Fine Grained Weld Structures

Superplastic welds can be obtained in certain Cr-Ni iron base alloys using filler metals of controlled Al-N contents and conventional welding procedures.

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Introduction

The combination of advantages that fine grains confer on metal structures is unique including, as it does, increased strength, toughness, and fatigue life. As a result, the desirability of using fine grained materials for many applications has become widely recognized, and methods for producing the small grains have been established. In cast structures the techniques include rapid cooling, inoculation, vibration, and electromagnetic stirring. The extrapolation of these techniques to refine the grain size of weld metals has, however, met with very limited success. Welds are still normally characterized by relatively large grains. This point was emphasized to us in research on welding of some superplastic iron-chromium-nickel alloys which in the wrought condition are ultra-fine grained (grain size about 2-3 microns). When tensile tested at...
Table 1. Compositions of Base Plates Used for Welds Shown in Table 2

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<th>No.</th>
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<th>Mn</th>
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<th>Ni</th>
<th>Ti</th>
<th>Al</th>
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Table 2. Welding Processes and Conditions Used for Welds in 26% Cr, 6.5% Ni, Bal. Fe Alloys and 

Experimental Procedure

Welding processes and conditions used for welding 26% Cr, 6.5% Ni stainless steel were investigated. The aim was to determine the effects of welding conditions on the microstructure and properties of the weld metal. The welding processes included gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), and manual metal arc welding (SMAW). The welding conditions were varied to assess their influence on the weld properties.

Results

The results showed that the choice of welding process and conditions significantly affected the microstructure and properties of the weld metal. The use of GMAW with higher current and voltage settings resulted in a finer-grained microstructure compared to GTAW and SMAW. Higher heat input was found to promote grain growth, while lower heat input led to a finer-grained structure.

Fig. 1 - A higher magnification view of the weld microstructure shown in Fig. 2.
Photomicrographs of the base metal/heat-affected zone/weld interface of these sections are shown in Fig. 2 and 3 with the weld deposit shown at the right. The base metal has a ferritic matrix with many finely dispersed particles of austenite. The grain size of the wrought alloy is not obvious in this photomicrograph but is roughly equal to the interparticle spacing. Rapid grain coarsening and partial solution of the austenite occurred in the heat-affected zone. In the aluminum-free weld deposit (Fig. 2), epitaxial growth was observed and a columnar grain structure developed. The junction of weld metal and heat-affected zone is indicated by arrows and was associated with the appearance of second phase particles in the coarse grained ferritic matrix.

Figure 3 shows an identical area in a joint made with an aluminum-containing filler metal of essentially the same composition as that used for the first weld. Again, the junction of weld and heat-affected zone may be discerned by the appearance of second phase particles in the ferritic matrix. The photomicrograph shows that initial growth from the wall was epitaxial for about 0.07 mm. The periodic array of the second phase particles in this first grain formed by the advancing solid-liquid interface suggests that the initial growth mechanism was planar. After growth proceeded in this manner for a very short distance, the mechanism of solidification changed abruptly and a fine grained structure resulted. An average grain size of 0.02 mm was measured in the fine grained weld as compared to 0.14 mm in the coarse grained weld.

Higher magnification views further illustrate the vast difference in size of coarse and fine grained weld structures (Figs 4 and 5). In both welds the matrix is ferritic and the grain boundary phases consist primarily of austenite with some fine carbides at their edge, as well as randomly distributed titanium carbo-nitrides. Top pass beads or single bead-on-plate welds had a fine grain structure which resembled in every way the other weld beads contained within a multipass weld.

Microprobe analysis of the fine grained welds showed that the austenite was enriched in nickel and depleted only slightly in chromium. Many of the particles in the center of the fine grained welds were found to be aluminum rich. Despite trials with a variety of etchants, it was not possible to show the columnar growth structure known to characterize this type of alloy. In fact, bend tests of polished samples also showed the characteristic deformation markings of a fine grained, equiaxed structure rather than a coarse grained, columnar structure.

The structure exhibited by the fine grained welds was found to be truly equiaxed when viewed in three planes as demonstrated in Fig. 6. This figure is a composite of three photomicrographs in the form of a cube and illustrates the same fine, equiaxed structure in all directions.

Examination of craters resulting from gas tungsten-arc bead-on-plate welds revealed smaller dendrites in aluminum-containing than in aluminum-free welds. Figures 7 and 8 show the respective sizes of dendrites near the center of the craters in an aluminum-free and an aluminum-containing weld. In both cases, dendrite size corresponded closely to the etched grain size present in the deposit preceding the crater.

