05 = 522 N/mm^2

For Batch 3939: UTS = 393 + 114 X 0.74 + 16 X 3.02 = 527 N/mm^2

In comparison with the data given in Table 3, the agreement is very good.

While the tensile properties remained nearly constant, the different oxygen content, as influenced by the different Mg additions to the coatings, had a profound effect on the Charpy V-notch toughness. In the first place, the low oxygen weld metal (300 ppm) was much tougher than the high-oxygen weld metal (470 ppm). Batch 3939 has fulfilled the AWS requirements (Table 3) very consistently and with a very high margin, while Batch 3935 failed those requirements in the standard PWHT condition. The beneficial effect of the lower oxygen content is evident at both the test temperatures, and this can be

Table 3 — Mechanical Properties Obtained and Compared with Those Specified in AWS A5.5-81 for E7016-C2L after PWHT at 620°C for 1 h

	All-Weld-Metal Test Pieces			
	Batch 3935, 0 = 470 ppm		Batch 3939, 0 = 300 ppm	
Properties Measured and Specified	PWHT 620°C/1 h	PWHT 580°C/1 h	PWHT 620°C/1 h	PWHT 580°C/1 h
Yield stress N/mm^2	429	431	438	449
Tensile strength N/mm^2	519	520	527	539
Elongation %	34.1	34.4	32.5	31.1
AWS minimum				
Yield stress N/mm^2	390	—	390	—
Tensile strength N/mm^2	480	—	480	—
Elongation %	25	—	25	—
	Charpy V-notch, J			
−73°C (−100°F)	99, 102, 103, 90, 99, avg 99	75, 116, 146, 78, 72, avg 97	119, 142, 165, 115, 158, avg 148	143, 120, 117, 151, 104, avg 127
−101°C (−150°F)	34, 10, 12, 14, 9, avg 16	40, 58, 27, 24, 12, avg 32	40, 32, 75, 87, 82, avg 63	59, 32, 96, 52, 66, avg 61
AWS(1) minimum				
−101°C (−150°F)	27 J	—	27 J	—

(1) Reject the highest and the lowest value and no other remaining value must be lower than 20 J.

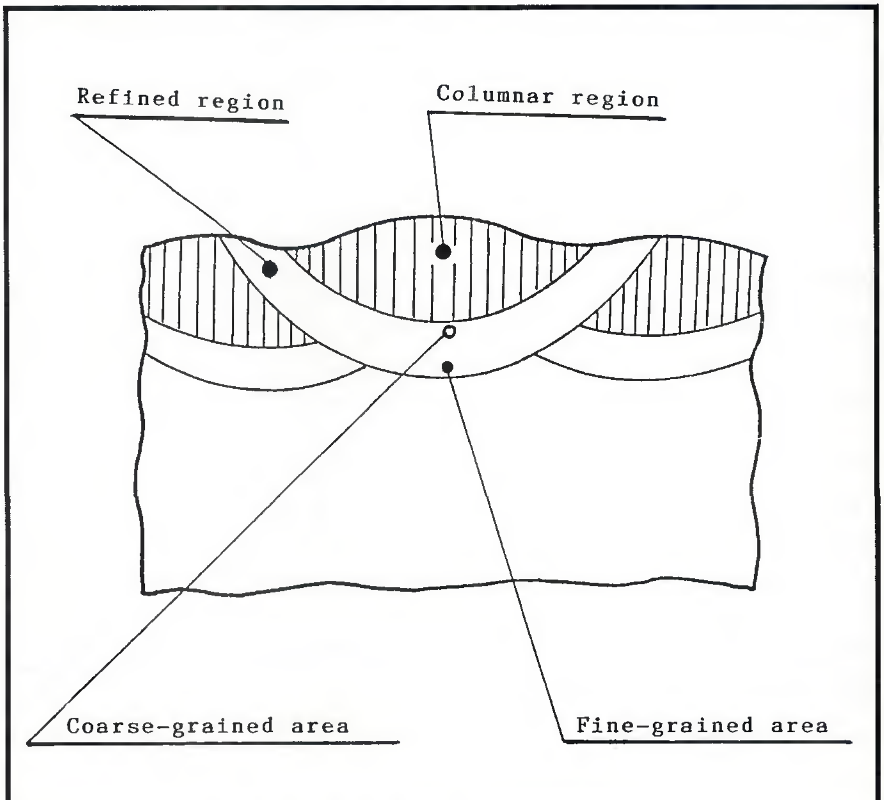

Fig. 2 — Columnar (as-deposited) and refined regions in the final passes of the weld metal subjected to detailed metallographic examination.

