Some Observations on the Stress Rupture Ductility of Welds

Particular features of the weld structure are found to be important contributors to the occurrence of low stress rupture ductility

BY N. KENYON

ABSTRACT. The stress-rupture ductilities of welds are frequently much less than those of wrought plates of similar composition. In an examination of the problem, tests were made on electron beam, gas tungsten-arc, and gas metal-arc welds and the ductilities of the welds compared with those of castings and wrought plate. Weld elongations are shown to vary with the welding conditions. The results are analyzed with reference to what is known about the initiation and propagation of creep cracks. Important structural features that have been found to contribute to low weld elongations are the nature of the solidification substructure and the shape and unusual stability of the grains.

Introduction

A proper balance between creep resistance and the creep extension that occurs before fracture is an important characteristic of many engineering alloys. Welding upsets this balance and the creep rupture ductilities of welds are frequently much less than those of wrought plates of similar composition. Weld elongations of less than 5% occur in a variety of alloys; they have been seen, for example, in stainless steels, high temperature iron-base alloys, nickel-base alloys, and to some extent in low alloy steels.[1]

There are, however, few documented instances where failure has been attributed to the low creep rupture ductility of a weldment.[2] It appears that designers are aware of the lack of ductility, and either place the joint away from the region of maximum temperature and stress, or they strengthen the weld by thickening it and using a filler metal composition that is stronger than the plate. Nevertheless the concern over low weld rupture ductility persists.[3-6] Evidence that the low ductilities are probably associated with the various forms of reheat cracking has given added impetus for research studies.

In the work reported here, we have examined the influence of structure on the creep rupture ductility of weld metal. Structural features that have been found to contribute to the low elongations are outlined.

Experimental Procedure

Materials

Hot rolled annealed sheet ($^1/_8$ in.) and plate ($^1/_2$ in.) of a Ni-Cr-Fe alloy were used for this study. Many of the welds were made with filler metal of the same composition as the base metals so that plate and welds with identical compositions could be compared. For sheet welds, strip cut from the sheet was used as a filler metal. Similarly, the filler metal used to make welds in $^1/_2$ in. plate was drawn from pieces of the base material. Additional welds were made with a filler metal composition slightly different from that of the plate. The compositions of the materials are listed in Table 1.

Welding

Sheet Welds. Sheet welds were tested because they can be completed in one pass and the complicating effects of weld reheats can therefore be avoided. Welds were made with the electron beam and gas tungsten-arc processes. Details are given in Table 2. Matching composition filler metal was used for the gas tungsten-arc welds; the electron beam welds were made without filler metal.

Plate Welds. Half-inch thick welds were made so that all-weld-metal specimens could be machined from them. Gas tungsten-arc welds were made with both filler metals A and B and gas metal-arc welds with filler metal B only. Details of the welding conditions are given in Table 3.

Examination and Testing of Welds

All the welds were checked by X-radiography and some were also examined metallographically. Transverse and longitudinal specimens were machined from the sheet welds, and all-

Table 1—Compositions of the Materials Tested

Material	C	Mn	Fe	S	Si	Cu	Ni	Cr	Al	Ti	Mg	Co	B
Sheet	.03	.13	7.0	.007	.32	.06	77.1	15.3	.04	.20	.01	.05	.003
Plate	.02	.19	7.12	.007	.32	.10	76.1	16.1	.15	.20	.03	.09	.003
Filler metal A[a]	.02	.19	7.12	.007	.32	.10	76.1	16.1	.15	.20	.03	.09	.004
Filler metal B	.02	.10	7.5	.005	.01	.03	74.0	16.0		(2.25Cb)			
Cast bars	.02	.11	6.6	.001	.13	.07	Bal.	15.9	.20	.32	.03	.06	.009

[a] Filler metal A made from pieces of the plate.

