Weldability Studies on High Performance Alloys in Thin Sheet Form

Arc spot weldability data are presented to indicate a relation between thickness-to-grain diameter ratio and hot crack sensitivity of thin gage cobalt and nickel base alloys

BY S. J. MATTHEWS

ABSTRACT. An investigation was undertaken to study the hot crack susceptibility of thin gage cobalt base and nickel base alloy sheet materials. Weldability tests were conducted on five different heats of Haynes alloy No. 188 (cobalt base) and on one heat of Haynes alloy 625, Hastelloy alloy X and Hastelloy alloy S (nickel base). Sheet gages ranged from 0.035 in. (0.9 mm) to 0.010 in. (0.25 mm) in thickness. Testing was accomplished using an arc spot hot crack susceptibility device.

It was found that hot cracking increases as sheet thickness decreases; however, this was shown to be related to the number of grains per cross section rather than thickness, per se. Hot cracking was the most severe when the thickness-to-grain diameter ratio diminished to value of less than 4. Fractographic studies on the cobalt base alloy suggest this may be due to greater ease of intergranular crack propagation when there are only a few grains through the cross section of the sheet. This hypothesis is supported by the observation that the longest individual heat-affected zone cracks were generally found in those materials with the lowest thickness-to-grain diameter ratio.

Introduction

Presently there is a distinct trend toward increased usage of thin gage sheet materials in high performance aerospace components. Recent market forecasts suggest this trend will continue, culminating in the use of very thin gages, less than 1 mm in thickness. There is serious concern that the oxidation and strength properties of these thin gage materials will not be commensurate with their thicker counterparts. Consequently, many research laboratories are actively engaged in measuring the properties of thin gage material. There is reason to suspect that weldability, like oxidation and strength, will also be detrimentally affected by reduced gage thickness, but little experimental work has been done in this area, and there is little information in the literature concerning the hot crack sensitivity of very thin sheet weldments. Therefore, a welding research investigation was undertaken to study the hot crack tendencies of high performance nickel base and cobalt base alloys in thin sheet form. The objective of the study was to develop a better understanding of the metallurgical variables (such as grain size) and their influence on weldability of thin gage material.

Materials

Alloy No. 188 (Ref. 1) was selected as the cobalt base, high performance material to be studied in thin sheet form. A majority of the work was conducted on this material since this alloy is a candidate for many thin sheet aerospace applications. Five random heats of mill annealed alloy No. 188 sheet material were obtained for study. The chemical compositions of these materials are reported in Table 1. Samples from each heat were cold rolled on a laboratory mill to nominal gage thicknesses of 10, 15, 20, 25, 30 and 35 mils (10 mils is equivalent to 0.25 mm). All thin sheet materials

S. J. MATTHEWS is associated with the Stellite Division of Cabot Corporation, Kokomo, Ind. 46901.

Paper was presented at the 56th AWS Annual Meeting held in Cleveland, Ohio, during April 21-25, 1975.
were annealed at 2150 °F (1177 °C) for ten minutes, rapid air cooled, pickled, and straightened, prior to weldability testing.

After annealing, a sample of each thickness, from each heat, was cross sectioned for metallographic examination and ASTM grain size determination. The average grain diameter corresponding to the measured ASTM grain size number was used to calculate the thickness-to-grain diameter ratio for each test material. Table 2 summarizes the sheet thicknesses, percent cold reduction and approximate grain diameter data for the experimental cobalt base material. Single heats of alloy X, alloy 625, and alloy S, representing typical solid solution strengthened nickel base alloy, were obtained in the form of 60 mil (1.5 mm) sheet. The nominal chemical composition of the nickel base alloys is given in Table 3. Each alloy was given two different final percent cold reductions and subjected to various annealing temperatures, resulting in a variety of grain sizes. The final gage thickness for all nickel base alloy test materials was 0.020 in. (0.5 mm). Table 4 documents the rolling and annealing schedules. Table 5 reports the resulting grain sizes and calculated thickness-to-grain diameter ratios, for the nickel base alloys.