Fine Grain Composition Range

In order to produce fine grains, the level of aluminum added to the 26 % Cr, 6.5 % Ni base was critical. Fine grains were only observed in the range 0.05-0.20% aluminum. The heats used to examine the effect of variation in chromium and nickel contents, shown in Fig. 9 superimposed on an isothermal cross section of the phase diagram, were split five ways over which the fine grained phenomenon occurred. At the higher chromium levels (> 40%) weld cracking was observed. Furthermore, although the alloys containing chromium in excess of 30% were of interest from the standpoint of fine grain size, attempts
to scale-up heat size were unsuccessful due to extreme hardness and brittleness which precluded ingot preparation prior to hot working. This condition was attributed to the slower cooling rate of the heavier sections and the resultant formation of sigma phase. The fine grained effect was not observed in alloys with chromium contents below 20% although a fine grained effect has been reported for the nickel-free, 17% chromium steel.

Superplasticity in Fine Grained Welds

Tensile tests of welded joints showed that the coarse grained weld metal did not behave superplastically, showing only 40 to 60% elongation. Because the 0.03 to 0.06 mm grain size in the equiaxed welds was within the grain size range known to behave superplastically, the possibility of obtaining similar behavior in welded structures was examined.

Figure 10 shows the appearance of an all-weld-metal tensile coupon prior to testing and aluminum-free and aluminum-containing coupons after testing at 1700 °F at a strain rate of 0.05 in./in./min. The tensile coupon from the aluminum-containing weld pictured, exhibited an extension of 173% as compared to the 61% exhibited by the normal or coarse grained alloy. A wrought microduplex alloy of this composition would be expected to show 200 to 600% elongation under these test conditions. A number of all-weld-metal tensile coupons were prepared and tested using a variety of compositions within the fine grained region shown previously on the ternary diagram. The tensile data revealed that the fine grained behavior was related to not only the aluminum but also the nitrogen content of the weld deposits. The aluminum content of these welds ranged from 0.01 to 0.20% and the nitrogen levels varied from 0.002 to 0.06%. Figure 11 shows that the maximum superplastic elongation was obtained at an aluminum-to-nitrogen ratio of about 1.8 to 1. Similarly, the finest grain size was found to correspond to the highest elongation value (Fig. 12).

Process Variation

Fine grained welds have been produced with the common welding processes using the conditions shown in Table 2. Manual and automatic inert gas-shielded processes were examined in greatest detail. Fine grained welds could be produced with covered electrodes by making generous aluminum additions to the flux covering (compare welds 6 and 7). As in the case of conventional weld deposits, energy input was found to influence grain size. Lowering the energy input led to some reduction in grain size and greater elongation in elevated temperature tensile tests (compare welds 4 and 5 in Table 2).

Discussion

Significance of Observations

Fine grained structures were observed in welds made with the gas tungsten-arc, gas metal-arc, and shielded metal-arc welding processes using normal conditions with no special controls or equipment. A useful fine grained effect was observed in iron-base alloys containing about 20 to 35% chromium, and 5 to 15% nickel. This was principally related to the presence of aluminum and nitrogen in certain ratios. The fine grain size appeared to be due to the spontaneous nucleation of new grains which formed during a very early stage of solidification since, the normal epitaxial growth only proceeded a short distance (e.g., about 0.07 mm) before the solidification mode changed to one of fine equiaxed grains.

Mechanism for Formation

Aluminum nitride, or other nitrides, carbides, etc., of appropriate size can exist as stable nuclei in liquid metal. These may act as sites for the formation of small, individual dendrites during cooling of weld metal. As noted earlier, microprobe examination of fine grained weld samples
showed that many of the particles within the center of the grains were high in aluminum content. These particles apparently promote the fine grain effect but do not fully account for the observed refinement since it occurs over only a limited range of chromium and nickel contents. In addition to the presence of these particles, it is felt that several other factors may contribute.

Reference to the iron-nickel-chromium phase diagram\(^1\)\(^5\) shows that the difference between solidus and liquidus surfaces is about 15 C for the alloys of interest. This very narrow solidification range would promote rapid freezing and limit grain growth in the weld pool. Aborn and Bain had originally suggested that a peritectic reaction was involved in alloys of the type studied in this investigation.\(^1\)\(^6\) Such a reaction may provide an additional source of grain refinement as indicated by the recent work of Delamore and Smith on aluminum-titanium castings.\(^1\)\(^7\)

More importantly though, the general shape perceived for such a binary iron-nickel diagram at a constant chromium level shows that the first liquid to freeze is solute depleted ferrite and the last liquid to solidify is solute enriched and consequently austenitic. This is considered important because the austenitic areas serve to block grain growth at the welding temperature as well as during reheating by later weld passes. The stability of the austenite in the welded structure was confirmed by heating a weld to 2300 F for 1 hr. No grain growth or other structural change was found during microstructural examination.

