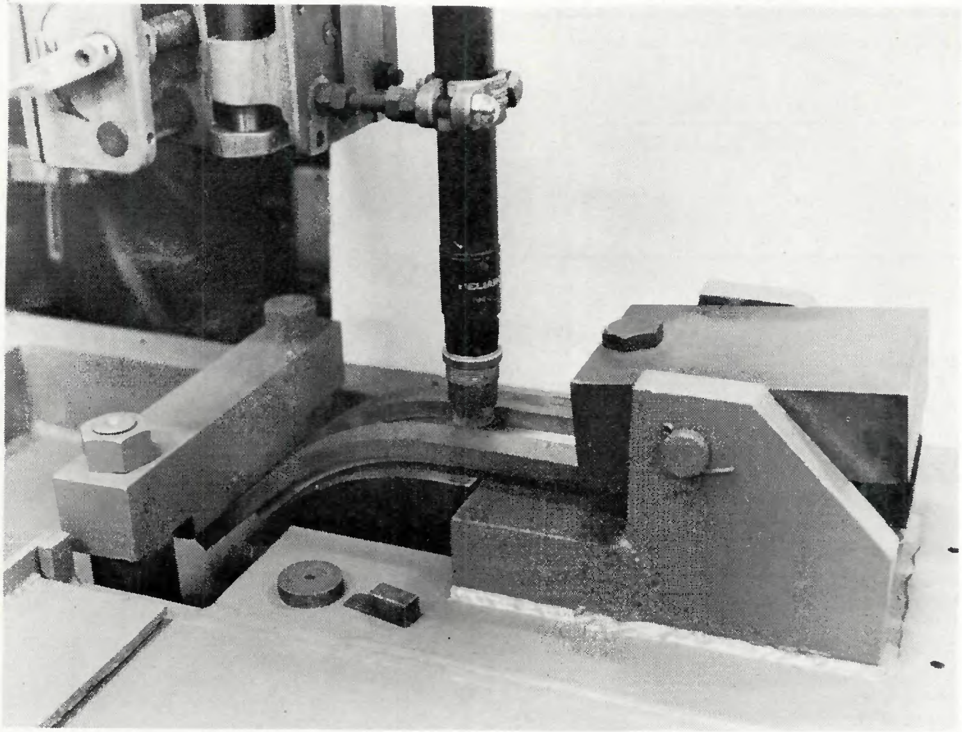

Test specimen mounted in Varestraint testing machine

Varestraint Testing of Nickel Alloys

BY A. C. LINGENFELTER

Test results show good correlation with actual experience in welding nickel alloys

ABSTRACT. Extensive Varestraint testing of nickel alloys has shown that the test is an effective method to evaluate the weldability of the alloys in terms of resistance to hot cracking. Good correlation was found between the degree of weldability indicated by the Varestraint test and actual welding experience for established alloys. The test method also accurately predicted the weldability of newly developed alloys.

Introduction

The AWS Welding Handbook defines weldability as "The capacity of a metal to be welded under the fabrication conditions imposed into a specific, suitably designed structure and to perform satisfactorily in the intended service." Properties such as operability, arc stability, susceptibility to porosity of weld metal, weld-metal fluidity, thermal-expansion characteristics, strength, fatigue properties, weld-metal oxidation resistance, corrosion resistance, resistance of base metal to underbead cracking, resistance of weld metal to hot cracking, and metallurgical effects of thermal cycling due to the heat of welding are but some of the factors to be considered when evaluating the particular weldability of a weld-metal/base-metal system.

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Of these properties, the resistance of weld metal to hot cracking has received substantial attention and is of prime importance in designing a weldable system. The Varestraint test developed by W. F. Savage and C. D. Lundin at Rensselaer Polytechnic Institute[1, 2] has proved to be a useful tool for the evaluation of hot-cracking sensitivity of weld metals. The test has proved to be sensitive to welding process variables and to compositional variations, reasonably reproducible, and economical to perform. The development of this test method substantially advanced the state of the art for measuring this particular facet of weldability.

A detailed description of the Varestraint test is available in the literature.[3] Briefly, the test involves deposition of a weld bead on a specimen supported in the manner illustrated in Fig. 1. At a predetermined point in the welding operation, the specimen is forced to conform to the contour of the radius block. Blocks of different radii can be used to provide a series of welds subjected to different controlled magnitudes of augmented strain. When the applied augmented strain is above the cracking threshold for the alloy, cracking occurs at the instantaneous location of the liquidus-solidus interface at the time of load application.

The Varestraint test program to be discussed was begun in 1966. Alloys of the nickel, nickel-copper, nickel-chromium-iron, and nickel-iron-chromium families have been evaluated with most of the effort expended in the last two families of alloys.

Objectives

The program had two principal objectives:

1. To determine the average or characteristic weldability in terms of Varestraint parameters for alloys which have an established history of weldability.
2. To relate the weldability as characterized by the Varestraint test to actual welding experience.

The principal interest was in a broad view of an alloy rather than the specific effects of minor elements or heat-to-heat variations. When the stated objectives are met for an alloy, a set of boundary conditions is established. These boundary conditions can then be used to judge the significance of compositional changes in established alloys and to provide a frame of reference for evaluating new alloys.

