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MASTER

Heterogeneity of Fusion Welds Determined by Use of ^{63}Ni -Tagged Filler Metal*

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ABSTRACT

Methods were developed for adding low-energy-level radioactive tracers to filler wires for studying weld-associated features such as cracking, dross formation, segregation, and incomplete alloying between base and filler metals. All of these have caused concern in a wide variety of materials used in commercial products.

For stainless steels and high-nickel alloys, two types of radioactive tracers were used for analyzing these problems: (1) a tracer (^{63}Ni) that dissolves homogeneously in the filler metal and thereby enables examination for cracks, porosity, surface dross, and alloying in the weld deposit; and (2) tracers (^{14}C , ^{35}S , and ^{33}P) that form segregates that could lead to weld cracking, low ductility, or selective corrosion. The radioactive isotopes selected are all pure beta emitters whose rays have low energy (all < 0.25 MeV). This type of tracer enabled examination of the metallurgical features by autoradiography with minimum film fogging and maximum resolution.

Alloying between base metal and filler metal, dross formation, and weld cracks were clearly delineated in stainless steel and high-nickel alloys, and the discrete microstructural regions were readily appraised. Whereas a high concentration of filler metal on the bottom side of root passes of multipass welds is generally sought to avoid cracking, the weld deposit in this region in some instances was essentially devoid of filler metal. Also, contrary to the widely held view that weld deposits are essentially homogeneous mixtures between filler metal and base metal, large compositional differences were found along fusion lines where base metal was concentrated within the deposit.

*Research sponsored by U.S. Army Edgewood Arsenal at Oak Ridge National Laboratory operated for the U.S. Atomic Energy Commission by the Union Carbide Corporation.

INTRODUCTION

When high-alloy weldments are appraised for critical applications, it no longer suffices to consider solely the soundness of the traditional weld deposit and heat-affected zone. Savage [1] has stressed the importance of distinguishing between discrete microregions within heterogeneous welds and the use of proper terminology in discussions of their properties. Other elusive features associated with weld quality are surface cleanliness and freedom from internal fissures, pores, or segregates.

Delineation and study of the origin and character of the foregoing weld features require highly complicated metallographic techniques, and often many questions remain unanswered [2]. Our purpose was to explore these features autoradiographically and metallographically.

SELECTION OF RADIOISOTOPES

The radioisotopes considered fall into two classifications: (1) those that are highly soluble in the matrix of the weld metal and thus can be evenly distributed in it, and (2) isotopes that concentrate in or are stoichiometrically linked with secondary phases, and, hence, can be selectively distributed.

An important factor considered in selecting isotopes was the characteristic radiation, which determines the degree of photographic definition and autoradiographic resolution. Isotopes that emit alpha or beta radiation are useful [3] and should be especially suited when free of stray gamma rays (which fog film); low-energy radiation helps assure good resolution.

Alpha rays, as a result of high energy release rates (short particle range) generally give very high photographic resolution. Unfortunately, however, alpha sources are few and usually emit supplemental rays that produce undesirable background fogging.

Beta emitters offer the best compromise for autoradiographic use. Beta particles have fairly low ranges, and those of lower intensity should give reasonably good photographic resolution. Fortunately beta-emitting sources are quite numerous and many of them do not have gamma or other contaminating rays [4].

The pure beta-emitting isotopes and their energies are listed in Table I. The tracers selected for our study are listed in Table II with their characteristics. Note that the maximum energies of all the isotopes selected are attractively low, and only ^{33}P has an undesirably low half-life. The isotope ^{63}Ni was used for conferring evenly distributed beta activity to welding wires. The structure and extent of alloying between filler metal and base metal in the various regions of heterogeneous welds were explored in welds prepared with tracer-containing filler metals on untraced base metals. The isotopes ^{14}C , ^{35}S , and ^{33}P link with intermetallic compounds and their associated eutectics and are being used to investigate the role of microsegregates in weld cracking and general weld behavior.