Table 2—Conditions Used To Make Electron Beam and Gas Tungsten-Arc Welds in ⅛ in. Sheet

Process	Joint design	V	Amp	Travel speed, ipm	Filler metal	Shielding
Electron beam	Square butt	130 kv	9 ma	30	None	Vacuum
Gas tungsten-arc	Square butt	10 v	260 a	8	Matching—fed manually	Argon

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Table 3—Conditions[a] Used To Make Gas Tungsten-Arc and Gas Metal-Arc Welds in ½ in. Plate

Process	Voltage, v	Current, amp	Travel speed	Filler metal feed, ipm	Filler metal	Shielding
Gas tungsten-arc	10	230	Various	20	A-B	35 cfh argon
Gas metal-arc	30	300	12 ipm	200	B	50 cfh argon

[a] See joint design below:

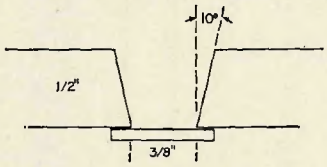

Table 4—A Comparison of the Rupture Ductilities of Wrought Plate and Gas Tungsten-Arc Weld of the Same Composition

Sample	Temp., ° F	Stress, ksi	Life, hr	Total elong., %
Plate	1200	25	74	66
Gas tungsten-arc weld	1200	25	43	11
Plate	1400	12	87	68
Gas tungsten-arc weld	1400	12	67	3
Plate	1600	5.3	92	62
Gas tungsten-arc weld	1600	5.3	56	1
Plate	1800	2.8	54	27
Gas tungsten-arc weld	1800	2.8	28	1.5

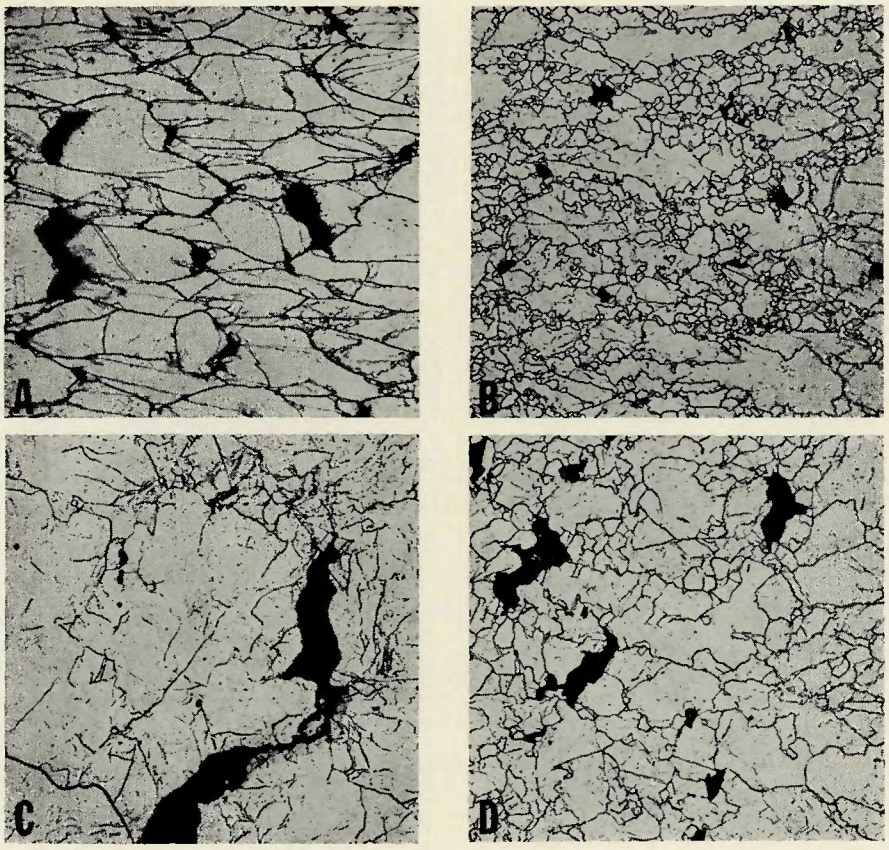

Fig. 2—The microstructures of the wrought plate after testing at: A—1200° F; B—1400° F; C—1600° F; D—1800° F. ×250 (reduced 28% on reproduction)

weld-metal, longitudinal specimens from the $^1/_2$ in. welds. Most samples were X-rayed before testing to confirm that they were crack-free.

Stress rupture tests were made at temperatures in the range 1200–1800° F, and at stresses selected to cause failure in approximately 100 hrs.

