Cracking in Type 309 High Temperature Fabrications and How to Combat It

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Part I

AISI type 309 heat resistant steel, which evolved to its present composition in the 1930's, is generally produced to a nominal 23% chromium, 14% nickel composition in the United States today. The actual chromium and nickel ranges of the AISI composition are 22-24 percent and 12-15 percent respectively. Most producers attempt to keep the nickel content on the high side of the range to reduce the amount of delta ferrite present during hotworking and subsequent possible sigma phase formation in service.

Type 309 was developed to improve on the scaling resistance of the early 18-8 type austenitic stainless steels at temperatures from 1500 to 2000°F, the maximum temperature suggested for this alloy. At temperatures below 1500°F, the scaling resistance of types 304 and 430 stainless steels generally will suffice.

Literature Observations

Although both type 309 parent metal and weld deposits are susceptible to sigma phase formation, the weld metal is both more rapidly and severely embrittled than the wrought material.(1, 2)* Sigma may form from either ferrite in duplex structures of austenitic stainless and heat resisting steels or from austenite, alone, in fully austenitic structures.(3, 4) Electrodes for welding type 309 are sometimes balanced so that the resulting weld deposit contains a certain amount of delta ferrite to reduce hot cracking susceptibility on solidification. The true role of ferrite is not fully understood. The most common theory pertaining to its ability to prevent hot cracking on solidification during welding concerns the greater affinity of the ferritic structure for certain harmful impurities affecting hot cracking.(5) A 5 to 10% ferrite content in the deposited filler metal is generally considered to be the amount required to produce a microstructure resistant to hot cracking on weld deposit solidification.(5, 6)

Extremely high ferrite contents in the weld normally are undesirable. This is due to the great tendency for ferrite in a weld deposit to convert to sigma in elevated temperature service. The effect of varying ferrite content on the tendency for hot cracking and embrittlement to occur in type 347 was investigated in 1950 and, at that time, it was found that the ferrite content should be just enough to provide sound crack-free welds.(7) Three years later, Shedden and Pumphrey mentioned the need for ferrite control in a general discussion of stainless steel weldments and placed the upper limit of 10% on delta ferrite to minimize sigma phase embrittlement.(8) Other recommendations on the maximum amount of ferrite that should be present in type 347 stainless steel weldments have been noted.(9)

Decreasing the amount of ferrite present in the deposited filler metal is an obvious way to

* Figures in parentheses refer to references listed at end of this article.

lessen the tendency for sigma phase to occur. An early step in this direction was the development of the so-called 16-8-2 (Cr-Ni-Mo) low ferrite electrode. This electrode was developed for, among other things, the welding of type 347 destined for high temperature service.[10] Other notations have been observed in the literature where a fully austenitic weldment has been employed successfully in joining stainless or heat resisting steels.[11, 12] The addition of nitrogen and/or manganese as alloying elements in filler metal has been employed to achieve a near fully austenitic weld metal deposit.[11]

Typical Failures Attributed to Sigma in Type 309 Fabrications

Three common applications for type 309 material in the sigma phase formation range are:

(1) inner covers for stack annealing furnaces in steel mills;

(2) radiant tubes used to heat aluminum ingots prior to hot-working; and

(3) sleeves and saggers used to bake carbon products.

Annealing Furnace Covers

In the case of type 309 parent-filler metal weldments in annealing covers, relatively rapid transformation of ferrite to brittle sigma phase may occur in the 1100 to 1700°F temperature range, resulting in room temperature cracking of the inner covers when they are removed from or set down upon annealing bases. When either AWS-309 or 310 electrodes are used to repair weld cracks, additional sigma phase is formed, resulting in new cracks occurring as the cycle repeats itself.

