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THE EFFECT OF SMALL ADDITIONS OF NIOBIUM ON THE WELDING BEHAVIOR OF AN AUSTENITIC STAINLESS STEEL[1]

A. J. Moorhead, V. K. Sikka and R. W. Reed

ABSTRACT

The mechanical property data for type 304 stainless steel show large variations in tensile, creep, and creep-fatigue properties. Previous researchers have attributed these differences to variations either in carbon and nitrogen content or in grain size, but we have found some heats which are stronger than can be explained by these factors and attribute this apparent anomaly to the strengthening effect of niobium. To systematically study the effect of niobium on the behavior of type 304 stainless steel, a low-niobium commercial heat was remelted with varying niobium additions — up to 1000 ppm. A standardized weldability test, the Spot Varestraint, was used to compare the propensity of various heats for hot cracking. We found that the fusion and heat-affected zone cracking behavior of the experimental heats was similar to that of a heat of commercial type 304, and much superior to that of a commercial heat of type 347 stainless steel. The superior resistance to fusion zone cracking was attributed to the presence of a small amount of delta ferrite in the microstructure of the weld nugget in the experimental materials. The outstanding heat-affected zone cracking behavior was at least partly attributable to backfilling of grain boundary separations in the experimental heats, as well as in the commercial type 304. We hypothesize that a relatively wide partially melted zone prevents backfilling of heat-affected zone cracks in the type 347 steels.

INTRODUCTION

Significant variations in mechanical properties and welding behavior have been observed between heats of austenitic stainless steels even when these materials have been purchased to tightly controlled ASTM or RDT specifications. These variations have often been attributed to the

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effects of minor alloying or residual elements.[2-4] Sikka et al.[5] have found that small quantities of niobium — in addition to the previously reported carbon and nitrogen[6] — strongly affect the time to rupture and minimum creep rate of commercial type 304 stainless steel. The effect of sizable additions of niobium on the welding behavior of austenitic materials — such as the niobium-stabilized stainless steels like type 347 — has been well documented.[7,8] As summarized in this paper our study evaluated the effect of small niobium additions on the weldability of austenitic materials and specifically of type 304 stainless steel. The results of the mechanical properties portion of this work are included elsewhere in these Proceedings.[5]

MATERIALS

This study used four heats of commercial material. The product form, grain size, and compositions are shown in Tables 1 and 2. Portions of two type 304 stainless steel plates, heats 9T2796 and 8043813, were machined into 3.18 by 25 by 25-mm (0.125 by 1 by 1-in.) blanks with the 25 by 25-mm dimension parallel to the original surface of the plate. The 3.61-mm-thick (0.142-in.) type 347 stainless steel sheet was purchased according to ASTM Specification A-167-74 in that thickness

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[2] *Effects of Residual Elements on Properties of Austenitic Stainless Steels, Am. Soc. Test. Mater. Spec. Tech. Publ.* 418, American Society for Testing and Materials, Philadelphia, July 1967.

[3] R. T. King, J. O. Steigler and G. M. Goodwin, *Creep Properties of a Type 308 Stainless Steel Pressure Vessel Weld with Controlled Residual Element*, ORNL/TM-4131 (May 1973).

[4] N. C. Binkley, R. G. Berggren and G. M. Goodwin, "Effects of Slight Compositional Variations on Type E308 Electrode Deposits," *Weld. J. (Miami)* 53(2): 91-s—95-s (February 1974).

[5] V. K. Sikka, A. J. Moorhead and C. R. Brinkman, "Influence of Small Amounts of Niobium on Mechanical and Corrosion Properties of Type 304 Stainless Steel," to be published as part of the Proceedings of ASTM Symposium on the Effect of Carbon, Nitrogen, and Residual Elements on the Austenitic Stainless Steels and Their Weldments, November 14–15, 1977, Atlanta, Georgia.

[6] J. J. Heger and G. V. Smith, *Elevated Temperature Properties as Influenced by Nitrogen Additions to Types 304 and 316 Austenitic Stainless Steel, Am. Soc. Test. Mater. Spec. Tech. Publ.* 522, American Society for Testing and Materials, Philadelphia, 1968.

[7] G. E. Linnert, "Welding Type 347 Stainless Steel Piping and Tubing," *Weld. Res. Counc. Bull.* 43, New York, October 1958.

[8] R. J. Christoffel, "Cracking in Type 347 Heat-Affected Zone During Stress Relaxation," *Weld. J. (New York)* 41(6): 251-s—256-s (June 1962).

Table 1. Product Form and Grain Size of Three Commercial Heats of Type 304, One Heat of Type 347, and Four Experimental Heats of Stainless Steel

Heat	Heat Symbol	Vendor	As-Received Form	Thickness (mm)	Thickness (in.)	Grain Size[a] As Received (ASTM)	Grain Size[a] As Received (μm)	Grain Size[a] Reannealed (ASTM)	Grain Size[a] Reannealed (μm)
			Commercial Heats Type 304						
8043813	813	Republic	Plate	25.4	1.00	3.8	84	4	78
9T2796	796	USS	Plate	50.8	2.00	0.26	280	0.26	280
337187	187	Allegheny Ludlum	Plate	38.1	1.50	2.1	150	2.3	140
			Type 347						
	347		Sheet	3.6	0.14			6-7[b]	
			Experimental Heats						
	187-1	ORNL	Strip	3	0.12			4-5[b]	
	187-5	ORNL	Strip	3	0.12			4-5[b]	
	187-6	ORNL	Strip	3	0.12			5-6[b]	
	187-7	ORNL	Strip	3	0.12			4-5[b]	

[a]Method of J. E. Hillard, "Estimating Grain Size by the Intercept Method," *Met. Prog.* 85(5): 92–102 (May 1964).

[b]Determined by comparison with ASTM Standard Grain Size Charts.