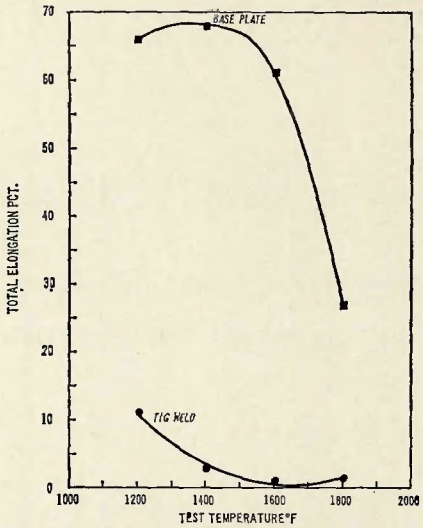

Fig. 1—Stress rupture ductilities of plate and gas tungsten-arc weld tested at same temperatures and stresses

Results

Comparison of Plates and Welds

The stress rupture properties of all-weld-metal specimens from gas tungsten-arc welds were compared with those base metal specimens of the same composition. The testing conditions and the results are given in Table 4. At the same stress and temperature, the welds exhibited much lower ductilities, and at 1400° F and above, weld elongations were below 5% (Fig. 1).

Metallographic examination of the broken specimens showed that the base metal had started to recrystallize when tested at 1400° F and that grain growth had occurred at the higher temperatures (Fig. 2). In the welds, on the other hand, there was no evidence of grain boundary movement until 1800° F, at which temperature there was a slight re-arrangement of the structure (Fig. 3). The weld structure appeared to be very stable, with pinned or immobile boundaries. The creep curves for plate and welds emphasize the difference in behavior and clearly illustrate the very low weld creep rates that lead to low ductility failures (Fig. 4).

The behavior of longitudinal samples from a gas tungsten-arc sheet weld illustrates the difference between weld and plate. These samples were machined along the length of the weld such that the gauge length contained parallel regions of weld, heat-affected zone, and base metal. One specimen was tested to failure, one to half, and one to three-quarters of the failure life. No cracks were seen in any portion of the gage length after exposure

for half the expected life (0.8% elongation). But at three-quarters of the life (1.3% elongation) it was noticeable that, although the sheet and heat-affected zone were crack-free, the weld portion contained grain boundary cracks (Fig. 5).

Effect of Heat Input on Weld Ductility

Since weld structure can be controlled to some extent by changing the welding parameters it was logical to see if a structure with better ductility could be produced in this way. Gas tungsten-arc welds were made in $^1/_2$ in. plate with matching composition wire and at three heat inputs obtained by varying the travel speed. Weld microstructures are shown in Fig. 6 and the ductilities of all-weld-metal specimens are in Table 5. At the highest heat input tested the ductility was increased; i.e., the weld made at 2 ipm had the best ductility.

