A Study of Weld Pore Sensitivity of Self-Shielded, Flux Cored Electrodes

An investigation revealed both nitrogen and oxygen content can affect the formation of porosity in welds made using FCAW-S electrodes

BY Q. WEI, Q. HU, F. GUO, and D. J. XIONG

ABSTRACT. Porosity in weld metal refers to the cavity-type discontinuities formed by gas entrapment during solidification. It is one of the most common defects of the self-shielded, flux cored arc welding (FCAW-S) process. In the present study, the causes and influence factors of pore formation in welds made by a self-shielded, flux cored electrode were investigated. The results of this study revealed nitrogen content is not the only main influence factor in the formation of porosity in welds made by an FCAW-S electrode; oxygen can also rapidly increase the number of pores in such welds. It was found aluminum and rare earths (RE) effectively reduce the pore sensitivity of welds. Of the two materials, aluminum has a stronger ability of reducing nitrogen than RE. Both aluminum and RE significantly reduce oxygen content in the weld.

Introduction

Self-shielded flux cored arc (FCAW-S) welding has become popular for many applications because it does not require equipment for gas shielding, resulting in simplicity of operation. Also, the electrode holder is simpler than the one used with auxiliary shielding gas. Development of all varieties of the self-shielded, flux cored electrodes (FCAW-S electrodes) has been, as a result, an area of great manufacturing and research interest (Refs. 1–4).

Q. WEI, Q. HU, and D. J. XIONG are, respectively, Associate Professor, Doctoral Student, and Professor at Beijing Polytechnic University, School of Materials Science and Engineering, Beijing, P.R.C. F. GUO (guofu@pilot.msu.edu*) is a Doctoral Student at Michigan State University, Department of Materials Science and Mechanics, East Lansing, Mich.*

Porosity in weld metal is one of the most difficult problems to be solved when developing an FCAW-S electrode. Since there is neither an outside protective atmosphere nor welding flux provided in the welding area, liquid weld metal can be easily contaminated by air. Pore sensitivity of a weld thus increases and is difficult to control. In production practice, porosity frequently appears in welds made by a FCAW-S electrode, which seriously impairs the quality of weld metal and influences the overusage of FCAW-S electrodes (Refs. 5, 6). Much research has been done to investigate the causes and prevention of pore formation in the weld metal of FCAW-S electrodes. The effects of metallurgical reaction (Refs. 5–11), as well as welding parameters (Refs. 7, 12–15) on the formation of weld porosity, have been two major areas of research. Various models and mathematical/thermodynamical evaluations of pore susceptibility were also presented in an effort to clarify the mechanism for pore formation (Refs. 8 , 11, 16). Typically, nitrogen is regarded as the determinative factor for formation of pores in welds made with FCAW-S electrodes (Refs. 5, 6, 8–11), but other research findings have concluded porosity was not well controlled by reducing nitrogen content only in the weld metal (Refs. 17, 18). Therefore, it is imperative the mechanisms and influence factors of porosity formation in a FCAW-S weld be thoroughly studied. The present study thus focuses on other factors influencing pore formation in the weld in addition to nitrogen content. The effects of simulative gaseous flow, oxygen content in the weld, as well as aluminum and RE alloy addition in the flux core, on pore sensitivity are presented.

KEY WORDS

Pore Sensitivity
Self-Shielded, Flux Cored Electrode
FCAW-S
Porosity

Experimental Method

The FCAW-S electrodes used in the experiment were CaF_2-Al-Mg type FCAW-S electrodes that meet AWS A5.20 E 70 T-G requirements. The electrodes consisted of a thin, low-carbon steel sheath surrounding a core of fluxing and alloying materials. The cross section of the electrode was 2.0 mm in diameter and O-shaped, as illustrated in Fig. 1.

In order to test pore sensitivity, the experiment conditions were varied as follows.

1) Added to shield the arc area was a simulative gaseous flow with different compositions (pure argon, pure oxygen, CO_2, air, and mixed gases with varying proportions of oxygen and argon, nitrogen and argon, oxygen and nitrogen), as shown in Table 1.

