Review of the Weldability of Incoloy Alloy 800

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ABSTRACT

Incoloy 800 is a single phased, austenitic, solid solution alloy with fine dispersion of gamma prime particles and carbides. In general, this alloy has good weldability and all the most common processes can be applied to it. With careful attention to edge preparation and fit up upto 8mm thick plates can be autogenously welded. This alloy is sensitive to segregation effects. It displays tendency to solidification cracking. There is some doubt about the susceptibility of this alloy to HAZ liquation cracking. Here the grain size plays an important role. This alloy can be welded either using high nickel fillers or matching composition filler materials. High heat-input welding processes like electroslag welding can be successfully used.

1. INTRODUCTION

The usefulness of any material can be decided ultimately by its fabricability especially in the case of boiler tubing where cold bending and weldability are the most important fabrication factors. The amount of reported work on the weldability of Alloy 800 is quite limited. One can consider Alloy 800 simply as an extension of austenitic steels to a 40 Fe 30 Ni 20 Cr composition or as an extension of the high nickel Inconel material. Actually, this uncertainty of this alloy generates interest in its weldability studies.

It is usually considered that fully austenitic weld metal should contain about 5% delta ferrite to give optimum weldability. But this condition does not apply to all steels because it is known that a 15% Cr, 10% Ni, 6% Mn austenitic stainless steel tubing has been successfully welded with virtually no delta ferrite in the weld metal. Similarly successful welds have been produced in Alloy 800 tubing with high nickel weld metal and this does not contain any delta ferrite.

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Liquation cracking is a problem in all austenitic stainless steel including Alloy 800 but can be minimized by correct welding procedures and choice of filler metal. In general, the alloy has good weldability and all the most common processes may be applied to it.

The present paper evaluates the literature available on the weldability of Alloy 800 and discusses the various problems encountered and the limitations of each of the welding processes attempted.

2.1 FUSION WELDING

In view of the rapid heating and cooling involved in any fusion welding process, the metallurgical weldability must be carefully considered. Alloy 800 is a single phased, austenitic, solid solution alloy with fine dispersion of gamma prime particles and carbides, the latter precipitating in the temperature range of 550-1100°C.

A tendency to hot cracking during solidification is reported in the welding of Alloy 800, as is encountered with austenitic stainless steels[1]. Varestraint test and Gleeble test have been extensively used in attempts to determine the causes for the hot cracking susceptibility of the lower nickel containing alloys (Fig. 1).

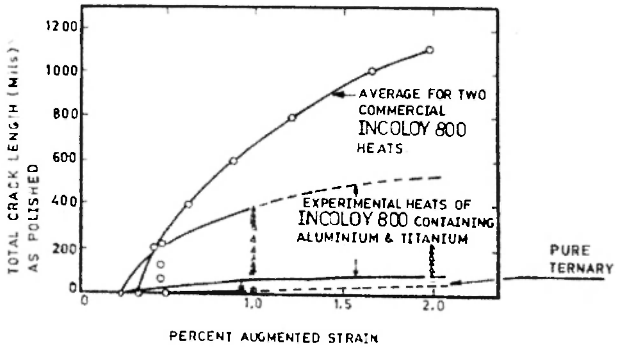

Fig. 1. Varestraint result for the experimental heat of Incoloy 800 composition. The results of two commercial heats have been included for comparison.

The aspects of solidification cracking in weld beads as they are laid viz., crater cracking and liquation cracking in HAZ adjacent to weld beads should be separately considered. Even though both are related to compositional and segregational effects one is a liquid state mechanism and the other essentially a solid state mechanism.

Lingenfelter[2] and Hack[3] using a 400 A plasma arc welding machine with 95% Ar, 5% H_2 gas studied the key hole regime of plasma welding of Alloy 800. Hack concluded that careful attention to edge preparation and fit up was necessary and having taken these precautions, 6mm material could be autogeneously welded very successfully. Lingenfelter extended the thickness to 8 mm. Both workers remarked on the absence of cracking in the welds although no reference to the crater area was made.

Taylor[4] attempted to weld Alloy 800 tubes to tube plates of various materials by an automated TIG process. He reported solidification cracking in the tail-off region in Alloy 800 to itself, to 2¼ Cr-1 Mo and to an Inconel alloy. In the joints of Alloy 800 to Inconel 82 filler overlays and to AISI 316 stainless steel, some weld metal cracking were noted. This work was apparently carried out by continuous current TIG welding and the author reported greater optimism for the welding of tube to tube butt welding with pulsed power. He concluded that for material of 4 mm thickness, filler metal would be necessary.

