Welding of Ductile Iron with Ni-Fe-Mn Filler Metal

A new filler metal system can be used with several welding processes to produce joints in ductile iron that match or exceed base metal properties up to 80,000 psi (552 MPa)

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ABSTRACT. The results described in this paper show that unalloyed ductile iron with up to 80,000 psi (552 MPa) tensile strength can be arc welded without preheat if Ni-Fe-Mn filler metal is used. This recently developed filler metal system has several metallurgical characteristics that provide advantages over other systems for joining ductile iron (and other cast irons).

The Ni-Fe-Mn system has been found to be useful with a variety of welding processes, offering the potential for increased utility and economy in welding of ductile iron. Evaluations of weldment structures and tensile properties are presented.

Finally, the effects of heat-affected zone microstructural features are assessed. The results indicate that satisfactory weldment properties do not depend solely on HAZ microstructure.

Introduction

Welding of Ductile Iron

Since the invention of ductile iron (DI) in 1948, the weldability of ductile iron alloys has been studied and many papers on the subject have been published. Despite the extensive investigation of welding of DI, there continues to be disagreement over whether the material is "weldable" or "unweldable." Much of the controversy can be eliminated by the recognition that DI is not an alloy, but rather a generic term for an alloy class or an alloy family. Beyond this, it must be understood that ductile iron alloys can range in properties from relatively low-strength, high-ductility structures to high-strength, low-ductility materials, and that the matrix phase in a given engineering DI can be ferrite, pearlite, or austenite.

Using the ASTM designations for cast irons, it is clear that the designation DI covers a wide property and compositional range. Key mechanical properties of ductile irons range as follows: tensile strength — 60 to 120 ksi (414 to 827 MPa), yield strength — 45 to 90 ksi (310 to 621 MPa), and elongation — 10 to 3% (Ref. 1). The composition can be an Fe-C-Si alloy heat treated to attain tensile properties or can be alloyed with Ni, Cr, Mo, etc., to achieve properties as cast (Refs. 2-6).

In general, most welding research to date has been restricted to the 60-45-10* grade (Refs. 3-10) of DI, but some work has been done on higher strength grades such as 80-60-03* (Refs. 2,11,12). Welding electrodes used to weld DI include low carbon steel, pure nickel, stainless steel and iron-nickel, with iron-nickel being generally recognized as the filler metal system capable of providing the highest strength weldments. Since joint efficiencies in cast iron welds rarely reach 100%, weldment strength is often expressed in terms of the fraction of base metal strength that is retained in the weld joint.

A long-standing uncertainty in the welding of DI is whether or not preheat is necessary (Refs. 1-4). This is not a question of the "weldability" of DI, because weldability refers to the ability of a material to be joined under the imposed fabrication conditions to form a structure that will perform satisfactorily in the intended application. Thus, a given grade of ductile iron might be weldable without preheat in one application, weldable only with preheat in another application, and unweldable in a third application where fabrication conditions prevent the application of preheat (or where the level of restraint imposed was excessive).

More often, researchers and users are concerned primarily with attaining certain specific target properties, such as yield strength, impact resistance and heat-affected zone hardness, rather than with weldability per se. Given the varying base metal compositions, structures, and properties combined with the diversity of filler metals, applications, and required properties, it is not surprising that there is controversy over the welding of ductile irons in engineering applications.

When unalloyed (Fe-C-Si) DI is welded, a preheat of about 425°C (800°F) is required to prevent the formation of martensite, but preheat increases the amount of iron carbide that forms in the HAZ (Ref. 4). The carbide phase can be more detrimental than martensite to mechanical properties, particularly as it becomes nearly continuous in the HAZ. Welding without preheat to produce a thin band of martensite is preferable to developing a continuous band of iron carbide in the HAZ of unalloyed DI.

Background to the Development of Ni-Fe-Mn Filler Metals

One reason that cast irons, including DI, are more economical than cast steels

Numbers used here and elsewhere in the paper are values for mechanical properties in the following order: tensile and yield strengths (ksi) and elongation (%).

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is that their solidification temperatures—solidus and liquidus—are lower, which allows melting and pouring at lower temperatures. The low solidus and liquidus temperatures are one cause of welding problems, since common filler metals for welding of cast iron—nearly pure Ni (AWS grade ENi-CI) and 55% Ni-balance Fe (ENiFe-CI and -CI-A)—solidify at higher temperatures than the base metal. When the weld metal solidifies before the "unmixed zone"* and high temperature HAZ, solidification stresses are concentrated in a narrow region of limited ductility. When the low-ductility area cannot accommodate the resulting strains, cracks form in the HAZ.

The primary characteristic of the Ni-Fe-Mn system leading to improved cast iron welding is a solidification range more compatible with the base metal. The Fe-Ni-Mn system has a liquidus temperature about 100°C (180°F) lower than the Fe-Ni system, and the solidus temperature is correspondingly lower. Exploration of the ternary Ni-Fe-Mn system has led to the recent development of NI-ROD† Filler Metal 44 and NI-ROD† Welding Electrode 44 (see Table 1 for composition).