2) Two series of FCAW-S electrodes were designed by separately changing the amount of RE alloys and Al in the flux core. Changes in the added RE alloys are shown in Table 2.

Two kinds of steel sheaths (H08A and H05Al) with different Al contents were used. The composition of the steel sheaths is listed in Table 3. The varied percentages of added Al powder in the flux core were 7, 9, 11, 13, and 15% when using the H08A steel sheath and 2, 4, 6, 8, 10, and 12% when using a H05Al steel sheath containing aluminum.

The weld metal specimens were prepared by welding two no-groove, low-carbon steel plates (150, 100, and 10 mm) with single-pass butt joint welding. Welding parameters are listed in Table 4. The amount of surface and inner pores in a

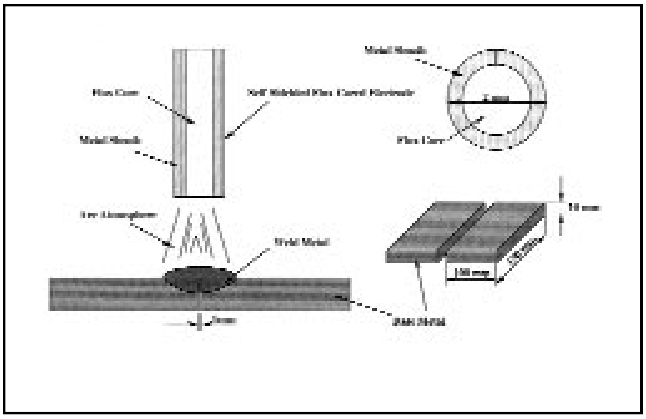

Fig. 1 — Illustration of experimental setup.

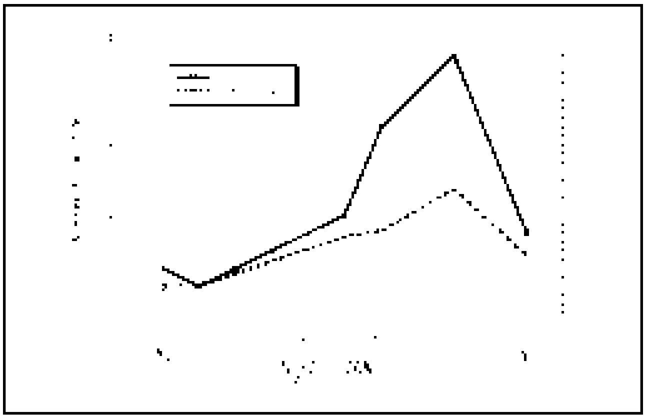

Fig. 2 — Effect of oxygen and nitrogen content on weld metal porosity.

Table 1 — The Composition of Simulative Gaseous Flow (%)

Gas Type Simulative Gas #	Ar	N_2	O_2	CO_2	Air
1	0	0	0	100	0
2	0	0	0	0	100
3	100	0	0	0	0
4	75	25	0	0	0
5	50	50	0	0	0
6	22	78	0	0	0
7	0	100	0	0	0
8	0	0	100	0	0
9	20	0	80	0	0
10	50	0	50	0	0
11	60	0	40	0	0
12	70	0	30	0	0
13	78	0	22	0	0
14	0	90	10	0	0
15	0	78	22	0	0
16	0	70	30	0	0
17	0	50	50	0	0
18	0	40	60	0	0
19	0	20	80	0	0

Table 2 — Effects of RE on O-Content, N-Content, and Porosity in Weld Metal

Type of Re Additives	Amount of RE Alloy Addition in the Flux Core (%)	Effective RE Amount in the Flux Core* (%)	Content of Oxygen (%)	Content of Nitrogen (%)	Number of Pores in Weld Metal
Ca-Mg-Ba-RE Alloy	1	0.041	0.0157	0.032	15
	3	0.123	0.0148	0.032	5
	5	0.205	0.0126	0.033	5
	7	0.287	0.0130	0.046	8
	9	0.369	0.0125	0.039	6
Ni-RE Alloy	3	1.050	0.0057	0.041	0
RE Metal Mixture	1	1.000	0.0035	0.044	0

