BY DAMIAN J. KOTECKI

Q: We fabricated a heavy-wall pressure vessel of 304L stainless for a seawater application. Out of concern for stress corrosion cracking in the seawater, we performed a stress relief heat treatment at 800°C (1475°F) for 12 hours. After the heat treatment, we found many cracks in the 308L welds made with all-position flux cored electrodes around nozzles, but none in the 308L submerged arc (SA) welds that assembled the main body of the vessel. We gouged out the cracked welds, welded with FCAW again, inspected the welds thoroughly without finding any cracks, then stress relieved again. After this second stress relief, we again found extensive cracking in the FCAW deposits only. We are aware that carbide precipitation and sigma phase precipitation can occur at the stress relief temperature. Since the welds and base metal are low carbon and since both the SA and FCA welds contained only about 8 to 10 FN before stress relief, we don't think that carbide precipitation or sigma phase precipitation are the causes of the cracking. Something seems to be different about the flux cored arc welds. What else could be the cause?

A: While it is true that a 12 hour "stress relief" at 800°C (1475°F) will produce both carbide precipitation and sigma phase precipitation in 308L weld metal, the damage to properties in low-carbon weld metal at 8 to 10 FN is unlikely to be serious enough to cause cracking. I believe you are correct to suspect that something is different about the FCAW deposits.

To put things in perspective, it is useful to review briefly the history of development of flux cored stainless electrodes. The first stainless steel electrodes for FCAW were developed in the late 1950s. These were relatively large-diameter electrodes (3/32 in. [2.4 mm] and larger), used mainly calcium fluoride (fluorspar) base or titanium dioxide (rutile) base slag systems, and were limited to welding in the flat and horizontal positions. Although some were designed for gas shielded welding, the vast majority were designed to be run without shielding gas. These self-shielded flux cored stainless electrodes dominated the flux cored stainless electrode market throughout the 1960s and 1970s. The self-shielded flux cored stainless electrodes to this day are limited to the flat and horizontal positions, largely because the metal transfer is by a large droplet that is strongly affected by gravity.

In the late 1970s, smaller-diameter gas shielded flux cored stainless electrodes began to appear in the market. Sizes of 1/16 in. (1.6 mm) were followed by even smaller diameters. In contrast to the large droplet metal transfer with the self-shielded electrodes, these electrodes produced a near spray transfer, especially in argon-CO_2 gas mixtures. Faster-freezing slag systems were developed that permit welding in the vertical and overhead positions. And the Japanese introduced a slag system high in SiO_2 that produces very attractive welding characteristics, slag detachment and weld surface appearance with such electrodes. However, the Japanese development, as described in the 1982 U.S. Patent No. 4,345,140, *Composite Wire for Stainless Steel Welding,* granted to Godai et al., introduced the inclusion of a small amount of certain low-melting oxides to obtain the attractive slag removal. This patent mentions lead oxide, bismuth oxide, and antimony oxide as possibilities for obtaining this effect. Variants on this patent were introduced by other electrode manufacturers, and the industry seems to have standardized on the addition of small amounts of bismuth-bearing compounds as the slag-removal additive. By about 1990, perhaps even earlier, the usage of small-diameter gas shielded flux cored stainless steel electrodes in the United States had exceeded that of the larger-diameter self-shielded flux cored stainless steel electrodes. Today, the small-diameter gas shielded flux cored stainless electrodes are by far the dominant stainless steel flux cored electrodes.

The vast majority of stainless steel weld deposits are put into service in the as-welded condition and see service at temperatures below about 250°C (480°F). However, there are certain notable exceptions, including casting repairs that are normally annealed, and weldments in the power-generation and process industries that see extended service at temperatures of 480°C (900°F) or higher. It is in these latter weldments that bismuth (and other similar elements) create problems. Although it may have been reported earlier in Japanese literature, perhaps the first publication of elevated-temperature problems with these FCA weldments in the western literature was by Nishiyama et al., Flux-Cored Wires for Stainless Steel Welding, in *Welding in the World,* Vol. 36, pp. 103–123, June 1995. This article describes premature creep failures in such weldments at temperatures as low as 650°C (1200°F).

The report by Nishiyama triggered a number of other investigations of the behavior of stainless steel FCAW deposits containing bismuth. On behalf of Commission IX of the International Institute of Welding, Farrar et al. (Position Statement on the Effect of Bismuth on the Elevated Temperature Properties of Flux Cored Stainless Steel Weldments, *Welding in the World,* Vol. 45, N5/6, pp. 25–31, 2001), summarized the reports available as well as the results of a round-robin of bismuth measurement in stainless steel FCAW deposits. They cited reports of reheat cracking at temperatures as low as 550°C (1020°F) in weldments containing approximately 200 ppm bismuth, the bismuth level that seems to be standard in such FCAW stainless steel electrodes. They further noted that experience and experimental data are lacking for stainless steel FCAW electrodes at temperatures below 1020°F. They also noted that there are certain stainless steel FCAW electrodes formulated without bismuth (less than 20 ppm) whose deposits do not exhibit reheat cracking or premature creep failure. Unfortunately, this information has not been well publicized, although the American Petroleum Institute has incorporated this 20 ppm limit for bismuth in stainless steel FCAW deposits in its Recommended Practice 582, *Welding Guidelines for the Chemical, Oil and Gas Industries.*

Your experiences seem quite clearly to be cases of reheat cracking. I understand that subsequent investigation has determined that the FCAW electrodes used did indeed contain bismuth additions.

For stainless steel weldments being designed for high-temperature service or intended to be given a PWHT, FCAW electrodes producing less than 20 ppm of bismuth in the deposit should be selected. Since electrode manufacturers do not generally publicize the bismuth level in their electrodes, I suggest that you contact a technical representative of any prospective FCAW stainless steel electrode manufacturer who might be chosen to supply electrodes for high-temperature service, or for PWHT. You should seek a supply of electrodes guaranteed to provide weld metal with less than 20 ppm of bismuth (and similarly free of any other element that can cause reheat cracking or premature creep failure).

There is no reason to impose this restriction on stainless steel FCAW electrodes that are not to be used for high-temperature service or PWHT. ♦

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