*The term refers to a very narrow region at the edge of the fusion zone where melting and solidification of the base metal occurs without mixing with the weld metal. It therefore represents an area of base metal that undergoes fusion without any change in composition. For a complete explanation, see Savage et al. (Ref. 13)

Table 1—Composition of Ni-Fe-Mn Filler Metal 44 and Ductile Iron Base Metals, Along With Base Metal Tensile Properties

Material	Composition, wt-% C	Mn	Si	Ni	Fe
Ni-Fe-Mn44	0.25	11.0	0.15	42.0	Bal
65-45-12	2.90	0.33	2.41	0.02	Bal
80-55-06	3.70	0.38	2.59	0.03	Bal

Base Metal Tensile Properties:

Cast iron grade	Yield strength MPa	Yield strength ksi	Ultimate tensile strength MPa	Ultimate tensile strength ksi	Elongation, %	Reduction in area, %	Hardness, R_B
65-45-12	323	46.8	481	69.8	13	14.7	79
80-55-06	413	59.9	693	100.6	6	4.7	95

In addition to the more compatible solidification temperatures, the Ni-Fe-Mn system has the advantage of matching closely the thermal expansion coefficient of DI (or other cast irons). The combination of these characteristics results in welds that solidify over a temperature range much closer to that of the base metal and which undergo similar thermal contraction upon solidification. Therefore, high solidification stresses are not placed on the partially melted heat-affected zone of the DI during solidification, and subsequent solidification stresses are reduced.

Most welding of cast iron has been performed with relatively low deposition rate processes; shielded metal-arc welding (SMAW) has been used extensively with the ENi-CI and ENiFe-CI grades of covered electrode (Ref. 14), and oxy-acetylene welding has been employed for some applications. Process limitations, combined with the metallurgical factors described above, have limited the welding of cast iron.

†Trademark of the Inco family of companies.

Prior to the development of Ni-Fe-Mn, the major advancement in filler metals for cast iron welding was NI-ROD FC 55, a flux-cored continuous welding wire for use with flux-cored arc welding (FCAW) and submerged arc welding (SAW). While the FC 55 product produces weldments with properties that match or exceed those of the 65-45-12 grade of DI, the FC 55 filler metal is somewhat limited in that it cannot be produced in diameters smaller than 2 mm (0.078 in.).

Materials

All materials used in this work were of commercial quality. The two heats of cast iron used were unalloyed and achieved their properties from heat treatment. The 65-45-12 was a ferritic iron as shown in Fig. 1, while the 80-55-06 was pearlitic, also shown in Fig. 1.

Procedure

Several different welders and heats of ductile iron were used to establish the

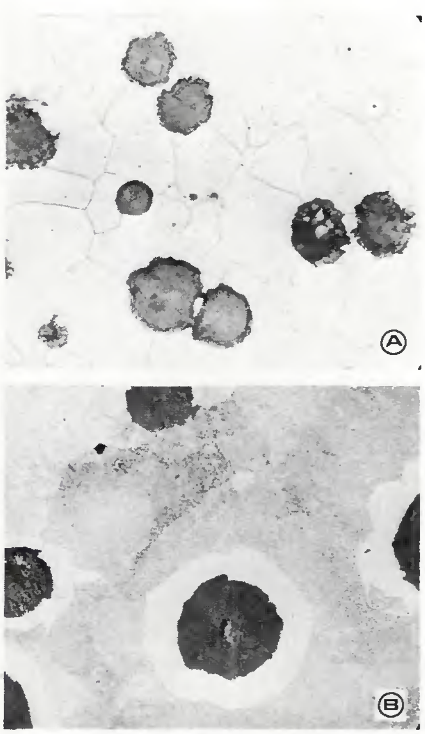

Fig. 1—Microstructures of the two ductile iron heats used in this work: A—65-45-12 ferritic; B—80-55-06 pearlitic. X500 (reduced 50% on reproduction)

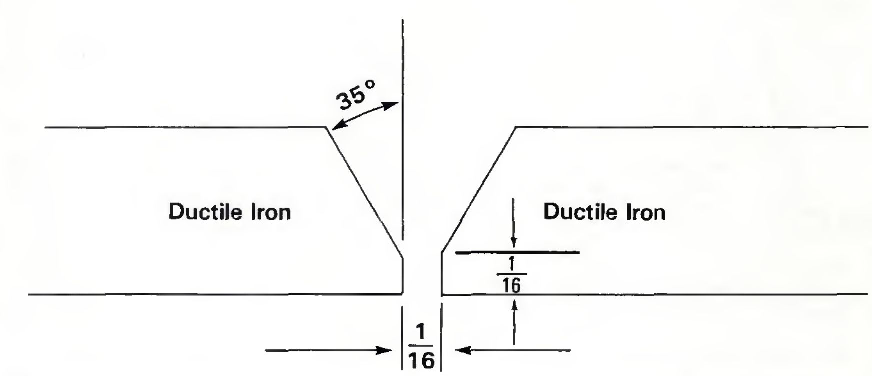

Fig. 2—Schematic of ductile iron weld joint design used to evaluate the Ni-Fe-Mn filler metal

Table 2—Gas Metal Arc Welding Variables Used With Filler Metal 44 and Five Different Commercial Shielding Gases[a]