Table I. Pure Beta-Emitting Isotopes and Their Energies

Isotope	Maximum Energy (MeV)	Isotope	Maximum Energy (MeV)	Isotope	Maximum Energy (MeV)
⁹⁰ Y	2.28	³⁶ Cl	0.71	³³ P	0.25
⁹⁷ Zr ^a	1.90	¹²⁷ Te	0.70	¹⁴⁷ Pm	0.22
³² P	1.71	^{113m} Cd	0.58	⁶⁶ Ni ^a	0.20
⁹¹ Y	1.54	³⁹ Ar	0.56	³⁵ S	0.167
³¹ Si	1.48	¹⁹ Be	0.55	¹⁴ C	0.156
⁸⁹ Sr	1.46	⁹⁰ Sr ^a	0.54	¹⁵¹ Sm	0.076
²¹⁰ Bi ^a	1.17	¹⁸⁵ W	0.43	⁶³ Ni	0.067
¹⁰⁹ Pd ^a	1.02	¹²¹ Sn	0.38	²²⁸ Ra ^a	0.05
¹⁴³ Pr	0.93	¹⁸⁸ W	0.35	²²⁷ Ac ^a	0.045
⁶⁹ Zn	0.90	⁹⁹ Tc	0.29	¹⁰⁶ Ru ^a	0.039
²⁰⁴ Tl	0.76	⁴⁵ Ca	0.26	³ H	0.018

^aDecays to daughter product(s) having other radiations that must be considered.

Table II. Characteristics of Selected Radioactive Tracers.
All are pure beta emitters

Isotope	Maximum Energy (MeV)	Half-Life	Distribution in Microstructure
⁶³ Ni	0.067	92 yr	Matrix
¹⁴ C	0.156	5.7×10^3 yr	Selective
³⁵ S	0.167	88 d	Selective
³³ P	0.25	25 d	Selective

MATERIALS AND PROCEDURES

Fabrication of Isotope-Traced Filler Metal Wires

For exploring the structure and alloying in heterogeneous welds, ⁶³Ni-tagged, 1/16-in.-diam wire was prepared in type 347 stainless steel, type 308 stainless steel, and Inconel 82 filler metals. Also procedures were developed for preparing 1/16- and 5/32-in.-diam wires of type 347 stainless steel filler metal tagged with ¹⁴C. These wires contained low and high concentrations of carbon, sulfur, and phosphorus for studying the effects of segregates on weld properties. Work in this area is now progressing.

Isotope ⁶³Ni was obtained locally as an aqueous 1 M HCl solution with a specific activity exceeding 5 Ci/g Ni and a radiochemical purity exceeding 95%, with about 0.1% ⁵⁹Ni.

Of several approaches considered for converting the isotope to a form suitable for incorporation in filler metals, the most practicable method was to electroplate ^{63}Ni from an aqueous solution onto a fine metal wire and incorporate the wire into an ingot of the filler metal by melting and casting.

We calculated that about $1 \text{ mCi } ^{63}\text{Ni}/\text{cm}^3$ was appropriate to incorporate in the welding wire to suitably expose an autoradiographic film in a period of 2 h. This concentration assumes a beta particle range of $1 \mu\text{m}$ and 10^7 total particles per square centimeter to expose the film. The calculated value proved to be reasonably close, since 24-h exposures on Kodak NTB-2 plates gave good autoradiographs.

The procedure established for manufacturing ^{63}Ni -containing filler metal wires consists of the following steps.

1. Conversion of the radioisotope from the aqueous form to a usable, solid form by electrodeposition on a nickel wire 0.020 in. in diameter by 1 ft long.

2. Preparation of a 1/2-in.-diam $\times$ 2 1/4-in.-long casting of the filler metal containing the isotope-plated wire of step 1 as a melting charge ingredient. The remainder of the charge consists of clippings from 1/16-in.-diam filler metal wire of certified type and composition. The charge is tungsten-arc melted six times to achieve good compositional homogeneity and then drop cast in a water-cooled copper mold.

3. Reduction of the pencil-shaped casting to a welding wire 1/16 in. in diameter (approx 110 in. long). First swaging at 650°C (1200°F) breaks up the cast structure; then acid cleaning removes any adhering oxide scale. Finally, alternately cold swaging and vacuum annealing at 1065°C (1950°F) reduces it to final wire size.

Step 1 required considerable experimentation, including conversion from a hydrochloric acid solution to a plating bath based on ammonium oxalate. After the isotope was plated out, it was secured to the wire by electroplating additional natural nickel over it by a conventional process. The melting operation of step 2 and the acid cleaning of wires from step 3 were conducted within radiological hoods with absolute filtering. A radiochemical analysis for ^{63}Ni on an arc-melted casting prepared by the above procedure found about 95% of the tracer supplied in the original source solution.

Figure 1 shows contact autoradiographs prepared of the sprue and the body of the ^{63}Ni -containing type 347 stainless steel casting that was fabricated by our standard procedure, and Fig. 2 is a contact autoradiograph of the end of the welding wire made from the casting. Note that good isotopic homogeneity is achieved at each stage of fabrication. The crack seen at the end of the swaged wire (Fig. 2) illustrates the effectiveness of this autoradiographic technique for delineating cracks. The wires used for the welding experiments were, of course, of good quality.

