Weldments in vessels and components for nuclear power generation must be of especially high quality due to the complexity and criticality of this demanding service. INCONEL alloys 600 and 690 have been widely used in nuclear construction, especially in the steam generation systems of reactors. A team of specialists from Special Metals Corporation discusses the application of this material in nuclear service.

# Nickel alloy welding requirements for nuclear service

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Steam generator tubes and through-wall nozzles and hardware and the required weld joints in nuclear power plants must exhibit strength, integrity and corrosion resistance. Since these welds are required for containment of potentially radioactive material, they must be made using specially designed welding products that are deposited with precision using carefully designed procedures.

INCONEL alloy 600 (UNS N06600) steam generator tubes and hardware were used in nuclear reactors for electric power generation beginning in the 1950's. Alloy 600 provided greatly improved resistance to stress corrosion cracking over grade 304 stainless steel. Unfortunately, the welding products available for joining alloy 600 at that time were not capable of producing weldments with the desired integrity for nuclear service.

Research into hot cracking in nickel-chromium-iron alloys started as early as 1946.[1] Early work conducted at the Research Laboratory of the International Nickel Company, Inc. in Bayonne, NJ, USA resulted in the development of welding products that became INCONEL Welding Electrode 182 (AWS A5.11 ENiCrFe-3) and INCONEL Filler Metal 82 (AWS A5.14 ERNiCr-3). These were the first NiCrFe-type welding products capable of depositing crack-free, porosity-free weldments in alloy 600.[2,3] Further work at Huntingon Alloys evaluated the cracking resistance of these products using Varestraint testing methods.[4]

While alloy 600 provided greatly improved service over 304 stainless steel it still was subject to stress cracking after long exposure to high purity reactor steam and primary water. As a result, INCONEL alloy 690 (UNS N06690) has essentially replaced alloy 600 for components of the nuclear steam generator.[5] The initial welding products used for joining alloy 690 were INCONEL Welding Electrode 152 (AWS A5.11 ENiCrFe-7) and INCONEL Filler Metal 52 (AWS A5.14 ERNiCrFe-7). B.B. Hood of Westinghouse and W. Lin of the Edison Welding Institute (EWI) evaluated the hot cracking resistance of these products and compared them with those used to join alloy 600.[6] These two EWI solidification cracking studies showed Filler Metal 52 to be more hot-cracking resistant than Filler Metal 82 and Welding Electrode 152 was more resistant than Welding Electrode 182. The next generation of nuclear welding products is comprised of INCONEL 52M and WE 152M. Like 52 and 152 these products are designed with 30% Cr with addition of B + Zr to provide resistance to ductility dip cracking. Furthermore, welds made with INCONEL Filler Metal 52M have been shown to exhibit a crack growth rate of less than 1/20 the rate of welds made with Welding Electrode 182 when tested in simulated primary water. (6.5 to 1.0 ppm Li, 1500 to 250 ppm B, and approximately 35 cm3 (STP) $H_2$/kg$H_2O$ and stress intensities between 26 and 43 MPa√m).[7] Table 1 lists some of the current nickel based welding consumables used for nuclear service.