Table 2. Chemical Composition of Three Commercial Heats of Type 304 and One Commercial Heat of Type 347 Stainless Steel

Heat Symbol	Composition, %															
	C	Mn	P	S	Si	Ni	Cr	Mo	Y	Nb	Ti	Co	Cu	Al	B	N
							Commercial Heats									
813[a]	0.062	1.87	0.044	0.004	0.48	8.95	17.8	0.32	0.022	0.020	0.002					0.033
796[a]	0.047	1.22	0.029	0.012	0.47	9.58	18.5	0.10	0.037	0.008	0.003	0.05	0.10			0.031
187[a]	0.068	0.83	0.018	0.008	0.59	9.43	18.2	0.07	0.060	0.002	0.003	0.06	0.15			0.031
347[b]	0.07	1.53	0.04	0.006	0.68	11.50	17.05	0.41	0.03	0.78	<0.01	0.12	0.20	0.01	0.001	0.039

[a]Analysis by ORNL of heat before fabricating into Spot Varestraint specimens.
[b]Analysis by outside laboratory of Spot Varestraint specimen after testing.

in the hot-rolled, annealed, and pickled condition. A third heat of type 304 was used as the melting stock in the fabrication of four experimental heats with the same nominal composition, but with varying niobium content. The fabrication sequence for these experimental 0.5-kg heats was as follows:

1. Melt six times using a nonconsumable tungsten electrode in an evacuated chamber backfilled with a partial pressure of argon;
2. Drop-cast into a 19.0-mm-diam (0.75-in.) water-cooled copper mold;
3. Hot swage at 1000°C to 12.7-mm-diam (0.50-in.) rod;
4. Forge a portion of the rod to flats at 1000°C;
5. Cold roll the flats to 3.0-mm-thick (0.12-in.) strip; and
6. Anneal in vacuum for 1.8 ks (0.5 hr) at 1065°C.

The chemical analyses of the experimental heats — one of heat 187 remelted, and three with niobium additions to produce ingots with 0.05, 0.07, and 0.1 wt % Nb — which were evaluated in this welding behavior study are given in Table 3. Note that in all cases the chemical compositions of the experimental heats fall within the range specified by ASTM A-240 for type 304 stainless steel plate.

EXPERIMENTAL PROCEDURE

In order to compare the welding behavior of two commercial heats of type 304, one commercial heat of type 347, and four experimental heats, a standardized weld cracking test known as the Spot Varestraint or Tigamajig test was used. The apparatus is pictured in Fig. 1 and shown schematically in Fig. 2. In this test a 25 by 152-mm (1 by 6-in.) coupon containing a solidifying gas tungsten-arc weld nugget is bent by a pneumatic ram around one of a set of radiused die blocks. The arc time is controlled by a timer for reproducibility, while a time-delay relay is used to regulate the time at which the ram is activated. In all our tests the ram was forced into the coupon just as the arc was extinguished. The bending of the specimen around a radius generates reproducible amounts of augmented strain in the fusion and heat-affected zones of the weld. Since strain, one of the factors responsible for

Table 3. Chemical Composition of Four Heats of Type 304 Stainless Steel Remelted at ORNL, Three of Which Had Niobium Additions[a]

Heat Symbol	Composition, %															
	C	Mn	P	S	Si	Ni	Cr	Mo	Y	Nb	Ti	Co	Cu	Al	B	N
							Experimental Heats									
187-1	0.052	0.96	0.029	0.009	0.44	9.48	18.22	0.14	0.06	<0.01	<0.01	0.10	0.12	0.01	0.001	0.029
187-5	0.049	0.94	0.028	0.009	0.43	9.53	18.13	0.14	0.06	0.05	<0.01	0.10	0.12	0.01	0.001	0.030
187-6	0.050	0.96	0.029	0.009	0.44	9.57	18.18	0.15	0.06	0.07	<0.01	0.10	0.12	0.01	0.001	0.028
187-7	0.051	0.95	0.029	0.009	0.43	9.51	18.10	0.14	0.06	0.10	<0.01	0.10	0.12	0.01	0.001	0.029

[a]Analysis by outside laboratory of Spot Varestraint specimen after testing.

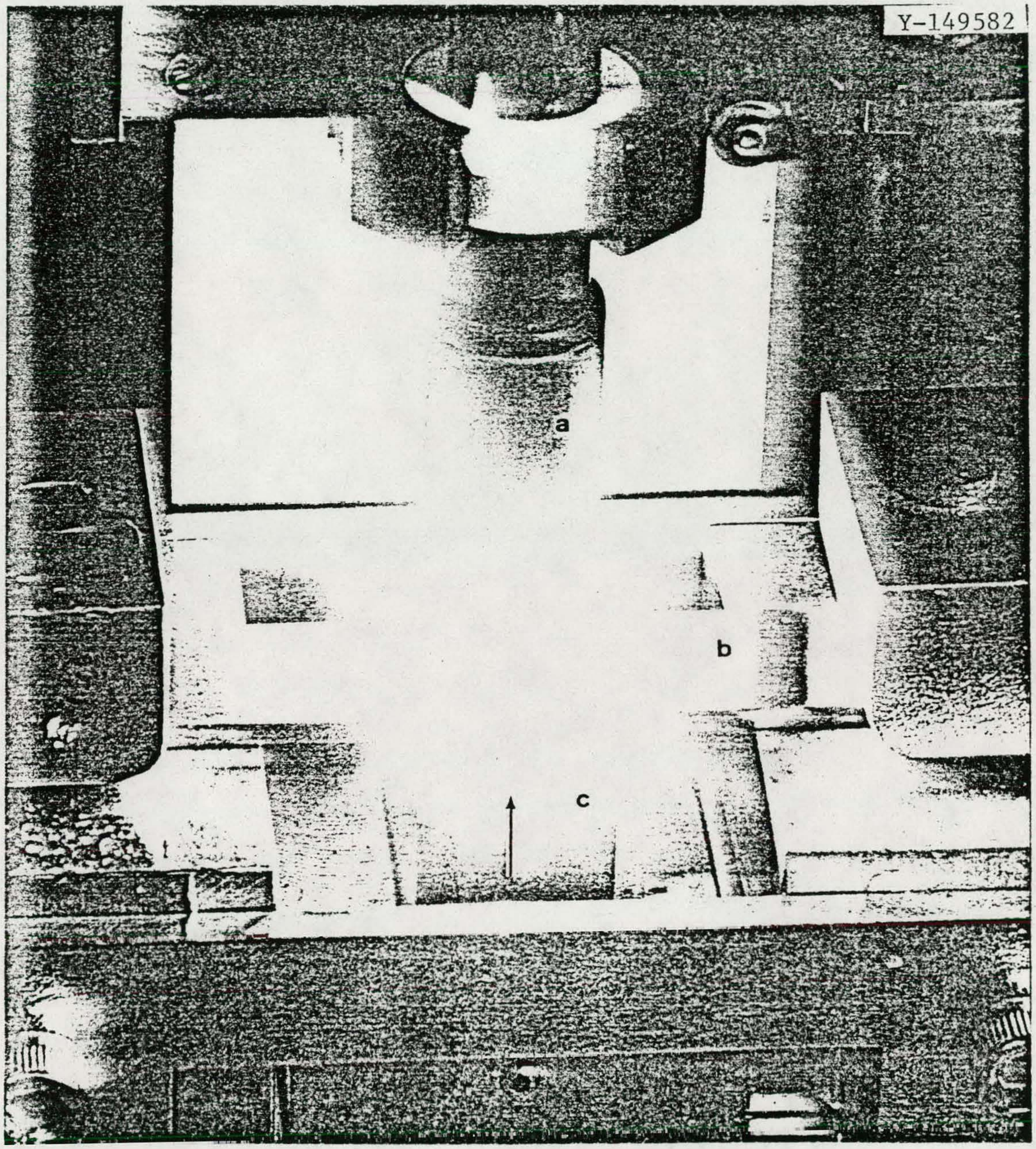

Fig. 1. Spot Varestraint Test in Progress Showing: (a) Gas Tungsten-Arc Torch, (b) Test Specimen Secured by Hold-Down Blocks, and (c) A Die Block. The motion of the die block to strain the specimen is indicated by an arrow.