The ^{14}C -traced type 347 stainless steel filler metal wires were prepared by a process containing few departures from that used for the ^{63}Ni -traced wires. Isotope ^{14}C was introduced during arc melting in elemental form enclosed within a ductile iron foil. Because the alloy work hardened

at a very high rate when the carbon, sulfur, and phosphorus concentrations (0.22, 0.050, and 0.060%, respectively) were high, the cold swaging operation was conducted with more frequent anneals. Also, the final stages of wire reduction were by bench drawing.

Figure 3 shows a macroautoradiograph of the sprue of the ^{14}C -tagged, high-segregate-containing drop casting from which the 5/32-in.-diam filler metal wire of type 347 stainless steel was prepared. While this autoradiograph indicates reasonably good macrohomogeneity with respect to ^{14}C distribution, a microautoradiograph at higher magnification shows that the tracer is preferentially distributed (Fig. 4). The "beta dots" in the autoradiograph appear to be associated both with a secondary particulate constituent (probably niobium carbide) and with carbon held in solid solution within the interstices of the prevailing dendritic structure.

Preparation of Weldments with Tagged Filler Metal Wires

Weldments were prepared with ^{63}Ni -tagged 1/16-in.-diam welding wires using a semiautomated gas tungsten-arc welding process within a radiological hood for containing ^{63}Ni . The base metals for two of the welds consisted of pairs of 12 x 6 x 1/2 in. plates prepared with a 100° included V-groove along their long edges. One butt-weld was prepared from 1/16-in.-thick sheet. Preliminary welding experiments on the various alloy combinations with untagged filler metal wires established welding parameters to give approximately 50% base metal dilution in weld deposits. Table III lists the various weldments prepared with the tagged wires along with the welding parameters used for the individual alloy combinations.

Table IV gives the chemical analyses of the filler metals and base metals. The analyses given for the filler metals represent the commercial wires from which the ^{63}Ni -containing welding wires were prepared. We expect that the actual chemical analyses of the tagged wires did not differ appreciably from the analyses given.

To investigate the character of the encrustations sometimes formed on the surfaces of welds, an additional series of welds was prepared for the Incoloy 800-to-Inconel 625, dissimilar-metal type listed in Table III. These welds were made under conditions that varied only with the purity of the welding gas atmosphere and the cleanliness of the base metal plates used.

Macro- and Microautoradiographic Techniques

Three different autoradiographic techniques were used to study the structure of welds: (1) the contact-film, macro method, (2) the liquid-emulsion, micro technique [5, 6], and (3) the strip-film micro technique. The first method was used for examining macrostructure (to 10x) in so far as it related to alloy mixing and/or diffusion between filler metal and base metal. The latter two techniques were used for examining microstructural detail (to 750x). By appropriately metallographically polishing and etching specimens before microautoradiographic examination, we were able to superimpose the metallographic structure on the autoradiograph and thus correlate the two classes of information.

Table III. Alloy Combinations Welded with ^{63}Ni -Tagged Filler Metal Wires^a

Base Metals	Filler Wire (1/16-in. diam)	Root Face (in.)	Current (A)	Voltage (V)	Travel Speed (in./min)	Filler Metal Addition Speed (in./min)
Type 347 stainless steel-to- type 347 stainless steel sheet, 1/16 in. thick	Type 347 stainless steel	b	51	8	5.5	6
Type 304 stainless steel-to- type 304 stainless steel plate, 1/2 in. thick	Type 308 stainless steel	0.010	180	11.5	5	36-38
Incoloy 800-to-Inconel 625 plate, 1/2 in. thick	Inconel 82	0.010	180	11.5	5	36-38

^aRoot opening was zero in all cases.

^bSquare groove, no bevel.

Table IV. Chemical Analyses by Vendor of Parent Metal and Filler Metal Alloys

Elements	Composition, wt %						
	Base Metals				Filler Metals		
	Type 347	Type 304	Incoloy 800	Inconel 625	Type 347	Type 308	Inconel 82
Ni	11.40	9.62	31.63	62.51	9.65	9.54	73.13
Cr	17.75	18.67	20.06	21.92	19.45	19.54	20.37
Fe	Bal	Bal	46.59	2.31	Bal	Bal	0.35
Mo				9.07		0.24	
Nb + Ta	0.79			3.53	0.87		2.50
W							
Al			0.24	0.20			0.03
Ti			0.27	0.25			0.40
Cu			0.48	0.01		0.20	0.03
Co							
C	0.070	0.06	0.04	0.02	0.047	0.04	0.02
Mn	1.62	1.23	0.83	0.01	1.75	1.78	2.96
S	0.005	0.007	0.007	0.007	0.005	0.012	0.007
P	0.027	0.022			0.015	0.019	
Si	0.75	0.67	0.34	0.14	0.55	0.25	0.16

The liquid-emulsion technique consists of melting the photographic emulsion and rolling or wiping it on the specimen surface with a glass rod. After exposure, the film is developed. The procedure for the strip-film technique is similar except that the autoradiographic film is stripped from a plate and floated in water onto the specimen surface.

