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EXAMINATION OF TWO BROKEN ICEBREAKER STUB PROPELLER BLADES

by

D. E. PARSONS

PHYSICAL METALLURGY DIVISION

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SUMMARY OF RESULTS

Examination of two broken propeller stubs cast in nickel-vanadium steel showed that both castings were embrittled by the presence of intergranular constituents. "Hairline" cracks were present in locations where they could act as stress-raisers in one of the castings. The cracks were identified as "hot-cracks" and had formed subsequent to precipitation of the intergranular phase. The crack surfaces were coated with a thin film of high temperature oxide but were not decarburized.

The steel conformed to the chemical composition specified for propellers at the time these units were cast (original blades for CCGS John A. MacDonald). The aluminum and zirconium contents were 0.08% and 0.05% respectively. The distribution of the pearlite tended to be heterogeneous with this phase present as networks outlining the ferrite grains of both castings.

The results of tensile and Charpy V-notch impact tests indicated that both castings were relatively brittle at all temperatures of testing.

Restriction of the residual aluminum content was recommended for large castings of this type used in the normalized and tempered condition.

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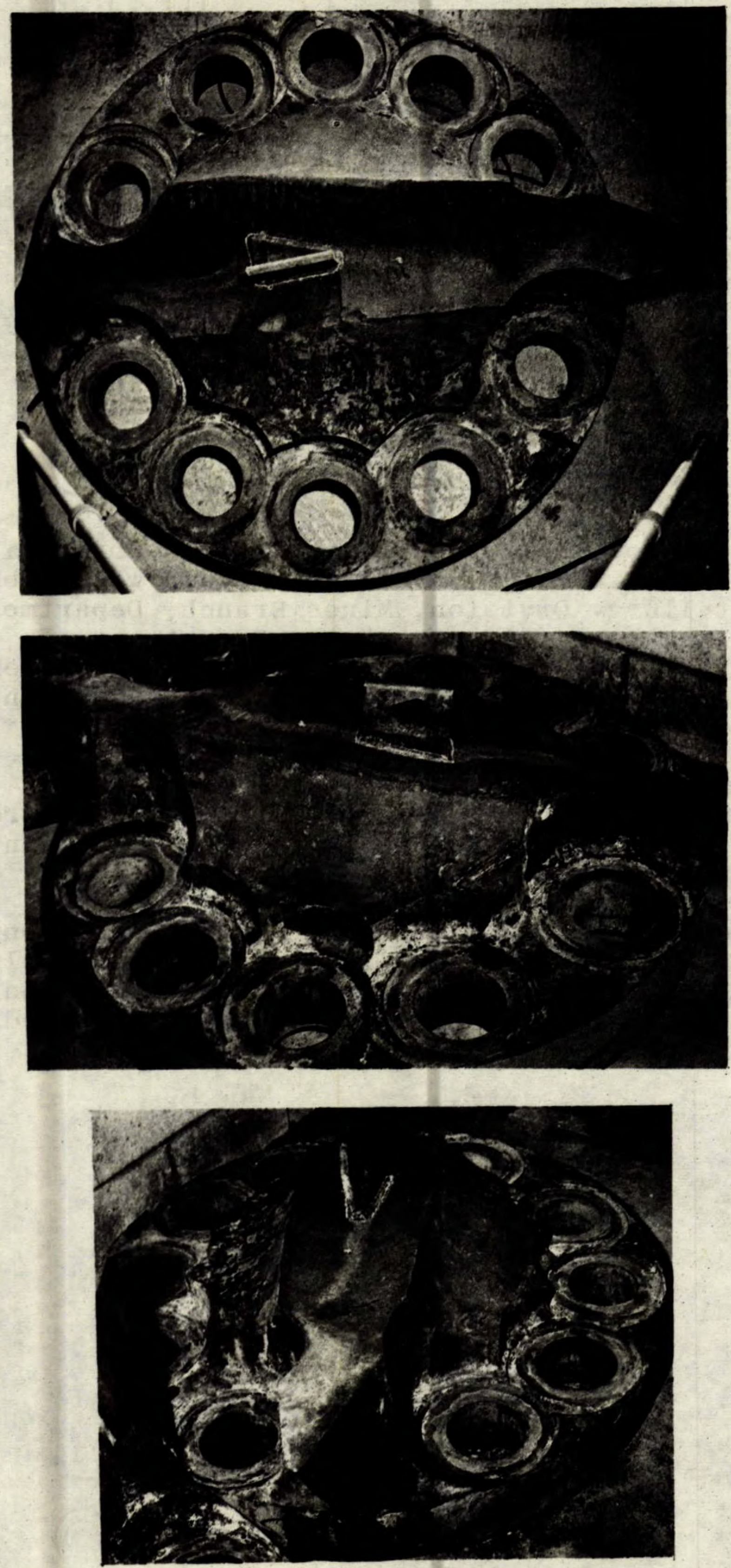
*Senior Scientific Officer, Ferrous Metals Section, Physical Metallurgy Division, Mines Branch, Department of Mines and Technical Surveys, Ottawa, Canada.

INTRODUCTION

Two broken propeller stub blades from the original equipment of the icebreaker CCGS John A. MacDonald were submitted to the Physical Metallurgy Division, Mines Branch, Department of Mines and Technical Surveys, Ottawa, by the Department of Transport, Shipbuilding Branch, Ottawa, for metallurgical examination. It was hoped that this examination would assist in judging whether these service failures were related to the material specified or to the manufacturing procedure.

The appearance of the broken stubs "S" and "R" are illustrated in Figures 1 and 2, respectively. The blade in each instance was lost and was not available for examination.

Both fractures showed little, if any, deformation and would be classed as "brittle-failures". Stub "S" had a relatively smooth fracture, whereas stub "R" was rougher and contained areas of coarse-grained, intergranular fracture commonly referred to as "rock-candy" fracture.