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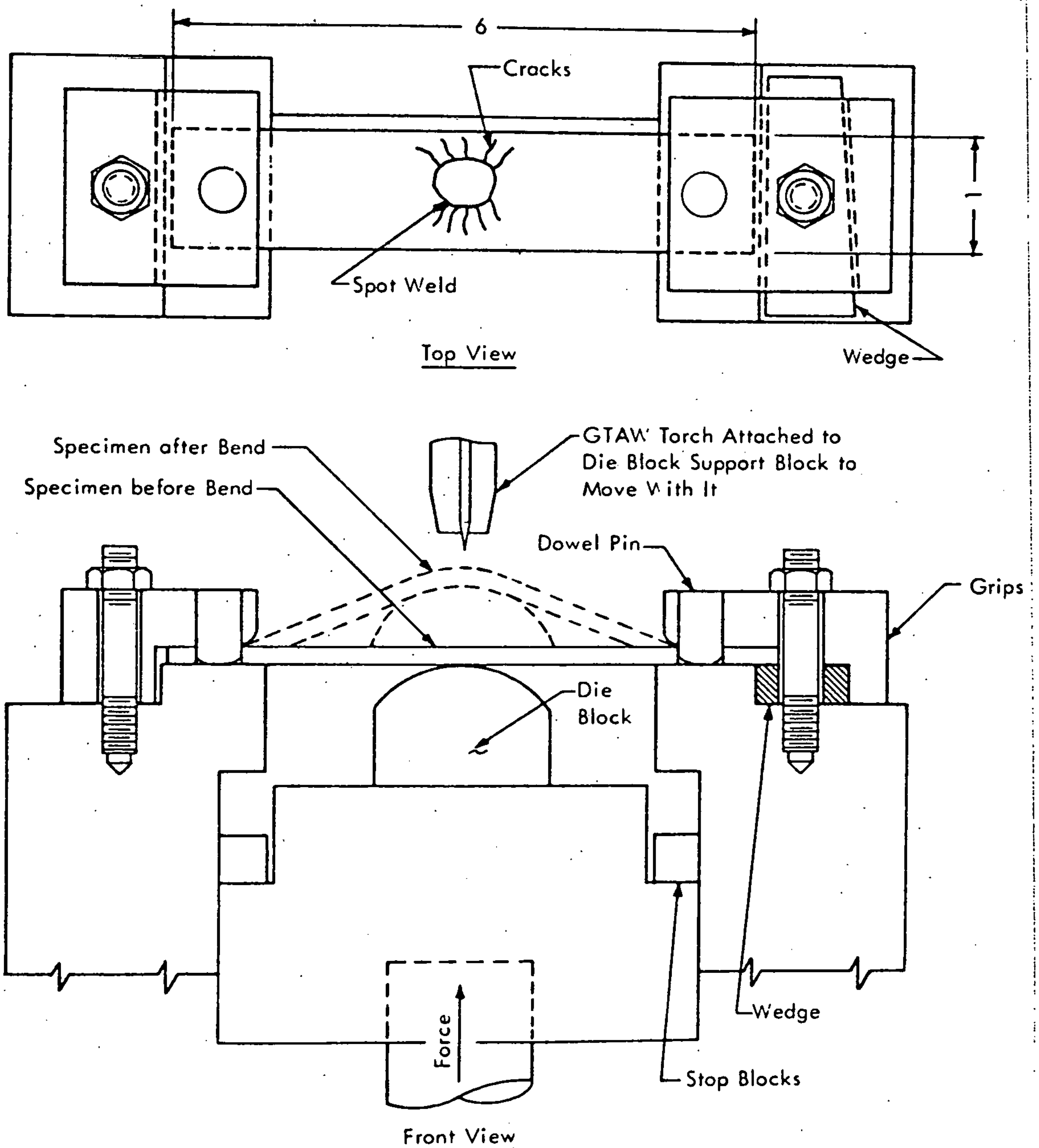

Fig. 2. Schematic of the Spot Varestraint Weldability Test Apparatus.

weld hot cracking, is then controlled, the effect of other factors such as composition can be determined. The original Varestraint (variable restraint) test was developed by Savage and Lundin[9] as a *reproducible means for augmenting the normal shrinkage strains in a weldment thereby simulating the large shrinkage strains characteristic of a highly restrained weldment*, as in heavy sections, in a laboratory specimen. The number and length of cracks developed during this test are related to the weldability of the material. The Spot Varestraint device was developed by Goodwin[10] to incorporate most of the desirable features of the Varestraint test and have the advantage of a smaller specimen size — that is, 25 mm by 152 for the Spot Varestraint as opposed to 51 by 305 mm for the standard Varestraint test.

In our study the scarcity of material available for testing made a modified or "compound" test specimen necessary. This compound specimen is shown in Fig. 3. It requires only enough of the material to be tested to fabricate five or six (3-mm minimum thickness by 25- by 25-mm) coupons to which 25 by 64-mm pieces of a commercial material are attached by electron beam welding. This specimen also has the advantage of allowing testing of small heats of experimental, wrought metals. In conventional specimens small quantities of experimental materials can be tested, but the material is deposited in a series of weld beads on a commercial material and the tests are therefore, on cast rather than on wrought microstructure.

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[9]W. F. Savage and C. D. Ludin, "The Varestraint Test," *Weld. J. New York* 44(10): 433-s–442-s (October 1965).

[10]G. M. Goodwin, *The Effect of Minor Elements on the Hot Cracking of Inconel 600*, Ph.D. Thesis, Rensselaer Polytechnic Institute, Troy, New York, June 1968.