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| | Ni | C | Mn | Fe | S | Cu | Si | Cr | Ti | Nb | P | Mo | Al | Other |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| INCONEL Alloy 600 | 72 min. | 0.15 max. | 10. 10.0 | 6.0- max. | 0.015 max. | 0.50 max. | 0.50 max. | 14.0-17.0 | - | - | - | - | - | - |
| INCONEL FM 82 | 67 min | 0.10 max. | 2.5-3.5 | 3.0 max. | 0.015 max. | 0.50 max. | 0.50 max. | 18.0-22.0 | 0.75 max. | 2.0 3.0 | 0.030 max. | - | - | 0.50 max. |
| INCONEL WE 182 | 59.0 min. | 0.10 max. | 5.0-9.5 | 10.0 max. | 0.015 max. | 0.50 max. | 1.0 max. | 13.0-17.0 | 1.0 max. | 1.0-2.5 | 0.030 max. | - | - | 0.50 max. |
| INCONEL Alloy 690 | 58.0 min. | 0.05 max. | 0.50 max. | 7-11 | 0.015 max. | 0.50 max. | 0.50 max. | 27-31 | - | - | - | - | - | - |
| INCONEL FM 52 | Balance max. | 0.04 max. | 1.0 max. | 7.0-11.0 | 0.015 max. | 0.30 max. | 0.50 max. | 28.0-31.5 | 1.0 max. | 0.10 max. | 0.02 max. | 0.50 max. | 1.10 max. | 0.50 max. |
| INCONEL WE 152 | Balance | 0.05 max. | 5.0 max. | 7.0-12.0 | 0.015 max. | 0.50 max. | 0.75 max. | 28.0-31.5 | 0.50 max. | 1.0-2.5 | 0.03 max. | 0.50 max. | 0.50 max. | 0.50 max. |
| INCONEL FM 52M* | Balance | 0.04 max. | 1.0 max. | 7.0-11.0 | 0.015 max. | 0.30 max. | 0.50 max. | 28.0-31.5 | 1.0 max. | 0.50-1.0 | 0.02 max. | 0.50 max. | 1.10 max. | 0.50 max. |
| INCONEL WE 152M* | Balance | 0.05 max. | 5.0 max. | 7-12.0 | 0.015 max. | 0.50 max. | 0.75 max. | 28.0-31.5 | 0.50 max. | 1.0-2.5 | 0.030 max. | 0.50 max. | 0.50 max. | 0.50 max. |

* Minor additions of boron and zirconium

Table 1: Nickel based alloys & welding consumables for nuclear applications

## Ductility dip cracking

In the mid-1990's, a naval research team discovered an unusual solid-state cracking phenomenon during a fabrication procedure using a 30% chromium welding wire. The cracking seemed to occur as solidification cracking, but after careful examination, it was found not to be associated with liquation or liquid phase. These cracks were characterized by clusters of fine re-crystallized grains that sometimes occurred at the crack tips. This solid state cracking came to be known as "cold cracking" as well as "reheat cracking", since it was not related to solidification cracking or hot cracking. Actually, a misnomer, "cold" cracking occurs in the range of 1400°F (760°C) – 1900°F (1038°C) in those alloys that are susceptible. Later work by Cola and Teter quantitatively demonstrated a pronounced ductility dip in the temperature range of 800°C to 1000°C and has more recently been researched by Ohio State University.[8,9]

Today this cracking phenomenon is more accurately described as ductility-dip-cracking (DDC).

## Research into ductility dip cracking

A research program was undertaken to study DDC and develop improved welding products for alloy 690. Various compositions were evaluated resulting in several interesting findings.[9]

The effects of oxygen, carbon and sulfur were investigated to determine their effect on the degradation of grain boundary ductility. To counter their effects, the addition of elements known to positively influence grain boundary strength, de-oxidation, and de-sulfurization was investigated.

The formation and influence of oxide and nitride "floaters" was also studied due to concerns that they could induce lack of fusion and/or porosity or become entrapped as inclusions. (See figure 1)

An account of the research program conducted at Special Metals Welding Products Company, which resulted in the development of improved consumables for welding alloy 690 follows.

## DDC research program results

A review of the open literature and

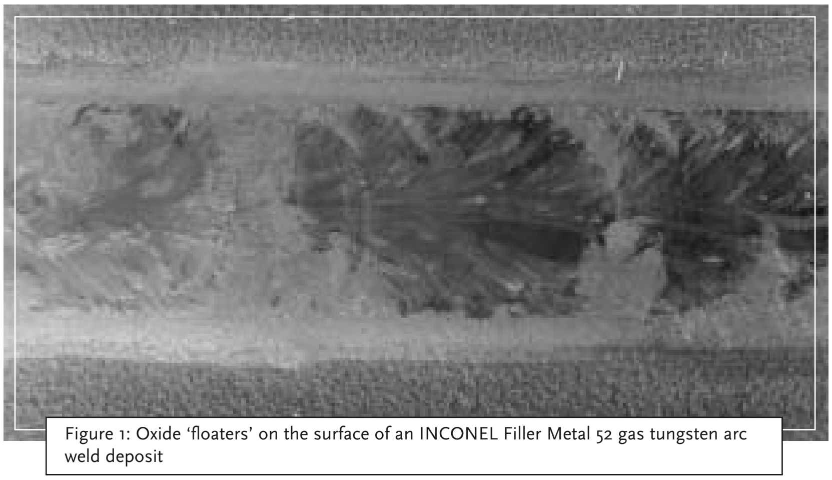

Figure 1: Oxide 'floaters' on the surface of an INCONEL Filler Metal 52 gas tungsten arc weld deposit

