GMA Weldability Characteristics of Lanthanide-Containing High-Strength Steels, Part 1: Arc and Metal Transfer

Arc and metal transfer were improved with a combination of rare earth metals in the electrode, electrode negative polarity and globular/spray mode

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ABSTRACT. Arc and metal transfer characteristics during GMA bead-on-plate welding were studied to understand and evaluate procedures to counteract the harmful effects of lanthanide or rare earth metals (REM) on the weldability of high-strength steels. The individual and combined effects of residual REM contents of plate and electrode wire (0.000 to 0.156%), type of wire (solid and flux cored), polarity, metal transfer mode setting and welding speed were evaluated from high-speed film documentation of the arc and from measurement of arc voltage and welding current. Moderate to significant variations in welding current, arc stability and metal transfer features were observed due to the influence of one or more of these six independent variables. Polarity of operation and/or the REM content of plates were found to affect the arc and metal transfer while welding with a REM-free solid wire. Significant improvements in arc and metal transfer resulted due to combined effects of straight polarity (electrode negative—DCEN) and globular/spray mode of operation, independent of the REM content of plates, while welding with solid electrode wires containing 0.04 to 0.156% REM. The presence of a higher REM content in the flux formulation (in relation to the plate) of the flux cored wire was also found to alter the metal transfer mode from globular-bridging to predominantly globular free fall.

Introduction

A variety of rare earth metal (REM) lanthanide-treated steels are available that offer a valuable combination of mechanical properties and technical advantages (Refs. 1–4). The optimum REM content of these steels, which is expressed as added amount (0.1 to 0.3%) or residual amount (equivalent to a REM/S ratio of greater than 3), depends on the composition of the steel, particularly with respect to minor elements like O, S, P, Sn and Pb; method of addition; time of addition during steel making; and on which form they are added (Refs. 1, 2). The advantages of using these steels have been tempered, however, by limitations which arise in welding them, *e.g.*, arc instability, incomplete penetration, improper bead shape (ropey welds), undercutting, etc. Accordingly, many industries are concerned about specifying REM-treated steels for applications that involve fusion welding processes.

REM-treated high-strength steels are highly attractive to a variety of industries such as pipeline, automobile, shipbuilding and oil rig platforms (Ref. 5). GMA and FCA welding processes are widely being used in such industrial applications because of their amenability for automation and robotics to achieve higher productivity with consistent quality. In the GMAW and FCAW processes, a good weld is made by transferring molten metal drops axially from a consumable electrode wire to the workpiece across a stable arc. Thus, the weld characteristics can be attributed primarily to the various events that take place during welding.

KEY WORDS

GMA Weldability
GMA Variable Effects
Rare Earth Metal/REM
Lanthanide Metal/REM
REM-Treated Steels
Cerium
High-Strength Steels
Arc/Metal Transfer
Straight Polarity
High-Speed Arc Film

The invariant weld characteristics such as the amount of spatter, bead shape, fusion zone (FZ) dimensions, recovery/loss of alloying elements, and the as-welded macro and microstructures can be related to the characteristics of arc, metal transfer, and weld pool behavior that constitute the events that occur during welding.

A number of process and material variables such as the magnitude and type of current, current density, electrode extension, shielding gas, power supply characteristics, material chemistry and characteristics have been found to influence the events during welding (Refs. 6, 7). Among these variables, the intentional and/or unavoidable minor elements present have contributed to the observed variation in arc and FZ dimensions in GTA and GMA welds made using identical welding conditions (Ref. 8).

Recently, the influence of minor amounts of REM in steels during GTA and GMA welding has been studied (Refs. 10–15) to understand and control their adverse effects on the final weld. These studies have illustrated the effects of REM on arc and weld pool behavior during low-current GTA welding and on the arc characteristics of short-circuiting GMA welding. Information relative to the effects of REM on metal transfer characteristics during GMAW is limited. In the present study (Ref. 16), the influence of the REM contents of the plate and electrode wire and of certain relevant GMA process variables on the arc and metal transfer were revealed through high-speed photography, and measurement of arc voltage and welding current. The

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Table 1—Chemical Composition of Steel Plates (wt-%)

Plate Designation	C	Mn	P	S	Al	Nb	N	Si	Ce[a]
151	0.08	1.04	0.013	0.013	0.038	0.078	0.006	0.019	0.003
31	0.08	1.00	0.013	0.012	0.040	0.085	–	–	0.007
30	0.10	0.99	0.015	0.012	0.055	0.087	–	–	0.010
33	0.08	0.99	0.012	0.011	0.050	0.074	–	–	0.016
32	0.07	1.02	0.015	0.011	0.048	0.088	–	–	0.020
35	0.08	1.01	0.013	0.011	0.052	0.077	–	–	0.022
34	0.09	1.01	0.015	0.011	0.050	0.075	–	–	0.023
112	0.08	1.09	0.013	0.009	0.058	0.076	0.010	0.010	0.037
152	0.08	1.06	0.014	0.006	0.051	0.082	0.009	0.032	0.078

(a) %REM = 2 × %Ce.

results have been interpreted to arrive at methods of overcoming the harmful effects of REM in steels.

Materials and Experimental Procedure

The experiments to be described were conducted on a laboratory scale using 6.35-mm (¼-in.) thick hot-rolled plates of 0.08C-1.04Mn-0.08Nb HSLA steels containing from 0.000 to 0.156% REM. Electrode wires (1.6-mm/1/16-in. diameter) of E70 grade, or equivalent, from different sources were used. Commercially available ER70S-1B wire was used as a reference wire to compare the performance of other wires. As there are no commercially available electrode wires containing REM, solid wires containing 0.04, 0.074 and 0.156% REM were made from the corresponding plate materials by slicing, section rolling and swaging. E70T-5, and E70T-5 with 0.061% REM flux cored wires were obtained from an electrode wire manufacturer. A mixture of 75% argon and 25% CO_2 at a flow rate of 18.9 L/min (40 cfh) was used as the shielding gas in all the experiments. Tables 1 and 2 show the composition of plates and electrode wires and the designations used in this paper.