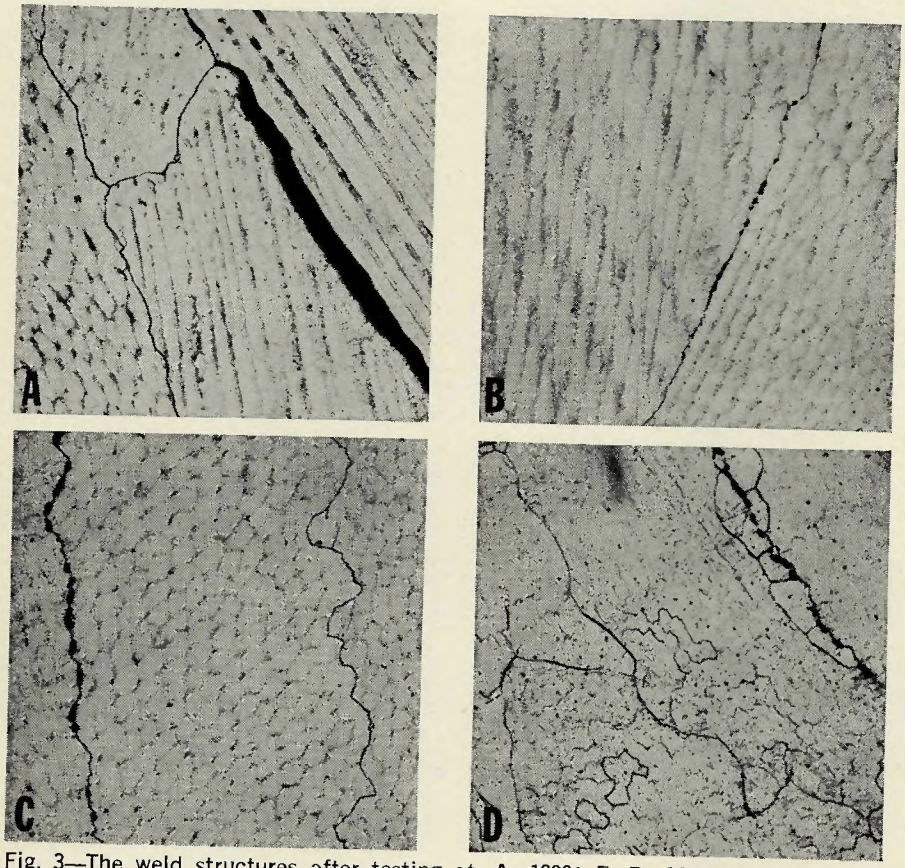

Fig. 3—The weld structures after testing at: A—1200° F; B—1400° F; C—1600° F; D—1800° F. ×250 (reduced 28% on reproduction)

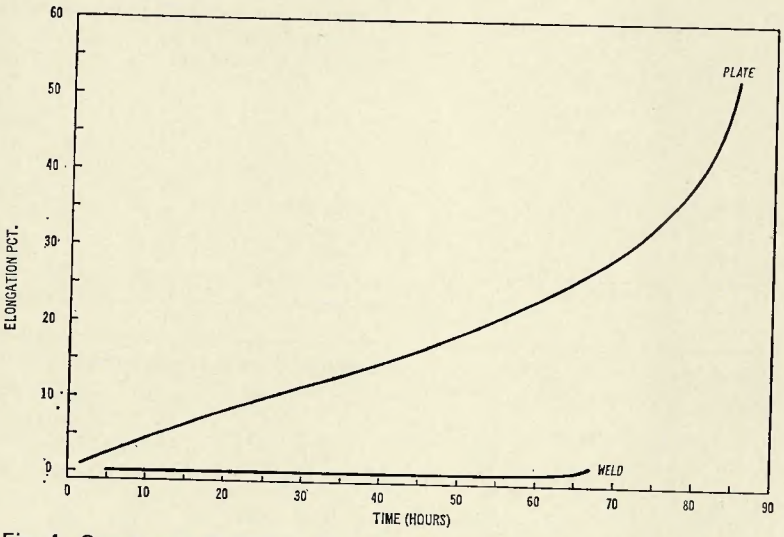

Fig. 4—Creep rate of plate and gas tungsten-arc weld tested at 1400° F and 12,000 psi

A Comparison of Gas Tungsten-Arc vs. Gas Metal-Arc Welds

Another way to vary structure in order to assess its influence on rupture ductility is to make welds with different processes and compare their behavior. The ductilities of gas metal-arc and gas tungsten-arc welds made with filler metal B are compared briefly in Table 6. At the same stress and temperature, the gas metal-arc weld had a shorter life and greater ductility. This is another indication of improved ductility being associated with a coarser structure made with higher heat input.

Gas Tungsten-Arc vs. Electron Beam

Stress rupture ductility is sensitive to purity; air-melted material, for example, has been shown to have less rupture ductility than vacuum-melted material of the same composition.[7] To see if the ductility of welds was similarly influenced by purity, electron beam sheet welds were made in vacuum and gas tungsten-arc welds with argon shielding gas.

Transverse specimens from these welds were tested at 1200° F and the ductilities were measured on a short gauge length so that only weld elonga-

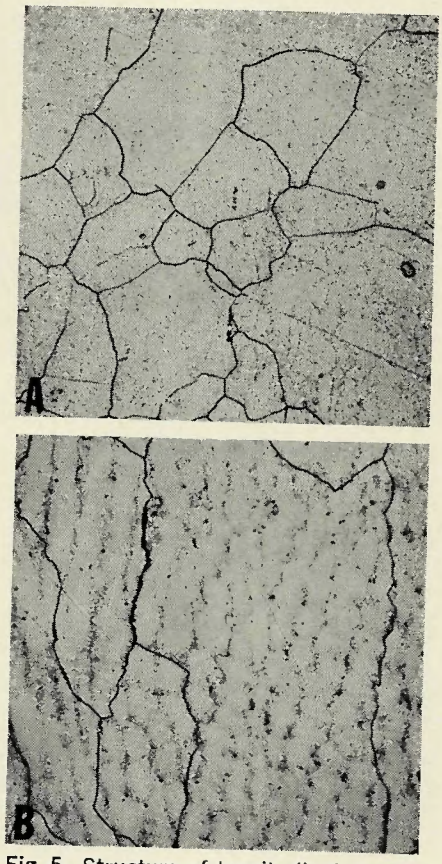

Fig. 5—Structure of longitudinal sample from sheet weldment after exposure at 1400° F. A—sheet after three-quarters of expected life; B—weld after three-quarters of expected life. ×250 (reduced 28% on reproduction)