All test materials were straightened, pickled and sheared into 1 by 6 in. arc spot weldability test samples.

### Table 1 — Chemical Analysis of Cobalt Base Haynes Alloy No. 188

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### Table 2 — Material Thickness and Grain Size Data for Cobalt Base Haynes Alloy No. 188

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*Specially processed to produce large grain size*

Test Procedure

An arc spot weldability test, often referred to as the "Tig-a-ma-jig device" was employed to document the weldability of the thin sheet materials. A description of this test, originally devised by the RPI Welding Research Laboratory, has been presented elsewhere (Ref. 2). Briefly, the test consists of depositing an autogenous gas tungsten-arc spot weld in the middle of a 6 in. long, 1 in. wide sheet specimen securely clamped at both ends. After a few seconds of arc dwell time, the sheet is bent by means of a radius die block mounted on a ram beneath the test specimen. Figure 1 is a schematic illustration showing the test arrangement. The test parameters used in this investigation are reported in Table 6. The net effect of the test is to create an actual heat-affected zone (HAZ) subjected to a controlled amount of strain while the HAZ is exposed to elevated hot cracking temperatures. Weldability data are usually gathered by totaling the lengths of all heat-affected zone cracks in the specimen and then plotting this number (TCL) versus the percent strain imposed on the specimen.

Three different radius bending blocks (1/4, 1/2 and 4 in.) were used for each specimen thickness creating three strain level conditions. The nominal percent augmented strain introduced to the outer fibers of each specimen was estimated by dividing the thickness by twice the radius of the bending block (t/2R). All materials were tested in triplicate at each strain level.

After all Tig-a-ma-jig tests were completed (over 430 individual tests), each specimen was examined for heat affected zone cracking independently by two different observers using a 40X and 60X binocular microscope, respectively. A few cobalt base alloy sheet specimens representing the thinnest gages (0.020, 0.015 and
Results and Discussion

Cobalt Base Alloys

The results for the five heats of cobalt base alloy No. 188 are presented graphically in Figs. 2 through 6 as plots of total crack length versus percent augmented strain (calculated using the t/R relationship). Each figure represents a different heat of material. Each curve plot represents a nominal specimen thickness. Each data point represents the average of six values (three tests examined by two different observers).

Examination of Figs. 2 through 6 reveals a distinct increase in hot cracking sensitivity as sheet thickness decreases, using the threshold strain criteria of comparing hot crack sensitivity (minimum strain required to first produce cracking). Similarly, the amount of augmented strain required to achieve 5 mils of cracking for each specimen thickness can be estimated from Figs. 2 through 6 by constructing a fiducial line parallel to the strain axis which intersects the total crack length axis at the 5 mil level. These estimates are summarized in Table 7. As specimen thickness decreases, less strain was required to produce cracking.

Perhaps a more significant observation was that the greatest level of hot cracking (total crack length magnitude) was experienced in the 0.010 in. sheet thicknesses. The average total crack length (average of all cracking experienced using three bending blocks) for the thinnest gage was about 16 mils, compared to approximately 6 mils average total crack length experienced by the heavier sheet thicknesses.

It should be noted that an interesting relationship can be observed by considering the values of the thickness-to-grain diameter ratio (t/d). Generally the thinner sheet thicknesses produced the smaller t/d ratios. Thickness-to-grain diameter ratio was investigated closely because of other studies (Ref. 3) which documented a distinct increase in minimum creep rate of a nickel base alloy as the number of grains per specimen diameter decreased.