	Weld no.				
	1	2	3	4	5
Gas	Argon	Linde Stargon	75% A/25 CO_2	98 A/2% O_2	CO_2
Wire feed, ipm	300	300	300	300	300
Voltage, V	28	29	27	27	27
Current, A	260-280	220-230	200	220	200
Gas flow, cfh	50	50	50	50	50
Travel speed, ipm	10	10	10	10	10
Heat input, J/in.	45,360	39,150	32,400	35,640	32,400
Contact tip to workpiece, in.	⅝	⅝	⅝	⅝	⅝

(a)Base metal—Ductile iron 65-45-12 (¾ in. thick, 1 × 3 in.). Welding wire—0.045 in. diameter NI-ROD Filler Metal 44, Heat Ho. Y60B3.

utility of the Fe-Ni-Mn system in welding ductile iron. Gas metal-arc (GMA), gas tungsten-arc (GTA), shielded metal-arc (SMA) and submerged arc (SA) welding processes were evaluated using Filler Metal 44 and Welding Electrode 44 with 19 mm (0.75 in.) thick sections of 65-45-12 and 80-55-06 ductile iron.

Joint Design

The joint configuration shown in Fig. 2 was used to evaluate the Ni-Fe-Mn system with GMAW, SAW, SMAW, and GTAW processes. A 35 deg bevel was machined into 19 mm (¾ in.) thick cast iron slabs 75 × 254 × 19 mm (3 × 10 × ¾ in.) to provide a 70 deg included angle for welding. The pieces were clamped into position for welding using a 1.6 mm (0.062 in.) root face and root gap, as shown in Fig. 2. The only exception to this joint design was for SMAW, where no root face was required.

Welding Process Details

GMAW. To determine the effects on properties of changes in shielding gas, semi-automatic GMAW was used with 1 mm (0.045 in.) diameter Ni-Fe-Mn filler metal to weld 65-45-12 ductile iron. The gases used were pure argon, Linde Stargon*, 75% argon-25% carbon dioxide, 98% argon-2% oxygen, and pure carbon dioxide. To evaluate the welding of both 65-45-12 and 80-55-06 DI to steel, the same process and filler metal was used with pure argon shielding gas.

A study of joint penetration and HAZ microstructure was conducted using the process and five shielding gases described above. In order to control as many variables as possible, the travel speed, welding wire feed speed, and contact tip-to-workpiece distance (electrode extension) were held constant. The current and voltage were allowed to stabilize at whatever value was required to provide a stable arc—Table 2. A single slab of 65-45-12 DI was cut into 25 × 75 × 19 mm (1 × 3 × ¾ in.) slices so that all beads were deposited on the same base metal.

GTAW. Both the 65-45-12 and 80-55-06 grades of DI were used to evaluate the Filler Metal 44 system. Welds were deposited manually using 2.4 mm (0.093 in.) filler metal and the conditions listed in Table 3.

SAW. To evaluate the SAW process, the Filler Metal 44 (Ni-Fe-Mn) system was used with Incoflux† 6 to weld 65-45-12 DI. Overlaying with the Ni-Fe-Mn system was assessed by using SAW to overlay a DI plate that had been given a ferritizing anneal. The resulting overlay was tested by means of a longitudinal face bend.

SMAW. A covered electrode using a nominal 42% Ni-11% Mn-Bal. Fe core welding wire was developed to complement the bare wire product; the electrode was evaluated with both the 65-45-12 and 80-55-06 grades of DI. Because of the combination of high weld metal strength of the Ni-Fe-Mn and the low ductility of the 80-55-06 grade, the machined surfaces of the joint were buttered with welding electrode 44 prior to joining. Buttering of the joint eliminated the HAZ cracking that had been experienced in earlier trials. Conditions for SMAW are listed in Table 3.

Evaluation

Once welding was complete, each weldment was examined visually and radiographically prior to sectioning for metallographic and mechanical property evaluation. Metallographic evaluation consisted of optical metallography and microhardness testing. Mechanical property evaluation was done using both cross-weld and all-weld tensile specimens.

Results and Discussion

Gas Metal-Arc Welding of DI with Ni-Fe-Mn Filler Metal

With GMAW a primary independent variable is the shielding gas, which affects

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Table 3—Conditions Used For Gas Tungsten Arc Welding and Submerged Arc Welding With Filler Metal 44 and Shielded Metal Arc Welding With Welding Electrode 44

		Submerged arc[b]		
	Gas tungsten arc[a]	Butt joint	Surfacing deposit[d]	Shielded metal arc[e]
Welding wire diameter, in.	0.093	0.062	0.062	0.125
Welding wire speed, ipm	Manual feed	225	—	Manual
Travel speed, ipm	7-10 (manual)	10	4.5	Manual
Voltage, V	18-19	32	33	24
Current, A	200	260	290	90

(a) Argon 20 cfh, 3 mm (⅛ in.) tungsten electrode.
(b) Contact tip-to-workpiece distance was 25 mm (1 in.).
(c) DC reverse polarity (electrode positive).
(d) DC straight polarity (electrode negative).
(e) Standard DC operation—reverse polarity.