Automated GMA bead-on-plate (BOP) welds were made on surface ground plates using a variable inductor, rectifier-type power supply. In a majority of cases, welds were made in the short-circuiting and globular/spray mode settings with both electrode-positive DCEP (reverse polarity) and electrode-negative DCEN (straight polarity) currents as shown in Table 3. A high-speed FASTAX camera was used to observe the arc and weld pool (where possible) during welding. The observations were recorded on Kodak Ektachrome film at 4000 frames/s, using three quartz-tungsten lamps of 1000 W each as a background source. The camera was less than 250 mm (9.8 in.) from the arc and the lens was protected by a shield.

The voltage across the arc was recorded (in selected cases) between the contact tube of the welding gun and the specimen plate using a Nicolet digital oscilloscope. The data were gathered at 4000 points/s, which is similar to the speed of filming during high-speed photography. Table 4 shows the actual current and voltage that were recorded as a result of a change in polarity, metal transfer mode, REM content of the plate and electrode wire, and the type of wire, for similar settings of the machine.

Results

The films and oscillographs were studied carefully to document information on metal transfer frequency, short-circuiting time, arc length, maximum diameter of droplets, direction of metal transfer, arc stability and amount of spatter (qualitatively). The observed metal transfer fea-

Table 2—Specification/Composition of 1.6-mm-Diameter Electrode Wires

Wire Designation		Equivalent Specification
1[a]	E70	ER70S-1B (AWS specification)
2	32	Same as 32 plate material
3	112	Same as 112 plate material
4	152	Same as 152 plate material
5[b]	E70T	E70T-5 (AWS specification)
6	E70T+	E70T-5, with 0.061% rare earths

(a) Electrodes 1, 2, 3 and 4 are solid wires.
(b) Electrodes 5 and 6 are flux cored wires.

Table 3—Bead-on-Plate GMA Welding Parameters[a]

Short-Circuiting Mode
- Current: 190 to 200 A
- Voltage: 20 V
- Travel Speed: 400 mm/min
- Wire Feed Speed: 2.13 m/min

Globular/Spray Mode
- Current: 320 to 330 A
- Voltage: 26 to 27 V
- Travel speed: 500 and 1000 mm/min
- Wire Feed Speed: 4.88 m/min for solid wire, 7.20 m/min for flux cored wire

(a) Refer to baseline condition, *i.e.*, without REM in plate or wire. Gas: argon/25% CO_2, flow rate:18.9 L/min, contact tube height: 19 mm.

Table 4—Variation of Current and Arc Voltage with REM in Plate and Wire for Different Preset Conditions

Weld Series[a] Designation	Welding Current (A) Plate 151	Welding Current (A) Plate 152	Arc Voltage (V) Plate 151	Arc Voltage (V) Plate 152
E70[b]-R[c]-S[d]	190	150–160	22.84	23.94
32-R-S	190–200	190–200	–	–
112-R-S	190–200	190–200	–	–
152-R-S	190–200	190–200	20.90	20.12
E70-S-S	110	110	25.58	25.80
32-S-S	Erratic		Erratic	
112-S-S	190–200	Erratic	20.28	20.24
152-S-S	Erratic		20.28	20.36
E70-R-P	320–330	300–310	–	–
32-R-P	350–370	325–350	–	–
112-R-P	350	350	–	–
152-R-P	325–350	325–350	25.00	25.26
E70-S-P	250–270	250–270	30.00	30.00
32-S-P	425–450	425–450	–	–
112-S-P	425–450	425–450	23.18	22.60
152-S-P	425–450	425–450	22.48	22.88
E70T-R-P	320–330	300–310	–	–
E70T-R-P	315–320	310–315	24.68	24.54

(a) Weld designation – Wire, polarity, metal transfer mode.
(b) Wire – E70, 32, 112, 152, E70T, and E70T+.
(c) Polarity – R (DCEP) and S (DCEN).
(d) Metal transfer mode setting – short circuiting (S), globular/spray (P).

tures were characterized by referring to other metal transfer studies (Ref. 17). The quality of welds were, however, judged from the appearance of the weld beads and their FZ characteristics (Ref. 18).

Short-Circuiting Mode
REM-Free Wire—ER70S-1B

Arc and metal transfer features of a steel without REM, shown in Fig. 1A, reveal stable arcing and excellent short-circuiting behavior with a high short-circuiting frequency (SCF) during DCEP welding. In contrast, the arc and metal transfer behavior shown in Fig. 1B, for a plate REM content of 0.156%, is far from a short-circuiting type. Significant differences in SCF, type of arc, arc length, maximum diameter of droplets and direction of metal transfer are evident from Table 5.

Oscillograph SCF measurements on 0.006 (86), 0.04 (36), 0.074 (16) and 0.156% (6 globules) REM-containing plates were carried out to ascertain trends and to check the measurements from high-speed films. The SCF measured from the oscillograph was 15% lower than that from the film for a low-REM plate (0.006%), but for higher REM content plates, excellent agreement was observed. Furthermore, the oscillographs shown in Figs. 2 A and B confirm the arc and metal transfer features from the high-speed film documentation. Thus, a strong influence of REM content (in the plate, over 0.04%) on SCF, arc and metal transfer is unequivocal. In other words, the presence of higher amounts of REM in the plate encourages the growth of large globules. Subsequently, arcing is established between globules and the weld pool and their transfer occurs due to globular-bridging. In addition, considerable flaring and wander of the arc typical of an unstable situation is also seen—Fig. 1B. These observations are in line with the results of Sasaki, *et al.* (Ref. 12), and Banks, *et al.* (Ref. 13), during GMA welding with CO_2 shielding.