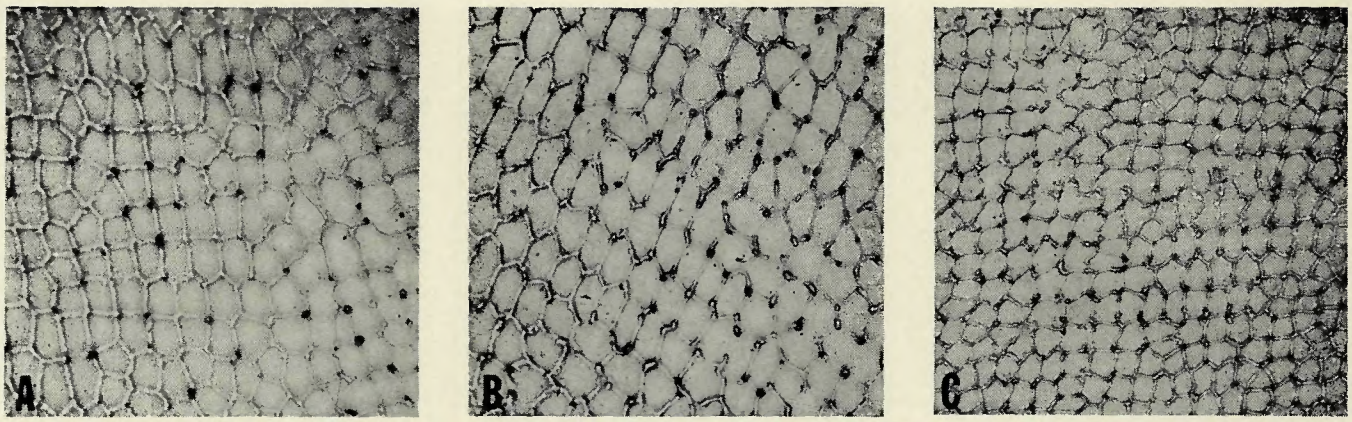

Fig. 6—The structures of welds made at heat inputs of: A—69,000 joules/in.; B—34,500 joules/in.; C—23,000 joules/in. ×250 (reduced 28% on reproduction,

tions were recorded. As Table 7 shows, there was little difference between the ductilities of gas tungsten-arc and electron beam welds and both were considerably less than that of the unwelded sheet.

The Stress Rupture Ductility of Castings

An obivious question that comes to mind when considering the poor ductility of welds is whether low ductility is characteristic of all cast structures. To explore this point, we made an air-melted heat of the Ni-Cr-Fe alloy and poured cast-to-size rupture bars and 1 in. diameter chill bars from which rupture specimens were machined.

The results (Table 8) show that while the castings had lower ductility than the wrought plate, their values are considerably higher than those of welds. Machined bars and cast-to-size specimens had similar properties. The microstructures of the castings are shown in Fig. 7.

Cast structures obviously can exhibit relatively high ductilities. An increase in the weld ductilities to the level of the cast bars would represent a substantial improvement.

Discussion

It is clear from the results that relatively large cracks (of the order of .005 in.) can form in welds at strains that are too low to produce such cracking in base metal. It is instructive, therefore, to compare the structures of welds and plates with reference to what is known about the initiation and propagation of creep cracks, and to see if there are structural differences that could account for the difference in behavior.

Crack Initiation

The start of cracking in the welds is the formation of cavities along the grain boundaries. For cavities to form, it has been shown that grain boundary sliding must occur.[8] The cavities form at jogs or corrugations in the boundaries as a result of the stress concentrations set up there when grain boundary sliding takes place[9, 10]. When testing wrought plate, the corrugations occur gradually along a grain boundary and appear to have a spacing equivalent to either the slip spacing or to the sub-grain size.[11] In welds, however, the grain boundaries are jogged in the as-welded condition, even before testing (Fig. 8). Cavity formation can, therefore, be expected at the jogs as soon as sliding begins, and this can be expected to contribute towards early failure.