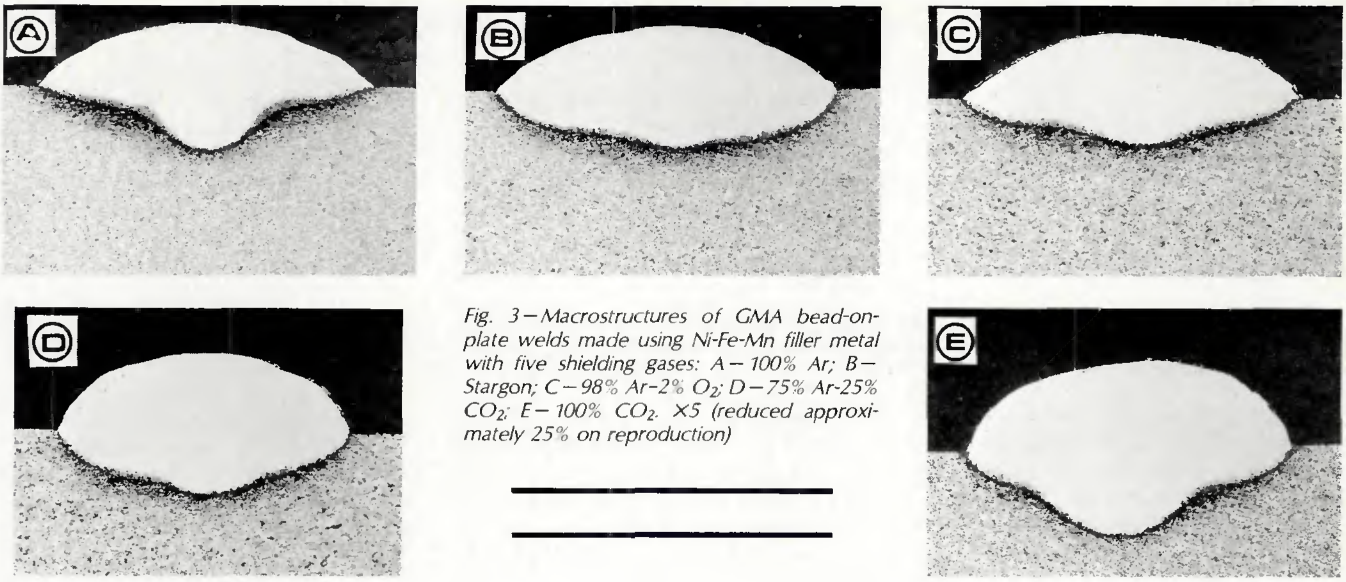


Fig. 3—Macrostructures of GMA bead-on-plate welds made using Ni-Fe-Mn filler metal with five shielding gases: A—100% Ar; B—Stargon; C—98% Ar-2% O_2; D—75% Ar-25% CO_2; E—100% CO_2. X5 (reduced approximately 25% on reproduction)

arc stability, penetration, and heat input—in particular, the effective heat input (due to differences in heat transfer characteristics). The effective heat input to the weldment largely determines both the microstructure of the HAZ and the mechanical properties of the weldment. Figure 3 compares the weld penetration patterns of weld beads made with the five shielding gases. As noted earlier, some conditions were held constant, but current and voltage were allowed to stabilize at levels that provided a stable arc. As a result the heat input varied as a function of the shielding gas used, as noted in Table 2.

The data in Table 4 and the macrographs in Fig. 3 indicate that all five gases can be used with the Ni-Fe-Mn filler metal system. The main difference among the five gases is the heat input and the wetting of the 65-45-12 DI by the filler metal. In the case of 100% argon, the heat input is approximately 30% greater than for the other four gases. This is probably why the wetting angle of the weld bead is better in this case; however, the argon-2% oxygen has about the same wetting angle as the 100% argon while operating at the same heat input as the other three shielding gases. Comparing the pure argon and the argon-2% oxygen mixture, the latter appears to be the better choice on the basis of bead contour and low heat input.

The carbon dioxide gas produces the deepest penetrating bead. This is beneficial when complete penetration is required in groove or fillet welds. Also, the carbon dioxide produces the highest deposition rate at a given current level. For example, when using 1 mm (0.045 in.) diameter welding wire at 240 A, the deposition rate for CO_2 is 5.4 kg/h (11.9 lb/h) as compared to 4.3 kg/h (9.4 lb/h) when argon is used.

Figure 4 shows the HAZ microstructures below the point of deepest penetration of the five weld beads. When comparing these microstructures, it is surprising that the lowest and highest heat input weldments have almost identical HAZ thicknesses and structures. From a microstructural viewpoint, it is desirable to minimize the amount of martensite and iron carbide present in the HAZ. Using this criterion, either the 100% argon or the 100% carbon dioxide appear to be the shielding gases providing the best weldments.

The evaluations to this point have been based on visual observation of the arc and examination of bead shape and microstructure. However, weldment mechanical properties are the most important evaluation criterion. The mechanical properties obtained with the five shielding gases are presented in Table 4.

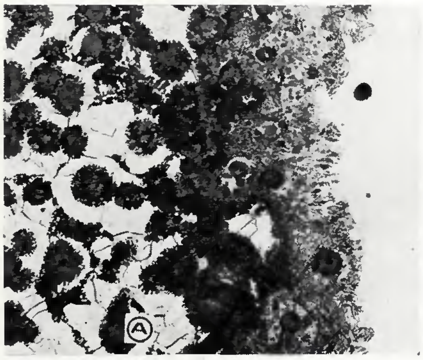
Mechanical test specimens were removed from multipass welds made without preheat and without control of interpass temperature. The exception to this practice was the weld made with carbon dioxide shielding, where the temperature between layers was controlled to decrease the amount of oxide on the bead surface in multi-layer welds. The microstructures and mechanical behavior of these multipass welds were different from those of the single layer welds described above.