The resolution attainable by these two techniques, aside from experimental refinements, depends upon the range of the beta particles and the thickness of the photographic film placed on the specimen. The liquid-emulsion technique can provide somewhat thinner films (down to 1 μm) and so affords slightly better resolution.

RESULTS

Autoradiographic and routine metallographic studies conducted on welds prepared with ^{63}Ni -tagged filler metal wires revealed three possibly inter-related features that could prove important to weld integrity: (1) weld cracking, (2) inhomogeneity of mixing between filler metal and base metal in the weld deposit, and (3) encrustations, or dross, formed on the weld surfaces.

Similar-Metal Welds in Types 347 and 304 Stainless Steel

Figure 5 compares a contact macroautoradiograph with a macrophotomicrograph of the butt weld prepared in 1/16-in.-thick type 347 stainless steel sheet with a ^{63}Ni -tagged 1/16-in.-diam type 347 stainless

steel filler metal. The weld region is clearly delineated in the autoradiograph, which indicates a slight compositional inhomogeneity in weld deposit in the form of a layer or onion-skin effect in the transverse section normal to the sheet.

Figure 6 shows a contact macroautoradiograph of a root pass made on the 1/2-in.-thick plate (with 100° included V-groove) of type 304 stainless steel with a ^{63}Ni -tagged 1/16-in.-diam type 308 stainless steel filler metal wire. Although the central region of the weld deposit reflects reasonably good mixing between filler metal and base metal, a region near the left-hand fusion line indicates an unusually high concentration of base metal that extends over a considerable distance in the vertical direction.

At higher magnification, use of the liquid-emulsion microautoradiographic technique after etching to bring out the microstructure showed the extent of ferrite distribution within this region (Fig. 7). Notwithstanding the substantial impoverishment with respect to filler metal, a thin network of ferrite phase still exists in the impoverished region. Welds made with the foregoing ferrite-containing filler wires were free of cracks and fissures, and the weld deposits showed virtually no evidence of surface encrustations.

Dissimilar-Metal Welds Between Incoloy 800 and Inconel 625 Joined with Inconel 82 Filler Metal

Figure 8 shows fusion welds made in widely differing base metals Incoloy 800 and Inconel 625 with the commercial Inconel 82 filler metal (tagged with ^{63}Ni), which is recommended for joining Incoloy 800. These welds feature both root and multipass regions and were made by the semi-automated gas tungsten-arc process using normal procedures for shielding the molten puddle during welding.

Figure 9 shows the face and root sides of one of the single-pass welds along with an autoradiograph of a cross section through the weld (location in photographs indicated by arrows). Figure 10 is a similar illustration for the multipass weld, and Fig. 11 shows still another autoradiograph of the multipass weld and depicts the individual weld passes forming the weld.

The foregoing autoradiographs and macrographs reveal vividly the character of weld cracks and show them in perspective with the features of alloy mixing and dross formation (Figs. 9, 10, and 11). The most noteworthy feature disclosed by the autoradiographs was the nonuniformity of alloy mixing in the root passes. Rather than consisting of a homogeneous mixture of base metal and filler metal as is often assumed, the root pass was frequently quite heterogeneous. In addition to a vertical layering effect similar to that obtained in the weld prepared in type 347 stainless steel sheet, relatively heavy and frequently nonsymmetrical segregates of the filler metal were noted (Figs. 9, 10, and 11). Most pertinent of all, autoradiographs often showed a severe impoverishment with respect to filler metal in the vicinity of the root surface. Since cracking frequently initiates in this region and special effort is often made to enrich the root pass in filler metal (low base metal dilution) to discourage cracking, this observation is significant indeed.

An analysis of the autoradiographs taken of the multipass weld (Figs. 10 and 11) provides a distinct pattern of filler metal distribution. The greatest inhomogeneity of composition occurs in the root pass, as might be expected. Also, base metal dilution is greatest here. Progressively decreased base metal alloying is present in the second and third layers of the weld deposit, and subsequent layers appear to be very high in filler metal content. In weld passes adjoining fusion lines, modest base metal dilution occurred along with isolated instances of base metal "washing" into the weld deposit (Fig. 11, top). These and other features were examined in more detail by the liquid-emulsion microautoradiographic technique, applied to the as-polished surface.