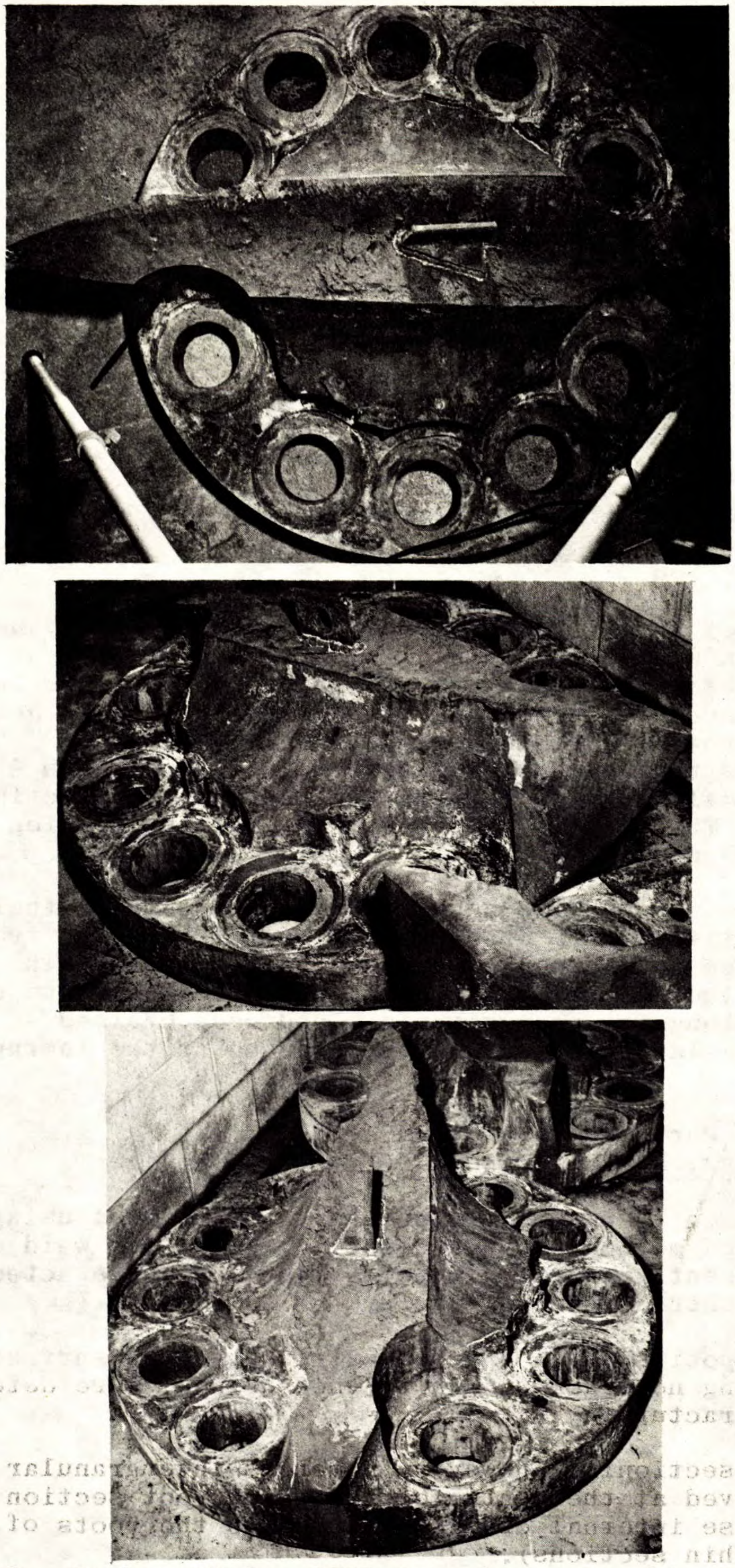


(a)

(b)

(c)

Figure 1. **Broken Blade, CCGS John A. MacDonald, Sample "S" (3 views). The fracture is brittle and shows no evidence of plastic deformation.**



(a)

(b)

(c)

Figure 2. <u>Broken Blade, CCGS John A. MacDonald, Sample "R" (3 views)</u>. The fracture is brittle and shows little evidence of plastic deformation. The fracture surface is more irregular than that illustrated in Figure 1.

PROCEDURE

Examination of the two stubs was made as follows:-

(1) Visual Inspection
(2) Magnetic Particle Inspection
(3) Sectioning and Re-inspection
(4) Chemical Analyses
(5) Tensile and Impact Results
(6) Deep Etch Tests
(7) Metallographic Examination.

(1) Visual Inspection

The fracture surfaces were cleaned and de-rusted using $HCl:SbCl_3$ solution and were examined for evidence of fatigue. No beachmarks were observed. However, the fractures were distinctive in having smooth areas on the concave side at the reduced section of each blade (arrows Figure 1a, Figure 2a). It was not determined whether these smooth areas were fatigue origins - or were due only to the smaller grain size present at the thin sections of the castings. The absence of beachmarks made the section effect appear more probable.

Fracture appeared to have occurred suddenly, rather than over a period of time with propagation in brittle fashion from the concave surface to the convex surface and from the thin sections towards the centre of the thick root-section. The edge of the fracture along the convex surface had been bruised - possibly when the blade separated from the stub at the instant of rupture.

(2),(3) Magnetic Particle Inspection, Sectioning, Re-inspection

The broken stubs were inspected (as-received) using the dry powder and prod method in an attempt to detect any weld crack or hot tear, adjacent to the fracture, which might have acted as a stress-raiser contributing to fracture.

Weld deposits were observed at the fracture surface but, prior to sectioning no cracks, open to the surface, were detected adjacent to the fracture.

(After sectioning, however, numerous intergranular cracks were observed at the centre of the thick root section and in some areas these internal cracks extended to the roots of weld deposits in the thin sections).

The blades were sectioned, as shown in Figure 3, to obtain transverse sections through the thick and thin parts of each stub. These slices were subsequently inspected by magnetic particle and deep-etch methods. Chemical analyses were made on metal from thin and thick sections from each casting. A $1\frac{1}{2}$ in. slice from each section was surface-ground and was deep-etched for 20 min in 1:1 HCl: water at 71 to 83°C (160-180°F). The remainder of each block was used to provide 0.505 in. diameter tensile and Charpy V-notch bars for determination of the tensile properties in the thin and thick sections and for determination of the Charpy V-notch impact transition temperatures.