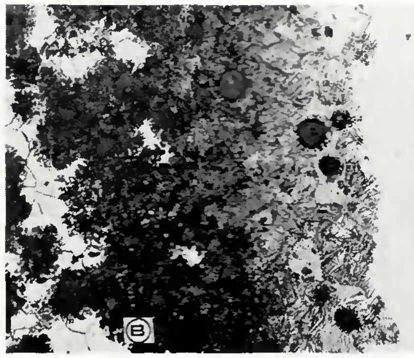
A sixth weldment was made between DI and steel to evaluate the Ni-Fe-Mn system as a filler metal for dissimilar metal

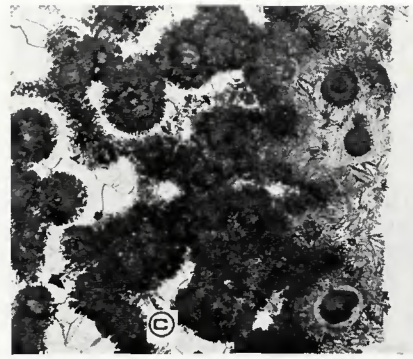
Table 4—Average[a] Cross-Weld Tensile Properties[b] of Ductile Iron (65-45-12) Weldments Made by GMAW With Ni Rod Filler Metal 44 and Five Different Commercial Shielding Gases

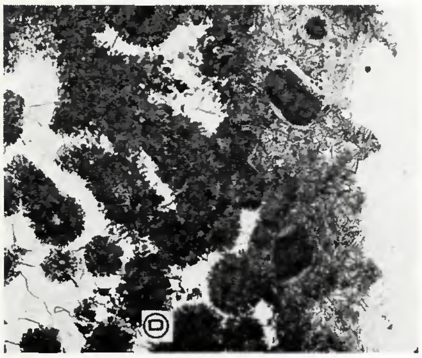
	Y.S.		U.T.S.				
	MPa	ksi	MPa	ksi	El., %	R.A. %	Failure location
Argon	366.2	53.1	445.1	64.5	2.3	10.7	2 HAZ/DI; 1 DI
Argon—2% O_2	387.3	56.1	481.6	69.8	5.0	20.5	1 HAZ/DI; 2 DI
Stargon	385.0	55.8	455.4	66.0	2.3	5.6	3 HAZ/DI
75%Ar-25%CO_2	397.4	57.6	493.0	71.5	3.0	8.5	2 HAZ; 1 HAZ/DI
Carbon dioxide[c]	389.9	56.5	498.6	72.3	2.7	14.0	3 DI
Argon[d]	367.5	53.3	477.1	69.2	3.7	1.6	HAZ

(a)Average of 3 tests.
(b)Y.S.—Yield strength; U.T.S.—ultimate tensile strength; El.—elongation; R.A.—reduction in area.
(c)This weldment was cooled below 95°C (200°F) between layers.
(d)Dissimilar metal weld of ductile iron to steel.









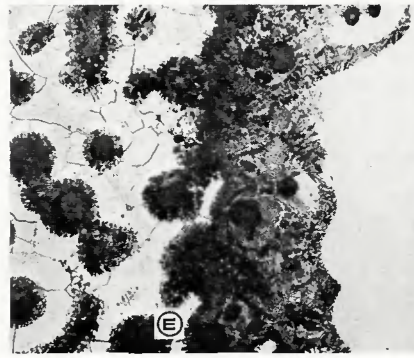


Fig. 4—HAZ microstructures of five GMA welds made with: A—100% Ar; B—Stargon; C—Ar-2% O_2; D—75% Ar—25% CO_2; E—100% CO_2. X200 (reduced 54% on reproduction)

welding. As shown in Table 4, argon was used as the shielding gas for this weld.

In reviewing the cross-weld tensile properties given in Table 4, which represent the average value of three tests, it is worth noting that the tensile strengths of the 65-45-12 slabs vary from slab to slab. To illustrate this point, cross-weld failures in the base metal, which measure the tensile strength of the DI, ranged from 445 MPa (64,500 psi) to 498 MPa (72,300 psi).

The data in Table 4 indicate that good weldments can be made with all five shielding gases. Highest cross-weld tensile strengths were achieved with carbon dioxide shielding, although differences were relatively minor. Cross-weld ductility is related to the differences in strength among the base metals, filler metal, and HAZ's, and is very dependent on the location of failure (HAZ and fusion line failures are often low ductility fractures).

While cross-weld ductility is only an indicator, the values in Table 4—especially the reduction in area data—suggest that argon-2% oxygen also provides particularly good weldment properties. While all five gases can provide satisfactory properties, the cross-weld strengths, tensile failure locations, and reduction in area data indicate that CO_2 and argon-2% oxygen provide the best weldment performance.

In comparison, changes in the GMAW shielding gases did not affect all-weld-metal properties. As shown in Table 5, the strengths, ductilities, and hardnesses of the six GMA weldment specimens were essentially equal.