*The percentage of RE in Ca-Mg-Ba-RE alloy is 4.1%. Thus, the effective amount of RE added to the flux core of the wire are 0.041%, 0.123%, 0.205%, 0.287%, and 0.369% corresponding to the percentage of Ca-Mg-Ba-RE alloy addition of 1%, 3%, 5%, 7%, and 9%.

100-mm length of cooled weld was visually examined and X-ray inspected. The minimum size of counted pores was 1⁄64 in. (0.4 mm) according to AWS A5.20. The experimental setup and basic dimensions of the base metals are also illustrated in Fig. 1.

Results and Discussion

Effect of Different Shielding Gases on Weld Porosity

Experimental results show no pores in weld metal welded in a pure argon or pure CO_2 atmosphere. A small amount of pores was found in metal welded in pure oxygen, pure nitrogen, mixed gas of oxygen and argon, mixed gas of nitrogen and argon, and air atmospheres. These results indicate the flux in the core of the experimental FCAW-S electrode can provide a gas and slag shield for hot metal that will prevent a different arc atmosphere from contamination and somewhat reduce weld pore sensitivity, as previously mentioned (Refs. 17, 18). The amount of pores increases rapidly under a mixed gas of oxygen and nitrogen and reaches an extreme value with a content of 80% oxygen - 20% nitrogen, as shown in Fig. 2. To be more specific, the number of pores increases with an increase in oxygen content up to 80% and nitrogen content up to 20%. The actual welding atmosphere of the FCAW-S electrode is air. The mixed proportion of oxygen and nitrogen in the air falls in the left side of the extreme value, where weld porosity increases with the increase of oxygen content in the arc area. In other words, oxygen enhances the possibility of pores being produced in the weld metal of an FCAW-S electrode. Therefore, it is important to prevent nitrogen from coming

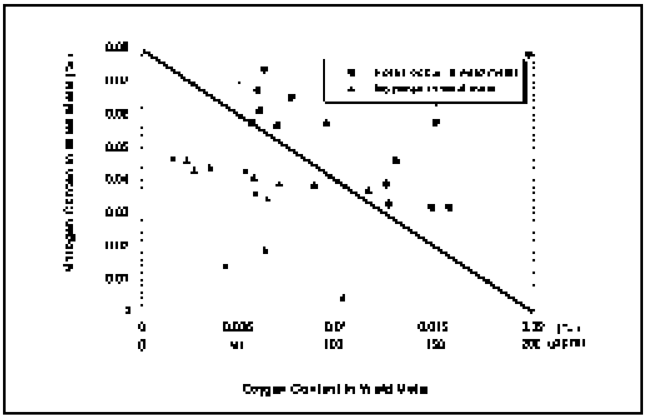

Fig. 3 — Correlation between oxygen content, nitrogen content, and pore formation in weld metal.

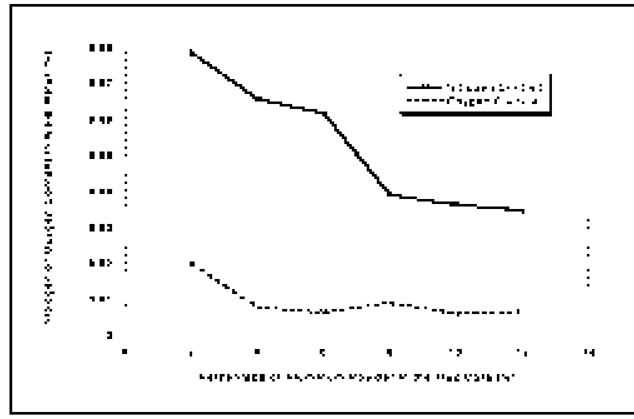

Fig. 4 — Effect of aluminum addition in the flux core on the oxygen and nitrogen content in weld metal.

into the arc area and to reduce the oxygen content in weld metal to obtain an acceptable porosity level in welds made using an FCAW-S electrode.