Selection of sound bars for mechanical testing was only possible after inspection of individual bars by the fluorescent wet magnetic particle method and elimination of test bars containing hairline cracks. (Radiographic inspection did not detect the presence of these tight cracks in the 0.505 in. diameter test bars).

The location and identity of the test specimens is shown in Figure 3. Test bars from similar locations in each casting were given the same code number prefixed by the letters "S" or "R".

The code numbers for tensile bars are shown in Table 1. The code numbers for Charpy V-notch impact bars and the test temperatures are listed in Table 2.

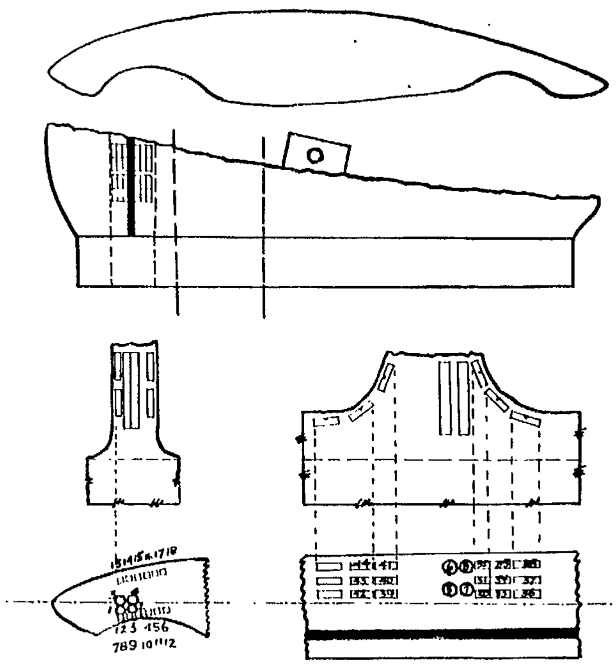


Figure 3. Sectioning procedure, location and identification of test bars.

TABLE 1

Identification of Tensile Bars With Respect to Casting and Section

Casting "S"		Casting "R"	
Bar No.	Location	Bar No.	Location
S-1	Thin Section	R-1	Thin Section
S-2	" "	R-2	" "
S-3	" "	R-3	" "
S-4	" "	R-4	" "
S-5	Thick Section	R-5	Thick Section
S-6	" "	* R-6	" "
S-7	" "	* R-7	" "
S-8	" "	* R-8	" "

TABLE 2

Identification and Test Temperature, For Charpy V-Notch Impact Bars

Test Temp. °F	Casting "S"		Casting "R"	
	Thin Section	Thick Section	Thin Section	Thick Section
-40	S-7, 20, 21	No Bars	R-6, 14, 18	No Bars
0	S-6, 18, 19	S-30, 38, 45	R-1, 10, 24	R-34, 39, 40
30	S-5, 8, 17	S-31, 37, 43	R-5, 13, 19	R-33, 35, 41
40	S-4, 9, 16	S-32, 39, 42	R-4, 12, 20	R-32, 36, 42
75	S-3, 12, 15	S-34, 40, 41	R-8, 11, 22	R-31, 38, 43
200	S-2, 11, 14	S-33, 35*, 36*	R-2, 9, 23	R-30, 37, 45

*Radiographed and rejected for mechanical test purposes.

(4) Chemical Analyses

The results of chemical analyses made on metal milled from sections across the thin and thick sections of each casting are shown in Table 3.

TABLE 3

Chemical Composition (Per Cent)

Element	Casting "R"		Casting "S"	
	Thick Section	Thin Section	Thick Section	Thin Section
Carbon	0.18	0.16	0.21	0.21
Manganese	0.84	0.84	0.80	0.80
*Silicon	0.84	0.84	0.91	0.90
Sulphur	0.019	0.019	0.037	0.033
Phosphorus	0.015	0.015	0.027	0.029
Nickel	1.68	1.70	1.80	1.80
Vanadium	0.14	0.13	0.13	0.13
Aluminum	0.08	0.08	0.07	0.08
Nitrogen	0.009	0.009	0.009	0.009
Titanium	N.D.	N.D.	N.D.	N.D.
Zirconium	0.04	0.04	0.05	0.05

*Revised specification restricts silicon content to 0.50% maximum.

The D.O.T. specification at the time these blades were cast required carbon 0.20% maximum, nickel 1.5% minimum, and vanadium 0.10 to 0.12%, subject to check analysis limits. These castings conformed to the chemical requirements of this specification* for cast steel icebreaker propeller blades.

No major variation in chemical composition was observed in comparison of thick and thin sections.

(5) Tensile and Impact Results

Eight 0.505 in tensile bars were cut from each casting. Four bars were taken from each of the thin sections and thick sections. Tensile results from these bars are listed in Table 4.

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*The specification has subsequently been revised (1963).

The carbon, silicon, aluminum and zirconium contents of these original blades were higher than those of later replacement blades (Mines Branch Investigation Report IR 62-106, January 3, 1963).

TABLE 4

Tensile Test Results, Castings R and S,
Thin and Thick Sections

Location Te of Tensile Bar	Bar No.	UTS kpsi	Yield Point kpsi	% El. in 2 in.	% RA
			CASTING - "R"		
Thin Section	*R-1	87.0	62.1	14.0	14.8
" "	**R-2	84.4	61.0	9.5	10.0
" "	R-3	86.5	61.3	17.0	21.3
" "	R-4	85.4	61.1	23.0	39.4
Thick Section	**R-5	73.8	55.1	Nil	Nil
" "	@ R-6	——	Hairline Cracks - (Magnetic Particle Test)		——
" "	@ R-7	49.0	49.0	2.0	3.9
" "	@ R-8	——	Hairline Cracks - (Magnetic Particle Test)		——
			CASTING - "S"		
Thin Section	S-1	86.2	61.2	15.0	18.1
" "	S-2	86.2	59.4	13.0	18.2
" "	S-3	85.8	59.0	16.0	19.9
" "	S-4	81.5	59.5	9.0	15.2
Thick Section	S-5	74.8	56.8	6.5	15.1
" "	*S-6	76.2	56.8	-	-
" "	Θ S-7	74.9	57.6	6.0	6.6
" "	Θ S-8	70.8	57.2	5.0	10.7

* - Broke at shoulder.
** - Broke outside elongation mark.
@ - Hairline crack present in test bar.
Θ - Broke outside middle third of gauge length.