Terminology

The Varestraint test results presented will be expressed in terms of:

1. *Average Total Crack Length* (TCL) — The arithmetic average of the total crack length of individual tests at a particular strain level.

Table 1 — Variation in Calculated Strain[a] as a Function of Specimen Thickness

Bending-block radius, in.	Calculated % augmented strain for thicknesses of 0.250-in.	0.350-in.
100	0.125	0.175
50	0.250	0.350
25	0.500	0.700
12.50	1.000	1.400
6.25	2.000	2.800

(a) Augmented Strain $= \frac{\text{Specimen thickness}}{2 \times \text{radius}} \times 100$

2. *Average Percent Augmented Strain* (% Strain) - The arithmetic averages of the calculated strain at a particular radius block.

3. *Cracking Threshold* — Strain level or radius block where cracking begins for the particular set of welding parameters.

4. *Average TCL/% Strain Ratio* — Arithmetic average of the TCL/% Strain ratio values for a particular strain level.

Experimental Procedure

The Varestraint test fixture used was patterned after the original unit developed at RPI. Radius blocks of 100, 50, 25, 12½ and 6¼ in. were used. Table 1 shows the maximum and minimum calculated strain produced by each of the radius blocks in the defined specimen thickness range. Bending bars of hot-rolled mild steel (1 in. x ½ in. x 12 in.) were used to assure conformance of the test specimen to the desired radius of curvature. All tests were on autogenous welds.

The gas tungsten-arc process was used with a conventional drooping-characteristic dc rectifier. The test sequence was automatic.

Materials

Table 2 shows the nominal chemical compositions of the alloys tested.

Test material was normally obtained from hot-rolled flat products. The thickness tolerance of a single heat of test specimens was nominally ± 0.010 in. Heat-to-heat test thickness variations fell within the range of 0.250 in. to 0.350 in. Tests were normally performed on material in the hot-rolled as-rolled condition. No correlation was found between temper and fusion-zone cracking. No data are available for the effect of temper on base metal cracking.

Specimen Preparation

Test specimens 2 in. x 12 in. x thickness were sheared or abrasive cut to size, flattened in a bending press, and hand ground on an abrasive belt grinder through 240 grit to provide a clean, oxide-free surface in the area to be welded. The surface was further cleaned with trichloroethylene prior to welding.

Test Parameters

Much of the early testing in this program was devoted to determining the effects of variations in test parameters, principally travel speed, specimen thickness, and amperage. Parameters such as arc length, electrode extension, inert gas composition, inert gas flow, electrode geometry, and specimen surface preparation were chosen by experience and were held constant.

Amperage was found to have the greatest effect on *Average Total Crack Length* (TCL). Figures 2 and 3 illustrate the effect.

Figure 4 illustrates the effect of amperage on bead width for various travel speeds and material thickness.

Because of the substantial effect of amperage variations on TCL, it was decided to use a fixed amperage for each alloy family tested in the 0.250 in. to 0.350 in. thickness range. As a further restriction, the fixed amperage was set such that it produced a weld width of 0.30 in. to 0.40 in. in each alloy family at a constant travel speed of 5 in./min. This travel speed was chosen principally because it produced the desired elliptical weld puddle.

Voltage was found to be a function of alloy and was noted to vary from heat to heat in a given alloy. No clear correlation was found between voltage and total crack length, although the voltage variations were intuitively considered a source of data scatter. No practical method was found to control the voltage beyond using a constant arc length.

The standard test conditions shown in Table 3 evolved for each of the alloy families. These parameters were applied for test material in the thickness range of 0.250 in. to 0.350 in. All test results discussed in this paper were developed using these standard test parameters.

Specimen Evaluation

Test specimens were evaluated in the as-welded condition using a bench binocular microscope capable of 60X magnification. If the surface was judged sufficiently clean, the