In DCEN, oscillographs similar to the one shown in Fig. 2C were obtained at both high- as well as low-REM contents. The arc observations carried out during welding showed considerable growth of globules, independent of the amount of REM in the plate. The sharp decrease in SCF and the promotion of huge globular growth appears to discourage the use of DCEN as a means of overcoming the problems associated with higher REM in plates as proposed in the literature (Refs. 11, 12).

REM-Containing Wires—32 (0.04%), 112 (0.074%), 152 (0.156%)

Tables 6, 7 and 8 list the salient features of arc and metal transfer during the short-circuiting mode with REM-containing solid electrode wires (32, 112 and 152 wires, respectively). With a DCEP current, the amount of REM present in the plate has little influence on the aspects of arc and metal transfer with all three REM-containing wires. As the REM content of the wire is increased from 0.04% (32) to 0.156% (152), the maximum diameter of the globules increases from 2.6 to 4.0 mm (0.10 to 0.16 in.). However, the globules tend to grow out of the arc and transfer by bridging. Thus, from a metal transfer point of view, the presence of 0.04 to 0.156% REM in the wire is not advantageous.

In electrode negative polarity, it was extremely difficult to establish a near-stable arcing situation. In spite of harsh arcing, the globules showed a tendency to grow into the arc, but their transfer was by globular-bridging.

The arc voltage profiles shown in Fig. 2 (D–G) are typical of short-circuiting mode with 32, 112 and 152 electrode wires. These voltage profiles indicate

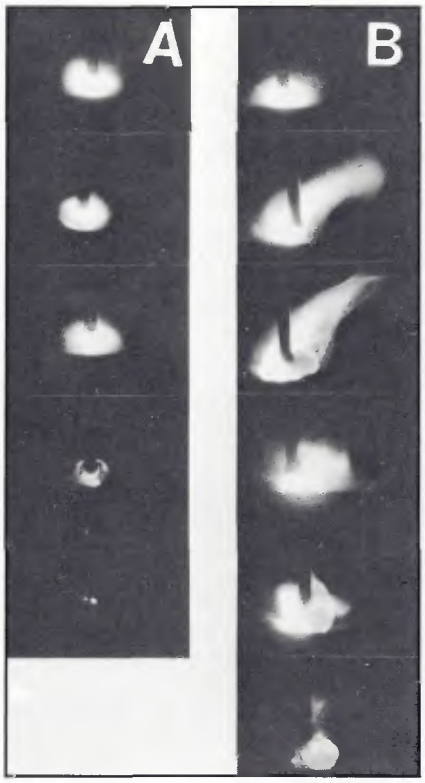

Fig. 1—Metal transfer features of E70 wire, DCEN short-circuiting mode. A—Plate 151; B—plate 152

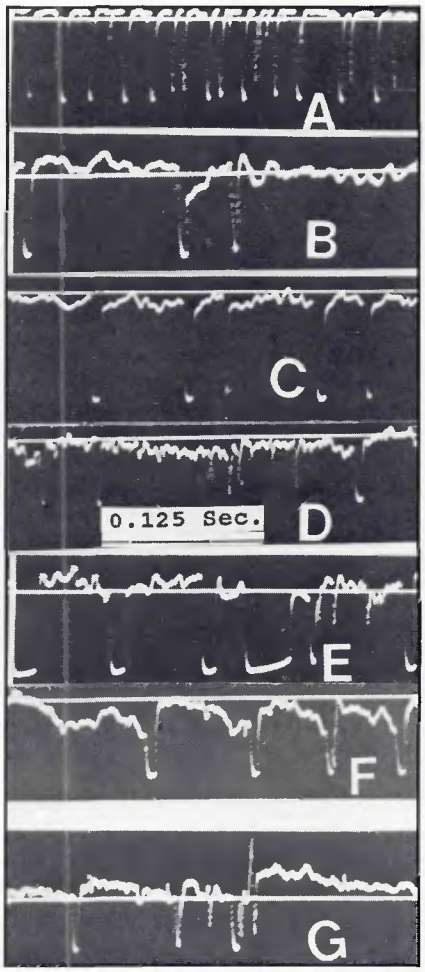

Fig. 2—Oscillographs of short-circuiting mode for: A—wire E70, DCEP; B—wire E70, DCEP; C—wire E70, DCEN; D—wire 112, DCEN; E—wire 152, DCEP; F—wire 152, DCEN; G—wire 152 DCEN

Table 5—Metal Transfer Features of E70 Solid Wire during DCEP Short-Circuiting Mode

	Percent REM in Plates	
	0.006 (151)	0.156 (152)
Type of arc	Smooth and stable	Flaring[a] and wandering
Arc length (mm)	2.45	3.40
Short-circuiting frequency (/s)	103	6 (globules)
Short-circuiting time (s)	0.003	0.009
Maximum diameter of drops (mm)	2.00	3.20 to 4.80
Growth direction of droplets	into the arc, axial	out of arc, nonaxial
Metal transfer type	Short-circuiting	Globular-bridging
Spatter	Nil	Very small
Quality of weld	Nice and uniform beads	Wavy, ropey and undercuts

(a) Uncontrolled deflection of the arc.

considerable fluctuations and irregular short circuits similar to that of E70-R-S152 weld—Fig. 2B.

Lesnewich (Ref. 19) has attributed the excessive growth of globules below a critical current (200 A) to the insufficient emissivity of the wire surface, even with activated wires. Agusa, *et al.* (Ref. 20), also noticed an unstable arc behavior with a 0.11% REM-containing wire below a critical current of 200 to 220 A in both DCEN and DCEP modes and recommend a constant-potential power supply together with automatic current and voltage regulation to achieve stability. In the present study there are signs of improvements in metal transfer, *i.e.*, decrease in drop size in DCEP with 32 wire (0.04% REM) and promotion of globular growth into the arc in DCEP operation.