Note: Cracks were present in 3 out of 4 of the tensile bars cut from the thick section of casting "R".

The tensile bar fractures showed strong evidence of intergranular, "rock-candy", embrittlement in these room temperature tests. Several bars contained hairline cracks that were only detected after magnetic particle or penetrant inspection. The low tensile-ductility results, the appearance of "rock-candy" facets on tensile bar fracture surfaces, and the presence of tight hairline cracks indicate a lack of ductility at all test temperatures.

The ultimate tensile strength and yield results were approximately 85 kpsi and 60 kpsi respectively in thin sections and were reduced to about 74 kpsi and 56 kpsi respectively in the heavy sections. Considerable scatter in elongation and reduction of area results was observed particularly in tensile bars cut from the thick sections where elongation and reduction in area values of 5 and 15% were typical. Three out of four tensile bars, taken from the heavy section of casting "R", contained hairline cracks. Two of these were not tested, one was tested inadvertently and gave an ultimate tensile result equal to the yield strength. The remaining uncracked bar was broken at 73.8 kpsi UTS and 55.1 kpsi YS, but the elongation and reduction in area were not measurable.

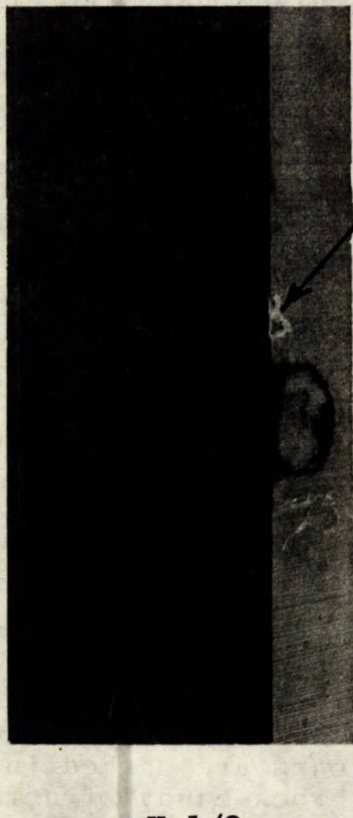
The appearance of a section through the thick part of casting "R" is illustrated in Figure 4 after machining and magnetic particle inspection. Areas containing cracks similar to those detected in the tensile bars are marked in the photograph. In the process of machining, a "rock-candy" fracture occurred at the corner marked by the arrow.

The results of Charpy V-notch tests made at temperatures of 93°C (200°F), 24°C (75°F), 4.4°C (40°F), -1.1°C (30°F), -17.7°C (0°F) using bars machined from the thin, and the thick sections of the two castings are shown in Table 5.

The Charpy V-notch impact strength was significantly lower at sea-water temperatures than at ambient temperature. The values obtained at ambient temperature were relatively low.

The Charpy bars were subjected to magnetic particle inspection prior to testing. Three bars from the thick section (R) were rejected.

The Charpy V-notch bar fractures were flat and contained cleavage facets. Six bars clearly showed intergranular fracture at test temperatures of -18 to 24°C (0 to 75°F).



X 1/2

Figure 4. **Section from Thick Part of Casting R. The edge surface corresponds approximately to the centre axis of the casting at the thickest section. Numerous hairline cracks were detected by wet fluorescent magnetic particle inspection and are circled. The arrow marks an area of rock candy fracture formed during machining.**

TABLE 5

Charpy V-Notch Impact Strength (ft-lb)

Casting "R" & "S" (three results at each temperature)

Test Temperature (°F)	Casting "R"		Casting "S"	
	Thin Section	Thick Section	Thin Section	Thick Section
200	50, 56, 54	38, 28, 29	44, 38, 32	34, 18, 52
75	18, 16, 12	20, 16, 25	15, 10, 8	10, 7, 8
40	10, 9, 8	12, 9, 18	8, 10, 9	10, 8, 10
30	13, 10, 8	9, 10, 10	5, 6, 6	4, 6, 3
0	8, 6, 5	7, 6, 7	2, 3, 2	3, 3, 3