Figure 9 provides evidence that cavities form in welds at the intersection of the cell and grain boundaries. (Movchan's polygonization theory of hot cracking[12] makes use of a similar observation, which suggests that the

Table 5—Effect of Heat Input of Weld Ductility

Welding conditions				Exposure conditions		Stress-rupture properties		
V	Amp	Travel speed, ipm	Heat input joules/in.	Temp., °F	Stress, ksi	Life, hr	Total Elong., %	% R.A.
10	230	2	69,000	1200	25	41	13	32
10	230	4	34,500	1200	25	37	11	13
10	230	6	23,000	1200	25	29	10	14
10	230	2	69,000	1400	12	45	[a]	19
10	230	4	34,500	1400	12	45	Nil	Nil
10	230	6	23,000	1400	12	48	[a]	5.3

[a] Could not be measured with accuracy.

Table 6—A Comparison of the Stress-Rupture Ductilities of Gas Metal-Arc and Gas Tungsten-Arc Welds Made With Filler Metal B

Sample	Temp., °F	Stress, ksi	Life, hr	Total elong., %	% R.A.
Gas metal-arc weld	1200	25	1133	19	25
Gas tungsten-arc weld	1200	25	1920	1.5	0.7
Gas metal-arc weld	1400	16	104	10	24
Gas tungsten-arc weld	1400	16	581	2	3.1

Table 7—The Stress-Rupture Ductilities of Sheet Welds Tested at 1200° F and 25,000 psi

Sample	Life, hr	% R.A.	Total elong. in ⅜ in.,%
Unwelded sheet	95	55	60
Gas tungsten-arc weld	55	13	13
Electron beam weld	50	7	14

Table 8—Stress-Rupture Properties of Cast Bars

Temp., °F	Stress, ksi	Life, hr	Total elong., %	% R.A.
1200	25	50	33	40
1400	12	32	42	33
1600	5.3	56	36	35

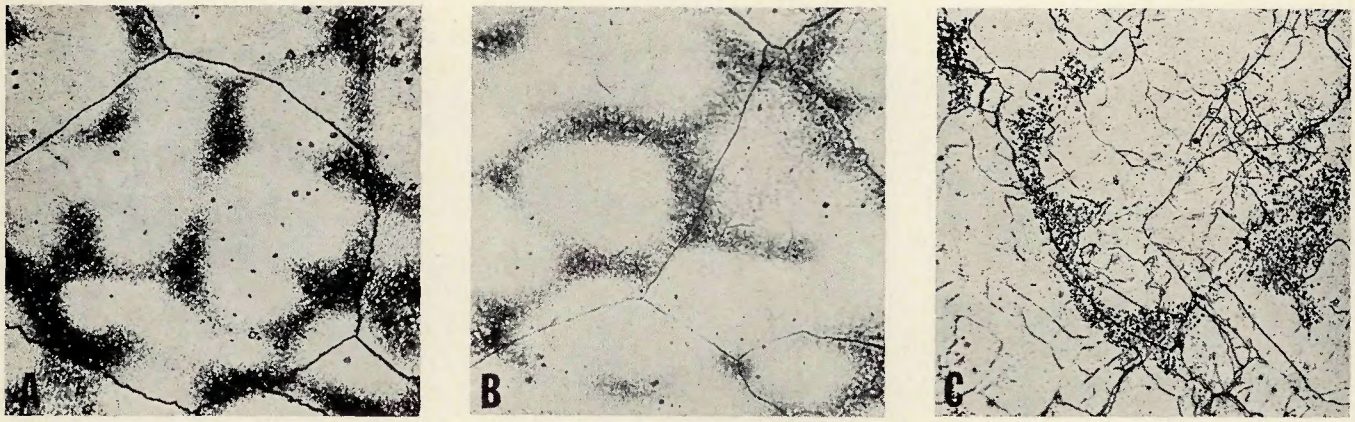

Fig. 7—The structures of cast bars after testing at: A—1200° F; B—1400° F; C—1600° F. ×250 (reduced 28% on reproduction)

cracking observed was of the ductility dip type.[3]) The solidification cell boundaries appear to be low angle boundaries,[13] and the jogs in the grain boundaries seem to coincide with the cell boundary intersections. These intersections will also be chemically different since the cell boundaries and sometimes the grain boundaries are regions of segregation, and are known to contain impurities. Impurities lower the cohesion of the boundary and thereby encourage cracking. McLean, for example, in an examination of several alloys, found cracks to be more frequent in bands of segregation.[14] Regions of segregation are also more likely to contain precipitates or inclusions and these will either crack or voids will form around them when grain boundary sliding occurs. Figure 10 shows an example.