Globular/Spray Mode
REM-Free Wire—ER70S-1B

Table 9 summarizes the results of the DCEP globular/spray mode at high (1 m/min, 3.28 ft/min) and low (0.5 m/min, 1.64 ft/min) welding speeds, while Fig. 3 illustrates the corresponding selected frames taken from the high-speed film documentation. Stable arc and tapering of the electrode wire tip are seen at both high as well as low welding speeds in the case of REM-free steel. However, the significance of welding speed is felt on metal transfer in the case of REM-free steel, *i.e.*, predominantly globular free fall at high speed and a high degree of projected spray at low speed, accompanied by occasional bridging of droplets due to the short contact tube height adopted. These observations indicate that with a 75% argon and 25% CO_2 shielding gas mixture it is not possible to attain a spray transfer similar to a higher argon mixture.

In the case of a high-REM-containing steel, the welding speed has little influence on the arc and metal transfer behavior. Reduction in drop frequency, growth of large globules and promotion of nonaxial repelled growth characterize the metal transfer features. In addition, considerable arc wander and flaring, longer and variable arc length are also noticed. Thus, higher amounts of REM in the plate promote undesirable arc and metal transfer features similar to short-circuiting mode—Fig. 1B.

In the DCEN polarity, the observations carried out during welding indicate an increase in arc voltage, decrease in current, and growth of large globules with identical welding conditions as in the DCEP polarity at both low and high REM in the plate. These results, which are similar to those of the short-circuiting mode, emphasize the unsuitability of DCEN polarity to overcome the problems of higher REM in plates from the arc and metal transfer point of view.

Table 6—Metal Transfer Features of 32 (0.040% REM) Wire during Short-Circuiting Mode

	DCEP		DCEN	
	0.006% REM	0.156% REM	0.006% REM	0.156% REM
Type of arc	Fairly stable		Unstable, with considerable circulation patterns on the surface of pool	
Arc length (mm)	1.70 to 2.60	1.70 to 2.60	Varies considerably	
Maximum diameter of droplets	2.60	2.60	1.70	3.20
Growth direction of droplets	Generally out of arc		Into the arc	Into the arc
Metal transfer	Globular-bridging		Globular-bridging	
Spatter	More	More	Less	Less
Quality of weld	Crowned and ropey beads		A lot of interruptions	

Table 7—Metal Transfer Features of 112 (0.074% REM) Wire during Short-Circuiting Mode

	DCEP	DCEN	
	0.156% REM (152)	0.006% REM (151)	0.156% REM (152)
Type of arc	Fairly stable	Unstable with circulations	Unstable
Arc length (mm)	1.70 to 2.60	Varies considerably	
Maximum diameter of droplets	4.10	3.40	3.20
Growth direction	Out of arc	Into the arc	Into the arc
Metal transfer	Globular-bridging	Globular-bridging	
Spatter	More	Less	More
Quality of weld	Crowned and ropey	Interruptions	

Table 8—Metal Transfer Features of 152 (0.156% REM) Wire during Short-Circuiting Mode

	DCEP	
	0.006% REM (151)	0.156% REM (152)
Type of arc	Fairly stable	Fairly stable
Arc length (mm)	1.50 to 2.60	1.70 to 2.60
Maximum diameter of droplets	3.70	4.10
Growth direction	Out of arc	Into the arc, occasionally out of arc
Metal transfer	Globular-bridging	
Spatter	More	More
Quality of weld	Crowned and ropey	Crowned and ropey

REM-Containing Wires—32, 112 and 152

The results of the arc and metal transfer studied with a 0.156% REM plate, shown in Table 10, do not reveal any significant difference due to the amount of REM in the wire during DCEP operation. Unlike the ER70S-1B wire (base level), REM-containing wires show a tendency to decrease the maximum size of droplets and promote their growth into the arc. Up to 0.074% REM in the wire, the metal transfer is generally by one or more of nonaxial free fall or projected spray with very small amount of globular-bridging. Repelled globular growth dominates at 0.156% REM in the wire and occurs occasionally with a low-REM wire. The large globules that are growing out of the arc shatter and cause heavy spatter in these welds. In Fig. 4, which shows the observed arc and metal transfer features, the tendency for tapering of the wire tips is also seen. Agusa, *et al.* (Ref. 20), also saw tapering of the electrode wire tip with REM-containing wires and recognized it to be the cause of improvements in the arc and metal transfer during DCEP polarity.

The results of arc and metal transfer with 32, 112 and 152 wires, shown in Tables 11 and 12 for DCEN polarity,

Table 9—Metal Transfer Features of E70 Solid Wire during DCEP Globular/Spray Mode

	Welding Speed			
	1 m/min		0.5 m/min	
	0.006% REM	0.156% REM	0.006% REM	0.156% REM
Type of arc	Stable	Flaring and wandering	Stable	Flaring and wandering
Arc length (mm)	3.80 to 4.00	3.0 to 5.00	1.50 to 2.00	>4.00
Drop frequency, (/s)	77	21	[a]	27
Maximum diameter of droplets (mm)	1.60	2.50 to 4.40	1.60	2.50 to 4.40
Growth direction of droplets	into the arc near axial	out of arc repelled	into the arc axial	out of arc repelled
Metal transfer type	Globular/spray and bridging	Globular and bridging	Spray/globular and bridging	Globular and bridging
Spatter	Nil	Moderate	Nil	Moderate
Quality of weld	Nice beads	Ropey	Smooth beads	Ropey

(a) Because of spray transfer, it was difficult to count the number of drops.

reveal certain strikingly different features compared to DCEP polarity. However, the variations due to different amounts of REM in the plate and wire are not appreciable. Arc constriction, short arc length and growth of smaller drops into the arc result in the transfer of metal drops by one or more of free fall and projected spray—Fig. 5. Due to short arc length, a certain amount of short-circuiting type of transfer is unavoidable. Further, steady and stable arc behavior and the absence of tapering of the electrode wire tip show a great resemblance to the results of Agusa, *et al.* (Ref. 20).

