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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.

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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

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

Element	Heat A	Heat B	Heat C	Heat D	Heat E
Cr	21.40	21.38	22.30	21.30	22.40
W	14.54	13.90	13.60	13.95	14.40
Fe	1.48	1.68	2.00	1.70	1.60
C	.10	.06	.13	.07	.08
Si	.25	.43	.28	.38	.31
Ni	22.30	22.60	22.00	21.70	22.10
Mn	.62	.76	.69	.72	.70
P	.008	.005	.013	.012	.010
S	.003	.001	.003	.006	.005
La	.03	.03	.04	.04	.03
Mo	.32	.44	.48	.29	.33
B	<.001	<.001	<.001	.003	.003
Al	.22	.24	.04	.18	.18
Co	(Bal.)	(Bal.)	(Bal.)	41.00	39.80
Cu	.001	N.A.	.01	<.01	.01

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

Heat	Thickness, in. Nominal	Initial	Final	Reduction, %	ASTM grain size	Grain diam, in.	Thick. to grain diam ratio
A	.010	.013	.009	31	6.5	.00145	6.2
A	.015	.029	.015	48	3.5-4	.00500	3.8
A	.020	.032	.020	37	3	.00490	4.1
A	.025	.048	.025	48	3.5	.00420	6.0
A	.030	.032	.0275	9	4.5	.00300	9.2
A	.035	.045	.034	24	3.5	.00420	8.1
B	.010	.018	.009	50	4-4.5	.00330	2.7
B	.015	.018	.013	28	3-4	.00420	3.1
B	.020	.020	.020	—	3-4.5	.00400	5.0
B	.025	.032	.024	25	5.5-6	.00185	13.0
B	.030	.040	.0295	26	5-6	.00205	14.4
B	.035	.048	.033	31	4	.00360	9.2
C	.010	.028	.009	68	4.5	.00300	3.0
C	.015	.028	.0145	48	5.5	.00205	7.1
C	.020	.032	.0195	39	4.5-5	.00270	7.2
C	.025	.045	.0245	46	5	.00240	10.2
C	.030	.032	.028	13	5.5	.00205	13.7
C	.035	.043	.035	19	5-5.5	.00200	15.9
D	.010	.032	.0095	70	4	.00360	2.6
D	.015	.032	.013	59	3.5-4	.00400	3.2
D	.020	.041	.019	54	3.5	.00420	4.5
D	.025	.041	.0245	40	4	.00360	6.8
D	.030	.041	.031	24	3.5	.00420	7.4
D	.035	.043	.035	19	3-3.5	.00455	7.7
E	.010	.018	.009	50	4	.00360	2.5
E	.015	.043	.014	67	4-4.5	.00330	4.2
E	.020	.043	.020	53	4	.00360	5.6
E	.025	.043	.024	44	4.5	.00300	8.0
E	.030	.043	.029	33	4-4.5	.00330	8.8
E	.035	.043	.034	21	4	.00360	9.4
A*	.030	.034	.030	12	2.5-3	.00545	5.5
B*	.020	.024	.021	12	1-1.5	.00920	2.3
E*	.030	.035	.030	17	1-1.5	.00920	3.3

*Specially processed to produce large grain size

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.

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 autogeneous 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 (1¾, 2½ 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

0.010 in.) were sectioned for conventional metallography and scanning electron microscopy.

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/2R 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 decreased, 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.

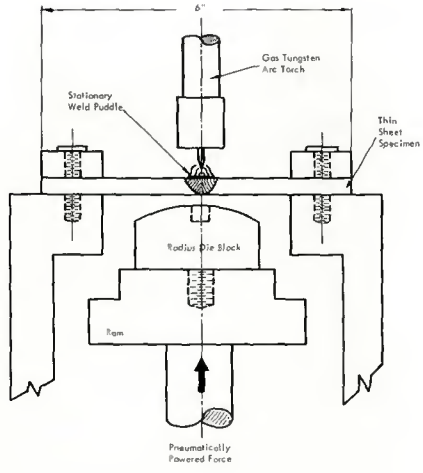

Fig. 1 — Simplified sketch of the Tig-a-ma-jig testing device

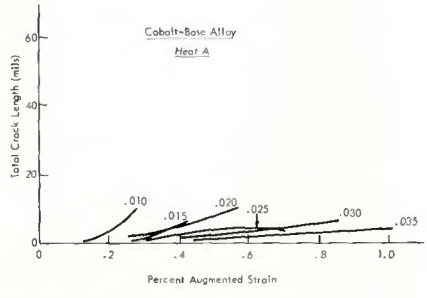

Fig. 2 — Tig-a-ma-jig data, thin gage alloy No. 188, heat A (each line represents a different sheet thickness, given in inches)