In one annealing cover investigated involving a maximum temperature of 1750°F with a normal operating temperature of 1350°F, cracks were found to occur in the parent metal at the weldment-parent metal interface. It is surmised that these cracks were caused by thermal stresses set up on heating and cooling resulting, in turn, from a difference in section between a 5/8" thick weld buildup on 3/16" thick parent material (note Figs. 1 and 2). This buildup was the result of repeated repair welds. Other factors which could have accelerated this cracking in the fusion zone are:

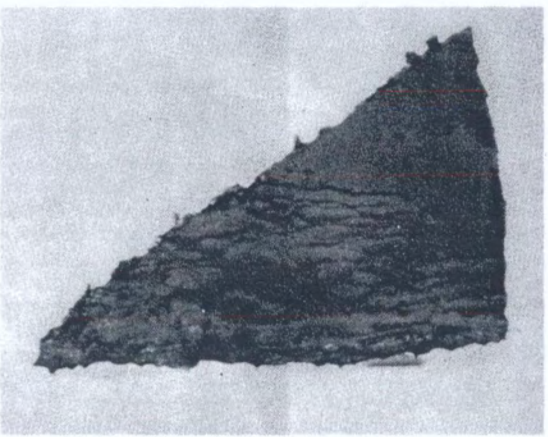

Fig. 1. 3/16" type 309 plate from cone section of annealing inner cover showing successive weld-repair-metal buildup of type 309 filler metal.

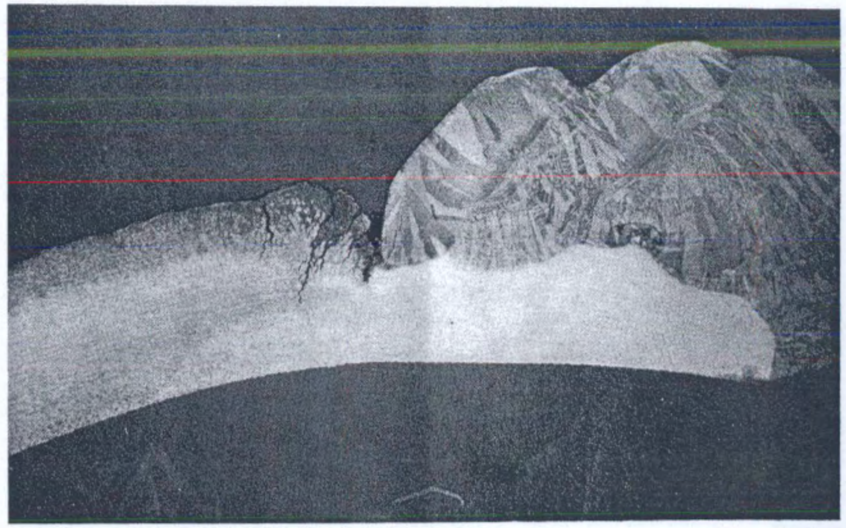

Fig. 2 Photomacrograph of weldment cross section from type 309 annealing inner cover welded with type 309 rod. Etchant, Marble's Reagent. Magnification 5X.

(1) the presence of sigma phase in the parent metal; and

(2) undercutting the parent metal during welding, resulting in a stress raising effect from which cracks might propagate more readily in the metal.

Of interest, in the metallographic investigation that accompanied this failure was the fact that the parent metal under the weldment contained slightly less sigma phase than that noted in the parent metal in locations well away from the weldment area. This is thought to be due to the fact that any sigma present in the parent metal under a weldment would have transformed, or partially transformed, to austenite as a result of heating during weld repair (Figs. 3 and 4).

Aluminum Ingot Heating Furnaces

Cracking of type 309 radiant tubes in aluminum ingot heating furnaces usually is initiated in the weldment zone. It is believed that such cracking is the result of transformation of ferrite to sigma phase at operating temperatures. Tube vibrations, particularly on startup, tend to propagate cracks in any embrittled sigmatized area. Fig. 5 shows a photomicrograph from a typical parent metal section of return bend from a type 309 radiant tube used in an aluminum ingot heating furnace (1350°F furnace temperature) after four years' operation. Note the amount of sigma phase present. The original weldment area showed at least one weld repair having been made utilizing type 310 rod.

Carbon Baking

Typical operations in carbon baking utilize saggers and sleeves made from 3/16" and 5/16" thick type 309 plate. Failure is again due to embrittlement, however, differing from the previously noted examples, because in carbon baking, embrittlement has been found to be primarily caused by carburization and not by the formation of sigma phase. Carbon contents of up to 5% have been noted in some failed type 309 sleeves.