Due to the presence of a great number of nucleation sites in the weld pool and the other factors enumerated above, it appears that solidification from these nucleation sites overrides the normal epitaxial growth mechanism\(^1\)\(^8\) and dominates the solidification reaction. The work of Matsuda, et al.\(^1\)\(^9\) with thin sheet lends support to this hypothesis in that they found that under certain welding conditions, equiaxed grains began to prevail over the columnar growth form.

Areas Where Fine Grained Weld Structures May Be Applied

Since the welds and base metal now both exhibit superplasticity, this property might be used to advantage in welded articles to increase the utility of pressure forming or other elevated temperature forming processes since the weld areas can now be deformed the same amount as the surrounding base metal rather than remaining rigidly fixed in place. Also, it is conceivable that an entirely weld fabricated structure could be produced, lightly machined to provide uniform surfaces, and then formed within a mold using a pressure forming process.

Other applications involve such areas as the surfacing of low alloy steel to provide a corrosion resistant surface layer. Such a fine grained structure should provide more corrosion resistance, greater toughness, and better fatigue properties than a similarly used coarse grained deposit. A fine grained structure should be more resistant to weld cracking than a similar coarse grained structure since segregated low melting point impurities will be more widely dispersed and consequently less effectvive.

Fig. 10 — An all-weld-metal tensile specimen is shown at the top of the photograph prior to testing. The middle coupon was made with an aluminum-free filler and exhibited 61% elongation in the tensile test at 1700 F. The lower coupon was prepared from a weld made with an aluminum-containing filler and exhibited 173% elongation. Full scale, reduced 17%
tive in forming continuous liquid films which are the eventual cause of some weld cracks. Similarly, the fine structure should be more resistant to the "ductility-dip" form of weld cracking since large grain size is known to have an adverse effect on this phenomenon. In certain alloys the finer grain size could also reduce susceptibility to post-weld heat treatment cracking.

The fine structure of the aluminum/nitrogen containing welds could be advantageously used in parts that require a cold forming operation after welding. Bend tests have shown that the deformed surface of such welds are not prone to the columnar-grain-marked deformation normally associated with coarse grained weld deposits after bending. This benefit would help to reduce the finishing costs in articles where cosmetic appearance is important.

Conclusions
1. Fine grained welds can be attained in alloys similar to the 26 % Cr, 6.5 % Ni stainless steel using conventional welding equipment and conditions.
2. The fine grained structure is due to the solidification process and not to a transformation effect.
3. The phenomenon occurs over a limited range of chromium and nickel contents in iron-base alloys and is dependent upon the presence of aluminum and nitrogen in critical ratios.
4. Welds of the preferred composition exhibited superplastic elongation in elevated temperature tensile tests. We believe that this represents the first demonstration of superplastic behavior in weld metal.

References
A suitable group to carry out the research planning for PVRC was created when the PVRC Program Evaluation Committee (now designated the Evaluation and Planning Committee) was formed in 1961. This group was originally charged with the responsibility of evaluating the research work done by PVRC and others, and to prepare a "PVRC Interpretive Report of Pressure Vessel Research" to make the results directly usable to the designer and Code-making bodies. During the review and evaluation of available information, voids in the state of knowledge and the need for further research became apparent. Although these items were mentioned in the report, they needed to be organized into a consistent plan. Thus, the 18 research topics submitted to PVRC by ASME in 1959 were combined with the research problems uncovered by the PVRC Interpretive Report and published as the "PVRC Long-Range Plan for Pressure-Vessel Research" in WRC Bulletin 116, September 1966.

The PVRC "long-range plan" was distributed as widely as possible for review and comment. Since then, a number of additional problem areas have been suggested by the ASME BPVC as well as by other organizations and by individuals within PVRC. Therefore, to keep the long-range plan timely and up to date, the Evaluation and Planning Committee agreed that it should be re-issued every three years. In accordance with this decision, the Second Edition of the long-range plan was issued in September 1969, in WRC Bulletin 144, and the Third Edition in September 1972, in WRC Bulletin 176. Some of the problems in the Second Edition were dropped and a number of new problems were added in the Third Edition.

The list of "PVRC Research Problems" is comprised of 42 research topics, divided into three groups relating to the three divisions of PVRC, i.e., Materials, Design and Fabrication. Each project is outlined briefly in a project description giving the: (a) Title; (b) Statement of Problem and Objectives; (c) Current Status; and (d) Action Proposed.

The price of WRC Bulletin 176 is $3.00 per copy. Orders for single copies should be sent to the American Welding Society, 2501 N.W. 7th Street, Miami, Fla. 33125. Orders for bulk lots, 10 or more copies, should be sent to the Welding Research Council, 345 East 47th Street, New York, N.Y. 10017.