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EXAMINATION OF CAST STAINLESS (Mn-Cr) STEEL PROPELLER - C.C.G.S. 'NARWHAL'

by

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PHYSICAL METALLURGY DIVISION

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SUMMARY OF RESULTS

A metallurgical examination was made on a broken and damaged port propeller removed from C.C.G.S. Narwhal, DOT depot ship at Dartmouth, N.S. This was an austenitic cast Mn-Cr propeller manufactured by Black-Clawson Kennedy Co., Owen Sound. The propeller had been in service since 1962 and failed by heavy impact and abrasion in icebreaking service. It was removed in March 1966.

Since this propeller had been in seawater service since 1962, in addition to inspection of damage, the propeller was also inspected in undamaged regions to observe any corrosion which might have occurred in salt water service. Only minor cavitation attack was observed for a depth of about 0.05 in. particularly in a zone near the trailing edge on the back face of blade tips. Except for this area only superficial staining was observed in the hub and root area such that superficial surface grinding would have restored the casting to the new condition.

The propeller casting was tough having a NDT temperature considerably below - 90°F and after loss of the first blade under heavy impact, the lead

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edges of the blades broke while the trailing edges bent. In one blade the trailing edge, bend-angle was in excess of 45°. The large bending stresses (in excess of the yield point) caused intergranular rather than transgranular cracking. Despite this, the blade withstood impact, abrasion and tearing with loss of only one blade. The fracture was columnar from the surface and tough, and was indicative of chill-casting. Final intergranular rather than transgranular rupture is considered normal in this air-quenched, austenitic cast steel, when stressed to rupture. The grain boundaries appeared to contain the minimum quantity of carbide with the only trace of pearlite in the root region. This is consistent with air-quenching of austenitic steels.

Wood and hardened ferritic steel (foreign) were observed, driven into and wedged in deep cracks parallel to the main fracture, where one blade was missing. Abrasion marks were also visible on the bent (ahead) surface of the blades.

It was concluded that there was nothing defective in the casting, on the contrary it had given practically corrosion-free service since 1962, and with superficial polishing appeared capable of restoration to new condition. (If necessary the presence or absence of cracking could be confirmed in dry dock by non destructive liquid penetrant inspection).

INTRODUCTION

On March 28, 1966, a broken cast stainless steel propeller was received for metallurgical examination by the Physical Metallurgy Division, Mines Branch, Department of Mines and Technical Surveys. This propeller was removed, after damage by striking a submerged wood and metal object, from C.C.G.S. "Narwhal", Dartmouth, N.S.

The covering letter, file 9172-N6 (S. Rep.) and letter number 03126D stated that the propeller was from the port side of the ship and that the ship was docked March 8-10, 1966 while this damaged propeller was removed and the spare propeller was fitted.

"The propellers are 4 bladed, solid, stainless steel, diameter 68 in., pitch 57.7 in., manufactured by Black-Clawson, Kennedy Co., Owen Sound. The port propellers being left handed".

IDENTIFICATION

The damaged propeller had the following stampings:

D Crown T	Lloyds	D 68 in.
C	T 3898A	P 57.7 in.
T 40-2	BCK	Heat 496-62
E 48.4	Owensound	L.H.
JRH 23-11-62		

The spare propeller fitted on March 8-9, 1966 had the following stampings:

D Crown T	Lloyds	D 68 in.
C	T 4559	P 57.7 in. at 63 in.
T 41.9	BCK	
E 62.3	Owensound	
JRH 20-11-63		

"The damaged propeller had one blade missing to within 3 in. of the hub, two blades half missing with remaining portions bent over, and the remaining blade heavily set over forward. Heavy fractures parallel to the bends were noted on the three remaining blades, the cracks being of a fibrous nature.

When the propeller was removed, the screwshaft was checked for straightness and found to be completely undamaged. The hull had a split indentation approximately 3 in. long adjacent to the propeller, probably as a result of being struck by a missing blade. This was repaired by a suitable small patch.