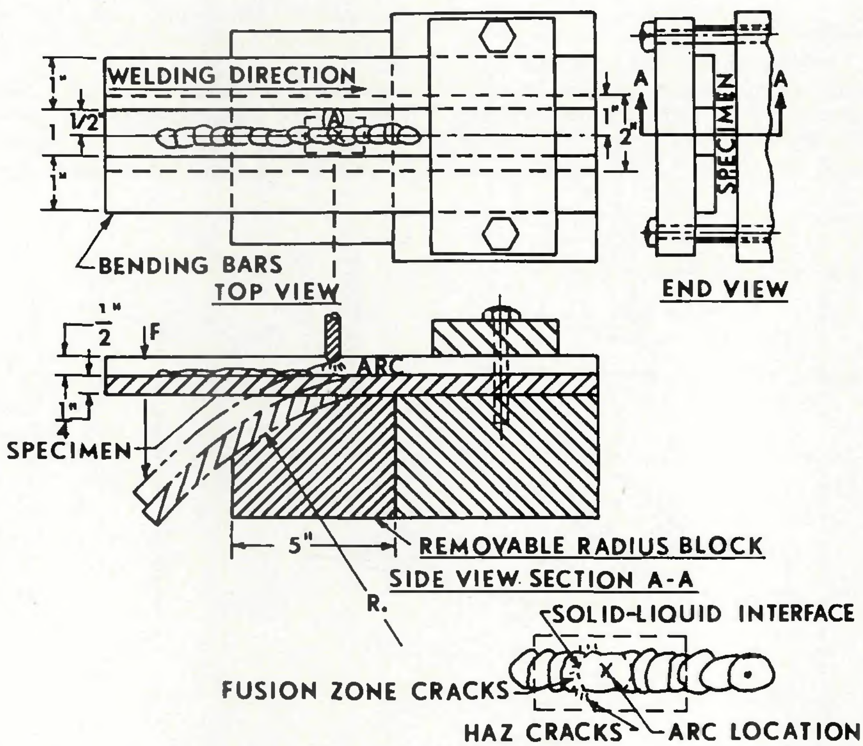

Fig. 1 — Schematic drawing of Varestraint test fixture

Table 2—Nominal Chemical Analysis of Alloys Tested — Weight Percent

Alloy	C	Mn	Fe	S	Si	Cu	Ni	Cr	Al	Ti	Others
					Nickel Alloys						
Nickel 200	0.08	0.18	0.2	0.005	0.18	0.13	99.5	—	—	—	—
Nickel 270	0.01	< 0.001	0.003	< 0.001	< 0.001	< 0.001	99.98	< 0.001	—	< 0.001	—
Nickel 271	0.11	—	0.001	< 0.001	0.023	—	99.77	—	—	—	0.051 Mg
Nickel 280	0.12	—	0.002	< 0.001	—	< 0.001	99.73	—	—	—	0.080 Mg, 0.012 Al_2O_3
					Nickel-Copper Alloy						
Monel* 400	0.15	1.0	1.25	0.012	0.25	31.5	66.5	—	—	—	—
					Nickel-Chromium-Iron Alloys						
Inconel* 600	0.08	0.5	8.00	0.008	0.25	0.25	76.0	15.5	—	—	—
Inconel 601	0.05	0.5	14.1	0.007	0.25	0.50	60.5	23.0	1.35	—	—
Inconel 604	0.02	0.10	7.50	0.005	0.10	0.03	74.0	16.0	—	—	2.25 Cb+Ta
Inconel 606	0.02	3.00	1.00	0.007	0.20	0.04	72.0	20.0	—	0.55	2.5 Cb+Ta
Inconel 625	0.05	0.25	2.5	0.008	0.25	—	61.0	21.5	0.20	0.20	9.0 Mo, 3.65 Cb+Ta
Inconel 706	0.03	0.18	40.0	0.008	0.18	0.15	41.5	16.0	0.20	1.75	2.9 Cb+Ta
Inconel 718	0.04	0.18	18.5	0.008	0.18	0.15	52.5	19.0	0.50	0.90	3.05 Mo, 5.13 Cb+Ta
Inconel 721	0.03	2.30	6.60	0.007	0.10	0.04	71.0	16.4	—	3.2	—
Inconel X-750	0.04	0.50	7.00	0.005	0.25	0.25	73.0	15.5	0.70	2.50	0.95 Cb+Ta
					Nickel-Iron-Chromium Alloys						
Incoloy* 800	0.05	0.75	46.0	0.008	0.50	0.38	32.5	21.0	0.38	0.38	—
Incoloy 825	0.03	0.50	30.0	0.015	0.25	2.25	42.0	21.5	0.10	0.90	3.0 Mo
					Experimental Alloys						
Inconel 617	0.07	0.04	—	0.008	—	—	54.0	22.0	1.0	0.35	9.0 Mo, 12.5 Co
Inconel 671		—	—	—	—	—	50.0	50.0	—	—	—

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crack length was measured on the as-welded surface. If oxide or surface films were present, a light etch was frequently used to prepare the as-welded surface for examination.

All crack-length determinations were made with a calibrated reticle at 30X magnification.

Test Reproducibility

Test-to-test variations in the total crack length determination of the order of ± 20% were not uncommon. This level of data scatter has been noted by others.[3] Data scatter was more pronounced at the very low strain levels. Because of data scatter at least three replications were used for each particular strain level, and an arithmetic average value was used to express test results.

Several other sources of data scatter were noted. The effects of welding parameters have already been described; maintaining tight control of parameters was considered essential.

A 10% variation in total crack length was common when a given test specimen was evaluated by different individuals. The greatest variations were noted during evaluation of specimens tested at the low strain levels. This was due principally to the small size and number of cracks.

The reproducibility of strain at each radius block was explored. Strain gauges were used to measure strain without an actual weld being made, and a dial-gauge indicator was used to measure the radius of curvature on the actual welded sample. Strain reproducibility was best at the high strain levels. Very small variations in radius of curvature translated into significant variations in strain at the low strain levels.