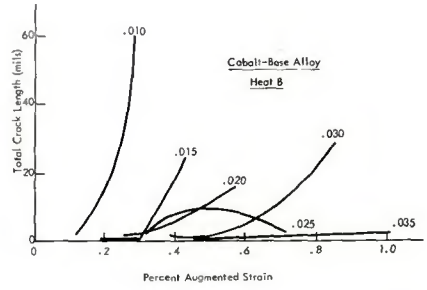

Fig. 3 — Tig-a-ma-jig data, thin gage alloy No. 188, heat B (each line represents a different sheet thickness, given in inches)

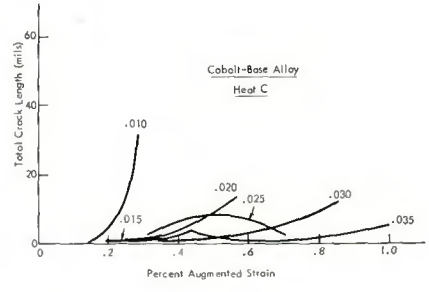

Fig. 4 — Tig-a-ma-jig data, thin gage alloy No. 188, heat C (each line represents a different sheet thickness, given in inches)

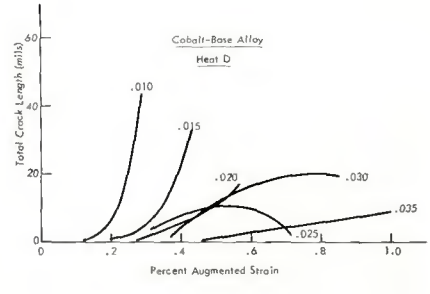

Fig. 5 — Tig-a-ma-jig data, thin gage alloy No. 188, heat D (each line represents a different sheet thickness, given in inches)

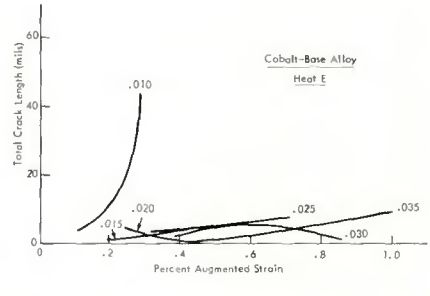

Fig. 6 — Tig-a-ma-jig data, thin gage alloy No. 188, heat E (each line represents a different sheet thickness, given in inches)

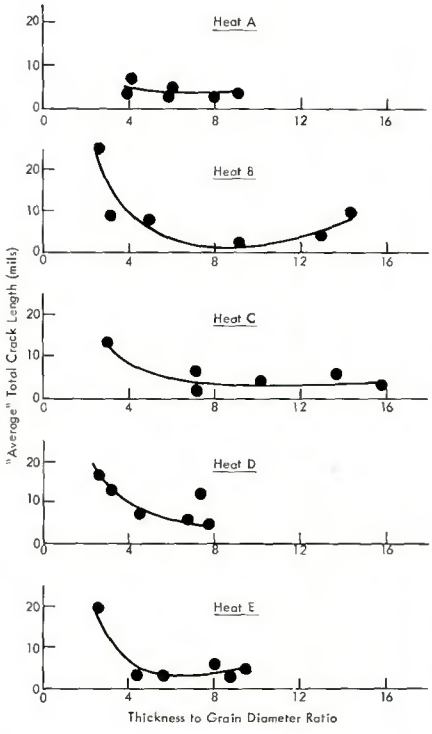

Fig. 7 — The Influence of thickness to grain diameter ratio on hot crack sensitivity of thin gage alloy No. 188. Total crack length value is an average of cracking experienced under all three strain level test conditions