Some weld pores of FCAW-S electrodes were observed to be similar to very small pinholes of nitrogen, while others were similar in appearance to wormholes of CO (Ref. 19, 20). Some pores with a different morphology, such as round pores, were also noted in the weld metal. So, it can be inferred the weld pores of the FCAW-S electrode are not simply N_2 or CO pores but a mixture of both N_2 and CO pores, and even more complicated combination pores of CO and N_2 according to pore morphology and weld metal oxygen and nitrogen content.

Table 3 — The Composition of Steel Sheathes

Type of Steel Sheath	C	Si	Mn	S	P	Al
H08A	0.06	0.029	0.26	0.009	0.015	0.035
H05Al	0.05	0.062	0.54	0.013	0.016	0.7

Table 4 — Welding Parameters

Current (A)	Voltage (V)	Travel Speed (mm/s)	Polarity
240–260	25–28	10–15	DCEP

Effect of Deposited Oxygen and Nitrogen Content on Weld Metal Porosity

As stated previously, oxygen and nitrogen content in weld metal affect the formation of weld pores. In order to determine the relationship between pore sensitivity and oxygen and nitrogen content in weld metal, a large number of data points with specific oxygen and nitrogen contents were collected and plotted in Fig. 3. The figure illustrates pore occurrence at certain oxygen and nitrogen levels and shows pores were formed only when the oxygen and nitrogen content in the weld metal were above the diagonal line. No porosity was evident in weld metal with oxygen and nitrogen content below the diagonal line. Therefore, the higher the oxygen and nitrogen content in the weld metal, the greater the pore sensitivity. In addition, an analysis of the experimental results from Fig. 3 found the average nitrogen content of weld metal produced with FCAW-S electrodes in the no-porosity condition can reach 400–500 ppm, a much higher level than that of weld metal produced with SMAW electrodes. However, the average oxygen content of weld metal produced with FCAW-S electrodes can reach as low as 16 ppm under the same condition, which is much lower than that of weld metal produced with SMAW electrodes. As a comparison, in the no-porosity condition, the nitrogen content is ~150 ppm in deposited weld metal produced with a titania-type SMAW electrode and is ~100 ppm in deposited weld metal produced with a low hydrogen-type SMAW electrode. The oxygen content in deposited weld metal of the titania-type SMAW electrode was ~650 ppm, and ~200–300 ppm in deposited weld metal produced with a low hydrogen-type SMAW electrode (Ref. 19). Therefore, it is evident the weld metal produced with an FCAW-S electrode is significantly affected by nitrogen in the air, which causes a dramatic increase in nitrogen content. The high nitrogen content in weld metal produced with an FCAW-S electrode is difficult to control to a lower extent (Refs. 17, 18). Consequently, to prevent the formation of pores in weld metal produced with an FCAW-S electrode, the oxygen content should be much less than that of weld metal produced with an SMAW electrode to compensate for the high nitrogen content. An example that is less than 100 ppm is shown in Fig. 3. This conclusion provided more experimental evidence that oxygen can enhance the possibility of pore formation.

A possible mechanism of nitrogen and oxygen deposition in weld metal can be explained by

$$\frac{1}{2}N_2 + \frac{1}{2}O_2 = NO$$

using the interaction between nitrogen and oxygen in the welding atmosphere.

The product of the reaction, NO, can be adsorbed on the surface of liquid weld metal, then decomposed into N and O under the action of its surface tension (Ref. 19). Meanwhile, the N and O atoms dissolve in liquid weld metal. Therefore, the formation of NO in the arc atmosphere ultimately increases both oxygen and nitrogen content in weld metal.