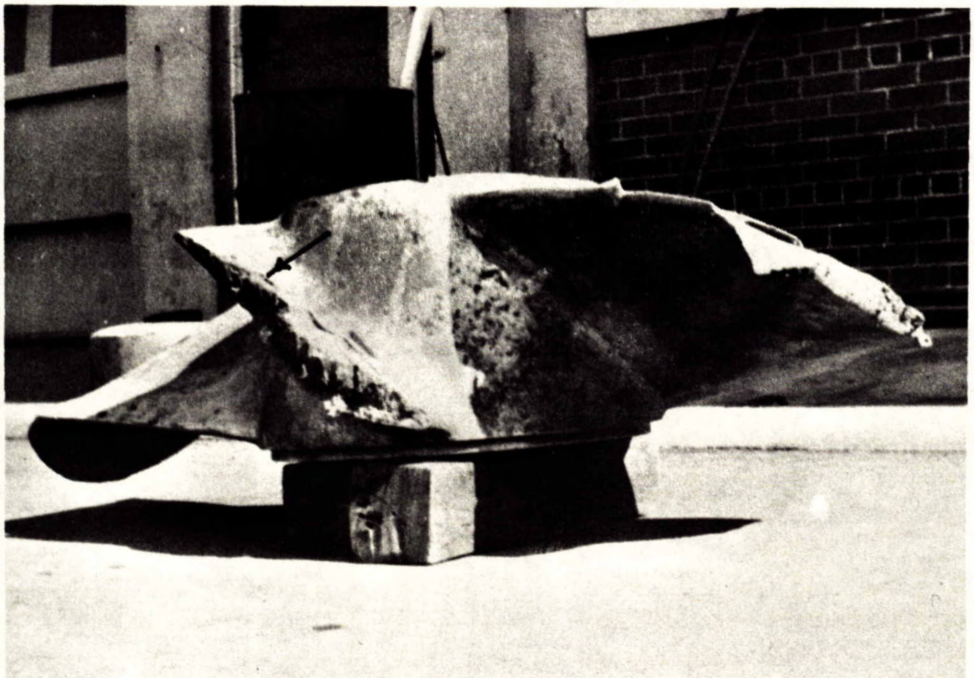
The Master reported that the damage occurred when a submerged object, believed to be a log, was struck by the port propeller. Deeply embedded pieces of wood in some of the cracks support the belief that it was a log*.

The vessel was icebreaking in the La Have River and the accident took place when turning off the Government Wharf in Bridgewater at approximately 8:49 a.m. Both engines were turning full ahead at the time".

A copy of Canadian Vickers Limited Drawing No. MA-281-141, "Arrangement and details of Propeller-Twin screw Depot Vessel for Department of Transport". June 5, 1962., was also included with the covering letter.

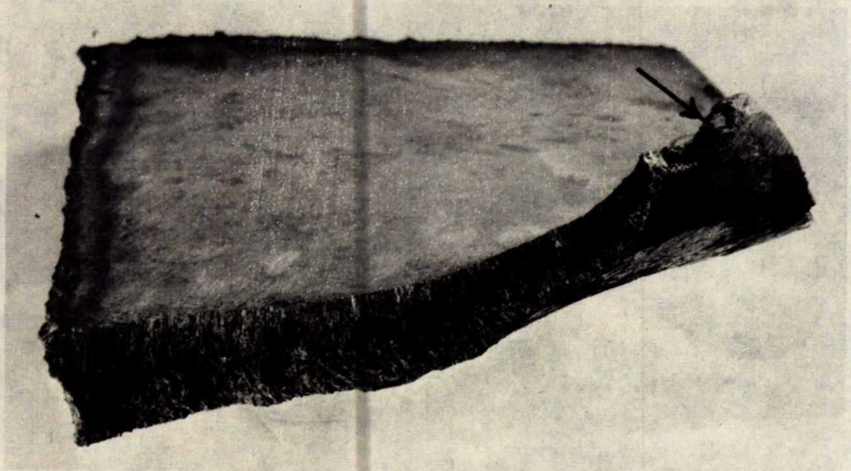
The appearance of the broken propeller blade is shown in Figures 1, 2, 3 and 4. Figure 2 illustrates the columnar fracture visible at the stub of the missing blade. The tips of the other blades were severely deformed, one blade tip, having bent through more than 45 degrees. Severe deformation of the blades caused the formation of numerous secondary cracks, where the metal was stressed to rupture.