Gas Tungsten-Arc Welding of DI with Ni-Fe-Mn Filler Metal

Argon was used for all GTA welds in this study, but helium could also have been used. Carbon dioxide or inert gas-oxygen gas mixtures should not be used to GTAW cast iron with the Fe-Ni-Mn system. Mechanical properties presented in Table 6 show that over 100% of the rated ultimate tensile strength and yield strength of the DI are recovered.

The cross-weld tensile specimen from the weldment in 65-45-12 DI failed in the base metal with a 5% elongation and 19.5% reduction in area. The specimen from the weldment made in grade 80-55-06 failed in the HAZ, but at a high ultimate tensile strength of 628 MPa (91,200 psi). The measured ultimate tensile strength of this 80-55-06 grade material was 694 MPa (100,600 psi); but, as noted earlier, strength varies from piece to piece. Using the measured base metal strength results in a joint efficiency for GTAW of greater than 90%. All-weld-metal tensile properties for GTAW are presented for comparison in Table 7.

The microstructures of the GTA welds appear quite different from the GMAW HAZ microstructures. This is probably due to the lower heat input of the welding process and the smaller size of the weld bead deposited by GTAW.

Table 5—All-Weld-Metal Tensile Properties of Ductile Iron 65-45-12 GMA Weldments Made with Filler Metal 44 and Five Different Shielding Gases

Gas	Yield strength		Tensile strength		Elongation,	Reduction in area,	Hardness,
	MPa	ksi	MPa	ksi	%	%	R_B
Argon	469.5	68.1	700.5	101.6	24.0	34.2	94
Argon (DI to steel)	432.3	62.7	684.7	99.3	31.5	38.9	97
Ar−2% O_2	475.1	68.9	725.3	105.2	34.0	44.1	93
Stargon	486.8	70.6	752.9	109.2	36.0	47.1	94
75%Ar-25%CO_2	496.4	72.0	768.8	111.5	32.0	40.2	97
CO_2	497.8	72.2	775.0	112.4	32.0	40.6	96

Table 6—Typical Cross-Weld Tensile Properties[a] of Ductile Iron (65-45-12) Weldments Made by SAW and GTAW

Welding process	Y.S. MPa	Y.S. ksi	U.T.S. MPa	U.T.S. ksi	El. %	R.A. %	Failure location
Submerged arc	340.6	49.4	497.8	72.2	6.0	8.2	DI
Gas tungsten arc	392.3	56.9	506.8	73.5	5.0	19.5	DI
Gas tungsten arc[b]	503.3	73.0	628.8	91.2	1.5	3.2	HAZ

[a] Y.S. — Yield strength; U.T.S. — Ultimate tensile strength, El. — elongation; R.A. — reduction in area.
[b] GTA weld in grade 80-55-06 base metal.

Table 7—Typical All-Weld-Metal Tensile Properties of Submerged Arc and Gas Tungsten-Arc Weldments

Cast iron grade	Welding process	Yield strength MPa	Yield strength ksi	Tensile strength MPa	Tensile strength ksi	Elongation, %	Reduction in area, %	Hardness, R_B
65-45-12	SAW	399.2	57.9	632.9	91.8	26.0	42.0	90
65-45-12	GTAW	542.6	78.7	788.8	114.4	24.0	43.6	94
80-55-06	GTAW	485.4	70.4	719.8	104.4	33.0	51.2	96

Very little untempered martensite is found in the HAZ of the GTAW, but this has not resulted in an increase in ductility of the weldment. In the place of the martensite found in the GMAW, a distribution of bainite, secondary iron carbide and secondary graphite was found at the fusion line of the 80 and 65 ksi (552 and 448 MPa) DI weldments, as shown in Fig. 5. The low cross-weld ductility shown in the limited tests of this non-martensitic microstructure confirms the observation of others (Ref. 4) that the untempered martensite of the as-welded HAZ can have mechanical properties equal to or better than other combinations of phases found in some DI weldment HAZ's, and it demonstrates that welding of DI without preheat or postheat is a viable approach. Avoiding the formation of martensite does not necessarily result in better weldment mechanical properties.

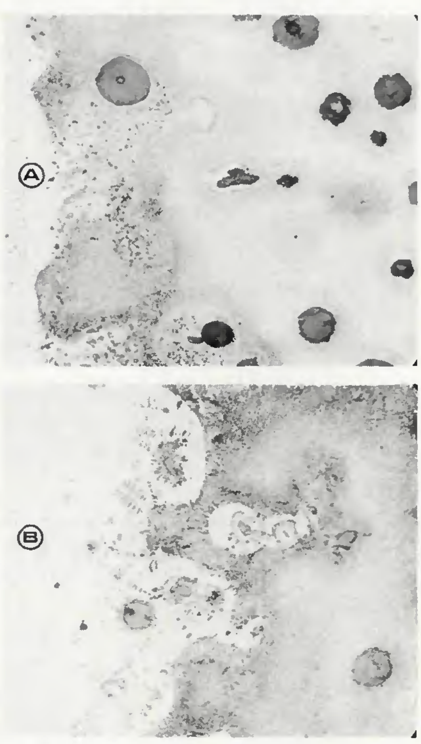


Fig. 5 — Typical HAZ microstructures of ductile iron GTA weldments made with Ni-Fe-Mn filler metal: A — 65-45-12 grade; B — 80-55-06 grade. X200 (reduced 54% on reproduction)

Submerged Arc Welding of DI with Ni-Fe-Mn Filler Metal

The SAW was also done without preheat or postheat, and Incoflux 6 was used with Filler Metal 44. The welding parameters used for SAW appear in Table 3. The tensile test specimens broke in the base metal well away from the HAZ and both yield and tensile strengths were above the specified minimum (Table 6); therefore, these submerged arc welds displayed complete retention of base-metal tensile properties.