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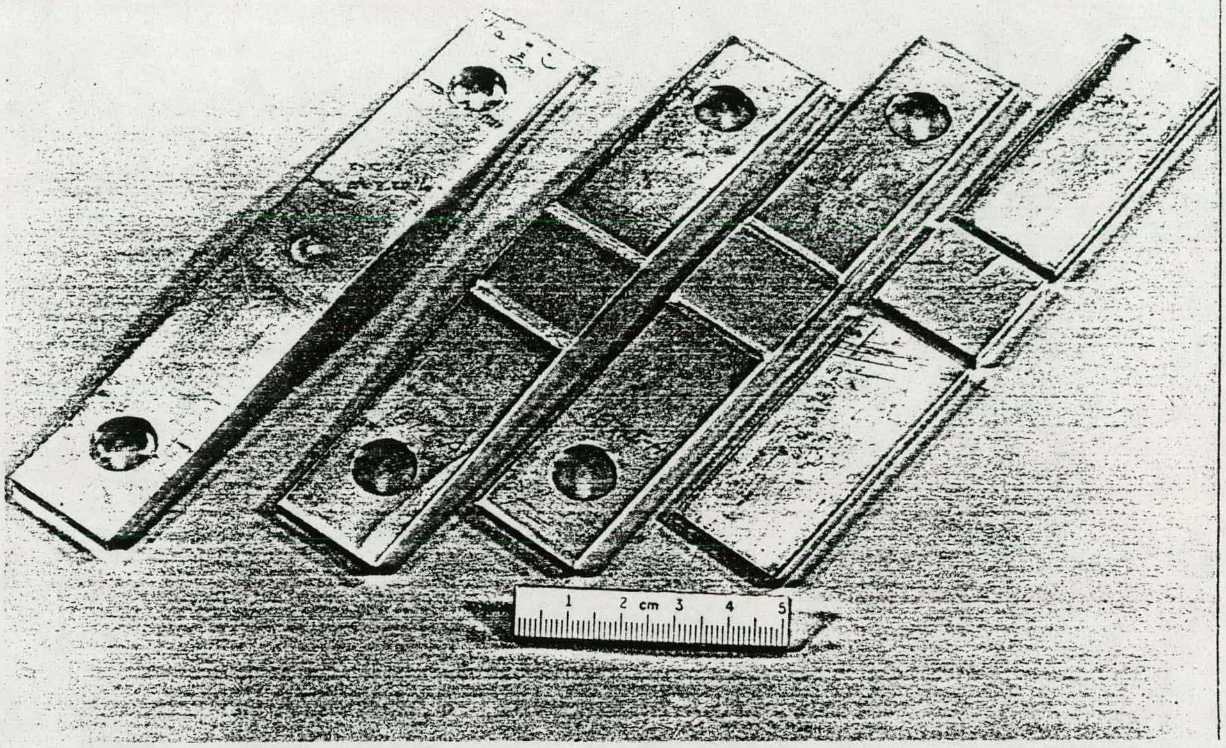

Fig. 3. Spot Varestraint Test Specimens. Standard specimen is at left with compound specimen shown (right to left) before assembly, after electron beam welding, and after testing.

Each heat of material was tested at four levels of strain — 0.6, 0.9, 1.3 and 1.9% — with the following arc spot parameters:

Arc current	73 A dcsp
Arc time	15 s
Arc gap	2.29 mm (0.090 in.) measured cold
Electrode	1.58-mm-diam, 2% thoriated W
	60° included angle with 0.25-mm-diam flat
Postarc time delay	none
Shield gas	argon
Spot size	about 5.0 mm (0.20 in.)

After testing the specimens were held under load in the fixture for 60 s before removal. The cracking data were obtained from the specimen surface at a magnification of 50× by a toolmaker's microscope with a digital output. The only cracks measured were those which lay in the partially melted or heat-affected zones (HAZ). Cracks that occurred in the fusion zone were not measured, but their presence or absence is important to weldability; therefore they were noted and will be discussed below.

From analysis of the data for each specimen the following indices of cracking sensitivity were obtained.

1. Cracking Threshold — the minimum augmented strain required to cause cracking with a given set of welding parameters;
2. Maximum Crack Length — the maximum-length crack near a given spot and a function of the width of the cracking-temperature range for a given set of welding parameters and a particular level of augmented strain;
3. Total Crack Length — the sum of the lengths of all cracks measured in a specimen; and
4. Average Crack Length — a mean found by dividing the total crack length by the total number of cracks.

After the cracking indices had been tabulated one central test section from each series of samples was removed for chemical analysis to verify heat identification. A second sample was mounted for metallographic examination with the surface of the coupon and weld spot being polished. A third coupon from each heat was mounted such that a transverse section of the weldment could be examined.

RESULTS AND DISCUSSION

Fusion-Zone Cracking Behavior

Photomacrographs of some of the arc spots after metallographic preparation are shown in Fig. 4. Only two of the experimental niobium-bearing heats are shown here (187-6 and 187-7), but the behavior of the other two heats was similar, and we would expect that if a fusion-zone cracking problem were to arise it would do so in the heats with higher niobium content. These photomacrographs are typical of all of the samples tested in that extensive fusion-zone cracking occurred in the type 347 stainless steel, but no cracks were observed in the commercial type 304 stainless