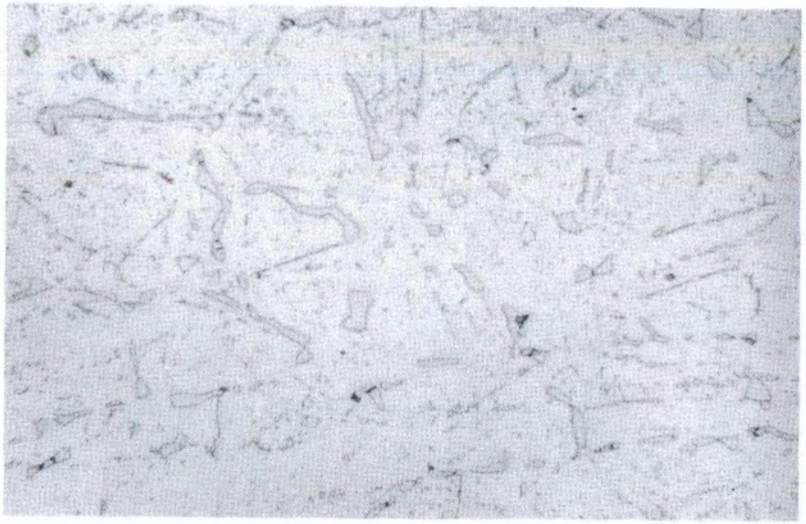

Fig. 3 Photomicrograph showing type 309 parent metal away from weldment area of annealing inner cover cone section. Sigma phase and some fine carbides can be noted in the austenitic matrix. Etchant, mixed acids. Magnification 500X. (Reduced 10%.)

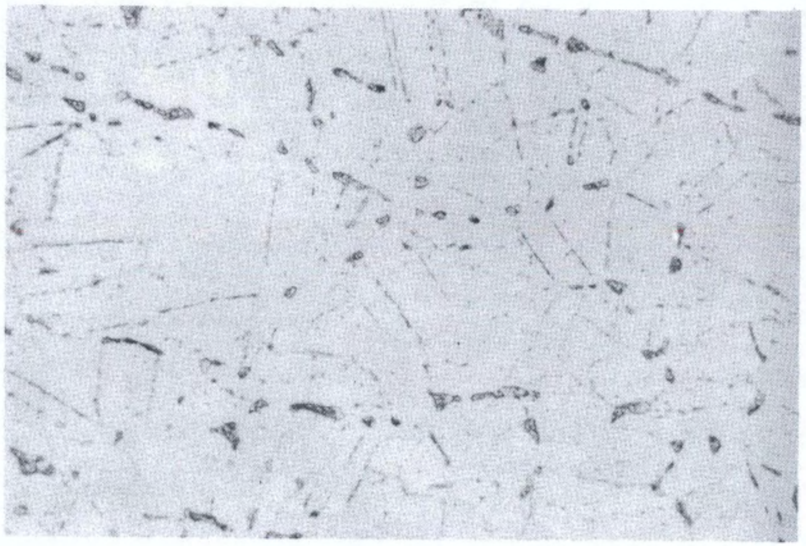

Fig. 4 View of type 309 parent metal under weld bead of annealing inner cover cone section. Note difference in darkness of sigma phase along with lesser amount present than in Fig. 3. Etchant, mixed acids. Magnification 500X. (Reduced 10%.)

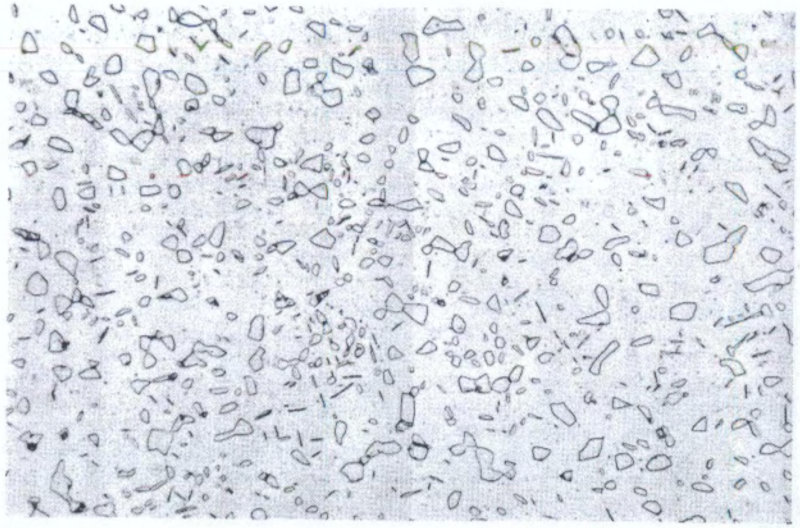

Fig. 5 All parent metal from return bend portion of a radiant tube from an aluminum ingot heating facility after four years of service. The 500X micrograph shows sigma phase present in an austenitic matrix. Etchant, mixed acids. (Reduced 10%.)