The oscillographs shown in Fig. 6 (A, B and C) are typical of DCEP polarity; DCEN polarity with 152 wire; and DCEN polarity with 32 and 112 wires, respectively. These oscillographs show a remarkable improvement due to the DCEN polarity, particularly with 32 and 112 wires, and resemble the oscillographs of projected spray transfer of Agusa, *et al.* (Ref. 20), and Watanabe, *et al.* (Ref. 21).

Flux Cored Wires—E70T-5 and E70T-5 with 0.061% REM

The results of the arc and metal transfer with E70T-5 wire, shown in Table 13 and Fig. 7, do not reveal any discernible variation due either to the welding speed or to the presence of REM in the steel plate. The growth of large globules in a nonaxial direction (repelled), and transfer of them by bridging, dominates the metal transfer. The occurrence of excessive bridging of globules can be attributed once again to the low contact tube height. In spite of the undesirable features of the arc and metal transfer, it appears that the flux facilitates the absorption of all the irregularities and restores proper bead shape even at a welding speed of 1 m/min (3.28 ft/min).

Appreciable improvements in the metal transfer are seen in Table 14 and Fig. 8 with the introduction of 0.061% REM into the flux formulation. When the REM content of the wire exceeds that of the plate, free-flight transfer dominates, drop size decreases and drops tend to grow into the arc. In addition, the wire becomes tapered and the arc attains stability. Conversely, when the REM content of the plate is greater than that of the wire, the arc and metal transfer show a strong resemblance to those of E70T-5 wire (REM-free). However, considerable dipping and tapering of the wire tip are clearly seen. The oscillographs shown in Fig. 6 (D and E) indicate a globular-transfer behavior typical of E70T-5 class wires (Ref. 22).

Table 10—Metal Transfer Features of 32, 112 and 152 Wires during DCEP Globular/Spray Mode on 152 Plate (0.156% REM)

	Wire Designation		
	32	112	152
Type of arc[a]	Not constricted Flared	Not constricted Flared	Not constricted Flared
Arc length (mm)	2.50 to 3.40	3.40 to 4.20	2.50 to 3.40
Drop frequency, (/s)	–	–	16
Maximum diameter of droplets (mm)	2.70 to 4.20	2.20	2.50 to 3.40
Growth direction of droplets	Into the arc, occasionally grows outside the arc		
Metal transfer type	Nonaxial globular, free fall, and projected spray	Close to axial free fall	Repelled globular
Spatter	Heavy, due to the explosion of large globules		
Quality of weld	Coarse and humped beads		

(a) Tapering of the electrode tip was noticed.

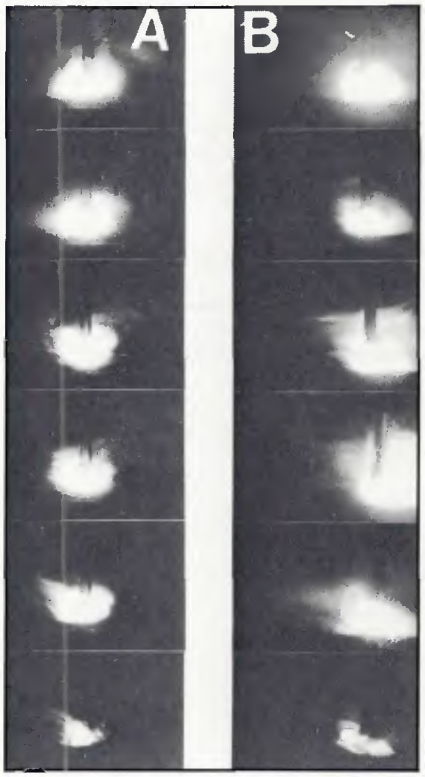

Fig. 3—Metal transfer features of E70 wire, DCEP globular/spray mode at a travel speed of 1 m/min. A—Plate 151; B—plate 152

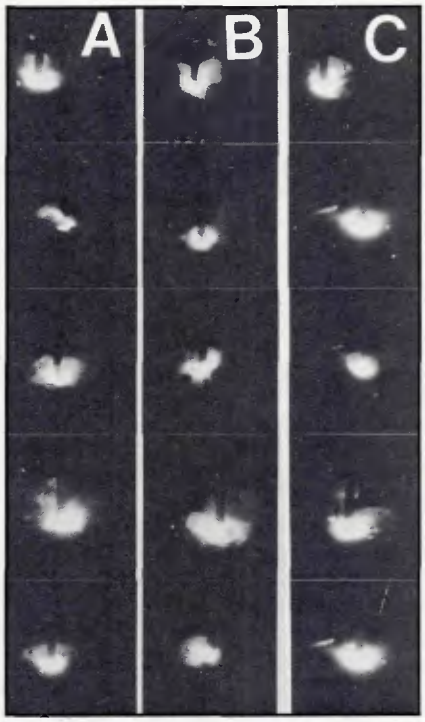

Fig. 4—Metal transfer features of REM-containing solid wires, DCEP globular/spray mode. A—Wire 32, B—wire 112; C—wire 152