Figures 12 through 14 show some details at the interface between the Incoloy 800 base metal and the Inconel 82 weld deposit, and Figs. 15 through 17 show details at the interface between the Inconel 625 base metal and the Inconel 82 weld (refer to Fig. 11, top, for locations). These microautoradiographs indicate that the fusion line of the weld is considerably sharper on the Incoloy 800 side than on the Inconel 625 side.

Some idea of the autoradiographic resolution obtainable by the liquid-emulsion technique, as applied to our system, is gained from Fig. 14. Apparently, a sliver of Incoloy 800 base metal, perhaps a surface burr, was belatedly taken into the puddle and did not mix well with the weld metal. Using this as an indicator, the resolution is judged to be at least 4 μm .

Figure 16 shows a weld microcrack that interfered with the rod application of the liquid emulsion. Apparently, during application part of the emulsion was drawn into the crack, perhaps by a capillary effect, so that the emulsion became thinner in the horizontal regions at the right of the crack. This decrease in thickness of the emulsion indicates an erroneous decrease in activity that might be misinterpreted as a decrease in the concentration of the ^{63}Ni isotope. The diagonal streaks, on the other hand, are regions that actually have lower concentrations of isotope and indicate impoverishment with respect to filler metal. Figure 17 shows the pattern of alloy mixing at the Inconel 625-to-Inconel 82 fusion line at the root face. The overall concentration of ^{63}Ni in this area, incidentally, is quite low, as was also seen in Fig. 11.

To reveal microstructural detail superimposed upon the autoradiographic features just examined, the same weld specimen was repolished and etched. The stripped-film microautoradiographs in Figs. 18 and 19 were taken along the Incoloy 800-Inconel 82 fusion line.

These micrographs reveal three of the discrete weld regions proposed by Savage [1] for appraising heterogeneous fusion welds. Figure 18 shows, in addition to the unaffected base metal at the far right: (1) the heat-affected zone (manifested as enlarged base metal grains), (2) the melted but unmixed base metal microzone (normally located just inside the weld fusion line), and (3) the mechanically mixed weld metal-filler metal deposit (region exhibiting the primary autoradiographic response from ^{63}Ni). The unmixed base metal microzone was much more clearly defined in some regions of the dissimilar-metal weld than in others. Figure 19 shows this zone more clearly at a location in the Inconel 82-Incoloy 800 fusion line region. Although the microzone is thought not to mix appreciably with the rest of the weld puddle during the stirring action associated with arc

forces [1], evidence for traces of ^{63}Ni is nonetheless seen along the characteristic cellular channels within the zone (Fig. 19). The isotope probably entered the zone to this small extent by thermally activated diffusion.

Surface Encrustations on Incoloy 800-Inconel 625 Welds Made with Inconel 82 Filler Metal

Several interesting features were disclosed in examining the encrustations formed on the Incoloy 800-Inconel 625 welds. First the encrustations were most often associated with the Inconel 625 side of the welds (Figs. 9 and 10). Although they appeared both on the root and face sides of root passes, they were generally much more prominent on the root side. The dross invariably was in relief with respect to the remainder of the weld metal surface, which featured the usual ripples and cellular weld metal solidification markings.

The surface character of the crust formed on the root side of the root passes (Figs. 9 and 10, bottom) suggests that it may be a remnant of the original bottom surface of the Inconel 625 plate, which had not become completely molten and appreciably mixed with the remainder of the weld pool. This seemed especially plausible when the metal structure was examined through the transverse section of the weld. Figure 20 shows the overall macrostructure of the weld along with a blowup of the structure where the crust joins with the Inconel 625 plate. The metallographic etchant used was selected for bringing out the cored structure, which sometimes is used for differentiating between metal that has become molten (cored) and has not.

Although it had been supposed that the region void of crust (containing solidification markings) adjacent to the Incoloy 800 base metal consisted of a homogeneous alloy mixture rich in filler metal, evidence of the tracer was not always found in a very substantial amount in this dross-free region (Figs. 9 and 10). Where the filler metal did appear to a significant degree on the root face, it appeared to show little preference for either the dross-free or the dross-covered region. For face sides of root passes, the dross as a rule contained a substantial concentration of the filler metal, as did also its substrate and the region of the surface free of crust (Fig. 9).

It is interesting to note that the weld metal deposited on the Incoloy 800 side of the dissimilar-metal weld always overlapped (wetted) the base metal, whereas, as noted previously, on the Inconel 625 side the base metal appeared to extend out over the weld (Figs. 9 and 10).