In carbon baking applications, the unbaked carbon is heated very slowly to about 1800°F, soaked out at this temperature for a day or two, and then cooled very slowly, generally to about 600°F prior to the removal of the baked carbon from the sleeve or sagger. These very slow heating and cooling rates involve many days spent in the sigma phase formation range during the usual 25-day-plus total cycle.

In one such application in which 5/16" thick type 309 sleeves last, at the most, about 25 bakes; 3/16" thick RA-330 (35 Ni, 19 Cr, 1.25 Si) sleeves have been in service for over 30 bakes with no signs of failure indicated.

Metallographic investigation of a sample from a type 309 sleeve revealed that, although the main cause of failure was carburization, up to 10% sigma phase had been noted.

Observations have also been made of totally non-magnetic carbon baking sleeves which were taken out of service due to severe cracking either in the deposited filler metal region of the weldment or in the parent metal-filler metal fusion zone. Although no metallographic examinations were made in this particular instance, the lack of magnetization in the area of the weldment as well as in the parent metal certainly indicated that any ferrite which would have been present there as a result of welding had transformed. This lack of magnetization also indicates that little, if any, carburization had resulted in this instance. Sigma phase formation was the suspected cause of failure.

Filler Metal for RA 330 Material

Carbon is a potent austenite former and has been used to achieve fully austenitic crack-free weld deposits in heat resisting alloys, particularly those with a high silicon content.[13, 14] Higher carbon content weldments often are more brittle than the lower carbon parent metal.[13] This factor makes any subsequent cold forming or shaping after welding more difficult. The amount of difficulty encountered is dependent on the severity of forming and the carbon content of the weldment. This was true in the case of RA 330 alloy which, when welded with RA 330-80 electrode (0.80 C, 0.85 Si, 19 Cr, 35 Ni), resulted in dilution to about 0.40 C in the deposited filler metal.

Thus forming problems were likely to be encountered when RA 330 plate and sheet material was welded exclusively with RA 330-80 electrodes. This shortcoming of the RA 330-80 composition caused Rolled Alloys, Inc., the distributor of RA 330 and RA 330-80, and the Teledyne McKay Company, the producers of RA 330-80, to begin searching for a substitute for a good portion of the carbon present in the RA 330-80 electrodes to overcome these disadvantages.

It was known for some time that other elements could reduce hot cracking in high silicon alloys similar in composition to RA 330.[11, 15] Review of the most likely substitutes for carbon suggested that manganese additions had the best chance of success in preventing hot cracking. Initial experimentation showed that a filler metal containing 0.20% carbon and about 5% manganese had as much resistance to hot cracking as the original RA 330-80 weld metal had. In addition, cold form-