*Inspection at P.M.D. laboratories showed that, in addition to wood, several foreign pieces of quenched and tempered steel were deeply wedged in cracks adjacent to the broken stub of the missing blade.



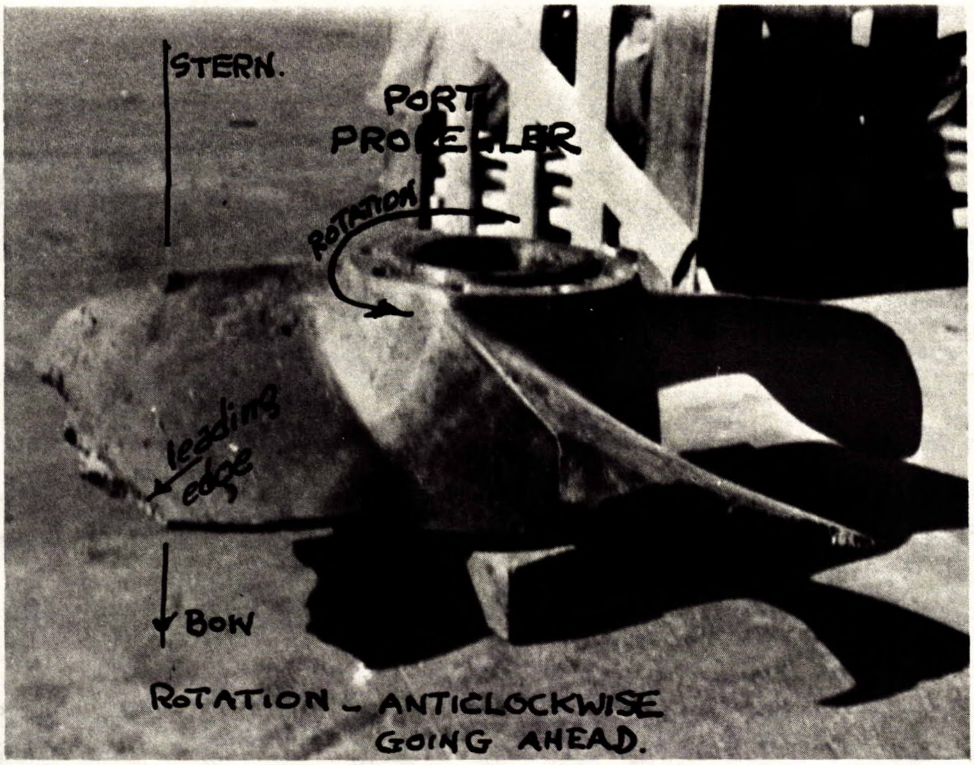
1/10 actual size

Figure 1. Stainless Steel Propeller C.C.G.S. Narwhal Showing Fracture and Stub of Missing Blade. Foreign pieces of steel were found wedged in a crack in the position marked by the arrow-adjacent to the main fracture.



approx. 1/3 actual size

Figure 2. Typical Columnar Fracture Surface (Chill-cast) and Embedded wood (arrow) is illustrated wedged in a crack near the blade-tip.



1/12 actual size

Figure 3. Illustrates Severe Deformation of Blade Tips. This view rotated 180° from that shown in Figure 1. The missing blade and stub are not visible in this photograph.

1/10 actual size

Figure 4. Broken Blade Tip Showing Columnar Fracture (arrow 1) and Nick (arrow 2). Same as figure 3 but rotated 90°. Some cavitation corrosion was observed near the blade-tip on the astern surface.

A Metallurgical examination was carried out as follows:

(1) Chemical Analysis of Millings.
(2) Metallographic Examination.
(3) Mechanical Tests - Bend Tests, Tensile Tests, Charpy V notch Tests.
(4) Drop Weight Tests on 3/4 in. x 2 in. x 5 in. samples cut from the hub region.