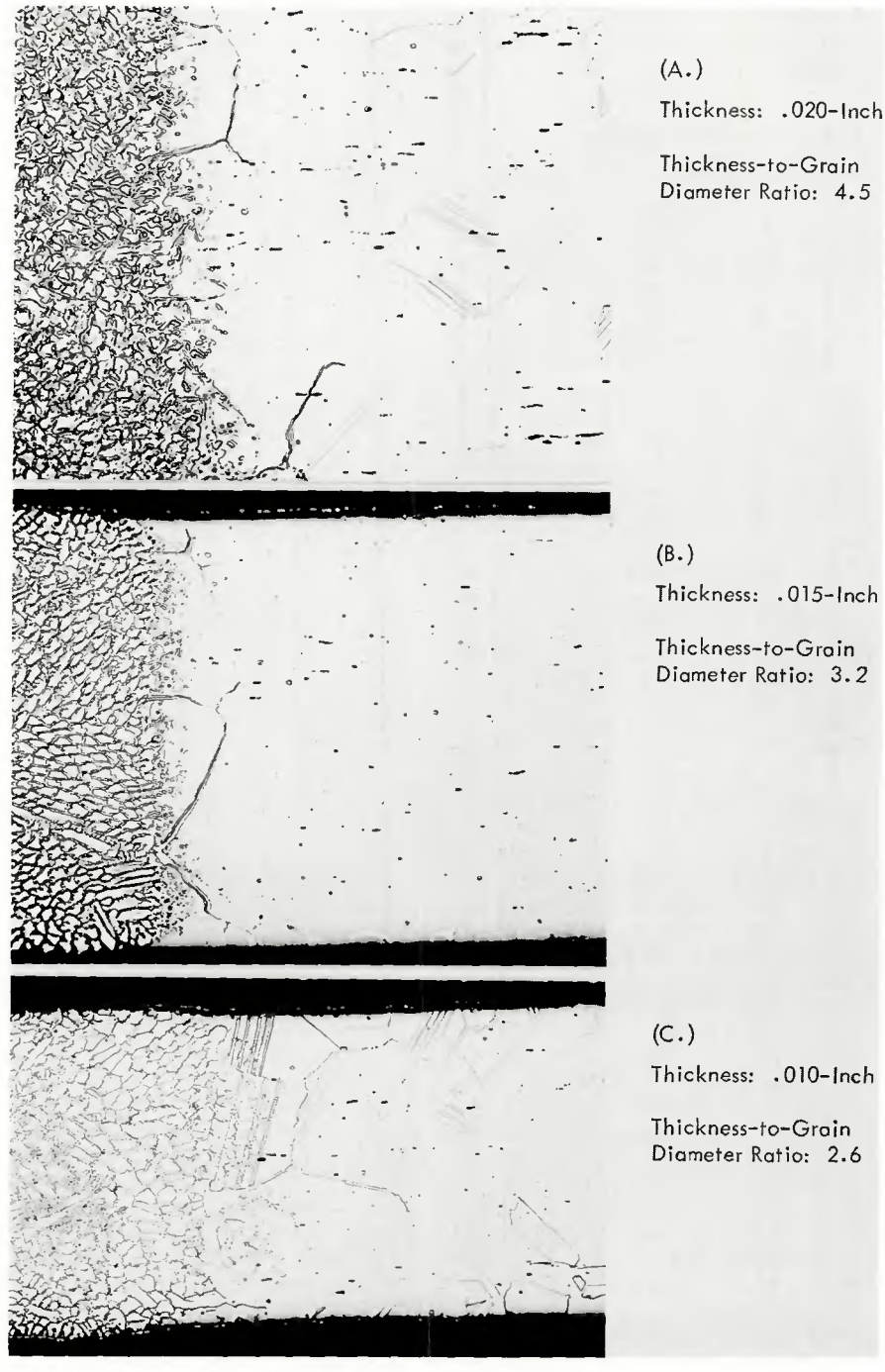

Fig. 8 — Longitudinal cross sections of Tig-a-ma-jig specimens, cobalt-base alloy No. 188, heat D, HCl-H_2O_2 etch. X200, reduced 25%

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. It is this 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.) happens to show 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-