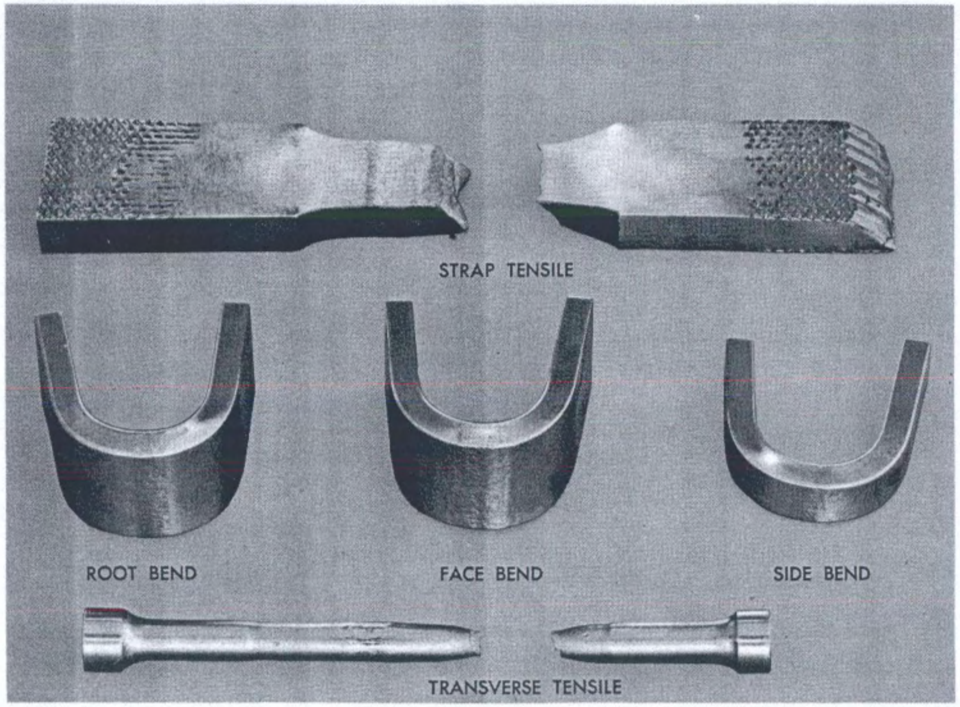

Fig. 6 Weldments of RA 330 welded with RA 330-04-15 illustrating both strength of the weld deposit metal and ductility of the overall weldment.

TABLE I—COMPOSITIONS

	C	Mn	Si	P	S	Cr	Ni	Mo	Cu	Pb	Sn
Type 309 11 Ga. Sheet Ht 531197	.05	2.00	.46	.015	.024	22.75	14.53	.23	.35	—	—
309-16 Electrodes	.063	1.61	.44	.020	.011	24.15	12.92	.18*	—	—	—
RA 330-04-15 Electrodes	.20*	5.50*	.75*	.015*	.008*	17.50*	33.50*	.20*	—	—	—
RA 330-04 Wire	.21	5.57	.82	.017	.006	18.52	34.64	.34	.14	.001	.003

* Calculated Composition

ing was considerably improved as can be noted in Fig. 6. Subsequent refinements resulted in a patented alloy, RA 330-04, of the following nominal composition: 0.20% carbon, 5.35% manganese, 19% chromium, 35% nickel, and 0.80% silicon. Bare wire and coated electrodes of RA 330-04 are available in a full range of sizes.

A review of the Schaeffler[16] diagram reveals that this filler metal composition is well within the confines of the fully austenitic region. The obvious question arises as to how a fully austenitic filler metal such as RA 330-04 would work when used to join type 309 heat resisting steel. Consequently, the following investigation was conducted:

Investigative Procedure

Pieces of 11 gauge type 309 sheet, approximately 6" x 15", were welded together along the longitudinal edge with 3/32" diameter AWS 309-16 coated electrodes, 3/32" RA 330-04-15 coated electrodes, and 1/8" RA 330-04 bare wire. The chemical analyses of these materials are shown in Table I.

Welding conditions are summarized in Table II.

The resulting 12" x 15" weldments were cut transversely to about one inch wide tensile and bend test specimens. Areas near both the start and finish of welding were discarded. Three one-inch wide specimens from each type weldment were then held at 1400°F for 1000 hours. Specimens were tested in both the as-welded and heat treated conditions. All specimens were ground flush prior to testing.

(To be continued)

TABLE II—WELDING PARAMETERS

	AWS 309 Electrode	RA 330-04 Electrode	RA 330-04 Wire
Amperes	85	75	50
Voltage	—	—	12
Polarity	Reverse (DC)	Reverse (DC)	Straight
Shielding Gas	—	—	100% argon at 17 cu ft per hr.
Gap	3/32-1/8"	3/32-1/8"	3/32-1/8"

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Part II

CRACKING FAILURES attributed to the presence of sigma phase in type 309 fabrications, including radiant tubes in aluminum ingot heating furnaces and annealing furnace covers, were explained in Part I. Also explained, were the metallurgical reasons for the development of new filler metal compositions to avoid this type of cracking. Tests weldments, for various welding and heat treated conditions, utilizing the new filler metals, are disclosed in this final installment.

Results

The results of these mechanical property determinations are shown in Table III.