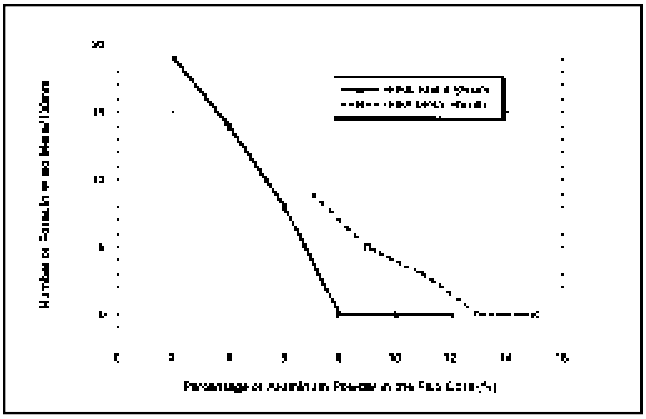

Fig. 5 — Effect of aluminum addition in the flux core on the formation of pores in weld metal with different metal sheaths.

Effect of Aluminum on Weld Metal Porosity

Aluminum is an effective element to reduce porosity in weld metal (Ref. 19). The changes of oxygen and nitrogen content in weld metal with the percentage change of aluminum powder in the flux core of the electrode are shown in Fig. 4. The decrease in both the oxygen and nitrogen content is obvious when aluminum powder in the flux core is increased, which proves aluminum has a powerful capability of deoxidizing and reducing nitrogen content.

However, only limited amounts of aluminum powder can be added to the flux core of the electrode because of its low density. Excessive additions of aluminum powder in the flux core will cause fabrication difficulties and lead to bad processing properties of the electrode. In order to reduce the aluminum powder in the flux core and to simultaneously make the weld metal porefree, a new type of metal sheath containing aluminum (H05Al) was used instead of the ordinary metal sheath (H08A). This new type of metal sheath (H05Al) overcame the problems related to the presence of large amounts of aluminum powder in the flux core. The change in the amount of pores in weld metal with the amount of aluminum powder in the flux core is illustrated in Fig. 5 for both H08A and H05Al metal sheaths. It shows the amount of pores was reduced with the increase of the percentage of aluminum powder in the flux core of the electrode for both metal sheaths. It was also found the amount of weld pores was reduced to zero only if the percentage of aluminum powder in the flux core reached 13% with H08A metal sheath. The content of residual aluminum in weld metal is 1.22 wt % in this condition. In contrast, when the electrode was fabricated with H05Al metal sheath, no pores appeared when the percentage of aluminum powder in the flux core reached 8%. In this case, the residual aluminum content in weld metal was only 0.84 wt %. The above comparison shows the electrode made with a metal sheath containing aluminum can increase the protective effect, and thereby decrease the pore sensitivity. The substitution of an H08A metal sheath with an H05Al metal sheath effectively reduces the residual aluminum content in weld metal and, consequently, improves its toughness. In addition, the fabrication process of the electrode becomes more convenient due to the reduced amount of aluminum powder in the flux core.

The experimental results and analyses discussed above suggest the mechanism for aluminum to reduce pore sensitivity can be based on the following:

1) Aluminum is a better deoxidant than titanium, carbon, magnesium, or zirconium (Ref. 20). Aluminum can reduce oxygen potential in the welding atmosphere. The reaction formulas of deoxidization are the following:

$$2Al + 3CO_2 = 3CO + Al_2O_3$$
$$4Al + 3O_2 = 2Al_2O_3$$

2) Aluminum can reduce the nitrogen concentration in weld metal by reducing O potential and the NO partial pressure in the welding atmosphere.

3) Aluminum and nitrogen have a great affinity for reacting with each other to form a stable aluminum nitride, which does not dissolve in molten steel but instead in slag. Therefore, it can be seen the higher the aluminum content in the flux core, the less the oxygen and nitrogen content in the weld metal, resulting in a lesser number of weld pores that will occur in the weld metal.

Effect of RE Alloy Addition on Weld Metal Porosity

The effects of three kinds of RE additives on oxygen content, nitrogen content, and porosity in weld metal were investigated in this study.