All-weld-metal properties are presented in Table 7. Figure 6 is an example of the HAZ microstructure; the HAZ in the submerged arc welds is narrower than that observed in weldments made by any of the other welding processes evaluated in this paper. A second difference is the absence of secondary graphite in the HAZ; the HAZ in these welds consists of coarse martensite and primary iron carbide. The martensite is continuous along the fusion zone, while the iron carbide appears intermittently along the fusion line.

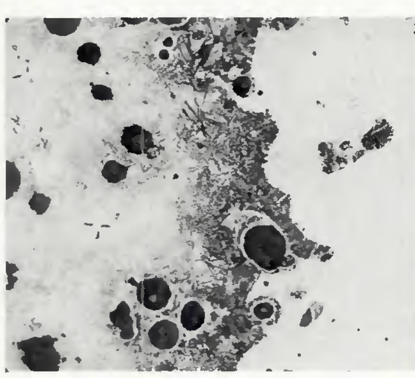


Fig. 6 — Typical HAZ microstructure of a submerged arc weldment in ductile iron made with Ni-Fe-Mn filler metal. X200 (reduced 50% on reproduction)

To determine if the Ni-Fe-Mn filler metal could be used to overlay ductile iron, a 19 mm (3/4 in.) slab was given a ferritizing anneal — 900°C (1650°F)/3 h + furnace cool to 690°C (1275°F)/5 h + furnace cool to 595°C (1100°F) + air cool. Incoflux 6 was used with the 1.6 mm (0.062 in.) diameter Filler Metal 44. Three layers were deposited on the ferritized DI, and the finished overlay was machined to a thickness of 9.5 mm (3/8 in.). A longitudinal face bend of 2T — two times the specimen thickness as the bend radius — was made; no defects were seen on the bent surface, as illustrated by Fig. 7.

Shielded Metal-Arc Welding of DI with Ni-Fe-Mn Filler Metal

Numerous brands of Ni(ENi-CI) and NiFe(ENiFe-CI and -CI-A) covered electrodes are commercially available; most

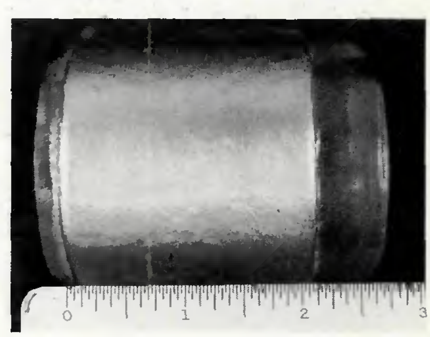


Fig. 7 — Outer surface of a tested bend specimen from a submerged arc overlay made on ductile iron with Ni-Fe-Mn filler metal

Table 8—Cross-Weld and All-Weld-Metal Tensile Properties of Ductile Iron Weldments Made by SMAW With Welding Electrode 44

Ductile iron grade	Test[a] direction	Yield strength MPa	Yield strength ksi	Tensile strength MPa	Tensile strength ksi	Elongation, %	Reduction in area, %	Hardness, R_B	Failure location
65-45-12[b]	AWM	462.6	67.1	653.6	94.8	13.7	15.2	94	—
65-45-12[b]	CW	364.7	52.9	490.2	71.1	8.3	15.3	—	DI
80-55-06[c]	AWM	477.1	69.2	624.0	90.5	12.0	13.2	93	—
80-55-06[c]	CW	446.8	64.8	580.5	84.2	3.0	1.6	—	HAZ

[a]Test direction: AWM—All-Weld-Metal; CW—Cross-Weld.
[b]Average of 5 tests.
[c]Prepared joint surfaces buttered with Ni-Fe-Mn before joining.

of the latter type are capable of producing 100% joint efficiency in welds of 65-45-12 grade DI. By comparison, the newly developed Ni-Fe-Mn covered electrode will produce a 100% joint efficiency in castings with tensile strengths greater than 483 MPa (70,000 psi). The all-weld-metal tensile strength (Table 8) of the Ni-Fe-Mn electrode is over 620 MPa (90,000 psi) with elongation greater than 12%. This contrasts with typical all weld metal ultimate tensile strength of 483 MPa (70,000 psi) and elongation of 16% for standard ENiFe-Cl grade.

Higher strength castings like the grade of 80-55-06 DI can also be welded with the Ni-Fe-Mn electrode. However, because of the low ductility of the higher strength castings, the joint surfaces must be buttered prior to joining. This procedure resulted in a cross-weld tensile strength of 580 MPa (84,200 psi), which is greater than the minimum ultimate tensile strength for the 80-55-06 grade—Table 8.