With the exception of the sigmatized samples, all tension specimens ruptured through the weldments. All cracks noted in bend specimen samples occurred in the weldments. The sigmatized samples showed a greater tensile strength and a lesser elongation than their as-welded counterparts in all instances.

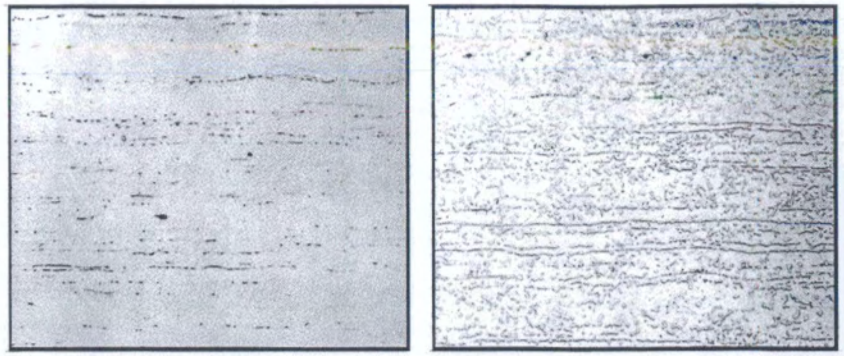
After sigmatizing, the type 309 parent metal-filler metal weldment fractured upon completion of only a 40° bend. Both of the RA 330-04 sigmatized weldments withstood 180° of bending, again around a diameter equal to twice the thickness of the sheet, although the bare wire weldment showed a few light cracks while the stick electrode weldment showed deeper cracks upon completion of bending. These may have been contributed to by precipitated carbides.

Metallographic examination was conducted on (1) the deposited metal, (2) fusion zones, and (3) the parent metal of all specimens. Photomicrographs of base metal, fusion zone, and weld metal in the as-welded and sigmatized conditions are shown in Figs. 7-11. Magne-Gage determinations revealed a base metal ferrite content just over 1% (Fig. 7A). Upon sigmatizing, metallographic observations estimate a sigma content of about 20% in the 309 parent metal (Fig. 7B). A considerable contrast in ferrite content can be noted between the RA 330-04 and type 309 filler metal deposits (Right hand side of Figs. 8A and 9A) in the as-welded condition. Again Magne-Gage determinations

TABLE III—WELDMENT MECHANICAL PROPERTIES

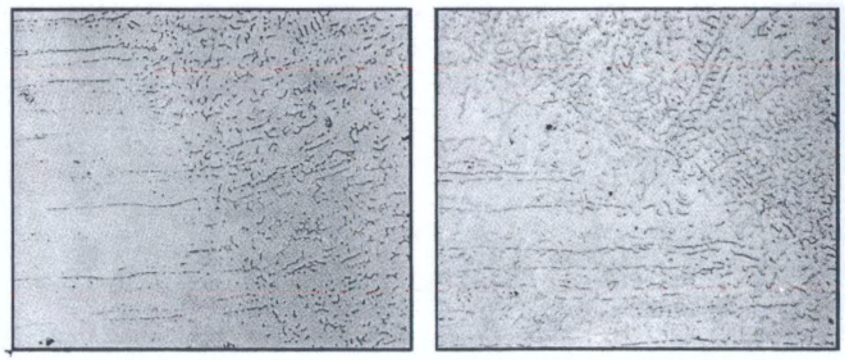
FILLER METAL	CONDITION	TRANSVERSE TENSILE PROPERTIES UTS (ksi)	0.2% OFFSET YS (ksi)	APPROX. EL. (%)	BEND OBSERVATIONS
309-16	As-welded	86.2	49.1	34.0	180°—no cracks
309-16	1400°F-1000 hrs.	90.1	*	21.0	40°—complete fracture
RA 330-04-15	As-welded	81.9	49.6	22.0	180°—single crack
RA 330-04-15	1400°F-1000 hrs.	92.1	*	20.0	180°—deep cracks entire width
RA 330-04 (bare wire)	As-welded	79.2	48.7	23.5	180°—no cracks
RA 330-04 (bare wire)	1400°F-1000 hrs.	86.6	*	15.0—	180°—few small cracks
Properties for 309 parent metal sheet (Ht 531197)		86	44.7	40.0	