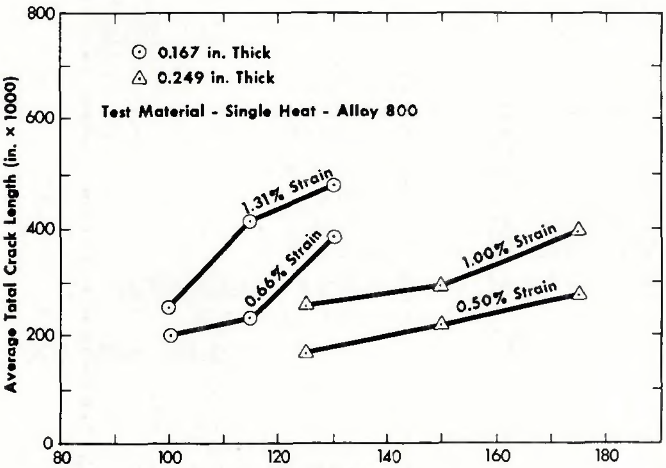

Fig. 2 — Effect of amperage on average total crack length for alloy 800. Travel speed was constant at 5 in./min

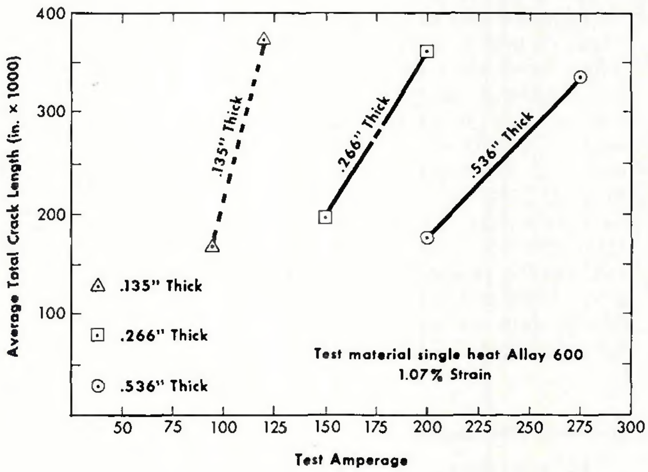

Fig. 3 — Effect of amperage on average total crack length for alloy 600. Travel speed was constant at 5 in./min

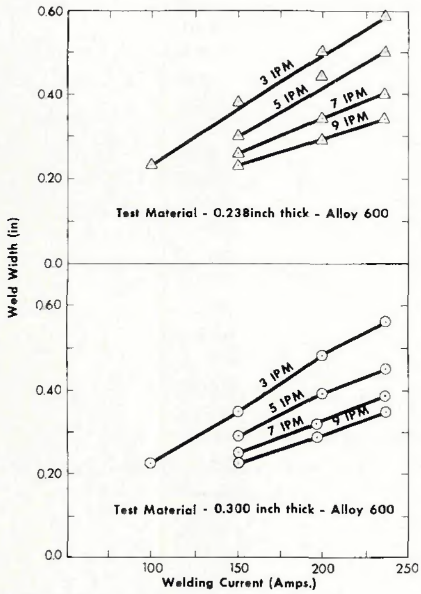

Fig. 4 — Effect of amperage on weld width as a function of thickness and travel speed

Table 3 — Standard Welding Conditions for the Varestraint Tests

Material thickness, in.	0.250 to 0.350
Bead width, in.	0.30 to 0.40
Amperage	
Ni alloys	280
Ni-Cu alloys	215
Ni-Cr-Fe alloys	190
Ni-Fe-Cr alloys	190
Voltage	10 to 14[a]
Travel speed, in./min	5
Electrode	0.093-in. diam thoriated tungsten
Electrode extension, in.	0.250
Electrode tip geometry	90-deg. included angle
Arc length, in.	0.090
Shielding gas	Argon
Gas flow, cfh	30
Gas cup[b] diam, in.	0.750

(a) Depended on alloy and amperage.
(b) Welding torch was equipped with gas lens.

Development of Characteristic Weldability

Figure 5 shows TCL versus % Strain data plotted for five commercial heats of alloy 600. It can be noted in Table 1 that the % Strain at a particular radius block can very substantially due to the heat-to-heat variations in specimen thickness. In order to account for these variations in strain, a TCL/% Strain ratio was introduced to express an average or characteristic weldability. Figure 6 shows the data for these same five heats plotted in terms of average TCL/% Strain. This average TCL/% Strain parameter will be used to express the characteristic weldability throughout this discussion. The number noted in parentheses after the alloy name indicates the number of heats making up the average or characteristic weldability.

Results and Discussion

Historical Weldability of Established Alloys

To relate Varestraint data to actual welding experience, the hot-cracking sensitivity of the alloys was considered in each of three situations: (1) Autogenous welding of the alloy as a base metal by the gas tungsten-arc process (GTA) in thicknesses up to 0.125 in. (2) Use of the alloy as a filler metal in multipass GTA welds. (3) Use of the alloy as a filler metal for multipass weldments using the gas metal-arc process (GMA) in the spray-transfer mode of operation. Experience has shown that a multipass GMA weld is the most demanding with multipass GTA and autogenous GTA following in decreasing order of severity.

All of the alloys considered can be autogenously GTA welded in thicknesses up to about 0.125 in. Hot cracking has sometimes been experienced during autogenous GTA welding under the high restraint encountered in the root pass of welds in heavy-wall pipe of alloys 600 and 800.

Alloys 600 and 800 are somewhat susceptible to hot cracking when used as a filler metal in a multipass GTA weld. Nickel 200, 270, 271, and 280 and alloy 400 are not particularly crack-sensitive, but they have limited usefulness as filler metals for either GTA or GMA because of their susceptibility to porosity. The remainder of the alloys are sufficiently crack-resistant to be used as GTA filler metal.