Besides the foregoing dissimilar-metal welds performed under normal welding conditions, others were made in which the quality of the gas shielding and the cleanliness of the base metal plates used were varied. This was done to gain further insight into the origin of the encrustations. The results of these experiments are given in Table V. These experiments clearly show, as would be expected, that the quantity of encrustations formed on weld deposits decreases as the quality of the shielding gas and cleanliness of the base metal plates is increased.

Table V. Amount of Dross Formed on Root of Welds Between Incoloy 800 and Inconel 625 Joined with Inconel 82 Filler Metal

Weldment Number	Base Metal Plate	Shielding Gas for Weld	Quantity of Dross
1	All surfaces machined	Argon - commercial welding grade	Low
2	All surfaces machined except root side consisted of original hot-rolled and descaled surface ^a	Argon - commercial welding grade	Medium
3	All surfaces machined	Same as above except 2% air was introduced in the purge gas	High
4	All surfaces machined and then plates vacuum degassed ^b	Welding performed in vacuum chamber back-filled twice with high-purity (99.999%) argon	Very low

^aAlthough the plates had been descaled after hot rolling, metallographic examination disclosed that more deeply embedded oxide particles still remained in the substrate.

^bHeated in vacuum 4 h at 800°F (425°C).

In weldment 2 (Table V) the root surfaces of the base metal plates were purposely left in their hot-rolled and descaled conditions (contained embedded oxide particles not removed by descaling) to assess the effects of this factor as opposed to machining all surfaces free of embedded oxide contaminants. The results indicated that embedded oxide is a significant contributing factor to surface encrustations (compare weldment 2 with 1).

The most important contribution to crust proved to be the quality of the gas shielding provided for the welding. Where the purge gas was contaminated with a small amount of air the amount of encrustation was high (weldment 3), whereas when we provided the cleanest possible welding conditions (weldment 4), the amount was very low.

These experiments would seem to support the premise that the observed encrustations are largely oxide dross and stem from air accidentally entering the welding atmosphere or from reactive contaminants in the base metal plates. All three of the alloys associated with the dissimilar-metal weld contained small amounts of titanium and aluminum, which are added for deoxidation, strengthening, and grain refining. Since both have extremely high affinities for oxygen and nitrogen, it is quite likely that the encrustations contain oxides and nitrides of these elements.

The concentration of the drosses on surfaces adjoining the Inconel 625 side of these welds could result from the Inconel 625 contributing more of the dross than the Incoloy 800. Another contributing factor may relate to the surface energy (i.e., dross attached to the Inconel 625 side during melting may represent lower total surface energy than dross unattached or attached to the Incoloy 800 side).

SUMMARY

We investigated weld-associated flaws such as cracks, incomplete alloying, segregates, and dross formation in welds of types 347 and 304 stainless steel (with types 347 and 308 stainless steel, respectively, as filler metals) and other welds joining Incoloy 800 to Inconel 625 (with Inconel 82 filler metal), using autoradiography and conventional metallography. By preparing welds with ^{63}Ni homogeneously distributed within filler metal and untagged base metals, many of these features were readily delineated and their character and origin studied. The isotope ^{14}C distributes selectively, and its introduction in type 347 stainless steel revealed the character of carbon segregation (both chemically combined and in solid solution) in this alloy. Isotopes ^{35}S and ^{33}P also distribute selectively, and these tracers are being used to investigate the roles of sulfide and phosphide segregates in weld cracking.

In multipass welds joining Incoloy 800 to Inconel 625 with ^{63}Ni -tagged Inconel 82 filler metal, a distinct pattern of heterogeneous alloying between filler metal and base metal was disclosed. The root pass showed the greatest inhomogeneity as well as greatest base metal dilution. Progressively decreased base metal alloying occurred in the second and third layers of weld passes, with subsequent layers appearing to be very high in filler metal content. In weld passes adjoining fusion lines, modest overall base metal dilution was noted, but at isolated locations along the fusion line base metal concentrated at points within the weld deposit. This, together with severe impoverishment of filler metal near the root face of the weld, is most significant, since weld cracking frequently initiates in these regions, and special effort is made to evenly distribute the filler metal to discourage cracking.

Surface encrustations found principally on the surfaces of the root pass of Incoloy 800-Inconel 625 welds (usually adjoining the Inconel 625 side) were related to contaminants associated with the shielding gas and the base metals together with the minor elements titanium and aluminum in filler and base metals. These crusts were characterized by autoradiography and appropriately labeled dross.