* Broke outside gauge lengths



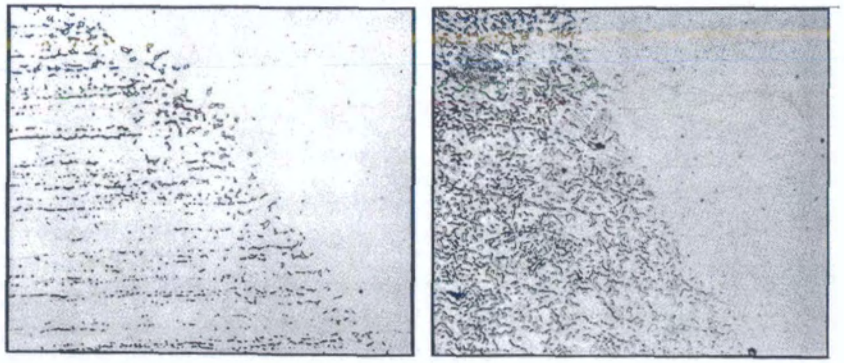
7A 7B

Fig. 7 Type 309 parent metal in the as-received condition (7A) showing about 1.5% ferrite present and after sigmatizing (7B) at 1400°F for 1000 hours showing about 20% sigma present. Magnification 235X, Etchant, Vilella's (Reduced 10%).



8A 8B

Fig. 8 Fusion zone between 309 parent metal and 309-16 weld deposit metal as welded (8A) and after sigmatizing for 1000 hours at 1400°F (8B). Magne-Gage ferrite content determination of weld deposit metal 7%. Parent metal on left hand side of micrographs. Magnification 235X, Etchant, Vilella's (Reduced 10%).



9A 9B

Fig. 9 Fusion zone between 309 parent metal (left hand side of 9A) and RA 330-04 bare wire. The deposit metal is fully austenitic while the ferrite content of the base metal as determined by a Magne-Gage was one percent in the as-welded condition. After sigmatizing (9B) about 20% sigma can be noted in the base metal (left hand side of 9B) while the weld deposit metal has remained fully austenitic. Magnification 235X (Reduced 10%). Etchant, Vilella's.

revealed a 7% ferrite content in the type 309 deposit metal (Fig. 10A) while the RA 330-04 deposit metal was free from ferrite (Fig. 11A). After a 1000-hour hold at 1400°F, the RA 330-04 weld metal was still fully austenitic (Fig. 11B). Sigmatizing the type 309 filler metal resulted in a slightly greater amount of sigma phase (about 25%) (Fig. 10B) than that noted in the parent metal (Fig. 8B).

Conclusions

A comparison of type 309 weldments joined with RA 330-04 and the type 309 weldment joined with type 309 filler metal revealed the following:

(1) At room temperature, as-welded property strength levels were similar. Also the ductilities were about equal.

(2) After exposure to 1400°F for 1000 hours, the following were noted:

(a) Tensile strengths at room temperature were equal.

(b) Ductility of the RA 330-04 weld metal was vastly superior to that of the AWS-309 deposit material as measured by the results of the bend test.

(c) RA 330-04 weld metal remained fully austenitic. The AWS-309 deposited filler metal contained 25% sigma phase.

(3) Based on the results of this investigation, type 309, although quite prone to form considerable amounts of sigma phase in the parent metal after long-time holds in the 1100-1700°F temperature range, as can be noted in Fig. 7, can have weldment cracking in service brought about by the presence of embrittling sigma phase lessened, if not fully eliminated, with the use of an austenitic deposit metal such as RA 330-04.