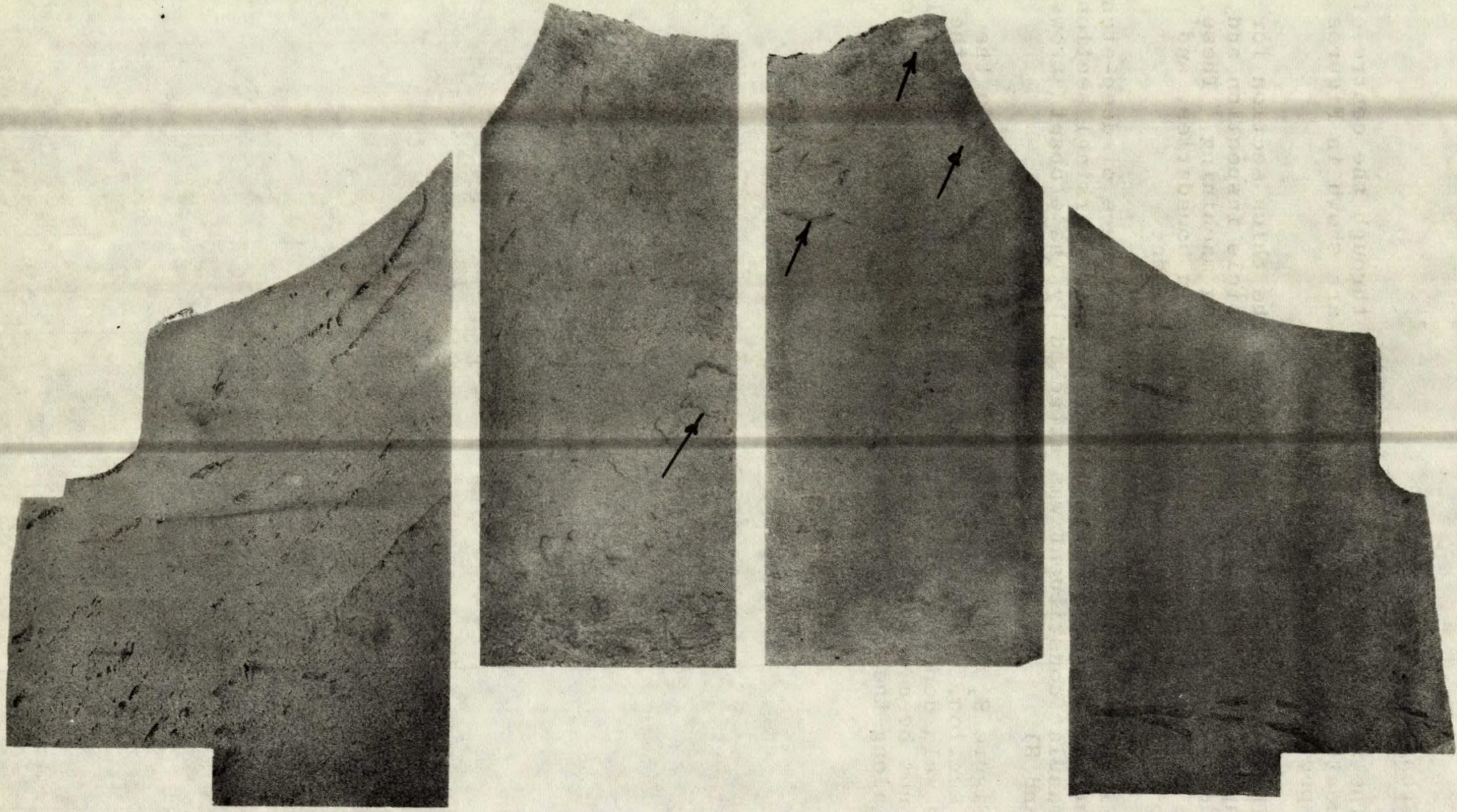
(6) Deep Etch Tests

The appearance of sections taken through the centre of the thick section for castings "R" and "S" are shown in Figures 5 and 6 respectively.

The hairline cracks, visible in the thick section for each casting, were detected by magnetic particle inspection and by the tendency to rock candy fracture during machining. These cracks were present in primary austenite grain boundaries, and appeared to follow the grain boundary constituent.

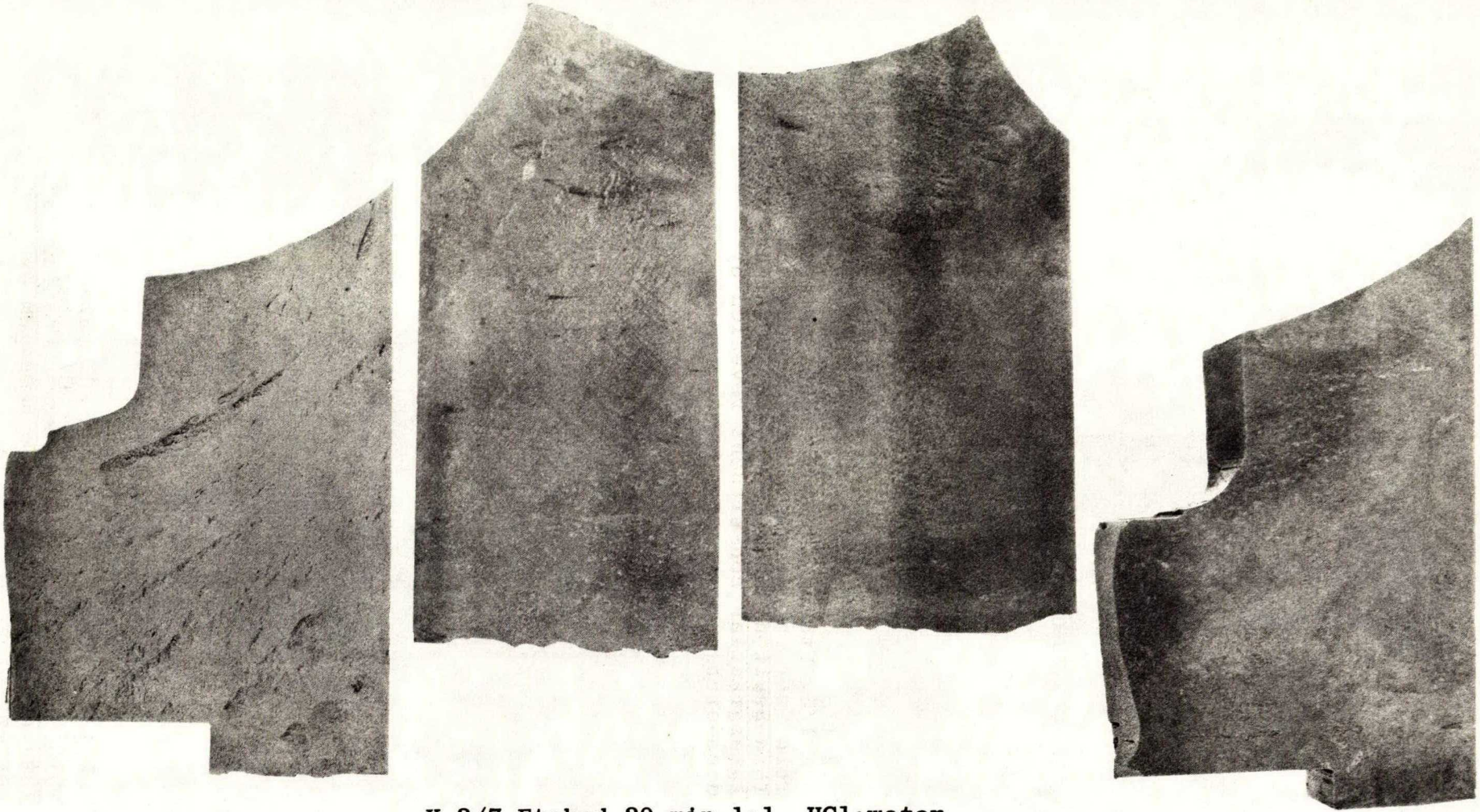
Figures 7 and 8 illustrate the appearance of deep-etched sections through the critically-stressed, thin (working) sections. The intergranular constituent was attacked by the etchant (arrows Figures 7 and 8).