Alloys 604 (ERNiCrFe-5), 606 (ERNiCrFe-3), 625, 721 (ERNiCrFe-6), and X-750 are highly crack-resistant filler metals when used under

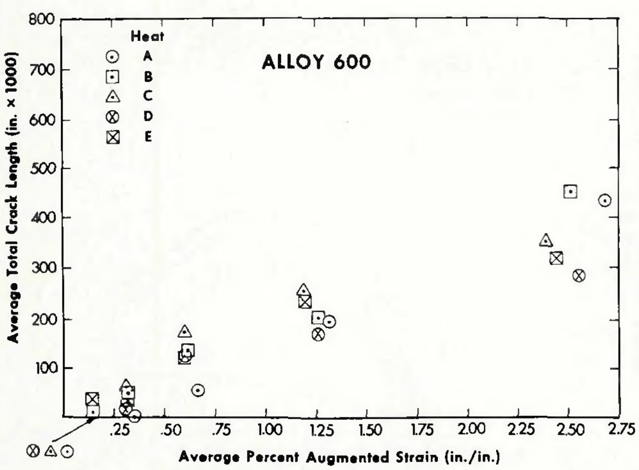

Fig. 5 — Average total crack length for five commercial heats of alloy 600

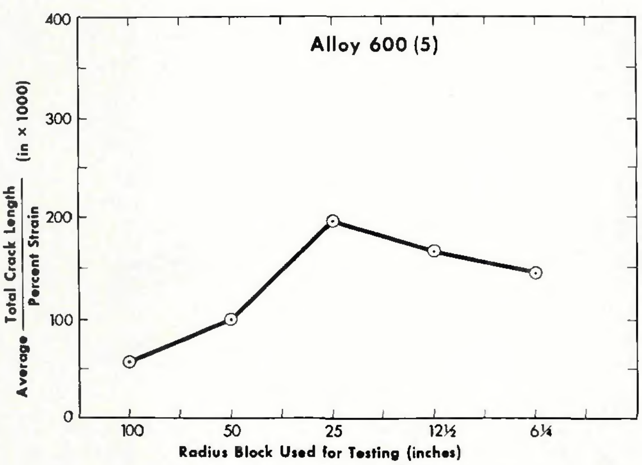

Fig. 6 — The average or characteristic TCL/% Strain ratio value computed for the five commercial heats of alloy 600 shown in Fig. 5

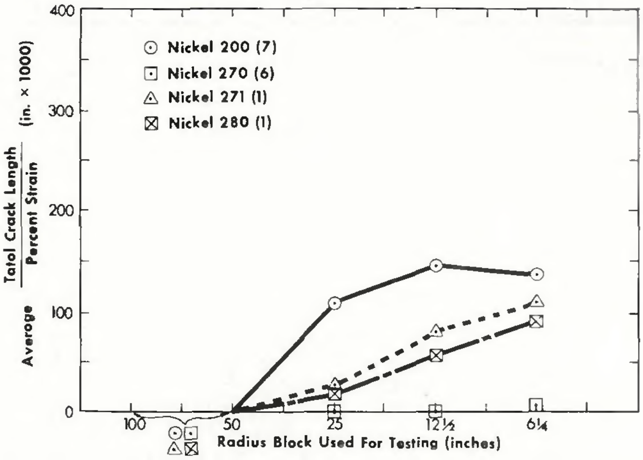

Fig. 7 — Characteristic TCL/% Strain values for the Nickel family of alloys

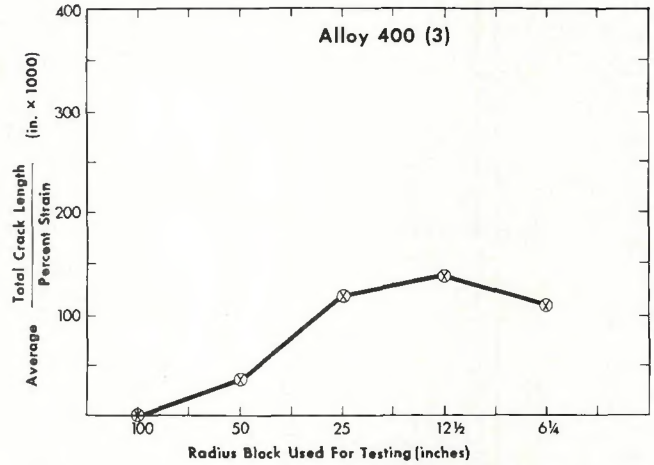

Fig. 8 — Characteristic TCL/% Strain values for Nickel-Copper alloy 400

the demanding conditions of the spray-transfer GMA process.

Alloys 706, 718, and 825 are used as GMA filler metals but with some reservations, particularly under conditions of high restraint.

Alloys 600, 601, and 800 are not considered sufficiently crack-resistant to be used as GMA filler metals.

Varestraint Characteristic Weldability

Figures 7 through 11 show the weldability of the various alloys as characterized by the Varestraint test results.

The comparisons of Nickel 200, 270, 271, and 280, as well as alloy 400, are principally of academic interest since, as has already been noted, the usefulness of these alloys as filler metals is limited more by porosity than by hot-cracking sensitivity.