Thus grain boundaries in welds contain regions where a stress concentration occurs in a zone of lowered cohesion and these regions are where the cavities form. Linking of these cavities will produce the grain boundary crack that can lead to failure, and it follows that the wider apart the cavities are, the more difficult will the linking be. Hence a larger cell size should make linking of the cavities more difficult and thereby lead to an improvement in ductility. This would account for the better ductilities seen in welds made with higher heat inputs because one result of increasing the heat input by lowering the travel speed is an increase in the cell size[15] (Fig. 11). Table 9 confirms this. The same reasoning might also explain the better ductilities seen in gas metal-arc as opposed to gas tungsten-arc welds.

Another feature of the welds observed during the stress rupture testing is the lack of grain boundary mobility. The weld grain boundaries appear to be pinned and show little tendency to migrate. This is important because migration of the boundaries is a primary method of reducing the stress concentrations set up when grain boundary sliding occurs.[16] Grant[17] has listed materials in order of decreasing ductility as their tendency to show migration decreases.

In the welds, therefore, there are ready-made jogs that coincide with regions of impurity segregation on a boundary that shows little tendency to migrate. This combination could be said to be ideal for cracking at low strains.

Crack Growth

There is still some controversy over the mechanism of cavity growth, the argument being principally whether growth is by continued grain boundary sliding or by the condensation of vacancies.[18] The vacancy condensation could be important in welds because structures, like weldments, that are quenched from high temperatures are usually thought to have high supersaturation of vancancies. This would be conducive to cavity growth.[8]

Once long cracks start to propagate down the boundaries, the obstacles to their growth are the grain boundary junctions or triple-points.[19, 20] Crack linkage across these obstacles involves plastic deformation and corresponding increases in ductility. Thus the more triple junctions there are, or the finer the grain size, the greater should be the ductility. Cocks and Taplin[20] have demonstrated this with copper. The ductility decreased as the grain diameter increased from 60 to 300 microns. Above this size there was little change in ductility because at the larger grain sizes few interlinkages were needed before the crack reached the critical size. In welds, the size and, perhaps