Fricker and Herero[5] have reported that upto 5 mm thickness, autogenous weld could be made with specially constructed automatic TIG heads and a sophisticated pulsed power source. They used long tail-off current decay to eliminate crater cracking. They had also experimented with autogenous welds in greater thickness with moderate success.

2.2 Factors leading to cracking

The first guide to the compositional effects in high nickel alloys was given by Pease[6]. According to him lead, sulphur, phosphorous, zirconium and boron were harmful to weldability whilst Aluminium, Titanium, Carbon, Molybdenum and Silicon had variable effects.

Lingenfelter[7] confirmed, using Varestraint test, that with commercial material, the resistance to hot cracking increased with increasing Nickel content from Alloy 800 to Alloy 600 to nickel itself. This result indicates the reason why high nickel filler metals are preferred to prevent cracking.

Lingenfelter's work[8] on solidification cracking in Inconel type material is interesting. Using electron probe micro analysis adjacent to cracks induced in Varestraint test, he established a segregation ratio from the composition measured within a weld metal grain cell and that of a boundary region. The author reported no significant segregation of Cr, Al, C, Ni, Fe or P, while niobium segregated very strongly along grain boundary and Si, Ti and Mn did to a significant degree. The accuracy of electron probe micro analysis on intercellular regions is rather baffling.

Slaughter et al[9] reported a 2½ fold concentration of Mn in Alloy 800 HAZ grain boundaries by electron probe micro analysis. But they did not associate cracking with this segregation.

HAZ grain boundary cracking may also be induced in Alloy 800 by copper alloys[10]. Usually copper is considered to be detrimental and is present around 0.5% in Alloy 800.

The results of Canonico et al[11] work using Gleeble test to study liquation cracking susceptibility of a series of pure alloys showed that increasing the (Ti+Al) content decreases the zero ductility temperature (ZDT) and the zero strength temperature (ZST) of Alloy 800. The results showed excessive scatter and are inconclusive. It was reasonably concluded that none of the alloys studied would be liable to liquation cracking. According to McKeown[12] experimental alloys made from high purity materials are so far removed from commercial alloys as to be of any value.

Another factor affecting liquation cracking is grain size. This factor becomes important after the introduction of Alloy 800H with a controlled large grain size. Widgery[13] showed a marked dependence of liquation cracking in a single batch of stainless steel on grain size.

Yeniscavich[14] working on high nickel filler metals found that the resistance to hot cracking increased as the working speed increased. He attributed this to the observed smaller grain size of the HAZ and weld metal. A small grain size in the weld metal conferred a hot cracking resistance. A fine grained parent material would produce an equivalent grain size in the weld due to epitaxial growth of the weld bead from the weld/parent interface.

To define the source of the increased cracking susceptibility of the lower nickel alloys, Canonica et al[11] studied the effect of minor element additions using both the Varestraint and Gleeble tests. They investigated the effects of processing variables and minor elements. The Varestraint test results indicated that the commercial heats of Alloy 800 were more sensitive to hot cracking than laboratory melted pure heats. From the work on alloys containing varying amounts of titanium and aluminium, no conclusion was possible due to scattered results. They could not isolate the effects of titanium and aluminium from the effects of other minor elements additions in the commercial heats. However, it was reported that by reducing the (Ti+Al) content to extremely low levels ($<0.06\%$) hot cracking was eliminated.

Wolstenholme[15] showed that Alloy 800 is susceptible to crater cracking in both autogenous welds and welds completed with filler metal EN82. The crater cracks investigated were restricted to root runs only. He showed the cracking to be associated with the segregation which occured during solidification. Segregation took place at the columnar grain boundaries where low melting point liquid film was present. The solidification crack surfaces were characterized by a decanted cell solidification morphology and decorated by TiC dendrites. The author inferred that the solidification cracking resulted from the depression of the solidus by carbon in solution in the molten segregates. He suggested an improvement by lowering the carbon content and by increasing the titanium content so that the concentration of carbon in solution in the liquid could be reduced by the precipitation of carbides. But this is a little impractical and, further, limiting carbon would also impose severe limitations on the properties of the material.

2.3 Fusion Welds With Added Consumables

Alloy 800 may be welded by all the usual techniques with the addition of filler metal. The filler metal contains a considerable amount of deoxidant mainly Niobium. Plasma arc welding with added filler and higher deposition rates are possible. MIG welding may also be carried out with both spray and globular dip transfer modes.

Work has been carried out for the suitability of the filler metals EN62 and EN82[14], both of which are high nickel filler alloys using the Gleeble test. The results of this work confirmed the higher hot cracking susceptibility of EN62, a factor which is now fully recognised and has resulted in the extensive use of EN82 in preference to EN62 (Fig. 2).