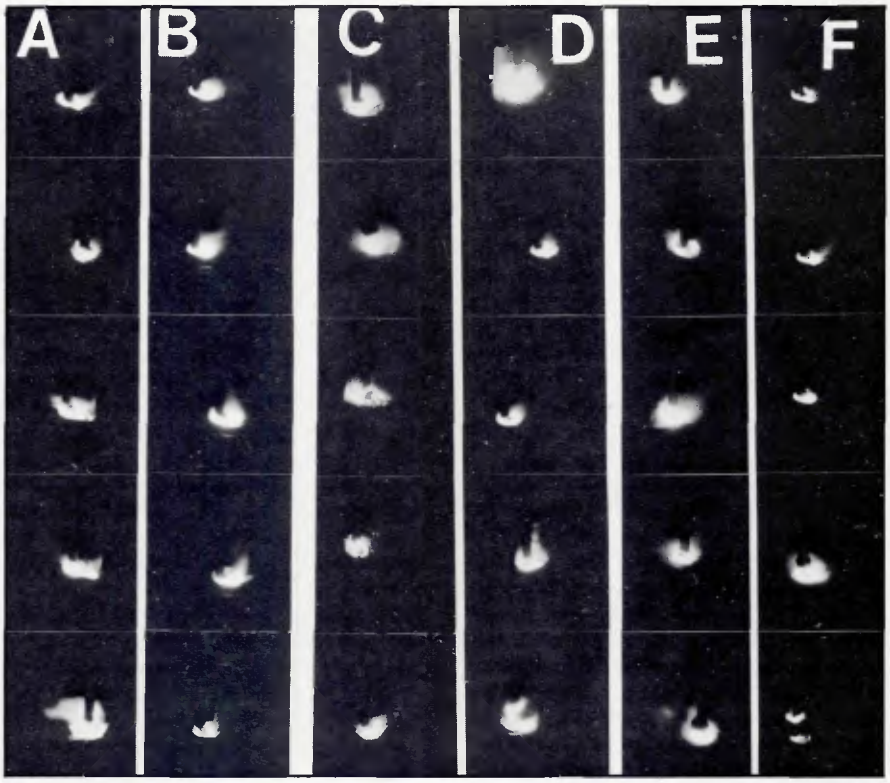

Fig. 5—Metal transfer features of REM-containing solid wires, DCEN globular/spray mode. A—Wire 32; B—wire 32; C—wire 112; D—wire 112; E—wire 152; F—wire 152

Welding Current and Arc Voltage

Significant to moderate variations in welding current and arc voltage from the base level values are evident in Table 4. The following results are unequivocal from the measurement of current and voltage during welding.

1) There is a significant decrease in welding current and an increase in arc voltage due to a change of polarity from DCEP to DCEN while welding with ER70S-1B wire on a REM-free plate in both short-circuiting and globular/spray modes.

2) The presence of 0.074% (and higher) amounts of REM in the plate alone has been found to decrease the current and increase the arc voltage moderately during DCEP welding.

3) Studies with REM-containing wires show a moderate to appreciable increase in welding current during DCEP and DCEN globular/spray modes, respectively, at both low and high amounts of REM in plates. However, during short-circuiting mode, no discernible difference in welding current is noticed due either to polarity or to REM content of the plate.

4) With flux cored wires, also, a slight decrease in the welding current is seen due to 0.074% and higher amounts of REM in the plate. This decrease gets moderated by the addition of REM into the flux formulation.

Table 11—Metal Transfer Features of 32, 112 and 152 Wires during DCEN Globular/Spray Mode on 151 Plate (0.006% REM)

	Wire Designation		
	32	112	152
Type of arc	Constricted but steady	Constricted but steady	Less Constricted but steady
Arc length (mm)	0.85 to 1.70	0.85 to 1.70	Slightly more
Drop frequency, (/s)	—	12	5
Maximum diameter of droplets	1.50 to 2.00	2.50	2.90
Growth direction of droplets	into the arc	into the arc	into the arc
Metal transfer type	Nonaxial projected spray, free fall, and bridging	Axial and nonaxial spray and globular	Axial projected spray
Spatter	Small	Small	Small
Quality of weld		Fairly smooth beading	

Discussion

Electrode Melting Rate and Metal Transfer

During GMAW, the electrode feed rate is varied to adjust the current desired. The electrode feed rate is equal to the melt rate when the arc length is fixed. In other words, for the same feed rate, when the machine settings are fixed as in the present situation, a decrease in current and an increase in arc length (and voltage) signify an increase in electrode melting rate, and the converse, with increase in current and decrease in arc length (and voltage). Essers and Walter (Ref. 23) have shown quantitatively that welding current has a significant role in altering metal transfer as it influences drop mass, frequency, velocity of impact and heat content of drops. Thus, any variation in melting rate can be expected to alter the metal transfer features during GMAW.

Electrode Activation, Melting Rate and Metal Transfer

Activation of electrode implies reduction in the work function and ionization potential by adding alkali, alkaline and

Table 12—Metal Transfer Features of 32, 112 and 152 Wires during Globular/Spray Mode on 152 Plate (0.156% REM)

	Wire Designation		
	32	112	152
Type of arc		Constricted but steady	
Arc length (mm)	0.85 to 1.75	0.85 to 1.75	Slightly more[a]
Drop frequency, (/s)	–	7	–
Maximum diameter of droplets	1.6	2.40	2.40
Growth direction of droplets	into the arc	into the arc	into the arc
Metal transfer type	Axial and nonaxial projected spray		Predominantly nonaxial globular
Spatter	Small	Small	Small
Quality of weld		Fairly smooth beading	

(a) Balling of electrode tip was observed.

Table 13—Metal Transfer Features of E70T Flux Cored Wire during DCEP Globular/Spray Mode

	1 m/min Welding Speed		0.5 m/min Welding Speed	
	0.006% REM	0.156% REM	0.006% REM	0.156% REM
Type of arc	Flared	More flared	More flared	More flared
Arc length (mm)	≤4.00	≤4.00	≤4.00	≤4.00
Maximum diameter of	3.00 to 4.80	3.00 to 4.80	3.00 to 4.80	3.00 to 4.80
Growth direction	Out of arc	Out of arc	Out of arc	Out of arc
Metal transfer		Nonaxial globular with bridgings		
Spatter	Less	More	Less	More
Quality of weld		No discernible differences in weld bead shape		