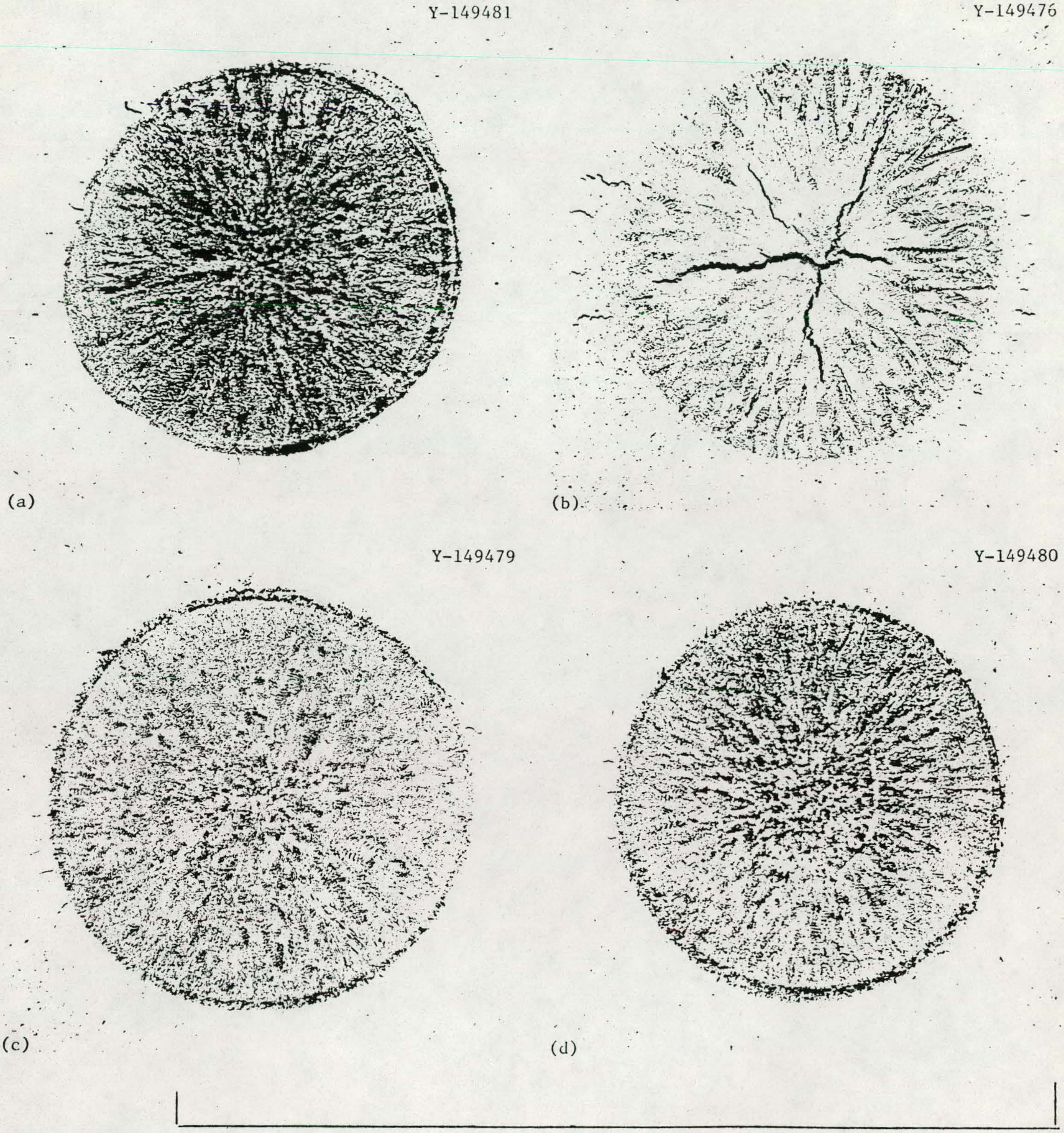

Fig. 4. Polished and Etched Surfaces of Spot Varestraint Test Gas Tungsten-Arc Weld Nuggets in Two Commercial and Two Experimental Heats of Austenitic Stainless Steel. (a) Heat 796: 0.008% Nb, commercial type 304 stainless steel. (b) Heat 347: 0.78% Nb, commercial type 347 stainless steel. (c) Heat 187-6: 0.07% Nb, commercial type 304 stainless steel with addition. (d) Heat 187-7: 0.10% Nb, commercial type 304 stainless steel with addition. Etchant: 50 HCl–10 HNO_3. 15×. Reduced 25%.

steel or in the experimental heats of type 304 stainless steel with niobium additions. Examination of these welds at higher magnification as shown in Fig. 5 revealed the reason for this difference in cracking behavior: all of the type 304 stainless steel materials — both commercial and experimental — contained a small amount of delta ferrite in their microstructures. It is a well-established fact[11,12] that the presence of this phase in the fusion zones of austenitic stainless steels greatly reduces weld hot-cracking. The presence of delta ferrite was confirmed by magnetic permeability measurements using a Magne-gage instrument and test procedures specified by AWS A4.2-74, "Calibrating Magnetic Instruments to Measure the Delta Ferrite Content of Austenitic Stainless Steel Weld Metal." All the type 304 stainless steel welds had a Ferrite Number (FN) of about 3, whereas the type 347 stainless steel had no measurable ferrite (i.e., FN = 0). The presence or absence of this beneficial phase is a well-established function of chemical composition[13] and a less well-known function of weld energy input, but exactly how its presence reduces hot-cracking has only been hypothesized.[14]

Heat-Affected Zone Cracking Behavior

A summary of the cracking data for all of the Spot Varestraint test specimens is given in Tables 4 and 5. Note that because of the limited amounts of materials available for testing this data is useful for comparison or screening, but is not purported to be statistically valid. The significant features of these results are:

1. The HAZ cracking behavior of the type 304 stainless steels with niobium additions (up to 1000 ppm) was similar to that of a commercial heat of type 304 stainless steel and much superior to that of a commercial heat of type 347 stainless steel, as illustrated in Fig. 6.

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[11] F. C. Hull, "Effect of Delta Ferrite on the Hot Cracking of Stainless Steel," *Weld. J. (New York)* 46(9): 399-s–409-s (September 1967).

[12] C. D. Lundin, W. T. DeLong and D. F. Spond, "Ferrite-Fissuring Relationship in Austenitic Stainless Steel Weld Metals," *Weld. J. (Miami)* 54(8): 241-s–246-s (August 1975).

[13] C. J. Long and W. T. DeLong, "The Ferrite Content of Austenitic Stainless Steel Weld Metal," *Weld. J. (Miami)* 52(7): 281-s–297-s (July 1973).

[14] J. C. Borland and R. W. Younger, "Some Aspects of Cracking in Welded Cr-Ni Austenitic Steels," *Brit. Weld. J.* 46(9): 399-s–409-s (September 1967).