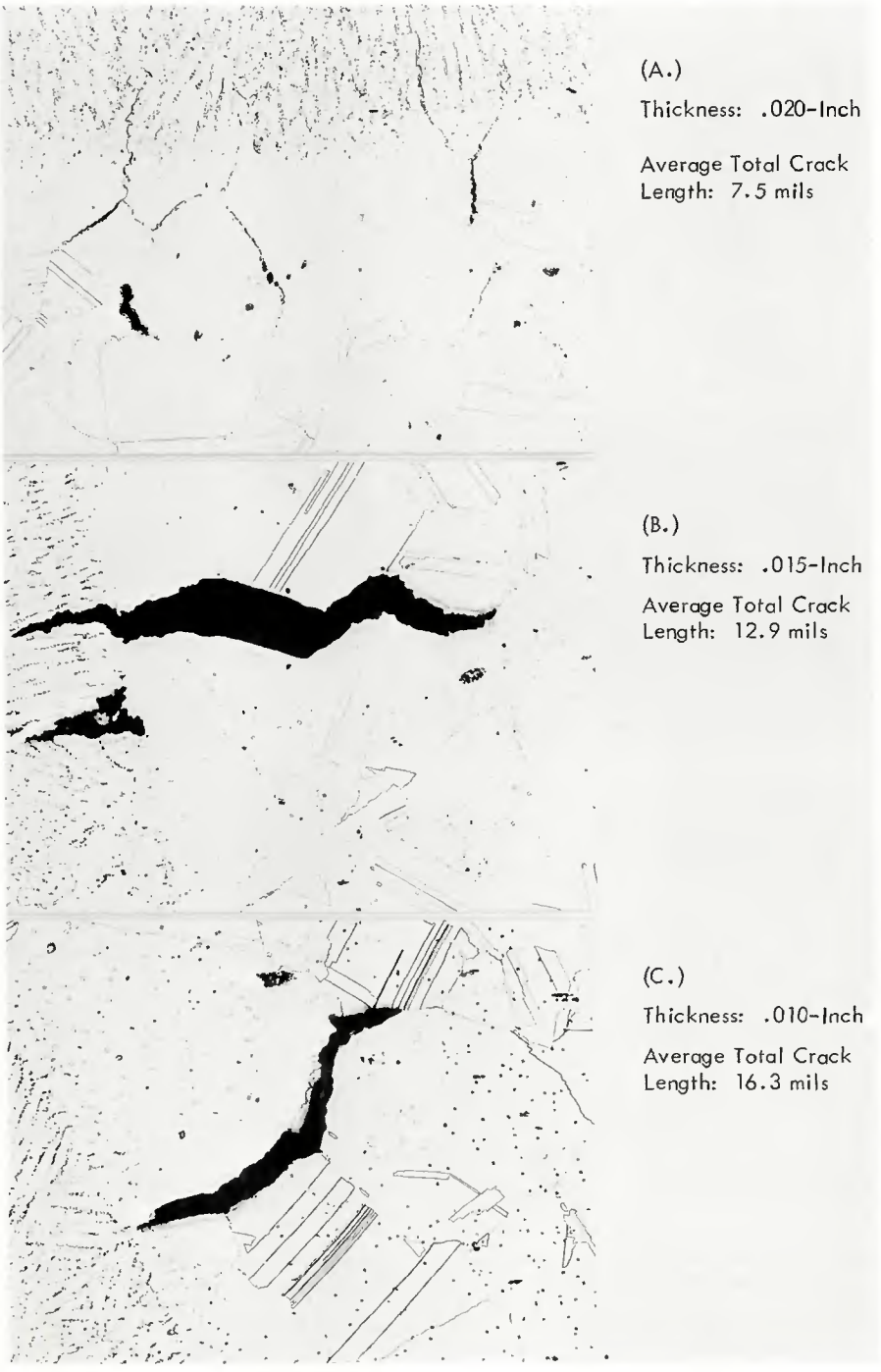

Fig. 9 — Top view section of Tig-a-ma-jig specimens, cobalt base alloy No. 188, heat D, HCl-H_2O_2 etch. X200, reduced 25%

Table 3 — Nominal Chemical Composition of Nickel Base Alloys

	Alloy X	Alloy no. 625	Alloy S
Ni	47.00	60.50	67.00
Cr	21.50	21.00	15.50
Mo	8.80	9.00	14.50
Fe	18.40	3.50	0.8
C	.07	.06	.006
Other		3.5 Cb	.02 La

Table 4 — Cold Rolling and Annealing Schedules for Thin Gage Nickel Base Alloys (a)

Condition	Approx. percent final cold reduct. (b)	Annealing temp., F	Annealing time, min	Cooling
A	40	1950	10	RAC
B	40	2150	10	RAC
C	40	2175	30	RAC
X	16	2050	10	RAC
Y	16	2150	10	RAC
Z	16	2200	30	RAC

(a) Starting gage = .060 in.; finish gage = .020 in.
(b) All materials were rolled to an intermediate gage and annealed at 2150 F/10 min/RAC prior to the final cold reduction.