ACKNOWLEDGMENTS

The authors wish to acknowledge the significant contributions of T. M. Kegley, Jr., in conducting the autoradiographic examinations and F. N. Case for developing and supplying radioisotopes in the needed forms. Acknowledgments are extended to J. J. Woodhouse and J. H. Mitchell for respectively assisting in assembling much of the welding equipment and making the welds. Also, thanks are due A. C. Schaffhauser and G. A. Reimann for fabricating the tagged welding wires. Finally, we acknowledge T. R. Housley for his many helpful suggestions.

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- Fig. 3. Photographic Enlargement of Contact Autoradiograph of Sprue of the 1-in.-diam, High-Segregate-Containing Type 347 Stainless Steel Casting. This casting incorporated 0.05 mCi ^{14}C per gram of metal. 3.5 $\times$.
- Fig. 4. Liquid-Emulsion Microautoradiograph of High-Segregate-Containing Type 347 Stainless Steel Casting of Fig. 3. As polished. 500 $\times$.
- Fig. 5. Butt Weld Prepared in 1/16-in.-thick Sheet of Type 347 Stainless Steel with ^{63}Ni -Tagged Type 347 Filler Metal Wire. (Top) Contact macroautoradiograph. 10 $\times$. (Bottom) Section from which autoradiograph was made. As polished. 10 $\times$.
- Fig. 6. Contact Macroautoradiograph of Weld Made on Type 304 Stainless Steel Plate with ^{63}Ni -Tagged Type 308 Filler Metal Wire. As polished. 10 $\times$.
- Fig. 7. Liquid-Emulsion Microautoradiograph of Filler Metal-Impoverished Region of Weld Deposit Prepared in Type 304 Stainless Steel Plate with ^{63}Ni -Tagged Type 308 Filler Metal Wire (Located by Arrow in Fig. 6). Polished and etched with glyceria regia. 250 $\times$.
- Fig. 8. Single-Pass and Multipass Regions of Weld Made with the ^{63}Ni -Tagged Inconel 82 Filler Wire. Base metals are Incoloy 800 (bottom) and Inconel 625 (top).
- Fig. 9. Root Pass Made Between Incoloy 800 and Inconel 625 with ^{63}Ni -Containing Inconel 82 Filler Metal. 5 $\times$. Top: surface of face side. Middle: contact autoradiograph of weld cross section. Bottom: surface of root side. Arrows on photographs locate section of autoradiograph. Evidence of weld cracking (surface on the face side of the weld) is seen in the autoradiograph along with inhomogeneity of mixing between filler metal and base metal.
- Fig. 10. Multipass Weld Made Between Incoloy 800 and Inconel 625 with ^{63}Ni -Containing Inconel 82 Filler Metal. 5 $\times$. Top: surface of face side. Middle: contact autoradiograph of weld cross section. Bottom: surface of root side. Arrows on photographs locate section of autoradiograph.
- Fig. 11. Contact Macroautoradiograph of Another Cross Section Through the Multipass Dissimilar-Metal Weld Made with ^{63}Ni -Containing Filler Metal. At the bottom, the confines of the individual passes are superimposed on the autoradiograph. 5 $\times$. The disruption extending through pass 3 on into pass 5 is a weld crack.

- Fig. 12. Liquid-Emulsion Microautoradiograph at a Point of Weld Overlap at Interface Between Incoloy 800 Base Metal and Inconel 82 Weld (Location A of Fig. 11). 50x.
- Fig. 13. Liquid-Emulsion Microautoradiograph at the Region of the Crack at Interface Between Incoloy 800 Base Metal and Inconel 82 Weld (Location B of Fig. 11). 50x.
- Fig. 14. Liquid-Emulsion Microautoradiographs at Location C (Root Interface Between Incoloy 800 Base Metal and Inconel 82 Weld). Top: sliver of Incoloy 800 in the weld deposit at 50x (see arrow). Bottom: same sliver of Incoloy 800 at 750x.
- Fig. 15. Liquid-Emulsion Microautoradiograph at Location D (Interface Between Inconel 625 Base Metal and Inconel 82 Weld). 50x.
- Fig. 16. Liquid-Emulsion Microautoradiograph Showing Microcrack (Location E) that Interfered with Rod Application of the Emulsion. Horizontal streaks are artifacts and do not indicate regions of low concentrations of ^{63}Ni isotope. Diagonal streaks are regions of low concentration of ^{63}Ni . 50x.
- Fig. 17. Liquid-Emulsion Microautoradiograph at Location F (Root Interface Between Inconel 625 Base Metal and Inconel 82 Weld). 50x.
- Fig. 18. Stripped-Film Microautoradiograph at Interface Between Inconel 82 Weld (Left) and Incoloy 800 Base Metal (Right). Etchant: 10 parts HCl, 1 part HNO_3 . 50x.
- Fig. 19. Stripped-Film Microautoradiograph at Location A in Fig. 18. 250x.
- Fig. 20. Macrostructure of Incoloy 800-Inconel 625, Dissimilar-Metal Weld Made with Inconel 82 Filler Metal. Etched with glyceria regia. (Top) Cross section of root pass (Inconel 625 at left). 10x. (Bottom) Structure at location indicated by arrow in top photograph. 100x.