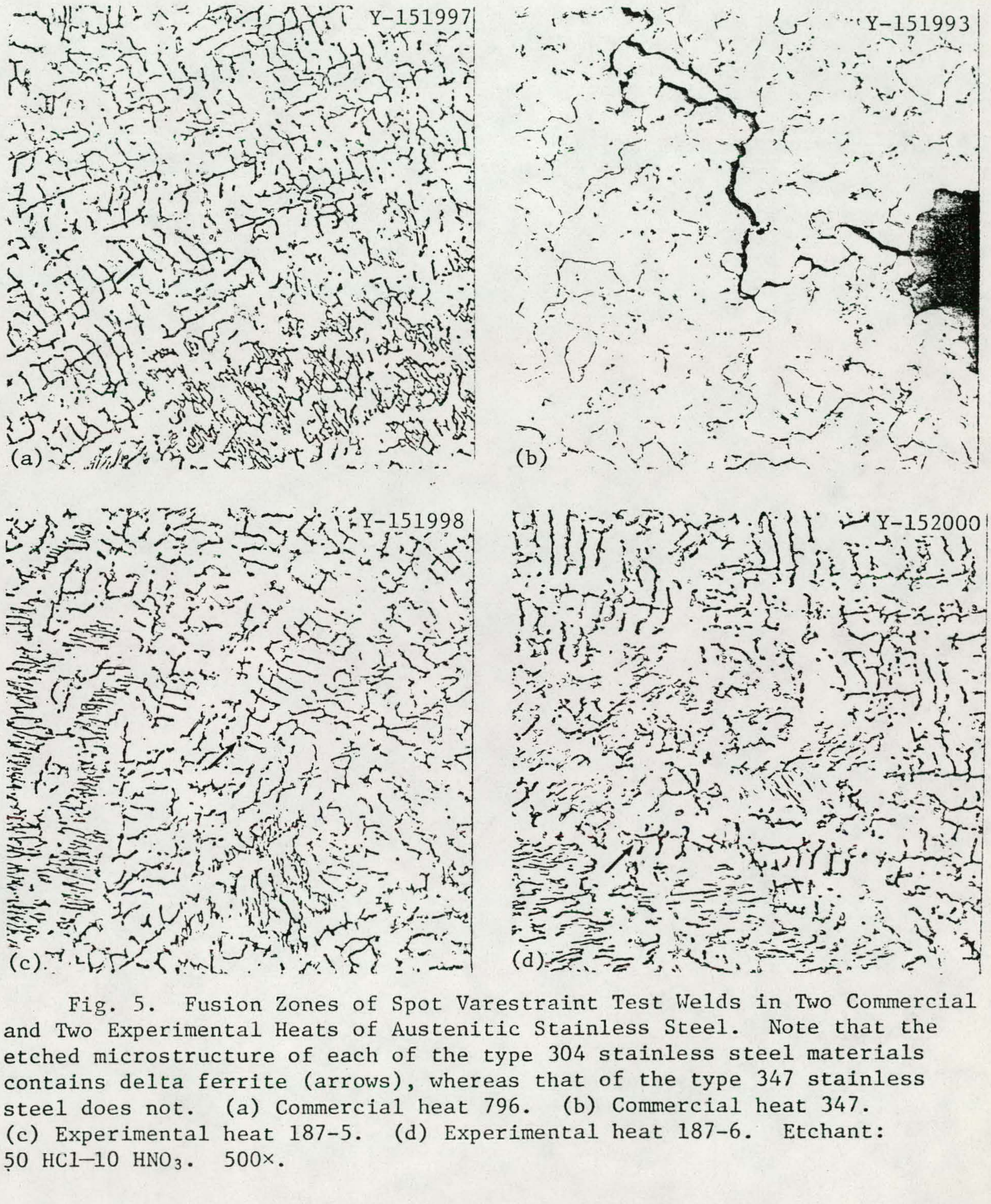

Fig. 5. Fusion Zones of Spot Varestraint Test Welds in Two Commercial and Two Experimental Heats of Austenitic Stainless Steel. Note that the etched microstructure of each of the type 304 stainless steel materials contains delta ferrite (arrows), whereas that of the type 347 stainless steel does not. (a) Commercial heat 796. (b) Commercial heat 347. (c) Experimental heat 187-5. (d) Experimental heat 187-6. Etchant: 50 HCl—10 HNO_3. 500×.

Table 4. Total Crack Length Data for Spot Varestraint Weldability Tests Conducted on Commercial and Experimental Austenitic Stainless Steels

Heat Symbol	Composition (wt %)		Total Crack Length[a] (mm) at % Augmented Strain of:			
	C	Nb	0.6%	0.9%	1.3%	1.9%
			Commercial Heats			
813	0.062	0.02	0	0.19	0.25	0.36
796	0.047	0.008	0	0.09	0.34	2.15
347	0.07	0.78	0.29	4.27	8.02	10.56
			Experimental Heats			
187-1	0.052	<0.01	0	0.42	0.57	1.06
187-5	0.049	0.05	0	0.28	0.51	2.41
187-6	0.050	0.07	0	0.34	0.82	3.03
187-7	0.051	0.10	0	0.26	1.03	1.48

[a]Crack length measurements on as-tested specimen using toolmaker's microscope at 50× magnification.

Table 5. Maximum and Average Crack Length Data for Spot Varestraint Weldability Tests Conducted on Commercial and Experimental Austenitic Stainless Steels

Heat Symbol	Composition (wt %)		Total Crack Length (mm) at % Augmented Strain of:							
			0.6%		0.9%		1.3%		1.9%	
	C	Nb	Max	Average	Max	Average	Max	Average	Max	Average
					Commercial Heats					
813	0.062	0.02	0		0.10	0.09	0.14	0.12	0.20	0.18
796	0.047	0.008	0		0.09	a	0.21	0.17	0.23	0.14
347	0.07	0.78	0.29	*a*	0.54	0.28	0.65	0.33	0.51	0.34
					Experimental Heats					
187-1	0.052	0.01	0		0.24	0.21	0.21	0.19	0.25	0.15
187-5	0.049	0.05	0		0.16	0.14	0.18	0.13	0.29	0.20
187-6	0.050	0.07	0		0.17	0.17	0.24	0.20	0.31	0.23
187-7	0.057	0.10	0		0.14	0.13	0.37	0.21	0.29	0.21

[a] Specimen had a single crack.