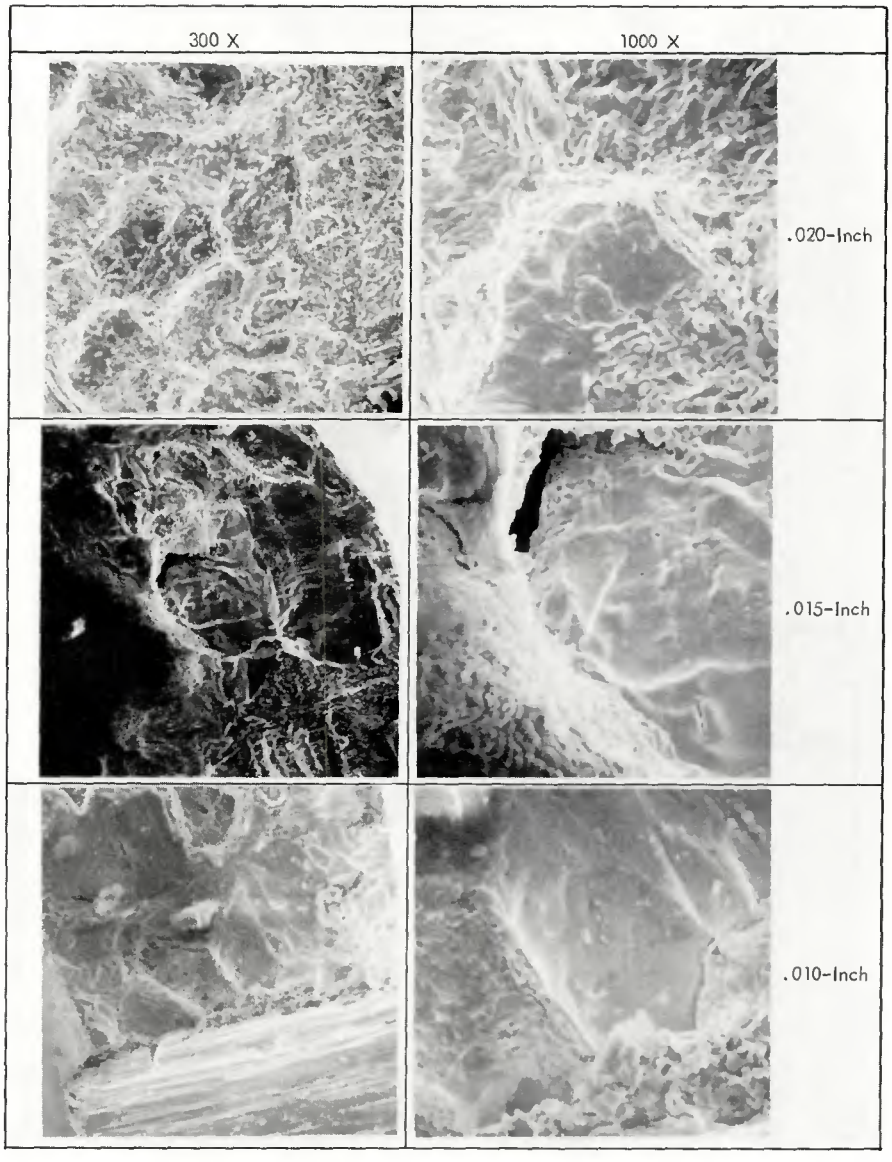

Fig. 10 — Scanning electron microscopy of heat-affected zone crack surfaces, cobalt-base alloy No. 188, heat D; reduced 38%