It was interesting that of the six heats of Nickel 270 tested, four were totally free of cracking through the 6¼ in. radius block, and two heats showed a very low level of cracking at the 6¼ in. block. Nickel 270 is extremely high-purity, full-density wrought nickel produced by powder metallurgy. Nickel 271 and 280 were produced from the same high-purity elemental nickel powder, but with small additions of various elements added to satisfy certain application requirements. Nickel 200 is high-purity nickel produced by conventional melting techniques. Nickel 200, 271, and 280 all show a cracking threshold at the 25-in. radius block as compared to the 6¼ in. radius block for the Nickel 270. The cracking, as might be expected, followed the alloy level. Similar effects have been noted by other investigators.[4]

There appears to be good agreement between weldability of the Ni-Cr-Fe and Ni-Fe-Cr alloys as characterized by the Varestraint results and actual welding experience if we assume that the cracking-threshold strain and cracking response at the very low strain levels are the principal indicators of hot-cracking resistance. The cracking-threshold strain value is a measure of the energy required to initiate cracking. Strain values above the cracking threshold in essence represent the energy absorbed in propagating the crack.

Those alloys which were described as highly crack-resistant do not show cracking at the 100-in. radius block, and they show either complete absence or a very low level of cracking at the 50-in. radius block. Those alloys described as less crack-resistant show increasing amounts of cracking at the 100- and 50-in. radius blocks.

The variation in TCL/% Strain ratio as a function of strain was interesting. At increasing strain levels above the cracking-threshold strain, the TCL/% Strain ratio increased rapidly, reached a maximum, and then decreased for most alloys tested.

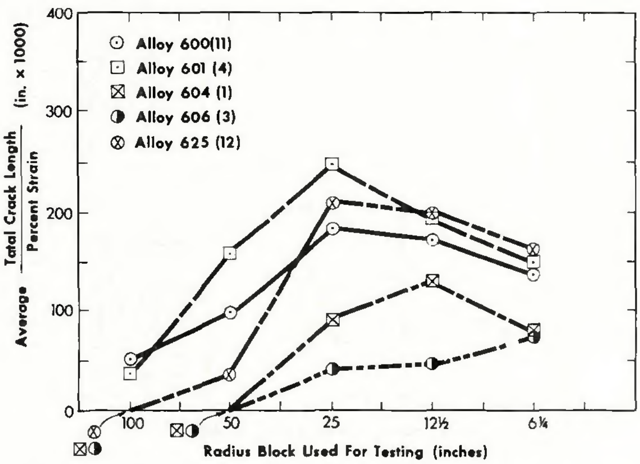

Fig. 9 — Characteristic TCL/% Strain values for several non-age hardenable Ni-Cr-Fe alloys

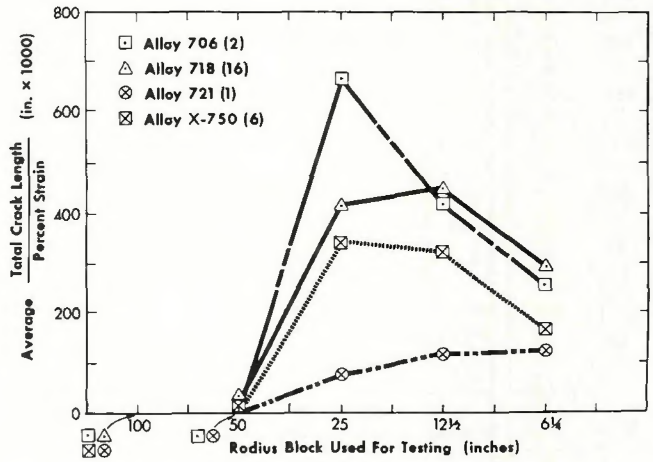

Fig. 10 — Characteristic TCL/% Strain values for several age hardenable Ni-Cr-Fe alloys