Table 2 shows the oxygen content and the porosity level decrease with the increase of Ca-Mg-Ba-RE alloy addition in the flux core. Note the nitrogen content was not affected by the change of alloy addition. Table 2 also indicates porosity was not completely eliminated and the oxygen content in weld metal was still high even with a 9% addition of the Ca-Mg-Ba-RE alloy in the flux core. Incomplete deoxidization due to the low content of RE in Ca-Mg-Ba-RE alloy (only 4.1%) may account for the high residual oxygen content in the weld metal. RE metal mixture was shown to have a strong ability to deoxidize. A small amount of RE metal mixture added in the flux core (only 1%) could significantly reduce the oxygen content and the pore sensitivity in the weld metal. However, because the RE metal mixture can be oxidized at room temperature and is extremely difficult to crush into powder form, it cannot be applied in industrial practice. Compared with the two types of RE additives mentioned earlier, Ni-RE alloy was also shown to have a strong ability to deoxidize and reduce pore sensitivity. The main advantage of this alloy is it can easily be added in the flux core of the electrode during fabrication. Therefore, Ni-RE alloy is suggested as the best RE additive among the three. RE elements reduce pore sensitivity by reducing oxygen content in weld metal due to their strong affinity with oxygen. The reaction product will eventually enter into slag in the form of RE oxide (RE_2O_3). As a result, oxygen content and CO pore sensitivity decrease dramatically with an increase in RE content in the flux core. The results in Table 2 also show there is no meaningful change in nitrogen content with the change of RE alloy addition in the flux core, which indicates the capability of RE additives to reduce nitrogen content in weld metal is weaker than aluminum.

Conclusions

1) Weld porosity of FCAW-S electrode is related to both oxygen and nitrogen content in weld metal. Oxygen can enhance the possibility of pore production in weld metal. Reducing oxygen and nitrogen potential in the welding atmosphere, as well as the oxygen and nitrogen content in weld metal, is the main measure of pore sensitivity reduction.

2) Aluminum and RE can effectively reduce pore sensitivity of the weld because both aluminum and RE have a strong ability to reduce oxygen content in weld metal. In this investigation, aluminum had a strong ability to reduce nitrogen content in weld metal and RE alloys had no meaningful affect on nitrogen content reduction in weld metal.

Acknowledgment

The authors acknowledge the support of the 8th Five-Year Key Technological Development Project Funds, administered through the Beijing Educational Committee, for help with this project.