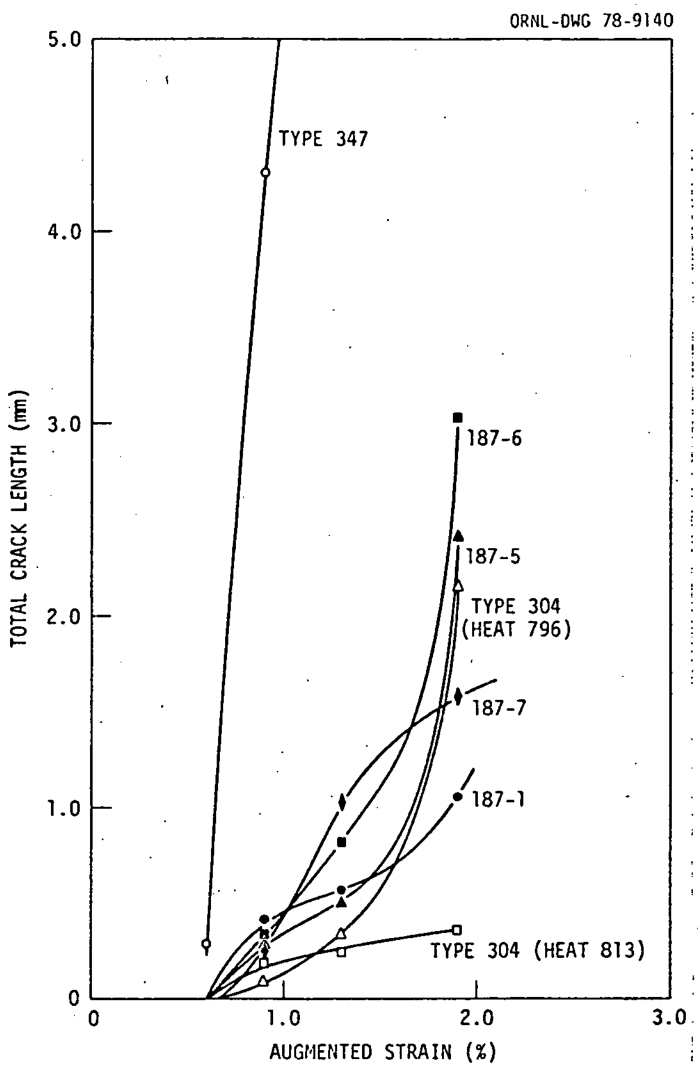

Fig. 6. Total Crack Length of Various Heats of Commercial and Experimental Austenitic Stainless Steels as a Function of Augmented Strain in Spot Varestraint Weldability Tests.

2. The cracking threshold for all of the type 304 stainless steel materials — commercial and experimental — was greater than 0.6% augmented strain but was less than 0.6% for the type 347 stainless steel.
3. The data for average crack length and maximum crack length do not correlate well with either niobium content or with percent augmented strain within a type of steel.

Metallographic examination of the test specimens at high magnification reveals an interesting and evidently significant difference in heat-affected zone cracking behavior between the type 304 stainless steel (both commercial and experimental) and the type 347 stainless steel materials. When the samples were etched with boiling Murakami's reagent to selectively reveal the δ-ferrite phase, several times molten metal from the weld puddle backfilled the grain-boundary separations in the HAZ of the type 304 stainless steel materials. These backfilled cracks can be clearly identified by the δ-ferrite extending into the HAZ in the type 304 stainless steel samples, as shown in Fig. 7. The backfilling of these separations eliminates them from consideration when the HAZ cracks were counted, thus giving a lower value for total crack length than had they not been backfilled. Backfilling was not observed in any of the type 347 samples studied metallographically and we attribute this to the following causes. The type 347 stainless steel has a rather wide (0.30-mm) partially melted zone (as shown in Fig. 8) between the fusion zone and HAZ. In the type 304 stainless steels, however, this region is either very narrow or nonexistent. We think this partially melted zone accommodates the strains produced by bending and solidification so that this region does not crack. Cracking does occur in the true HAZ, but as there is no path for molten metal from the fusion zone to reach these cracks, backfilling cannot occur. This observation has been confirmed by Lundin[15] who has observed this phenomenon in other classes of material. Apparently HAZ cracks can only be backfilled in those systems containing a very narrow partially melted zone. Thus, wide partially melted zones are detrimental to weldment cracking behavior.

Although a number of authors[7,16] have indicated that the base metal grain size has a significant effect on the tendency for HAZ cracking (in general, the smaller the grain size the lower the cracking tendency), we do not think that our results are greatly in error resulting from variations in grain size. First, five out of the seven heats tested had very similar grain sizes (ASTM 4-5). Second, the one alloy that displayed the greatest hot-cracking tendency (the heat of type 347) also was the material that had the smallest grain size (ASTM 6-7), and we would anticipate that if heat-treated to a larger grain size its HAZ cracking propensity would be even greater.

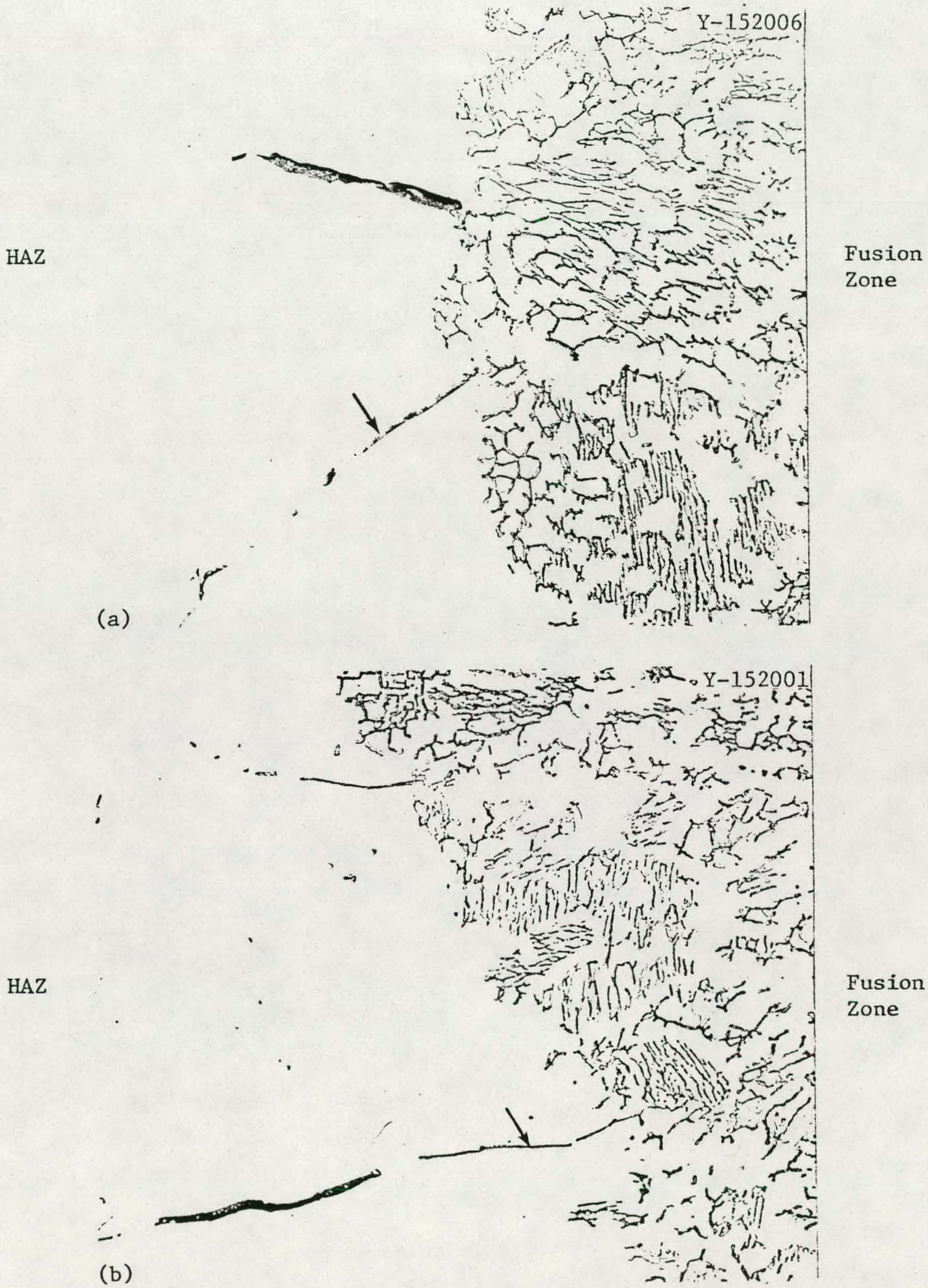

Fig. 7. Typical Backfilled Grain Boundary Separations (Arrows) in the Heat-Affected Zones of Two Type 304 Stainless Steel Materials. (a) Commercial type 304 stainless steel (heat 796). (b) Experimental heat 187-6 (0.07 wt% Nb). Etchant: 50 HCl–10 HNO_3. 500×.