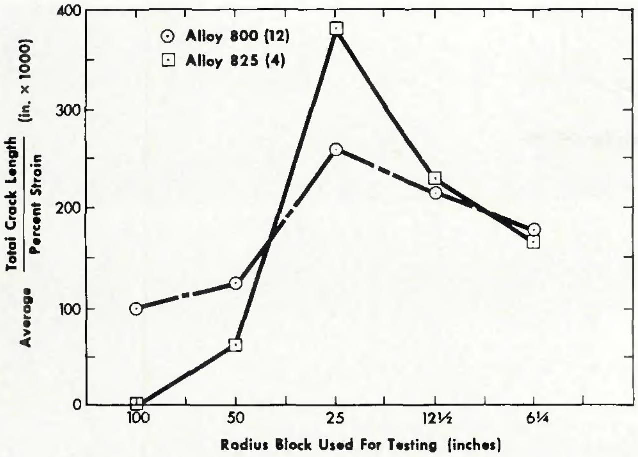

Fig. 11 — Characteristic TCL/% Strain values for Ni-Fe-Cr alloys

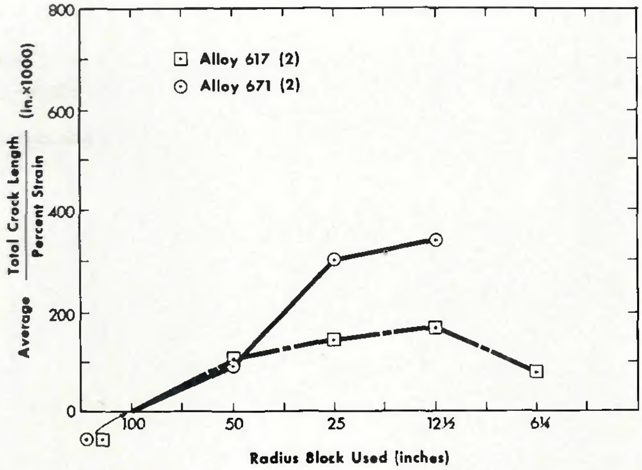

Fig. 12 — Characteristic TCL/% Strain values for experimental alloys 617 and 671

Because a temperature gradient exists along the dendrite grain boundary, it has been suggested[3] that there is a characteristic temperature range for each alloy in which the crack once initiated, can propagate readily. As the crack moves along the dendrite grain boundary, the temperature decreases and the ductility increases. An increasing amount of strain energy is absorbed by plastic deformation, and less crack extension/unit strain occurs.

Evaluation of Experimental Alloys

The Varestraint test was used for the preliminary weldability evaluations of two newly developed materials, alloys 617 and 671. Figure 12 shows the results. Using the data already presented for the established alloys as basis for judgment, the results indicated that these two alloys should have adequate crack resistance for autogenous GTA welding, for use as filler metal in multipass GTA welding, and possibly for filler metal in GMA welding.

The weldability predicted by the Varestraint results has agreed quite well with the actual welding experience available thus far. Both alloys can be readily welded with autogenous GTA, and are adequately crack resistant to be used as filler metal for multipass GTA welds.

Figure 13 shows side-bend tests from a ⅝-in.-thick alloy 617 butt joint welded by the multipass GTA process and alloy 617 filler metal. Preliminary results with GMA and pulsed-arc processes using alloy 617 filler metal have been promising but are inconclusive at this time. No GMA weld data are available for alloy 671.

Another material evaluated was a 34Ni, 20Cr, 1.25Si, Balance Fe alloy. Figure 14 compares the Varestraint results for this alloy with those for alloy 800. The results indicate the alloy is highly crack-sensitive. Figure 15 shows the cracking that occurred in the third pass of a multipass GTA weld. The filler metal in this case was of the same composition as the base material.

This particular example illustrates both the strength and weakness of the test method. The test predicted accurately the crack sensitivity. However, the alloy is readily weldable with the gas tungsten-arc, gas metal-arc, and shielded metal-arc processes if filler metals modified to provide crack resistance are used. If results are not carefully interpreted within the limit of the test usefulness, a distorted picture of an alloy can result.

Base-Metal Cracking

Base-metal cracking tendencies were considered in this program, but only in a qualitative fashion. Most of the Ni-Cr-Fe and Ni-Fe-Cr alloys show light base-metal cracking at

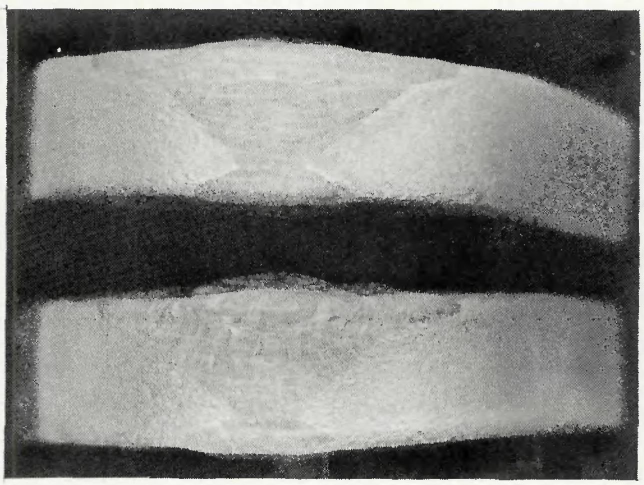

Fig. 13 — Side bends from ⅝ in. alloy 617 butt joint. Base metal and filler metal of the same composition

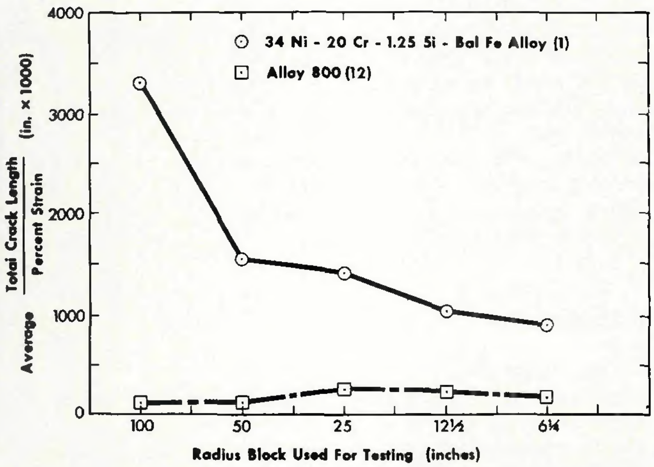

Fig. 14 — TCL/% Strain values for a single heat of 34Ni-20Cr-1.25Si-balance Fe alloy compared to characteristic TCL/% Strain values of alloy 800