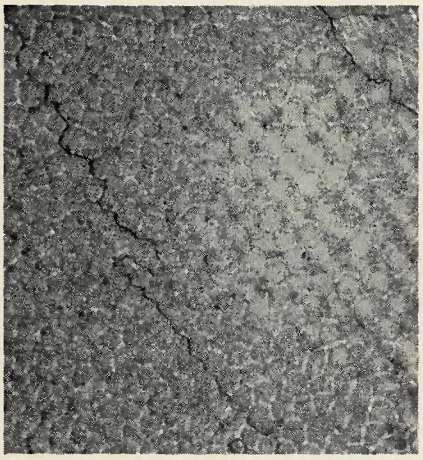

Fig. 8—Structure of a gas tungsten-arc weld showing jogged grain boundary

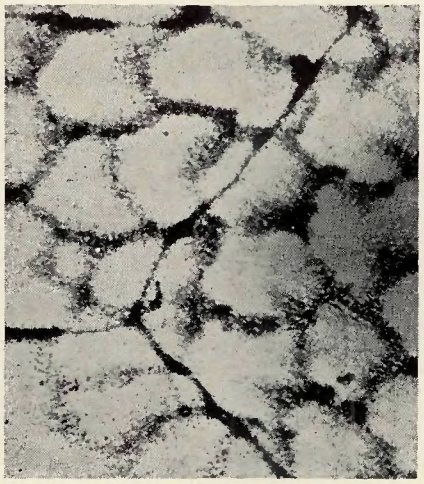

Fig. 9—Cavities forming at intersections of cell and grain boundaries

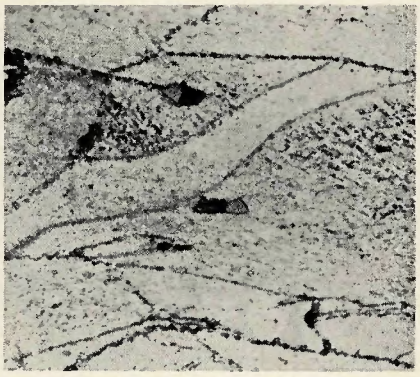

Fig. 10—Voids forming adjacent to inclusions

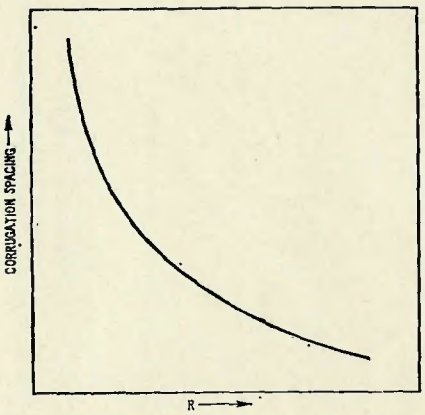

Fig. 11—Schematic of variation of corrugation spacing with growth rate (after Rutter and Chalmers). Decreasing travel speed causes a decrease in R and therefore an increase in corrugation spacing

more important, the shape of the grains are such that very long cracks can form along the boundaries of the columnar grains and can reach a critical size before ever encountering a triple junction (Fig. 12). These long grain facets are very evident on the fracture surfaces (Fig. 13).

Other Considerations

Other features, which have not been studied here, are known to affect stress rupture ductility. The nature of the grain boundary carbide, for example, is important,[21] and carbide morphology depends on the degree of supersaturation and therefore on cooling rate. Fast rates produce a cellular form which is detrimental to ductility.[22]

Another factor which is likely to be important also concerns carbide precipitation, in this case that which occurs within the grains during the stress rupture testing. This intragranular precipitation strengthens the grains in relation to grain boundaries and thereby concentrates the deformation within the boundaries and hinders the intragranular slip which can relieve stress concentrations. This kind of dynamic strain hardening was shown to be responsible for high temperature brittle failures of AISI 347 stainless steel weldments. The heat of welding took the CbC into solution and then during service at elevated temperature, strain induced precipitation of the carbide occurred within the grains.[23] We have a small amount of evidence that a similar mechanism

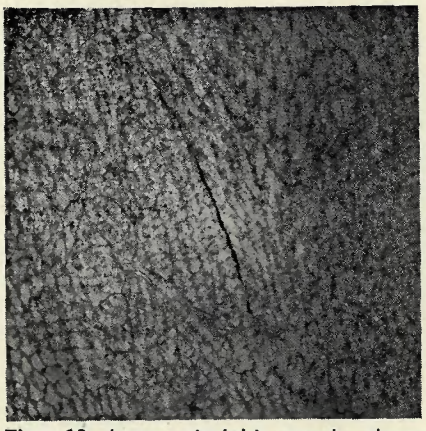

Fig. 12—Long straight crack down boundary of a single grain

might be active in the Ni-Cr-Fe alloy. Tensile tests at 1400° F on sheet welds revealed pronounced serrated yielding which was not evident when the unwelded sheet was tested. Serrated yielding has been attributed to carbide precipitation occurring during testing.[24]

Conclusions

The following features have been outlined as important contributors to the occurrence of low stress rupture ductility in welds:

1. Grain boundary jogs coincide with regions of segregation at the intersections of the cell and grain boundaries and consequently cavities form readily because stress concentrations occur in regions of low cohesion.
2. The weld grain boundaries are pinned and grain boundary migration cannot operate to relax the stress concentrations set up by grain boundary sliding.
3. The long columnar grain boundaries in the welds permit long cracks to form without encountering the grain junctions that normally act as obstacles to crack growth.
4. There is no evidence that the low ductilities of welds are caused by a lack of purity or cleanliness in the weld structure.

Table 9—Cell Size As a Function of Heat Input

Heat input, joules/in.	Cell size, microns
69,000	20.7
34,500	19.7
23,000	18.4

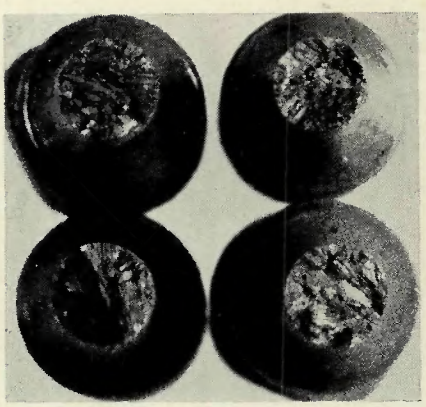

Fig. 13—Fracture surfaces of gas tungsten-arc welds after stress rupture testing

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