The values of average total crack length are plotted versus thickness-to-grain diameter ratio in Fig. 7. A separate curve is plotted for each heat, bearing in mind the phenomenon of heat-to-heat variation in hot crack susceptibility. In general, there appears to be a distinct increase in hot cracking sensitivity when thickness-to-grain diameter ratio diminished to a value of less than 4, especially when t/d approaches a value between 2 and 3. Briefly, referring to Figs. 2 through 6, it was apparent that Heat A (Fig. 2) was the only heat whose 10 mil gage thickness did not experience a large magnitude of heat-affected zone cracking. Inspection of Table 2 reveals that the 10 mil thick specimens of Heat A possessed a thickness-to-grain diameter ratio of over 6. Ten mil thick specimens of the other four heats possess thickness-to-grain diameter ratios of less than 3 and correspondingly exhibited extensive heat-affected zone hot cracking (See Figs. 3 to 6).

In order to examine further the importance of t/d ratio, three heats of cobalt base alloy sheet material were specially processed in order to produce somewhat thicker sheet (0.020 and 0.030 in.) with larger than normal grain size. This was accomplished by introducing a small amount of cold reduction followed by a one-hour annealing operation at 2200 F. The resulting thickness-to-grain diameter ratios are documented in Table 2. The hot cracking susceptibility of these large grain materials is reported in Table 8 and is compared to the average total crack lengths of identical heats of the same thicknesses but with smaller grain sizes. Table 8 again shows that as the thickness-to-grain diameter is decreased, the level of hot cracking increases.
Fig. 7 — The influence of thickness to grain diameter ratio on hot crack sensitivity of thin gage alloy No. 188. Total crack length value is an average of cracking experienced under all three strain level test conditions.

Metallography and Scanning Electron Microscopy

Figure 8 illustrates the microstructure of longitudinal cross sections through Tig-a-ma-jig specimens from Heat D representing sheet material thicknesses of 0.020, 0.015 and 0.010 in. The Tig-a-ma-jig fusion zone is visible along the left-hand portion of each photomicrograph. Attention is drawn to the presence of grain boundary liquation in a narrow region of heat-affected zone material immediately adjacent to the weld fusion zone. This is liquid, temporarily present in the heat-affected zone grain boundaries, that is believed to be the main cause of hot cracking in this family of alloys. It is of interest to note that evidence of liquation is present in all three materials, regardless of thickness or thickness-to-grain diameter ratio.

Figure 9 shows top view photomicrographs of Tig-a-ma-jig samples from the same heat and the same thicknesses as shown in Fig. 8. The pattern of cracking is intergranular and considered typical of Tig-a-ma-jig cracking in this family of alloys.

Scanning electron microscopy (SEM) images of typical heat-affected zone crack surfaces are shown in Fig. 10 at 300X and 1000X magnifications for the 0.020, 0.015 and 0.010 in. gage thicknesses of Heat D. Preparation of the SEM specimens was quite tedious and involved carefully saw cutting (using a low speed diamond disc) into the outer extremities of a given crack, allowing separation of the fracture surfaces. Examination of the SEM images shown in Fig. 10 reveals the following features:

1. The crack surfaces associated with the heavier thicknesses (0.020 in.) exhibit grain boundary liquation over almost all of the grain surfaces visible in the microscopic images. The evidence of liquation was evidenced by the generally roughened appearance, reminiscent of solidification substructure associated with freezing liquid.

2. The crack surfaces associated with the thinner gage (0.015 in.) shows some evidence of intergranular grain separation (smooth features) without the presence of liquation (roughened appearance) over the entire fracture surface.
3. The proportion of smooth appearing grain boundary separation in relation to the roughened liquated regions is even more prominent within the crack surface associated with the thinnest gage material (0.010 in.).

The SEM observations suggest the following hypothesis: intergranular cracking, once nucleated in the heat-affected zone due to the existence of a liquated grain boundary, can propagate more easily in ultra thin gages where the number of grains per cross section (i.e., t/d) can potentially be quite low (about 3). Greater ease of crack propagation in the thinnest gages would tend to produce longer cracks and thus reflect the increase in total crack length magnitudes reported earlier for the 0.010 in. thick weldability samples. Table 9 reports the maximum individual heat-affected zone crack length observed in each group of cobalt base alloy test materials. Seven test materials produced a maximum crack length of 10 mils or greater and were found to have an average thickness-to-grain diameter ratio of only 3.2. The remaining test materials possessing maximum crack lengths ranging from 2 to 7 mils were characterized by an average thickness-to-grain diameter ratio of 8.5, thus substantiating the above hypothesis.