Table 4 — Percentages of Different Macroscopic Regions in the All-Weld Metal Lying ahead of the Charpy V-Notch

Batch	Sample	Columnar Region %	Refined Region Total %	Refined Region Coarse-Grained %	Refined Region Fine-Grained %
3935	620°C/1 h	4	96	17	79
	580°C/1 h	0	100	20	80
3939	620°C/1 h	0	100	31	68
	580°C/1 h	5	95	27	70

Table 5 — Prior Austenite Grain Size (width) in the As-Deposited Columnar Regions of the Final Passes

Batch	Sample	Width of Prior/Columnar Austenite Grain, μm
3935	620°C/1 h	72
	580°C/1 h	65
3939	620°C/1 h	70
	580°C/1 h	68

taken as indicative of the influence of oxygen/oxides on both the fibrous and cleavage fractures.

Secondly, at the high oxygen level (470 ppm), the lower PWHT temperature of 580°C was beneficial to toughness as shown previously (Refs. 15, 16). Using this nonstandard (*re:* AWS) PWHT, it might be just about possible to meet the AWS Charpy V-notch requirement of 27 J (20 ft-lb) min at −101°C with Batch 3935. About ten years ago, oxygen contents were generally higher in the weld metals deposited from flux-covered electrodes, and therefore, the interest in the use of 580°C PWHT at that time is understandable.

However, by using Mg additions to produce low oxygen (300 ppm) weld metal, the effect of the different PWHTs has been eliminated (see Batch 3939 in Table 3). If anything, the standard AWS PWHT (620°C/1h) gave a slight improvement in the Charpy V-notch toughness.

Metallographic Examination

Metal Matrix Microstructure

Table 4 gives quantities of the different macroscopic regions lying ahead of the Charpy V-notch, which was placed on the weld metal centerline where two passes meet in each layer — Fig. 1. These results show that as far as experimental precision would allow, in each weld metal the Charpy V-notch sampled similar amounts of the different macrostructural regions, *i.e.*, nearly 100% of the refined material.

Although this would not be important for the correlation with toughness in the present deposits, it was of interest to quantify the microstructure in the top passes, within and below the final layer (Fig. 2), because in many production welds the V-notch would not lie mainly in the all-refined macrostructure. Also in this work, it was of interest to know how closely the two weld metals with the different oxygen contents became matched in their microstructural condition.

Table 5 shows the widths of the prior austenite grains in the columnar regions — Fig. 2. They were very similar, if not identical within the experimental precision, for all four samples examined. This means that the increased oxygen content and the associated inclusions did not impede the austenite grain growth at the high (470 ppm) oxygen level.

Table 6 shows the volume fractions of the various microstructural constituents determined within the columnar regions of the top pass — Fig. 2. The determination was carried out according to the scheme described by Davey and Widgery (Ref. 19). The as-deposited transformed microstructures of all samples were very similar, with about 40% being occupied by the acicular ferrite and 50% being occupied by the primary ferrite networks at the prior austenite grain boundaries. The increased oxygen content in Batch 3935 did not promote the nucleation of an increased volume fraction of the primary ferrite, as might have been expected from the experience with C-Mn weld metal.

And finally, Table 7 gives the results of grain size measurements in the fine-grained areas of the reheated regions under the final capping passes — Fig. 2. The mean linear intercept "d" is expressed as $d^{-1/2}(mm^{-1/2})$. Again all the samples showed near-identical microstructural condition in their fine-grained regions.

The results in Tables 5–7 show that despite the different oxygen contents, the two batches gave weld metals with almost identical microstructures. Clearly, the addition of 3%Ni has overridden any effect of inclusions on the nucleation of transformation products, and especially of the acicular ferrite.

Nonmetallic Inclusions

Metallographic specimens in the as-polished condition were examined to see whether or not the two different oxygen contents would be reflected in the appearance of nonmetallic inclusions. Because of the concern with segregation and the subjectivity of such an examination, two operators were employed with the task of producing photographs of appearances which were perceived as representative.

Figure 3 compares the incidence and size of the typical nonmetallic inclusions photographed by Examiner 1 (JLT). It is clear that the high-oxygen (470 ppm) weld metal contained much larger in-

Table 6 — Quantitative Survey of Different Microstructural Constituents within the Columnar Regions of the Top Passes

Batch	Sample	Microstructural Constituents, % AF(1)	PF (G)(2)	PF (I)(3)	FS(4) (A) FS (NA)
3935	620°C/1 h	42	50	—	8
	580°C/1 h	37	49	3	11
3939	620°C/1 h	41	51	—	8
	580°C/1 h	39	52	2	7

(1) AF—Acicular ferrite.
(2) PF (G)—Primary ferrite at the prior austenite grain boundaries, *i.e.*, ferrite networks.
(3) PF (I)—Primary ferrite polygonal grains within the prior austenite grains, *i.e.*, intragranular ferrite.
(4) FS—Ferrite with second phases (carbides, retained austenite), either aligned (A) or nonaligned (NA).