Fig. 1. Contact Autoradiographs of 1/2-in.-diam Type 347 Stainless Steel Casting Containing 0.14 mCi/g ^{63}Ni . (a) Contact print of sprue, 1 $\times$. (b) Photographic enlargement of body of casting, 6 $\times$.

Fig. 2. Photographic Enlargement of Contact Autoradiograph of Swaged Type 347 Stainless Steel Welding Wire. Wire was made from casting containing 0.14 mCi ^{63}Ni . Note crack at end of wire produced during swaging. 22x.

Fig. 3. Photographic Enlargement of Contact Autoradiograph of Sprue of the 1-in.-diam, High-Segregate-Containing Type 347 Stainless Steel Casting. This casting incorporated 0.05 mCi ^{14}C per gram of metal. 3.5x.

Fig. 4. Liquid-Emulsion Microautoradiograph of High-Segregate-Containing Type 347 Stainless Steel Casting of Fig. 3. As polished. 500x.

Fig. 5. Butt Weld Prepared in 1/16-in.-thick Sheet of Type 347 Stainless Steel with ^{63}Ni -Tagged Type 347 Filler Metal Wire. (Top) Contact macroautoradiograph. 10 $\times$. (Bottom) Section from which autoradiograph was made. As polished. 10 $\times$.

Fig. 6. Contact Macroautoradiograph of Weld Made on Type 304 Stainless Steel Plate with ^{63}Ni -Tagged Type 308 Filler Metal Wire. As polished. 10x.

Fig. 7. Liquid-Emulsion Microautoradiograph of Filler Metal-Impoverished Region of Weld Deposit Prepared in Type 304 Stainless Steel Plate with ^{63}Ni -Tagged Type 308 Filler Metal Wire (Located by Arrow in Fig. 6). Polished and etched with glyceria regia. 250 $\times$.

Fig. 8. Single-Pass and Multipass Regions of Weld Made with the ^{63}Ni -Tagged Inconel 82 Filler Wire. Base metals are Incoloy 800 (bottom) and Inconel 625 (top).

Fig. 9. Root Pass Made Between Incoloy 800 and Inconel 625 with ^{63}Ni -Containing Inconel 82 Filler Metal. 5 $\times$. Top: surface of face side. Middle: contact autoradiograph of weld cross section. Bottom: surface of root side. Arrows on photographs locate section of autoradiograph. Evidence of weld cracking (surface on the face side of the weld) is seen in the autoradiograph along with inhomogeneity of mixing between filler metal and base metal.

Fig. 10. Multipass Weld Made Between Incoloy 800 and Inconel 625 with ^{63}Ni -Containing Inconel 82 Filler Metal. 5 $\times$. Top: surface of face side. Middle: contact autoradiograph of weld cross section. Bottom: surface of root side. Arrows on photographs locate section of autoradiograph.

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Fig. 14. Liquid-Emulsion Microautoradiographs at Location C (Root Interface Between Incoloy 800 Base Metal and Inconel 82 Weld). Top: Sliver of Incoloy 800 in the weld deposit at 50 $\times$ (see arrow). Bottom: Same sliver of Incoloy 800 at 750 $\times$.

Fig. 15. Liquid-Emulsion Microautoradiograph at Location D (Interface Between Inconel 625 Base Metal and Inconel 82 Weld). 50x.

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Fig. 17. Liquid-Emulsion Microautoradiograph at Location F (Root Interface Between Inconel 625 Base Metal and Inconel 82 Weld). 50x.

Fig. 18. Stripped-Film Microautoradiograph at Interface Between Inconel 82 Weld (Left) and Incoloy 800 Base Metal (Right). Etchant: 10 parts HCl, 1 part HNO_3 . 50 $\times$.

Fig. 19. Stripped-Film Microautoradiograph at Location A in Fig. 18.
250 $\times$.

Fig. 20. Macrostructure of Incoloy 800-Inconel 625, Dissimilar-Metal Weld Made with Inconel 82 Filler Metal. Etched with glyceria regia. (Top) Cross section of root pass (Inconel 625 at left). 10 $\times$. (Bottom) Structure at location indicated by arrow in top photograph. 100 $\times$.