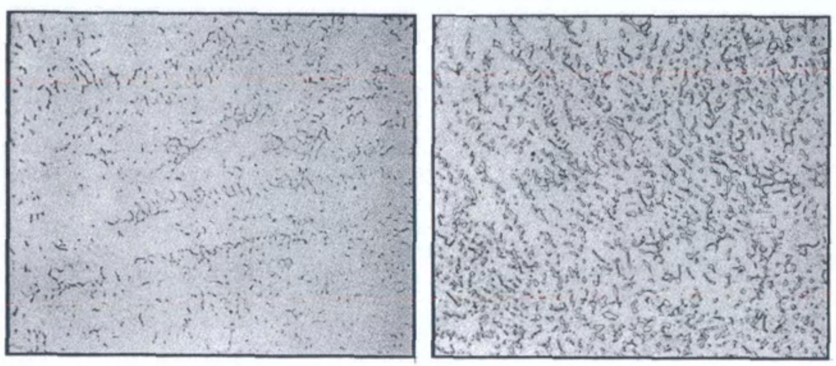
In applications involving temperatures from 1100°F to 2200°F, a non-sigma forming, scaling resistant alloy such as RA 330 will most invariably provide longer life in service than type 309. The added cost of RA 330 (ASTM B-536) over type 309 generally is more than offset by this increased service life. The primary exception occurs in a high sulfur content, reducing environment. The high nickel content of RA-330 makes it less resistant to sulfidic attack than the 14% nominal-nickel-content type 309 material.

The reasons for the superiority of RA 330 over type 309 heat resisting steel are:

(1) Greater scaling resistance under cycling oxidation conditions where temperatures in excess of 1800°F are involved.

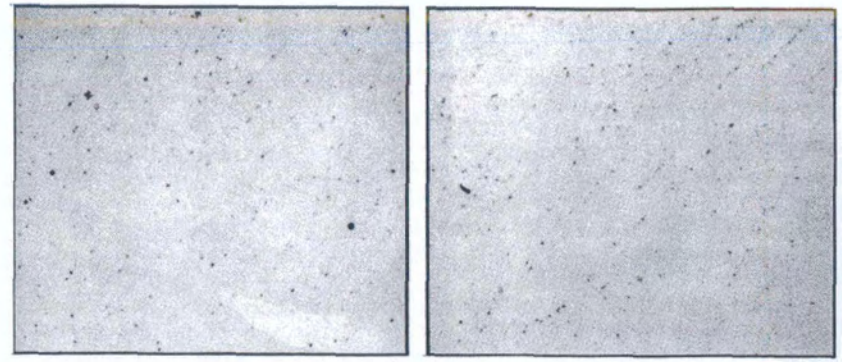
(2) Immunity to sigma phase formation. Recent metallographic examination of RA-330 material after exposure to 1400°F for over 12,000 hours has failed to turn up any trace of sigma phase. This is in contrast to metallographic changes observed in type 309 when held in the sigma phase formation range.

(3) Greater resistance to deformation at elevated temperatures. The stress required to cause a minimum creep rate of 0.0001% per hour in the 1400 to 1600°F temperature range for RA 330 is almost twice that required



10A 10B

Fig. 10 Type 309-16 weld deposit metal in the as-welded condition and in the sigmatized condition (10A and 10B, respectively). Magnification 235X (Reduced 10%). Etchant, Vilella's.



11A 11B

Fig. 11 RA 330-04-15 weld deposit metal in the as-deposited condition (11A) and sigmatized for 1000 hours at 1400°F (11B). Microstructure, austenite + grain boundary carbides. Magnification 235X (Reduced 10%). Etchant, Vilella's.

to produce the same minimum creep rate in type 309 at 1400°F and almost four times this load at 1600°F.[17] Thus RA 330 is stronger in the sense that it resists deformation better under the same load at elevated temperatures than does type 309.

(4) RA 330 possesses greater resistance to carburization than does type 309. The higher silicon content of RA 330 more than offsets the greater chromium content of type 309 in preventing carburization. Tests conducted a number of years ago on castings of the general 35 Ni-15 Cr composition showed about a two- to three-fold increase in weight percent change for material with a nominal 0.50% Si content than for material with over one percent silicon when subjected to carburizing conditions. Metallographic examination revealed about the same ratio of increase in carbon depth of penetration when 0.50% silicon content material was compared with 1% silicon content metal.[18]

In conclusion, sigma phase, forming in the type 309 parent metal, may eventually cause failure regardless of whether or not an embrittled filler metal exists. A more economical approach, when cost per unit of operating time is taken into account, would be to construct a fabrication, whose ultimate end use would be in the 1100°F to 1700°F temperature range, out of RA 330. This would (1) prevent the formation of embrittling sigma phase in both the parent metal and filler weldment metal, (2) increase resistance to carburization, and (3) provide greater strength at elevated temperature, thus introducing the possibility of a thinner, less costly, cross section.

Acknowledgments

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