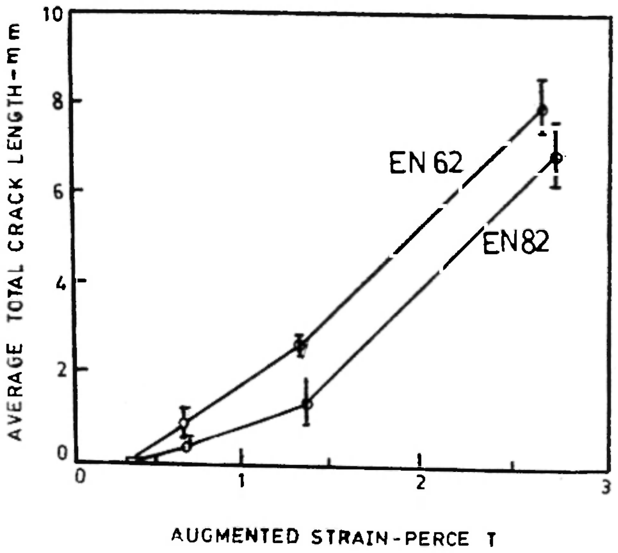

Fig. 2. Varestraint test results on filler metal EN 82 and EN 62.

Although welds in Alloy 800 have generally been made using a high nickel filler of the EN82 type, welding products with a more closely matching chemical composition have been developed. For certain applications where preferential corrosion may occur in the high nickel component or where differences in thermal coefficient of expansion cannot be accepted, such matching consumables are to be preferred. Such consumables should have, in addition to matching thermal coefficient of expansion and corrosion resistance, freedom from sigma phase formation.

Recently filler metal Incoloy 88[16] has been developed which matches the Alloy 800 composition. It is recommended for use to about 550°C. It was specifically introduced for use in sodium cooled nuclear reactors to combat possible nickel transfer from high nickel alloys. But it is liable to embrittle after long exposure at 750°C. This filler metal has good tolerance to Iron dilution and has good weldability as well. A manual metal arc electrode of similar composition to Incoloy 88 is also available as Incoloy 188 but data on this electrode behaviour is limited.

3. ELECTROSLAG WELDING

In recent times much interest is being shown in using Incoloy 800 in heavier sections such as for heavy wall pressure vessels. Electroslag welding can show great economic and technical advantages over other joining methods especially for thicker sections. The major metallurgical advantage is the refining of the weld metal which gives clean and dense deposits. The work of Kenyon et al[17] on electroslag welding Alloy 800 is of interest. They showed that the material could be successfully welded in 25 mm and 112 mm thicknesses. It is particularly significant that they could produce sound joints with Inconel 82 filler as well as with filler metal having same composition, as the base metal because it is known that the latter is not ideal for welding with other processes. There seems to have been no problem on transfer of reactive elements such as titanium and aluminium from filler wire to weld pool. The electroslag weld deposits they obtained were uniform in composition from top to bottom with low sulphur levels. The strength of weld deposits were lower than those of annealed base metal at room temperature but came close to them at elevated temperatures. The more the thickness of the plates welded the less strong was the weld metal. The ductility of the welds at room as well as at high temperatures was unusually high. There appears to be no explanation to this behaviour which possibly could be attributed to the large grain size encountered in the weld metal. It is also noted that no cracking of side bend test specimens were observed in their work inspite of the fact that the welds were exposed to high temperatures for larger interval of time which is characteristic of electroslag welding. In other words, the HAZ liquation cracking in Incoloy 800 is not so easily induced as one is led to believe by other workers.

4. ELECTRON BEAM WELDING

Arata et al[18] investigated the effect of the welding conditions on the characteristics of the weld geometry and weld defects concerning the heat resistant superalloys for the nuclear plants. The weld defects they came across were root porosity and microcrack. They pointed out that to evaluate the susceptibility to root porosity of various alloys, the important criteria are bead energy density, object distance from the lens and the focal length of the lens which focusses the electron beam. According to them, iron base superalloys such as Incoloy 800 and austenitic stainless steel 316 are more susceptible to root porosity as compared with nickel based superalloys such as Hastelloy and Inconel. Incoloy 800 and stainless steel 316 have almost equal susceptibility to root porosity. It was recognised from the effect of the heat input on the microcracking percentage that microcrack was apt to occur at the heat input larger than the critical value. In this respect, stainless steel 316 is superior to Incoloy 800.