Figure 9, however, illustrates typical cracks in the thick root section. These cracks (arrows) were detected at the root of the weld deposits prior to etching. Either the original cracks had not been completely removed or after welding new cracks had formed along the grain boundary.



X 2/7 Etched 20 min 1:1, HCl:water

Figure 5. Deep-Etched Sections through Stub "R" (Heavy Section). Intergranular hairline cracks are illustrated (arrows).

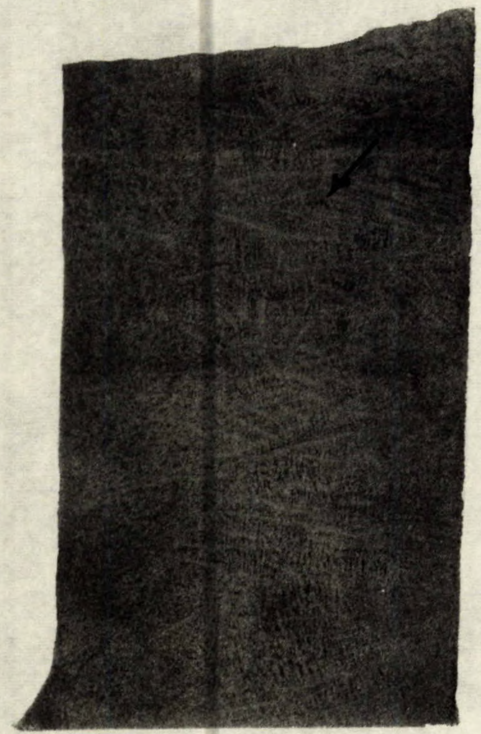


X 2/7 Etched 20 min 1:1, HCl:water

Figure 6. Deep-Etched Sections through Stub "S" (Heavy Section). This casting appeared to be free from hairline cracks.

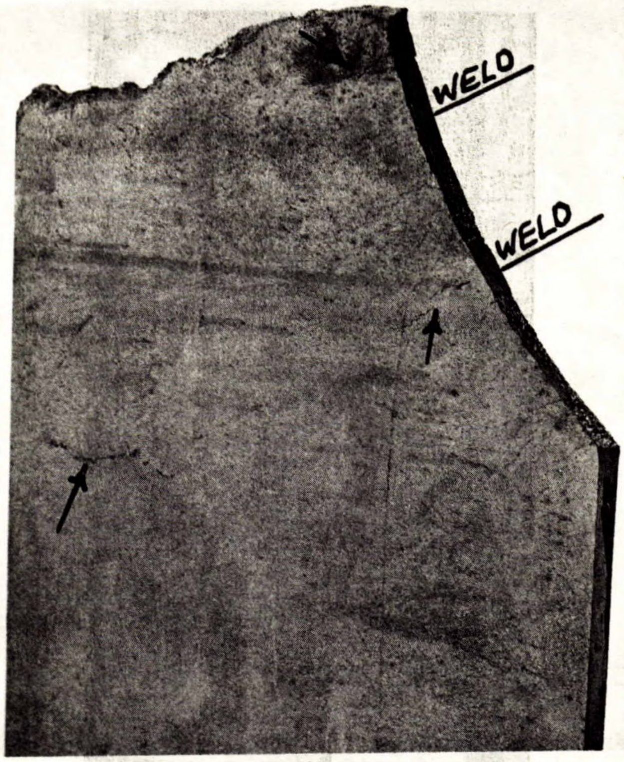
X 1/3 Etched 20 min 1:1 HCl water

Figure 7. Thin Section, Stressed Region, Casting "R". Intergranular constituent revealed by deep-etching (arrow).



X 1/2 Etched 20 min 1:1 HCl water

Figure 8. Thin Section - Stressed Region, Casting "S". Intergranular constituent revealed by deep-etching (arrow).



X 1/2

Figure 9. Casting "R", Thick Section, Illustrates Intergranular Hairline Cracks. The cracks marked by the arrows were detected in the "as-machined" condition (prior to etching).

The appearance of tensile bar R-8 taken from the same area as illustrated in Figure 9 is shown in Figure 10.

X 1

Figure 10. Casting "R", Thick Section, Tensile Bar R-8. Rock candy facets are associated with hairline cracks.

(7) Metallographic Examination.

Samples were cut from broken tensile bars (from the thick section of castings "R" and "S") for examination of the microstructure and particularly to observe if cracks were associated with aluminum nitride precipitate in the primary austenite grain boundaries.

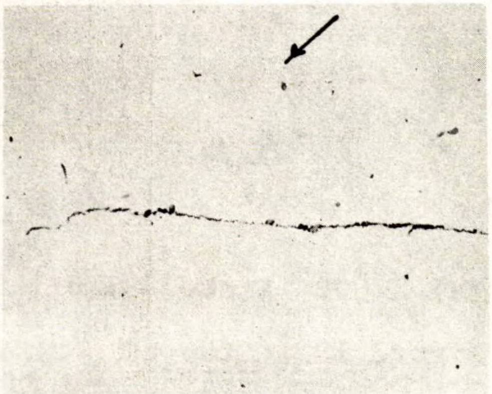
The appearance of the microstructure observed in sample "R" is illustrated in Figures 11, 12 and 13. The microstructure of sample "S" is similarly illustrated in Figures 14, 15 and 16.

The microstructure of casting "R" contained a grain boundary constituent, believed to be AlN, eutectic sulphides, hairline cracks and network distribution of pearlite. All these effects were traceable to deoxidation practice and to the slow cooling rate obtained in this thick section.

Similarly, casting "S", while free from hairline cracks, contained the intergranular constituent, eutectic sulphides and pearlite in network form.