References

1. ASM Committee on Flux Cored Arc Welding. 1983. *Metals Handbook*, Vol. 6, 9th ed., p. 96. Metals Park, Ohio: American Society for Metals.
2. Gustafsson, B., and Widgery, D. 1989. Cored wires. A review. *International Journal for the Joining of Materials* 1(3): 6–13.
3. Anon. 1991. What's new in welding consumables? *Welding and Metal Fabrication* 59(3): 138, 140–142.
4. Hesbrook, W. G. 1993. Adopting self shielded wire for shipbuilding. *Welding and Metal Fabrication* 61(5): 223–224.
5. Wegrzyn, J. 1992. Porosity and toughness of self shielded flux cored wire weld metal. *Welding International* 6(9): 677–682.
6. Wegrzyn, J. 1993. Toxicity, porosity and impact strength; problems in welding with self shielding cored wires. *Welding International* 7(9): 677–682.
7. BuKi, A. A. 1984. Self-shielding properties of welding wires. *Welding Production* 31(10): 13–16.
8. Zhang, Z., Chen, B., Zhang, W., and Feng, L. 1997. Investigation on mechanism of fixing nitrogen in self shielded flux cored arc welding. *China Welding* 6(1): 25–30.
9. Yeo, R. 1997. It's quicker by tube — welding with self-shielded cored wires. *Welding and Metal Fabrication* 65(3): 13–14.
10. Gruszka, W. 1989. Surfacing and welding using cored wire electrodes. *Welding International* 3(6): 492–496.
11. Gonzalez, J. C. 1987. Simple method to estimate nitride and nitrogen contents in self-shielded FCAW (flux cored arc welding) weld metal. *Journal of Materials Science Letter* 6(1): 111–112.
12. Ramirez, J. E., Han, B., and Liu, S. 1994. Effect of welding variables and solidification substructure on weld metal porosity. *Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science* 25(10): 2285–2294.
13. Yeo, R. B. G. 1993. Electrode extension often neglected when using self-shielded cored wires. *Welding Journal* 72(1): 51–53.
14. Stenbacka, N., and Svensson, O. 1987. Some observations on pore formation in gas metal arc welding. *Scand. J. Metall.* 16(4): 151–153.
15. Stenbacka, N., and Runnerstam, O. 1990. Aspect of pore formation on GMAW (gas metal arc welding). *Welding and Metal Fabrication* 58 (10): 553–554.
16. Redchits, V. V., and Froloc, V. A. 1996. Calculation and analytical evaluation of the gas pore formation susceptibility of metals and alloys in fusion welding. *Welding International* 10(1): 76–79.
17. Wei, Q., and Xiong, D. J. 1998. The influence of oxygen, nitrogen and hydrogen on porosity in the weld of SSFCW. *Academic Journal of Beijing Polytechnic University* 24(3): 89–92.
18. Wei, Q., and Xiong, D. J. 1997. Study on pore sensitivity of self-shielded flux-cored wire with high BaF2 slag system. *Proc. 8th National Welding Symposium*, eds. S. Wang, and L. Wang, Vol. 2, pp. 95–97. Beijing: China Machine Press.
19. Zhou, Z., and Zhang, W. 1988. *Welding Metallurgy and Weldability of Metals,* pp. 53, 66. Beijing, China Machine Press.
20. Chen, B. 1982. *Base of Metal Weldability*, p. 43. Beijing: Tsinghua University Press.

Preparation of Manuscripts for Submission to the *Welding Journal* Research Supplement

All authors should address themselves to the following questions when writing papers for submission to the Welding Research Supplement:

- Why was the work done?
- What was done?
- What was found?
- What is the significance of your results?
- What are your most important conclusions?

With those questions in mind, most authors can logically organize their material along the following lines, using suitable headings and subheadings to divide the paper.

1) **Abstract.** A concise summary of the major elements of the presentation, not exceeding 200 words, to help the reader decide if the information is for him or her.

2) **Introduction.** A short statement giving relevant background, purpose and scope to help orient the reader. Do not duplicate the abstract.

3) **Experimental Procedure, Materials, Equipment.**

4) **Results, Discussion.** The facts or data obtained and their evaluation.

5) **Conclusion.** An evaluation and interpretation of your results. Most often, this is what the readers remember.

6) **Acknowledgment, References and Appendix.**

Keep in mind that proper use of terms, abbreviations and symbols are important considerations in processing a manuscript for publication. For welding terminology, the *Welding Journal* adheres to ANSI/AWS A3.0-94, *Standard Welding Terms and Definitions.*

Papers submitted for consideration in the Welding Research Supplement are required to undergo Peer Review before acceptance for publication. Submit an original and one copy (double-spaced, with 1-in. margins on 8 ½ x 11-in. or A4 paper) of the manuscript. Submit the abstract only on a computer disk. The preferred format is from any Macintosh® word processor on a 3.5-in. double- or high-density disk. Other acceptable formats include ASCII text, Windows™ or DOS. A manuscript submission form should accompany the manuscript.

Tables and figures should be separate from the manuscript copy and only high-quality figures will be published. Figures should be original line art or glossy photos. Special instructions are required if figures are submitted by electronic means. To receive complete instructions and the manuscript submission form, please contact the Peer Review Coordinator, Doreen Kubish, at (305) 443-9353, ext. 275; FAX 305-443-7404; or write to the American Welding Society, 550 NW LeJeune Rd., Miami, FL 33126.