**Nickel Base Alloy Weldability Results**

The thickness-to-grain diameter relationships discussed above are not limited to cobalt base alloys but are pertinent to nickel base alloys as well. Figures 11, 12 and 13 summarize the relationship between hot crack susceptibility and thickness-to-grain diameter ratio for alloys S, X and 625, respectively. Each data point represents the average total crack length experienced by the sheet sample subjected to all three strain level conditions — each condition replicated twice.

The same relationship described by Fig. 7 is apparent. Hot crack sensitivity increases as the number of grains per cross section decreases. Alloys X and 625 become the most crack sensitive when the thickness-
to-grain diameter ratio approaches a value of 4 or less. The magnitude of cracking is greater than the level of cracking shown by the alloy No. 188 data. However, this is consistent with previous unpublished weldability studies on these alloys in thicker (0.060 in.) sheet form.

Alloy S data do not show a dramatic increase at the lower value of thickness-to-grain diameter ratio. A detailed explanation of this is beyond the scope of this discussion. Briefly, it can be rationalized by assuming that a reduced amount of carbide liquation occurs in this alloy (nominal carbon of 0.005%) causing less cracks to nucleate in the heat-affected zone and, hence, less propagation even in very thin sheet.

Conclusions

The following conclusions were based upon the experimental evidence documented in this report:
1. Sheet materials with small thickness-to-grain diameter ratios are more susceptible to heat-affected zone hot cracking than sheet materials characterized by larger thickness-to-grain diameter ratios.
2. Hot cracking is apparently most severe when the thickness-to-grain diameter ratio decreases to a value of 4 or less.

Table 6 — “Tig-A-Ma-Jig” Parameters for Thin Sheet

| Electrode: | EWTh-2, 040 diam |
| Tip shape: | EWTh-2, 040 diam |
| Arc gap (cold): | .060 in |
| Arc dwell time: | 2.5 seconds |
| Arc cutoff time: | 0.2 seconds |
| Argon flow: | 20 cfh |
| Weld current, A | Specimen thickness, in. |
| .010 | .10 |
| .015 | .15 |
| .020 | .20 |
| .025 | .25 |
| .030 | .30 |
| .035 | .35 |

Table 7 — Hot Cracking Strain Versus Sheet Thickness for Cobalt Base Alloys

| Est. augmented strain to produce 5 mils cracking (avg. of 5 heats) | Sheet thick., in. |
| .91 | .035 |
| .60 | .030 |
| .46 | .025 |
| .38 | .020 |
| .37 | .015 |
| .18 | .010 |
this paper were performed on laboratory processed material, manipulated to produce a variety of different grain sizes. The data are not to be interpreted as the basis for guaranteed minimums on mill produced sheet, but rather are presented merely to communicate an important trend between thickness-to-grain size ratio and weldability. Fortunately, a majority of thin sheet alloys are fabricated by brazing techniques rather than by joint fusion. However, fabricators of high performance alloys in thin sheet form should be apprised of minimum thickness-to-grain diameter ratios and their influence on heat-affected zone hot crack susceptibility. Any forming operation which requires cold working and subsequent annealing prior to a fusion jointing operation should be conducted such that the resulting thickness-to-grain diameter ratio will be greater than 4.

Acknowledgments
The author wishes to acknowledge the expert technical assistance of R. L. Baker, J. L. Rubush and L. P. Malin, members of the Stellite Division Technology Welding Laboratory, and to B. E. Lewis who performed the scanning electron microscopy.

References

Discussions
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