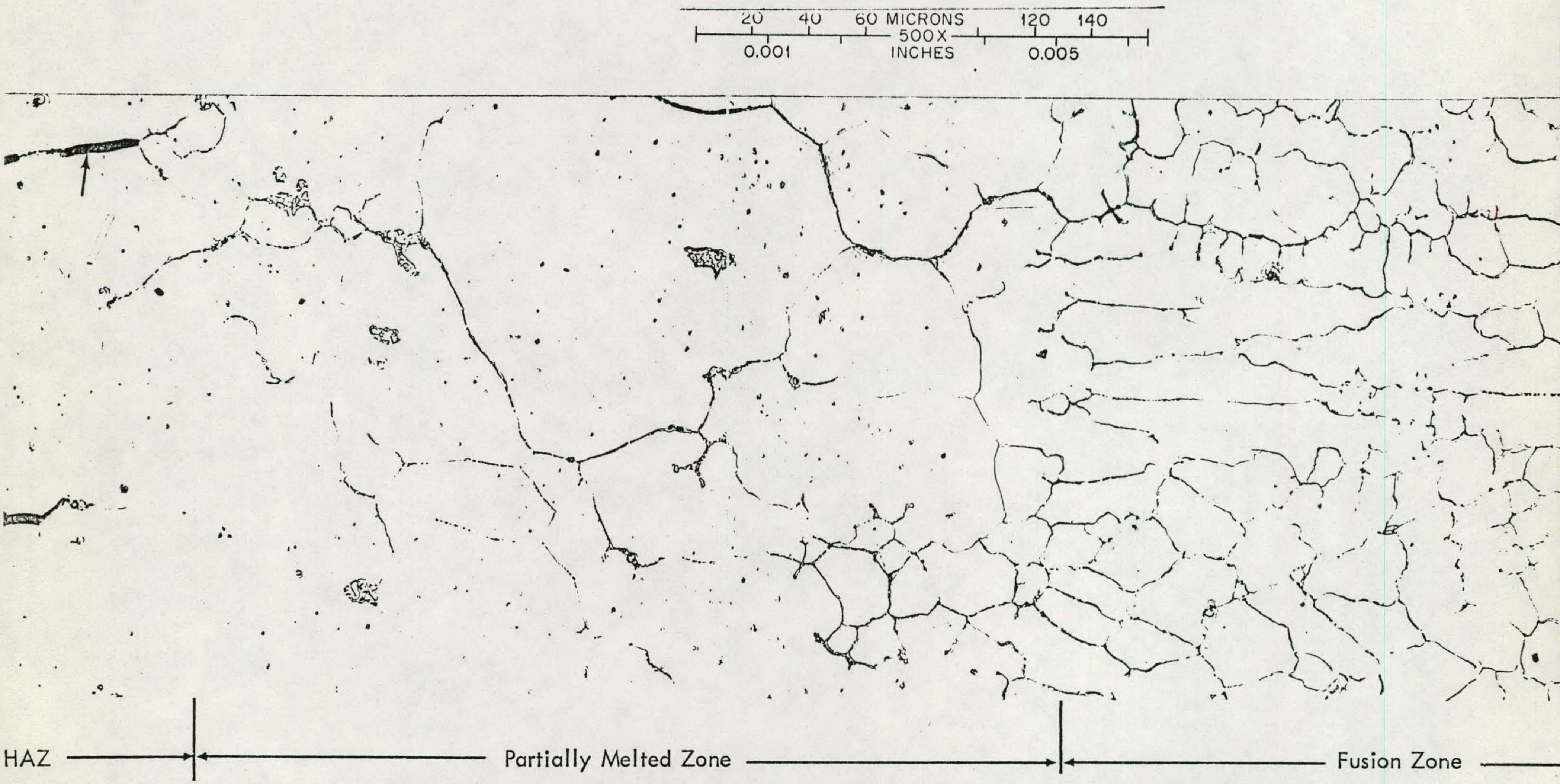

Fig. 8. Spot-Varestraint Weldment in Commercial Type 347 Stainless Steel Showing the Extensive Partially Melted Zone Backfilling of Heat-Affected Zone Cracks (Arrows) by Molten Metal from the Arc Spot. Etchant: 50 HCl–10 HNO_3.

15. C. D. Lundin, University of Tennessee, Knoxville, Tennessee, private communication, November 10, 1977.

16. P. P. Puzak, W. R. Apblett and W. S. Pellini, "Hot Cracking of Stainless Steel Weldments," *Weld. J. (Miami)*, 35(1): 9-s–17-s (January 1956).

CONCLUSIONS

From our study of the effect of niobium additions on the welding behavior of some austenitic stainless steels we draw the following conclusions.

1. The compound Spot Varestraint specimen allows us to evaluate the welding behavior of small quantities of wrought base metals.
2. The fusion-zone cracking behavior of the type 304 stainless steel with niobium additions up to 1000 ppm was similar to that of commercial type 304 stainless steel — as no fissures were detected in either material in this study — and was greatly superior to that of a commercial heat of type 347 stainless steel.
3. The presence of delta ferrite in the weld nugget minimizes fusion-zone cracking in the commercial and experimental type 304 stainless steels.
4. The HAZ cracking of experimental heats of type 304 stainless steel with niobium additions up to 1000 ppm was similar to that of commercial type 304 stainless steel but was much less than that of commercial type 347 stainless steel.
5. Fewer cracks were observed in the weld HAZ in the type 304 stainless steel materials because some grain boundary separations were "backfilled" with molten metal from the fusion zone. On the other hand there was a wide partially melted zone in the type 347 stainless steel weldments which apparently prevented backfilling of HAZ cracks.

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