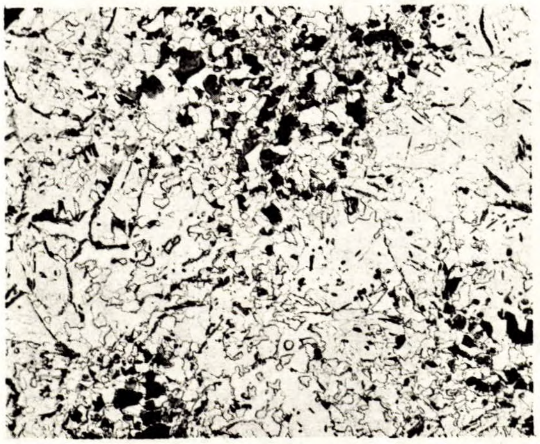
Tensile bars from both castings also contained "fisheyes" indicating retention of hydrogen in porous (interdendritic) areas.

(a) X100 as-polished



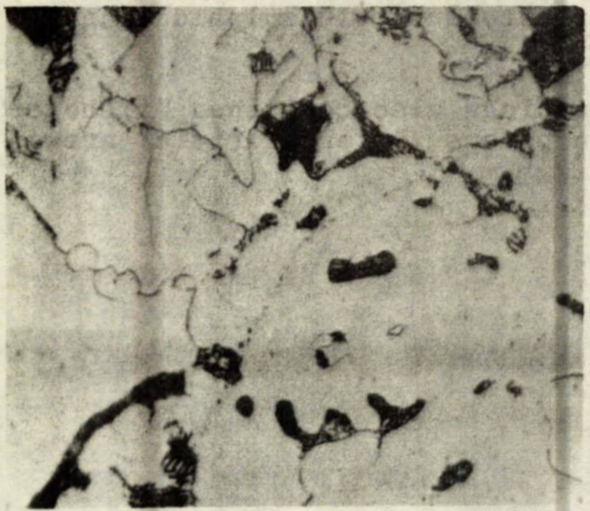
(b) X100 as-polished

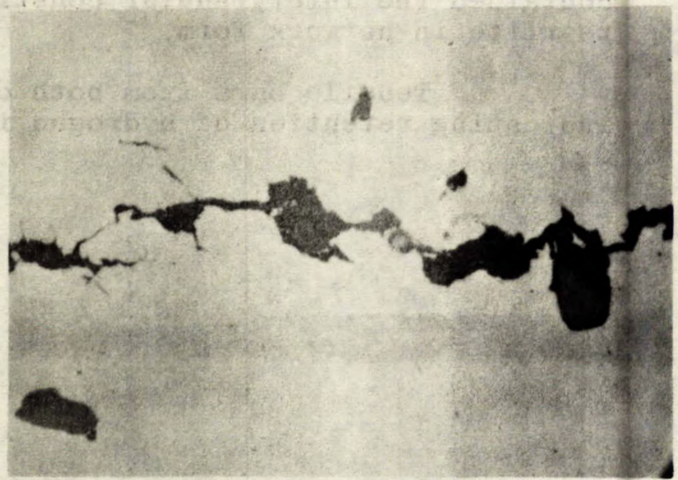
Figure 11. Stub "R", Thick Section. Zirconium nitride (arrow), alumina, and eutectic sulphides. An oxidized intergranular hairline crack and grain boundary constituent are illustrated in photomicrograph (b).



X100 Etched 2% Nital

Figure 12. Stub "R", Thick Section. Illustrates the heterogeneous distribution of pearlite. Pearlite is distributed in dendritic form and outlining ferrite grains.



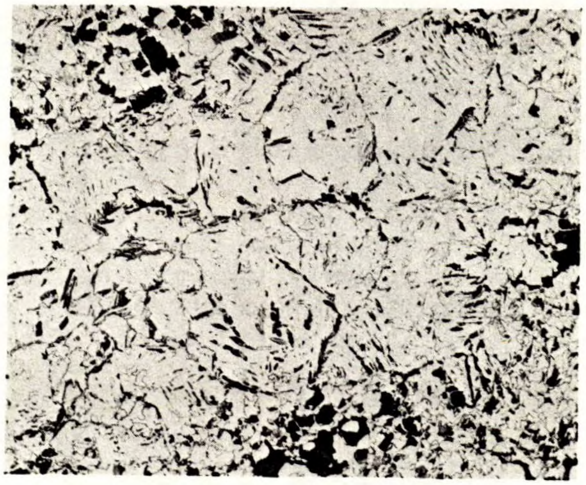


(a) X1000 Etched 2% nital **(b) X1000 Unetched**

Figure 13. **Stub "R", Thick Section. Prior austenite grains are outlined with a constituent believed to be AlN (a). Photomicrograph (b) shows that the hairline crack formed after solidification of the sulphides, and that oxidation of these sulphides occurred. The crack contains a thin film believed to be FeO.**

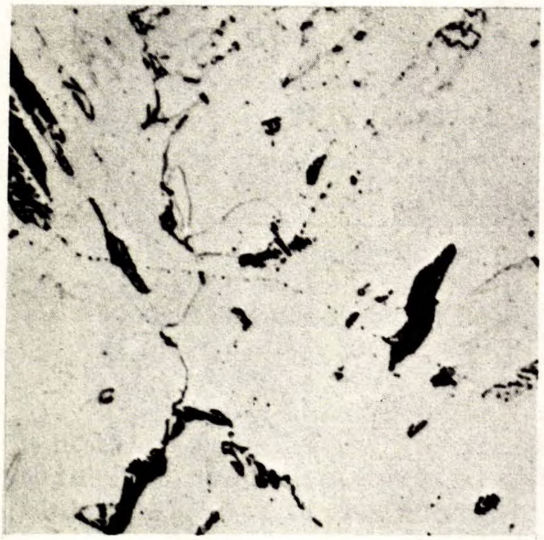
(a) X100 as-polished **(b) X100 as-polished**