Table 5 — Material Thickness and Grain Size Data for Nickel Base Alloys

Alloy	Condition (table 4)	ASTM grain size no.	Approx. grain diam, in.	Final gage in.	Thick. to gr. diam ratio
X	A	6.5-9	.0010	.0225	22.5
X	B	6-7.5	.0014	.022	15.7
X	C	2	.0071	.0215	3.1
X	X	4-5.5	.0027	.0215	8.0
X	Y	5	.0024	.0215	9.0
X	Z	1-2.5	.0077	.021	2.7
625	A	8-8.5	.0008	.0215	26.2
625	B	4.5	.0030	.021	7.0
625	C	3.5-4	.0039	.021	5.4
625	X	5.5-6	.0019	.021	11.0
625	Y	4-4.5	.0033	.021	6.4
625	Z	2.5-4	.0046	.020	4.3
S	A	7-7.5	.0011	.022	20.0
S	B	4	.0036	.0215	6.0
S	C	3.5	.0042	.022	5.2
S	X	5	.0024	.021	8.8
S	Y	4-4.5		.021	6.4
S	Z	1.5-3	.0065	.021	3.2

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:	45 deg incl. angle
Arc gap (cold):	.060 in.
Arc dwell time:	2.5 seconds
Arc cutoff:	0.2 seconds
Argon flow:	20 cfh

Weld current, A	Specimen thickness, in.
10	.010
12	.015
14	.020
17	.025
19	.030
22	.035

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

Table 8 — Hot Crack Sensitivity of Specially Processed Cobalt Base Alloy Sheet Material

Heat	Nom. thick., in.	Thick. to gr. diam, ratio	Avg. total crack length, mils
A*	.030	5.5	9.3
A	.030	9.2	3.6
B*	.020	2.3	10.1
B	.020	5.0	8.0
E*	.030	3.3	7.2
E	.030	8.8	1.5

*Indicates specially processed sheet given small reductions and long annealing times to produce large grain size.

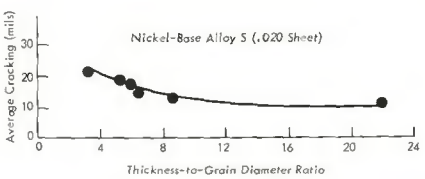

Fig. 11 — Summary of hot crack sensitivity versus thickness to grain diameter ratio for thin gage alloy S

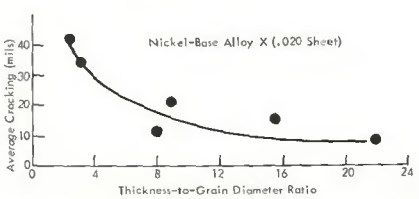

Fig. 12 — Summary of hot crack sensitivity versus thickness to grain diameter ratio for thin gage alloy X

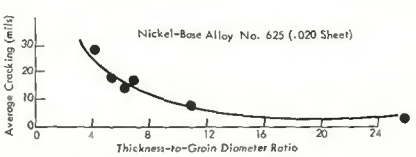

Fig. 13 — Summary of hot crack sensitivity versus thickness to grain diameter ratio for thin gage alloy No. 625

3. The increased hot crack sensitivity in low thickness-to-grain diameter ratio in materials is apparently a manifestation of greater ease of intergranular crack propagation, once the heat-affected zone hot crack originates at a liquid grain boundary.

Closing Comments

The experiments documented in 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 joining operation should be conducted such that the resulting thickness-to-grain diameter ratio will be greater than 4.

Table 9 — Maximum Observed Heat-Affected Zone Crack Lengths* in Cobalt Base Alloy

	Max. crack length, mils	Heat	Thick., in.	Thick. to grain diam ratio
Max. crack length equal to or greater than 10	13	D	.015	3.2
	11	C	.010	3.0
	10	D	.010	2.6
	10	B	.010	2.7
	10	B	.015	3.1
	10	E	.010	2.5
	10	E	.015	4.2
				3.2 Avg.
Max. crack length less than 10	7	B	.020	5.0
	6	A	.010	6.2
	6	D	.030	7.4
	6	E	.035	9.4
	5	A	.035	8.1
	5	B	.030	14.4
	5	B	.020	7.2
	5	C	.030	13.7
	5	C	.035	15.9
	5	D	.035	7.7
	4	A	.015	3.8
	4	A	.030	9.2
	4	B	.035	9.2
	4	E	.025	8.0
	3	A	.020	4.1
	3	B	.025	13.0
	3	C	.015	7.1
	3	C	.025	10.2
	3	D	.025	6.8
	3	E	.030	8.8
	2	A	.025	6.0
	2	E	.020	5.6
				8.5 Avg.

*Observed at 60X in Tig-a-ma-jig specimens tested using the 1¾ in. bending block.

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