Figure 2: Electro slag strip clad deposit cross sections with INCONEL 52M weldstrip (0.5mm x 60mm) and INCOFLUX ESS2

review of DDC encountered in internal studies resulted in a proposed cracking mechanism. It was determined that some cell boundaries or grain boundaries exhibited less high-temperature ductility than the cell/grain interiors. When susceptible alloys were exposed to strain at elevated temperature (as occurs in any highly restrained, multi-pass weldment), the ductility limit of the grain/cell boundary can be exceeded and a crack may develop. The crack may be arrested as the stress is reduced at the crack opening and the energy released may be absorbed during re-crystallization at the crack tip. Several research programs contributed to improved understanding of grain boundary mechanics.[10,11,12] The products that resulted from this study were INCONEL Welding Electrode 152M (AWS A5.11 ENiCrFe-7), INCONEL Filler Metal 52M bare wire and weldstrip consumables (AWS A5.14 ERNiCrFe-7A) by Special Metals Welding Products Company.[13] All of these consumables are capable of producing welds that are resistant to hot cracking, DDC, and oxide build-ups and are included in table 1.

### Newly developed welding consumable product variants for surfacing the nuclear industry

The most recently developed products to complete the family of nuclear welding consumables are INCOFLUX ESS2, INCOFLUX SAS2 and INCONEL weldstrip 52M. These products are designed for quick and efficient weld overlay of tubesheets and vessel components which require resistance to PWSCC. Work was performed by Special Metals (formerly Inco Alloys Int'l) in the early 1990's for development of a flux and weld deposit that provided all of the benefits described in the recently developed 'M' type consumable for welding alloy 690. The result of this work was presented at an EPRI / INCO sponsored Symposium for Nuclear Designers and Fabricators.[14] The work showed that INCONEL alloy 690 strip in conjunction with neutral and active fluxes resulted in weld deposits that nominally passed the quality tests at that time.

Subsequent work performed at Special Metals has shown that the deposits made using alloy 690 strip with neutral or active fluxes suffered from DDC type cracking. It was not until INCONEL Weldstrip 52M was used, that a consistent weld deposit was achieved that was resistant to hot-cracking, root-cracking and DDC. The INCOFLUX ESS2 and INCOFLUX SAS2 surfacing fluxes in conjunction with INCONEL 52M weldstrip (AWS A5.14 EQNiCrFe-7A chemistry) results in weld deposits that meet the compositional limits of the INCONEL Welding Electrode 152M (AWS A5.11 ENiCrFe-7 deposit chemistry). See figure 2 and table 2.

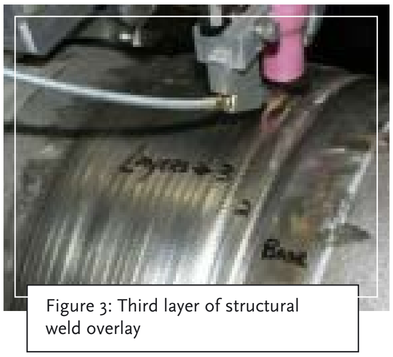

Figure 3: Third layer of structural weld overlay

### Case history nuclear repairs with INCONEL Filler Metal 52M

Extensive parameter development research has enabled installation of NDE-acceptable structural overlays; however, the susceptibility of ERNiCrFe-7 to rejectable UT indications has driven industry to INCONEL Filler Metal 52M. One factor of particular interest is the potential that INCONEL Filler Metal 52M allows installation of struc-