Table 7 — Measurement Results for the Equiaxed Fine-Grained Areas in the Reheated Regions under the Final Capping Passes

Batch	Sample	Mean Linear Intercept (d) Expressed as: $d^{-1/2}$, $mm^{-1/2}$
3935	620°C/1 h	13.4
	580°C/1 h	13.1
3939	620°C/1 h	13.2
	580°C/1 h	13.0

clusions (Fig. 3B) than could ever be seen in the low-oxygen (300 ppm) weld metal — Fig. 3C and 3D. Also, the frequency of the smaller inclusions (Fig. 3A) was much higher in the high-oxygen weld metal than in the low-oxygen weld metal — Figs. 3C and 3D.

Figure 4 makes a similar comparison of the nonmetallic inclusions in the high- (Fig. 4A) and low-oxygen (Fig. 4B) weld metals photographed by Examiner 2 (JCG). Again, larger inclusions have been found with the increased oxygen content. After counting 25 different areas at a magnification of 500X, the volume fractions of nonmetallic inclusions obtained were as follows: Batch 3935 (470 ppm): 0.034%; Batch 3939 (300 ppm): 0.015%, for the two samples illustrated in Fig. 4A and 4B.

Conclusions

With two different Mg powder additions (4 and 6%) to the covering of E7016-C2L electrodes, it was possible to produce two 3%Ni low-alloy steel weld metals that had different oxygen contents (470 and 300 ppm, respectively), but which otherwise were very similar in the following respects:

1) The standard chemical composition of the two weld metals was very close.

2) The weld metal nitrogen contents were very close at about 100 ppm.

3) The resulting tensile properties were very similar.

4) The microstructures quantified under the light microscope were virtually indistinguishable.

Yet the two weld metals had markedly different Charpy V-notch toughness at −101°C (−150°F) after PWHT at either 620°C for one hour or