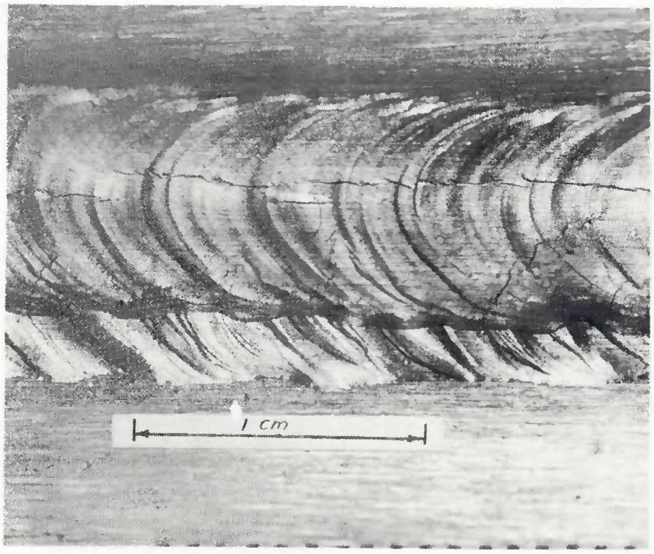

Fig. 15 — Hot cracking observed in the third pass of a GTA weld in 34Ni-20Cr-1.25Si-balance Fe alloy. Base metal and filler metal are the same composition

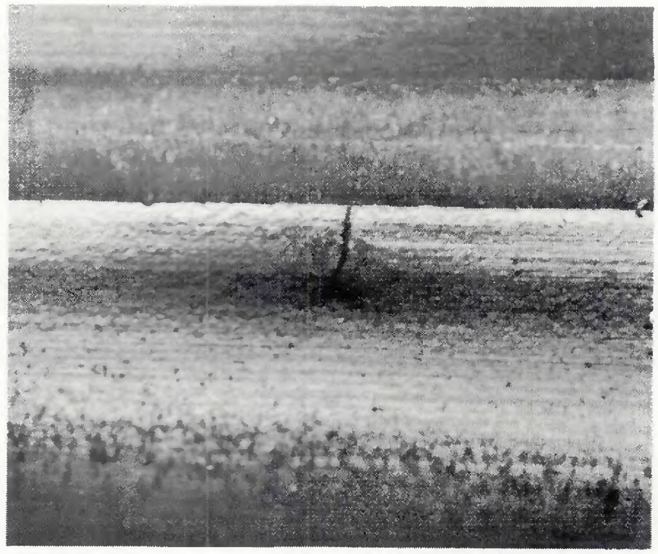

Fig. 16 — Heat-affected-zone cracking on the root side of a GTA weld in a 5/16-in. diam, 0.021-in. wall, alloy 800 welded tube. Cracking believed to be caused by copper contamination

the high strain levels of the 12½-in and 6¼-in. radius blocks. These results have not been correlated with actual welding experience; therefore, it is difficult to interpret their significance.

The test method was used to reproduce, experimentally, base-metal cracking believed to be due to copper contamination of the heat-affected zone in an alloy 800 production weld. Figure 16 shows an example of heat-affected-zone cracking in a small-diameter alloy 800 welded tube. X-ray analysis scans have shown a high copper concentration in the area of the crack. Figure 17 shows a Varestraint specimen which had a very small quantity of copper introduced selectively into the area of one heat-affected zone prior to welding. The copper was introduced by lightly rubbing the test surface with a copper tube. Base-metal cracking occurred in the copper-contaminated heat-affected zone at the 25-in. radius block, which represents a strain level well below that which normally produces base-metal cracking in alloy 800. The opposite heat-affected zone, uncontaminated, was free of cracking. Similar phenomena were noted in recent work by Matthews and Savage.[5]

Conclusions

The Varestraint test has been shown to be a highly useful tool for exploring a particular facet of weldability, namely hot-cracking sensitivity. The challenge lies in properly interpreting the data within the limits of the test's usefulness, and in relating the data to real situations. Useful and accurate estimates of the weldability of a material can be made when these relationships are defined.

Extensive Varestraint testing of nickel alloys has shown that:

1. The cracking-threshold strain value and the cracking response at low strain levels are the most significant indicators of hot-cracking resistance.
2. Weldability as characterized by the Varestraint test has good correlation with actual welding experience for established alloys.
3. The weldability of experimental alloys can be accurately predicted by the Varestraint test.

Acknowledgments

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Special recognition is given F. I. Consaul for his diligent effort in performing much of the test work discussed.

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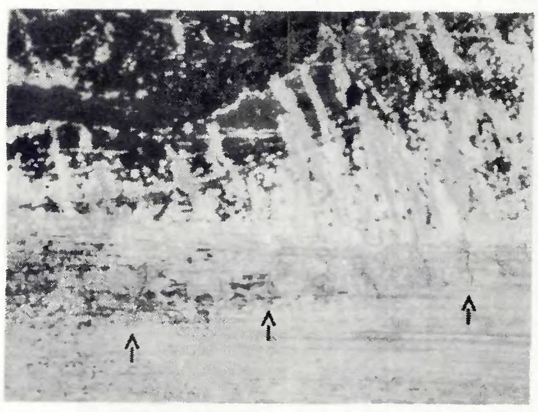

Fig. 17 — Heat-affected-zone cracking in a purposely copper-contaminated alloy 800 Varestraint test sample (% Strain, 0.6)