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**CHEMICAL COMPOSITIONS**
**INCONEL® weldstrip 52M - heat number NX4721TK**

| Element | Strip | Layer 1 | Layer 2 | Layer 3 |
|---|---|---|---|---|
| C | 0.015 | 0.028 | 0.024 | 0.022 |
| Mn | 0.69 | 1.25 | 1.27 | 1.22 |
| Fe | 8.14 | 11.7 | 8.55 | 8.31 |
| S | 0.001 | 0.002 | 0.002 | 0.002 |
| Si | 0.13 | 0.23 | 0.23 | 0.2 |
| Cu | 0.02 | 0.01 | <0.01 | <0.01 |
| Ni | Bal. | Bal. | Bal. | Bal. |
| Cr | 29.47 | 28.4 | 29.4 | 29.8 |
| Al | 0.11 | <.001 | <.001 | <.001 |
| Ti | 0.21 | 0.02 | 0.02 | 0.02 |
| Nb | 0.8 | 1.22 | 1.32 | 1.19 |
| B | 0.001 | <.001 | <.001 | <.001 |
| Zr | <0.01 | - | - | - |
| P | 0.004 | 0.007 | 0.006 | 0.007 |

Table 2: INCONEL Weldstrip 52M and INCOFLUX ESS2 weld deposit chemistry by layer


Figure 4: INCONEL® Filler Metal 52M (ERNiCrFe-7a) structural weld overlays

tural weld overlays using orbital, circumferential weld progression. See figure 3: Orbital weld repair performed by WSI.[15] The need for orbital welding is based largely on the fact that double-uphill weld progression results in increased welding time, thereby increasing radiation exposure levels for welding operators.

INCONEL Filler Metal 52M does not rely on aluminum and titanium as primary de-oxidizers, and this metallurgical difference was considered a potential contributor to a reduction in the oxides/contaminants whose entrapment can lead to UT indications.

Welding Services Inc. initiated the preparation of a mockup coupon to assess the weldability of INCONEL Filler Metal 52M. The test coupon consisted of a 12” diameter pipe section with a nominal wall thickness of 0.844”. The coupon was horizontally mounted in pipe stands, enabling deposition of circumferential weld overlays on the pipe OD surface to be accomplished in the 5G position. Pipe ends were capped and a flow of cool water was initiated in the pipe in order to simulate welding on a large heat sink. Two structural weld overlays were installed using WSI’s proprietary welding parameter controls (i.e., the controls developed to achieve acceptable deposit quality when using ERNiCrFe-7A). One of the overlays used double-uphill progression, the other used orbital lateral progression. Figure 4 shows the two weld build-ups on the pipe coupon nearing completion.[15]

Figure 5 shows the configuration of the weld coupon, the deposition process for the overlays, and the final weld configuration. After weld completion, the structural overlays were shipped to Electric Power Research Institute (EPRI) in Charlotte, NC, USA for nondestructive evaluation.[15]

## Non–destructive testing of the INCONEL Filler Metal 52M structural weld build-ups

The overlays were initially examined by surface dye penetrant to look for indications of porosity or cracking. The surfaces had been machined smooth by WSI. No significant indications were detected. The two overlays were then evaluated using contact ultrasonic testing, similar to that used for field applications. This is an automated scanning method that used multiple angle beam inspections. The two mockups showed no rejectable indications in the 0°, 45°, 60° and 70° angle beam scans.

## New DDC-resistant welding products for the nuclear industry

The technology derived from this study was incorporated into the design of improved welding products for joining alloy 690 and overlaying for nuclear construction and repair applications. The weldments from the resulting products, designated INCONEL Welding Electrode 152M (AWS A5.11 ENiCrFe-7) and INCONEL Filler Metal 52M and INCONEL weld-strip 52M(AWS A5.14 EQNiCrFe-7A), (UNS# N06054), offer improved resistance to DDC (cold cracking). In addition, they also exhibit excellent resistance to solidification cracking (hot cracking) while producing reduced incidences of floaters, inclusions, and porosity. These benefits should result in significant improvements in ultrasonic (UT), radiographic (RT), and liquid penetrant (PT or LPI) weld inspection results. Thus, the nuclear reactors of the future should be safer and more reliable to continuously supply the electricity needed by our expanding world.

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Figure 5: P3-Group 3 pipe coupon with orbital (bottom) and double-up (top) weld build-ups

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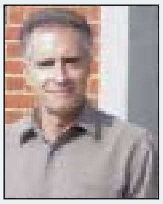
## About the authors



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