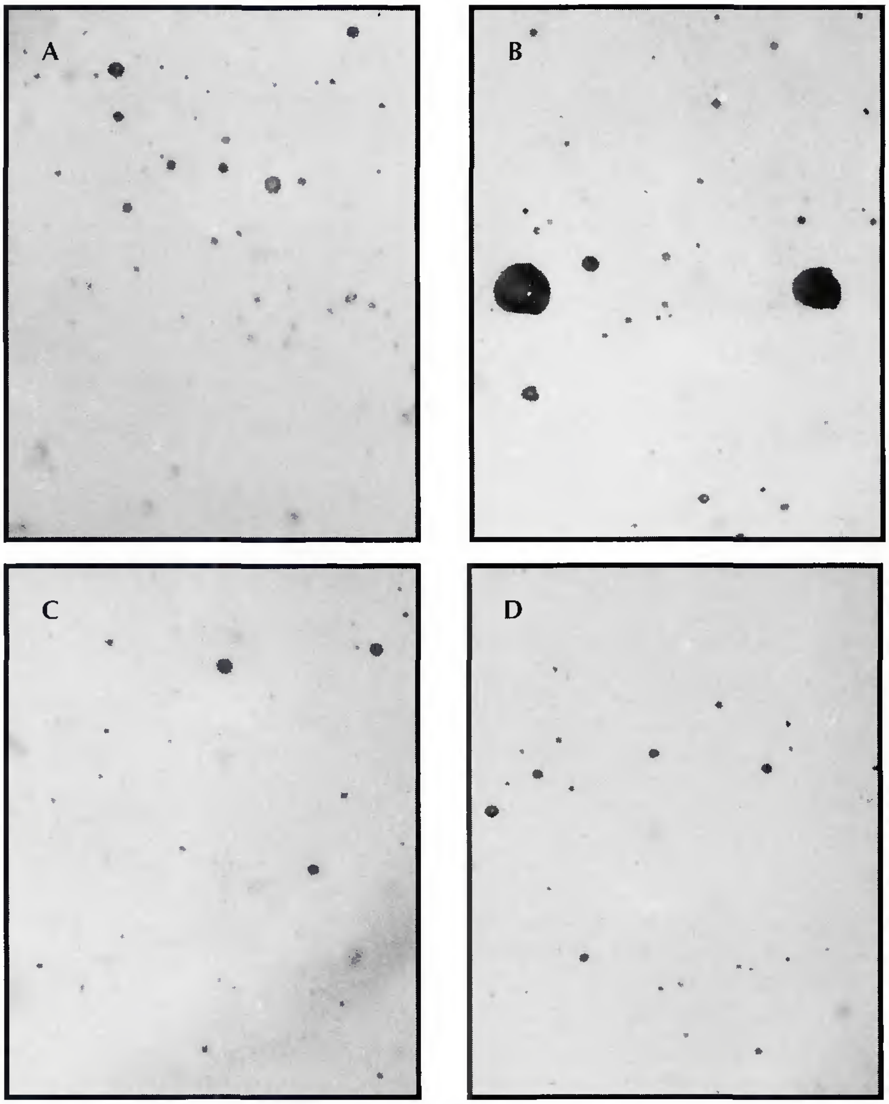

Fig. 3 — Appearance of typical nonmetallic inclusions at two different oxygen levels. A and B — High-oxygen weld metal, 470 ppm O; C and D — low-oxygen weld metal, 300 ppm O. 500X.

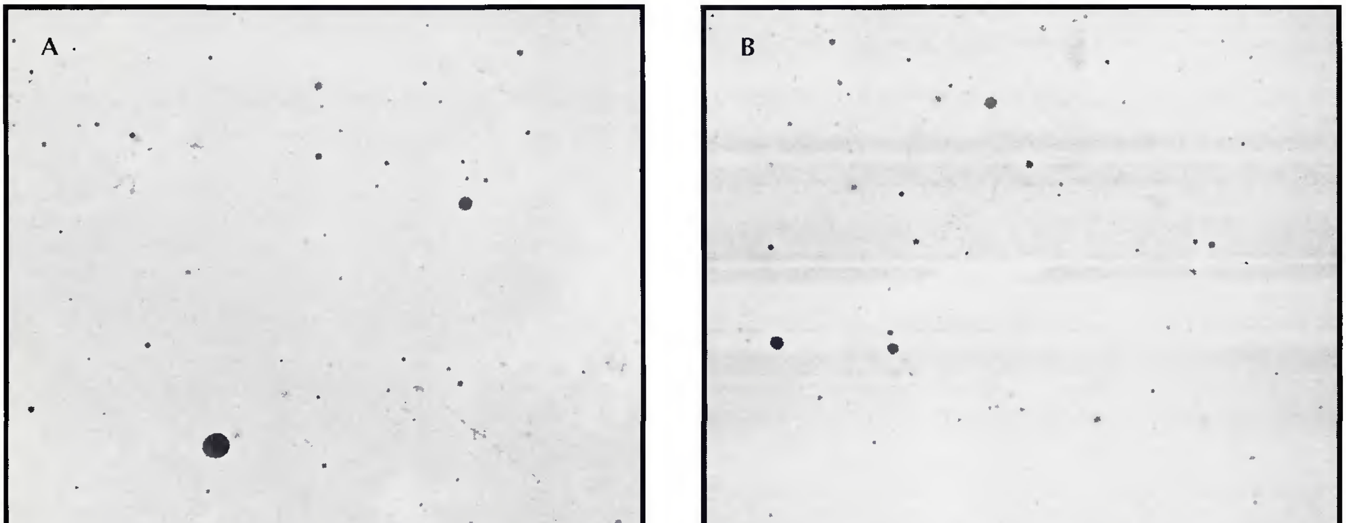

Fig. 4 — Typical nonmetallic inclusions. A — High-oxygen weld metal, 470 ppm O; B — low-oxygen weld metal, 300 ppm O.

580°C for one hour. The high-oxygen weld metal was completely brittle, giving on average only 16J (12 ft-lb) after the PWHT at 620°C. The low-oxygen weld metal was quite tough, giving on average over 60 J (44 ft-lb) after the PWHT at 620°.

With all factors 1 through 4 listed above being equal, the difference in toughness was clearly associated with a larger size and a greater number of nonmetallic inclusions in the high-oxygen weld metal than was the case with the low-oxygen weld metal. This was in line with published knowledge on the detrimental effects of the nonmetallic inclusions in both fibrous and cleavage fracture mechanisms in ferritic steel weld metal.

Mg-powder additions to the coatings of basic, low-hydrogen electrodes are a powerful means for the control of oxygen content in the weld metal, without too much interference with other elements. This can be beneficial in various low-alloy steel weld metals. The toughness of high-strength Mn-Ni-Cr-Mo weld metals can be improved. In the Cr-Mo weld metals, in which oxide inclusions are detrimental to creep-rupture life and ductility, property improvements can be achieved.

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