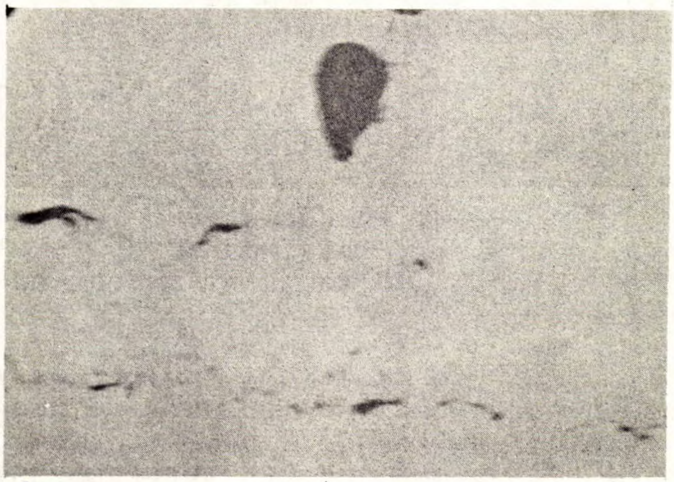
Figure 14. **Stub "S", Thick Section. Zirconium nitrides (arrow), eutectic sulphides, and gas porosity are illustrated. Al_2O_3 inclusions are visible in (a).**



X100 Etched 2% nital

Figure 15. Stub "S", Thick Section. Illustrates the distribution of some of the pearlite outlining ferrite grains and present on cleavage-planes within the ferrite grains.





(a) X1000 Etched 2% nital

(b) X1000 Unetched

Figure 16. Stub "S", Thick Section. Prior austenite grain boundaries are outlined with a constituent believed to be AlN (a). Photomicrograph (b) illustrates an area filled by sulphide prior to solidification.

DISCUSSION

The castings were embrittled by grain boundary constituent (AlN) and by the presence of internal cracks located in the primary austenite grain boundaries. The grain boundary constituent (AlN) can form during solidification at temperatures below 1315°C (2400°F) particularly under conditions of slow cooling with aluminum contents in excess of 0.02%. The nitrogen content of the steel also contributes to the formation of this constituent.

The internal cracks were slightly oxidized but were not decarburized, suggesting that these had formed at intermediate temperatures, after solidification of sulphide and precipitation of nitride but prior to recrystallization.

After sectioning, open cracks were observed at the roots of some of the weld deposits. The presence of these cracks could be due either to failure to completely eliminate the original defect prior to welding, or to propagation of the defect subsequent to welding and formation of second generation cracks. The extent to which hydrogen contributed to cracking was not established however, some tensile test bar fractures showed evidence of hydrogen in addition to the prominent intergranular and cleavage aspects.

Cracks and grain boundary constituent in the working region of the propeller blades would cause a stress-raising or notch effect.

Pearlite networks were observed within and outlining ferrite grains. This condition is attributed to slow cooling - (mass effect) and to insufficient hardenability for the thick section.

Type 2 eutectic sulphides were present and were attributed to mass effect and to use of zirconium in combination with aluminum for deoxidation. The contribution of these sulphides to embrittlement and fracture was judged to be of minor importance in comparison with AlN, cracks and pearlite distribution.

The intergranular constituent and any associated cracks were oriented parallel to the columnar crystals and normal to the surface in the thin section of the casting. In the thick sections the prior austenite grains were not oriented and, consequently, the intergranular cracks were not aligned with respect to the surface of the casting.

CONCLUSIONS

(1) Failure of both stubs in impact service was probably related to the embrittled condition of the castings and to the presence of cracks in the stressed area of the blades.

(2) The difficulty experienced in eliminating cracks may have been due to incomplete magnetic particle inspection, or to the propagation of original defects after welding. The presence of oxide on crack surfaces would indicate that the cracks formed at an elevated temperature rather than during low temperature impact service.

(3) The steel conformed to the requirements of the specification with respect to chemical composition. The total residual aluminum and zirconium contents were of the order of 0.08% and 0.05% respectively.

(4) The sulphide inclusions tended to be present in eutectic form in both castings.

(5) The distribution of pearlite was not uniform. In some areas pearlite outlined ferrite grains and was present in acicular form within the ferrite grains.

(6) The tensile and yield strengths of the castings, as measured in the thick section, were considerably lower than those measured in the 4 in. section. The measured tensile ductility values in the castings did not meet the specified coupon values.

(7) The intergranular constituent was due to the slow cooling rate obtained in these castings, coupled with excessive aluminum addition (for this section), relatively high nitrogen content and inability to eliminate this phase by usual heat treatment procedure.

(8) The formation of aluminum nitride phase in these castings was possibly aggravated by use of aluminum and zirconium, in combination, for deoxidation purposes.

RECOMMENDATIONS

(1) The addition of aluminum for this heavy-section, normalized and tempered casting should be restricted to 0.020% maximum, acid-soluble content. This restriction also necessitates control of the sulphur content to minimize eutectic sulphides.

(2) The specification should allow for adjustment of the alloy content in relation to section size and cooling rate of the casting, to obtain better distribution of pearlite. (Addition of 0.50-0.75% molybdenum might be beneficial).

(3) Castings could be examined by ultrasonic inspection, in addition to magnetic particle inspection, to ensure that hairline cracks are not present. Final inspection, including ultrasonic inspection, could be made after heat treatment, weld-repair and machining, to DOT standards.

(4) The specification for nickel-vanadium icebreaker propeller castings should relate aluminum addition to section size and should allow balanced addition of chromium and molybdenum in excess of residual quantities when required by DOT to achieve adequate hardenability in heavy sections. Silicon content of steel for low temperature impact service should not exceed 0.50% maximum.

(5) The revised specification should also allow DOT selection of alternate materials for trial in icebreaker service.

(6) When possible, the casting section should be minimized by design.

(7) The hydrogen content of the casting should be minimized, for example, by use of dry sand moulds. If green sand moulds are required, use of vacuum-degassed metal would tend to minimize difficulty due to gas and deoxidation. (Steel propellers have been manufactured using degassed metal).

(8) Consideration should be given to use of higher stress relief temperature after welding, for example 650°C (1200°F) to minimize secondary hardening due to vanadium.