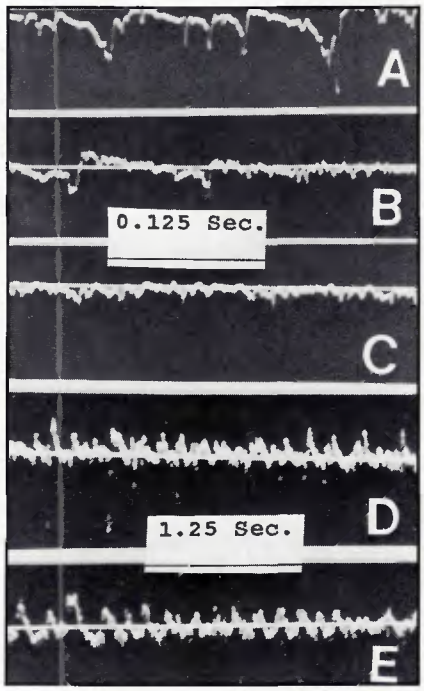

Fig. 6 – Oscillographs of globular/spray mode with different wires and polarity. A – Wire 152, DCEP, B – wire 152, DCEN; C – wire 112, DCEN; D – wire E70T+, DCEP; E – wire E70T+, DCEP

rare earth elements or their compounds as invisible wash coatings, or by alloying (Refs. 6, 7). This concept was patented by Muller (Ref. 24) and later developed by Lesnewich (Refs. 25, 26) to achieve stable arc welding, control of electrode melting rate and acceptable metal transfer during DCEN GMA welding. It was proposed that activating elements, when present in the electrode (cathode), reduce the melting rate by consuming the energy supplied to the wire through electron emission because of their low work function. However, it was also recognized that the anode processes were less sensitive to activation treatment.

REM in Plate Alone

The influence of REM in the plate on the arc and metal transfer observed so far is very similar to the observations made by Sasaki, *et al.* (Ref. 12), Agusa, *et al.* (Ref. 20), Li and Patchett (Ref. 11), and Banks, *et al.* (Ref. 13). These authors have tried to explain the influence of REM in the plate based on: work function, ionization potential, cathode jet formation and/or pinch force. Based on the results of this study, an attempt has been made to combine the influence of all aforesaid physical characteristics to logically explain the observed arc and metal transfer features.

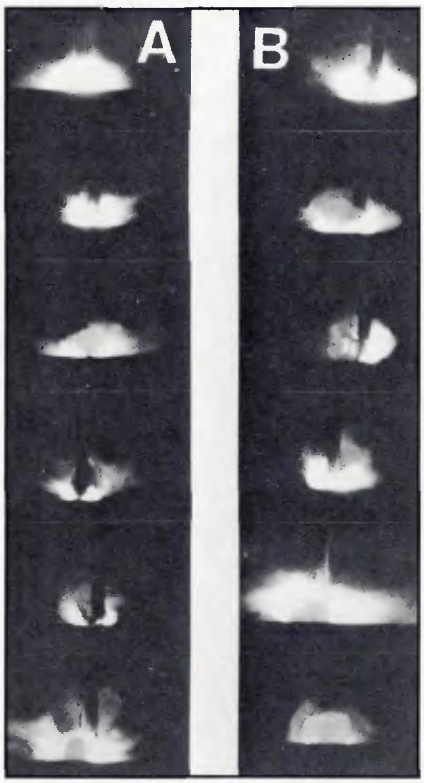

Fig. 7 – Metal transfer features of E70T flux cored wire, DCEP globular/spray mode at a travel speed of 1 m/min. A – Plate 151; B – plate 152

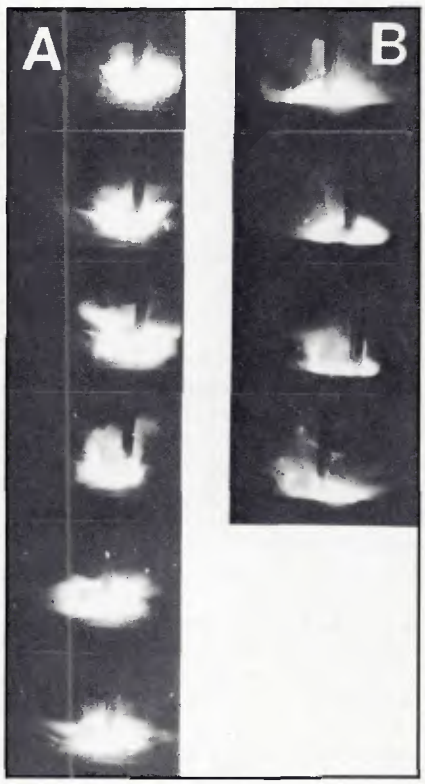

Fig. 8 – Metal transfer features of E70T+ flux cored wire containing 0.061% REM, DCEP globular/spray mode. A – Plate 151; B – plate 152

Table 14—Metal Transfer Features of E70T+ Flux Cored Wire during DCEP Globular/Spray Mode at 1.0 m/min Welding Speed

	0.006% REM (151)	0.156% REM (152)
Type of arc	Stable	Flared
Arc length (mm)	≤4.00	≤2.00
Drop frequency, (/s)	22	16
Maximum diameter of droplets	3.00 to 4.00	3.00 to 4.00
Growth direction	into the arc	out of arc
Metal transfer	Nonaxial free flight	Globular-bridging with considerable dipping
Spatter	Less	More
Quality of weld	Uniform bead shape	

It is well understood that REM in steels are generally associated with nonmetallic inclusions (Ref. 1). In DCEP welding, REM present in the plate (cathode) can be expected to reduce its work function, promote cathode-jet formation and confine the arc due to activation. Cathode jets can transfer more energy to the wire electrode (anode) and increase its melting rate at a given feed rate which results in an increase in arc length, decrease in welding current and an increase in arc voltage. A decrease in current further encourages the growth of large globules because of a sharp decrease in pinch force (Ref. 27). These effects are significant at higher REM content of plates and even with flux cored wires in both short-circuiting and globular/spray mode settings. Some researchers (Ref. 12) believe that electrons emitted from the plate can support huge globules for longer duration. However, this concept needs further scrutiny because of the insignificant mass of electrons.