The SMAW was done without preheat or postheat, but with a minor change in joint design that resulted in the removal of the root face from the root portion of the weld joint. Microstructurally, this was the most nonuniform specimen examined in this investigation. Due to the inherently intermittent heat input and slow travel speed of the SMAW process, there were areas of the HAZ that were completely devoid of martensite. These areas contained secondary carbides and graphite, while similar positions in the HAZ at other locations in the weld contained extremely coarse martensite. Therefore, the HAZ of this type of weld is extremely heterogeneous, as shown in Fig. 8. Mechanical property evaluation resulted in all transverse tensile specimens breaking in the base metal well away from the HAZ.

Summary and Conclusions

The Ni-Fe-Mn filler metal system has been demonstrated to be capable of welding DI without preheat or postheat and retaining 100% of the base metal tensile properties. It has also been demonstrated that DI weldments containing iron carbide, secondary graphite, and/or

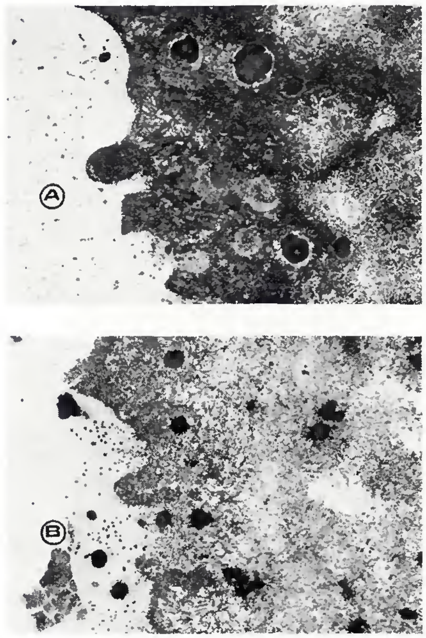


Fig. 8—Typical HAZ microstructures from a SMA weldment made in ductile iron with Ni-Fe-Mn covered electrode, showing two locations in the same cross section. X200 (reduced 50% on reproduction)

martensite in the HAZ can have useful tensile properties. Therefore, HAZ microstructure alone cannot be used to predict weldment performance.

Additionally the Ni-Fe-Mn filler metal system has been shown to be suitable for use with all of the fusion welding processes normally applied to cast irons. This paper has not attempted to evaluate the fatigue or impact properties of weldments; if these properties are important in a particular application, then they must be tested.

1. Ductile iron can be welded without preheat or postheat using the Ni-Fe-Mn filler metal.

2. Weld joints with strengths equal to those of the 65-45-12 base metal were made with the Ni-Fe-Mn filler metal using the GMAW, GTAW, SMAW and SAW processes.

3. With special preparation consisting of buttering the joint surfaces, SMAW was used with the Ni-Fe-Mn covered electrode to produce a weld joint with yield and tensile strengths above the minimum for high strength 80-55-06 ductile iron.

4. These results show that, while HAZ microstructure is important, it is not the sole determinant of cross-weld tensile properties in ductile iron welds.

References

1. Pease, G. R. 1960. The welding of ductile iron. 1960. *Welding Journal* 39(1):15-95.
2. Medana, R., Natale, E., and Remodino, M. S. 1978. High strength welding of ductile iron castings. *AFS transactions,* pp. 611-615.
3. Nippes, E. F., Savage, W. F., and Owczarski, W. A. 1960. The heat-affected zone of arc-welded ductile iron. *Welding Journal* 39(11):465-s to 472-s.
4. Kotecki, D. J., Braton, N. R., and Loper, C. R., Jr. 1969. Preheat effects on gas metal-arc welded ductile cast iron. *Welding Journal* 48(4):161-s to 166-s.
5. Voigt, R. C., and Loper, C. R., Jr. 1983. A study of heat-affected zone structures in ductile cast iron. *Welding Journal* 62(3):82-s to 88-s.
6. Gretskii, Ya. Ya., Korschina, G. M., and Vasil'ev V. G. 1981. Effects of the arc welding thermal cycle on the structural and mechanical properties of high strength irons. *Avt. Svarka* 6:9-12.
7. Bates, R. C., and Morley, F. J., Jr. 1961. Welding nodular iron without post-weld annealing. *Welding Journal* 40(9):417-s to 422-s.
8. Askeland, D. R., and Birer, N. 1979. Secondary graphite formation in tempered nodular cast iron weldments. *Welding Journal* 58(11):337-s to 342-s.
9. *Welding ductile iron—current practices and applications.* Mountainside, New Jersey: Ductile Iron Society.
10. Bishel, R. A. 1973. Flux-cored electrode for cast iron welding. *Welding Journal* 52(6):372-381.
11. Davila, M. A., Olson, D. L., and Freese, T. A. 1977. Submerged arc welding of ductile iron. *AFS transactions,* pp. 79-86.
12. Johansson, M. 1971. Austenitic-bainitic ductile iron. *AFS Transactions,* pp. 117-122.
13. Savage, W. F., Nippes, E. F., and Szekeres, E. S. 1976. A study of weld interface phenomena in a low alloy steel. *Welding Journal* 55(9): 260-s to 268-s.
14. *Specification for welding rods and covered electrodes for welding cast iron* (A5.15-82). 1982. Miami, Florida: American Welding Society.