5. VACUUM BRAZING

In tube to tube plate configurations where all tubes are brought to a tube plate, accessibility is limited. The tube to tube plate, joint by its nature produces a severe restraint condition and hence adds to welding problems by increasing the susceptibility to fissuring and hot cracking in fusion welding of alloy 800. Vacuum brazing was explored by Clarke Chapman Ltd. because not only were problems of accessibillty eliminated but there were additional benefits of simultaneous joining, internal cleanliness and heat treatment. The combination of vaccum atmosphere and high brazing temperature eliminates the need for brazing fluxes by improving the wetting of the joint surfaces through the reduction of surface oxides.

Henderson et al[19] investigated the vacuum brazing of Alloy 800 tubes into a 2½ Cr-1Mo low alloy tube plate because of their potential use in the steam generating equipment for high temperature gas cooled reactors and sodium cooled fast reactors. Moreover this joint represents one of the most difficult joints to fabricate because of the different thermal expansion coefficients of the alloys.

Three vacuum brazing techniques were studied by them. Capillary brazing : A brazing process which depends primarily on joint fit up of sufficient accuracy to ensure a flow of brazing alloy through the joint by capillary action. Braze bonding : a brazing process involving the preplacing of the brazing alloy onto one joint surface and applying sufficient pressure for a specific time at a temperature to produce melting of the brazing alloy and some diffusion into the parent materials. Diffusion bonding : which is more or less similar to braze bonding except that diffusion is the predominant factor in such a case.

They found out that a repetitive, reproducible and simple surface preparation was most important for the braze and diffusion bonding. The capillary brazing was not influenced much by the surface condition because the alloys they used—Ni-Cr-Si and Ni-Cr-P alloys—were self-fluxing. In capillary brazing, both the amount of brazing alloy and the brazing time should be kept to a minimum, because of the erosive nature of the brazing alloy, Ni-Cr-Si being more corrosive than the other due to the much higher brazing temperature.

In the other two methods, the amount of brazing alloy was kept to a minimum and the brazing time set to produce a joint with an optimum amount of diffusion. Both the braze and diffusion bonded specimens showed superior joint strength compared to the capillary brazed specimens.

When these joints were subjected to a temperature of 600°C for 2000 hrs, the capillary brazed specimens showed no evidence of carbon migration. But the structure of the Ni-Cr-Si alloy distinctly deteriorated. Diffusion of the braze bonding alloy into the parent materials occured as evidenced by a distinct change in structure and corresponding decrease in hardness of the brazing alloy. Diffusion bonded specimens showed carbon migration from the ferritic material to the Alloy 800 tube corroborated by the increase in hardness in both the nickel bonding layer and the area of Alloy 800 closest to the joint.

6. PRESSURE WELDING PROCESSES

Incoloy 800 can be welded to itself or to steels by friction welding. Due to superior hot strength of Alloy 800, longer burn-off is required in this alloy than in stainless or C-Mn steels. So, due allowance must be made in monitoring the welding process.

Holko[20] investigated friction welding of Alloy 800 pins to Alloy 800 tubes and observed that if the welds were post-weld heat treated, Alloy 800 friction welds attained the base metal microstructure and creep rupture strength.

Adams et al[21] friction welded Alloy 800 to a 2½ Cr-1 Mo steel to produce bimetal studs which were designed to overcome a particular dissimilar metal joint giving fusion welding problems. They observed good room and high temperature tensile properties. Henderson and Campbell[19] used friction welding for making joints directly between tubes and tube plates in Alloy 800. They produced sound welds with good ambient temperature fatigue strength.

Due to the ductile nature of Alloy 800, explosive welding of wrought alloy becomes possible. A process pioneered by the Yorkshire Imperial Metal Co., as 'YIMPACT' makes use of explosive welding to make tube to tube plate joints by inserting a plug of explosive into the end of the tube[12]. Explosive cladding of tube plates is becoming more common.

Alloy 800 has been resistance stud welded to itself and to AISI 310 steel on a high temperature kiln[22]. In most of the service failures, the joint line was preserved and failure took place in the HAZ of the Alloy 800.

7. SUMMARY

It may be concluded that with suitable control of composition and grain size alongwith correct welding procedures, Alloy 800 can be welded without cracking problems even with high heat input welding processes using either high nickel filler wires or a matching electrode. But the alloy is sensitive to segregation effects. There is no doubt that the alloy displays a marked tendency to solidification cracking. But there is less agreement about the susceptibility of the alloy to HAZ liquation cracking. This is due to the poor understanding of the segregating elements and phases. This can be avoided by strict compositional control. There is very limited information available on the welding of this material by less conventional processes.

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