When the polarity is changed to DCEN, the plate becomes the anode. All the adverse characteristics of DCEN polarity on arc and metal transfer are noticed with and without the presence of REM in the plate. This clearly indicates that a mere change of polarity is not a good proposition to overcome the problems of REM in plates, as suggested by Li and Patchett (Ref. 11). These observations clearly show that activation of a nonwire type of anode has very little influence on the arc and metal transfer features.

REM in Electrode Wire Alone

In the normal DCEP polarity, REM in the wire (anode), because of their low ionization potential, presumably decrease the energy available for melting the electrode. A measurable increase in current, a decrease in arc length and arc voltage observed, particularly in the high current range (globular/spray), for the same wire feed rate imply a decrease in melting rate. Tapering of the electrode tip indicates a decrease in the area of the anode or an increase in current density. An increase in current and current density, and a decrease in melting rate, decrease the size of globules and improve the metal transfer. These observations indicate that the effects of activation of the anode are significant when the anode is in the form of a wire.

The effects of REM in the wire are highly significant in the DCEN polarity, *i.e.,* when the wire is cathode. Now REM in the wire reduce the work function and aid electron emission to keep the wire from melting excessively. This results in a considerable reduction in the melting rate. Reduction in the electrode melting rate for the same wire feed rate implies a sharp increase in current, short arc length and a decrease in the arc voltage. The increase in current increases the pinch force, frequency and velocity of drops, and decreases the drop size. All these effects mean a favorable arc and metal transfer condition.

However, in the low-current region (short circuiting) the contribution of REM in the wire is not encouraging in either of the polarities. This indicates that a minimum current level has to be maintained to achieve the beneficial effects of REM in the wire. A similar observation has been made by Agusa, *et al.* (Ref. 20), and Lesnewich (Ref. 26).

REM in Plate and Wire

Both in DCEN and DCEP, very little change is noticed with REM in the plate from that of REM in the wire alone. These observations further emphasize that effects of REM in an electrode of wire form is dominant over REM in the plate, and can be described by the mechanisms of REM-containing electrode wires.

Flux Cored Wires

Arc and metal transfer features are different from those of solid wires due to the presence of the flux. The metal transfer features of a flux cored E70T-5 wire are highly unfavorable. But the addition of REM to the flux formulation appears to promote more of the free-fall type of transfer instead of huge globular bridging. Once again, the presence of the REM in the wire seems to be dominant over effects of the REM in the plate.

Conclusions

Flaring and wander of the arc, increase in arc length, nonaxial growth and transfer of large globules, decrease in metal transfer frequency, increase in arc voltage and a decrease in current result due to higher amounts of REM (0.074 and higher) in the plate in both the short-circuiting and globular/spray modes with DCEP current and REM-free wire.

Spray transfer typical of that obtained with a high-argon shielding gas cannot be achieved with a 75% argon and 25% CO_2 gas mixture even at very high currents. The transfer is invariably of a projected spray, even in the absence of REM.

A decrease of the welding speed from 1 to 0.5 m/min does not show any improvement in the arc and metal transfer in the presence of REM in the plate.

While welding with ER70 wire, a change of polarity from DCEP (reverse polarity) to DCEN (straight polarity) promotes unfavorable arc and metal transfer characteristics independent of the level of REM in the plate.

Arc and metal transfer show appreciable improvement due to straight polarity and globular/spray metal transfer mode settings while welding with 0.04 to 0.156% REM-containing solid wires. However, the influence of the REM content of plates on the various events that occur during welding are not significant.

Projected spray and/or free-fall type of metal transfer with reduced arc length, a sharp increase in current and a decrease in the arc voltage result due to the DCEN globular/spray mode of operation with all the three REM-containing wires. It appears that the utilization of REM-containing wires in DCEN welding is a good method to overcome the problems of REM in steels.

Metal transfer features during the short-circuiting mode with REM-containing wires do not show any significant difference due either to the REM content of plates or wire, or the polarity of operation. The arcs tend to be highly unstable during electrode positive polarity operation.

It is possible to improve the metal transfer in the case of flux cored wires by having a greater amount of REM in the flux in relation to that of the plate.

The effects of REM when present in the wire electrode dominate the effects of REM in the plate electrode.

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Revised WRC Bulletin 297
September 1987

Local Stresses in Cylindrical Shells Due to External Loadings on Nozzles—Supplement to WRC Bulletin 107 (Revision I)

By J. L. Mershon, K. Mokhtarian, G. V. Ranjan and E. C. Rodabaugh

This Revised Bulletin 297 is intended as a replacement for the current supplement to Bulletin 107 and is specifically applied to cylindrical nozzles in cylindrical vessels. It replaces WRC Bulletin 297, August 1984. The changes in the text, figures and tables to update the 1984 edition of Bulletin 297 are described in the "Foreword to Revision I."

This revised Bulletin was prepared by the Subcommittee on Reinforced Openings and External Loadings of the Pressure Vessel Research Committee of the Welding Research Council. The price of Revised Bulletin 297, September 1987, is $24.00 per copy, plus $5.00 for postage and handling. Orders should be sent with payment to the Welding Research Council, Suite 1301, 345 E. 47th St., New York, NY 10017.

WRC Bulletin 335
August 1988

A Review of Area Replacement Rules for Pipe Connections in Pressure Vessels and Piping

By E. C. Rodabaugh

Pressure vessel and piping codes have used the area replacement concept for at least 50 years. This concept requires that the metal cut out by an opening be replaced by reinforcement within a prescribed zone around the opening. During the past 20 years, a substantial amount of information has accumulated which indicates that the area replacement concept, in some applications, is excessively conservative. Alternative rules are given in this report for the two extremes of their application: 1) for all reinforcing in the nozzle and 2) for all reinforcing in the vessel.

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