(1) Chemical Analysis of Millings

TABLE 1

Sample	C	Mn	Si	S	Cr	Ni	N_2	Origin
Casting	0.15	11.97	0.81	0.016	15.87	5.21	0.26	Narwahl Casting
Orig. Spec. *	0.10	15.0	-	-	16.0	5.0		Published Composition *

*Composition of Mn-Cr cast propeller stainless steel as reported in "A Study of Materials for Marine Propellers", by Donald M. Harris, The William Kennedy and Sons Ltd., Society of Naval Architects and Marine Engineers, Feb. 10, 1959, also., published "International Shipbuilding Progress", Vol. 6, No. 57 - May 1959, 208-209.

(2) Metallographic Examination

A section at the tip of one blade was polished and deep-etched. The appearance of this section, in the etched condition, is shown in Figure 5.

Approx. 1/2 actual size etched HNO_3 + HCl + HF in H_2O

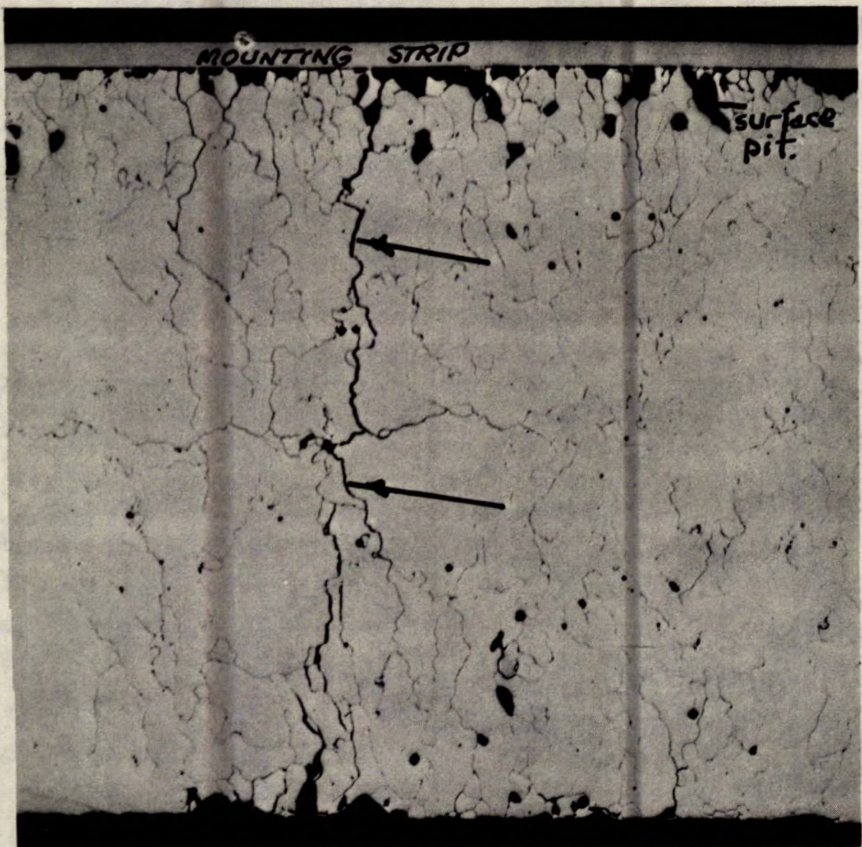
Figure 5. <u>The Columnar (chill-cast) Macrostructure present in the casting is illustrated.</u> The integranular cracks (fracture) illustrated (arrows) are secondary and occurred at the same time as the main fracture.

The surface of the casting was examined to estimate the depth of corrosion which had occurred during service (1962-1966) prior to fracture. Samples were examined from the thin and thick sections Figure 5, and from the surface of the hub. The grains were relatively large and were outlined with fine carbide,not visible in the as-polished condition, but visible after etching. Intergranular oxidation for a depth of several grains had occurred in service at the tip of the blades but was shallower in the root region and was absent in the hub sample. Traces of pearlite were visible in grain boundaries in the root area of the blade but were absent at the tip of the blade and in the hub sample.

Typical secondary cracking associated with the fracture and damage of the propeller is illustrated in Figure 6.

Approx. 1/3 actual size

Figure 6. Tip of Bent Blade (Flame cut) Showing Secondary Cracks and Rupture Caused by Impact of Blade. This blade had bent about 45° without separation. When fracture did occur it followed an interdendritic path.



"cavitation"
pitting and
intergranular oxidation
(0.03 in.)

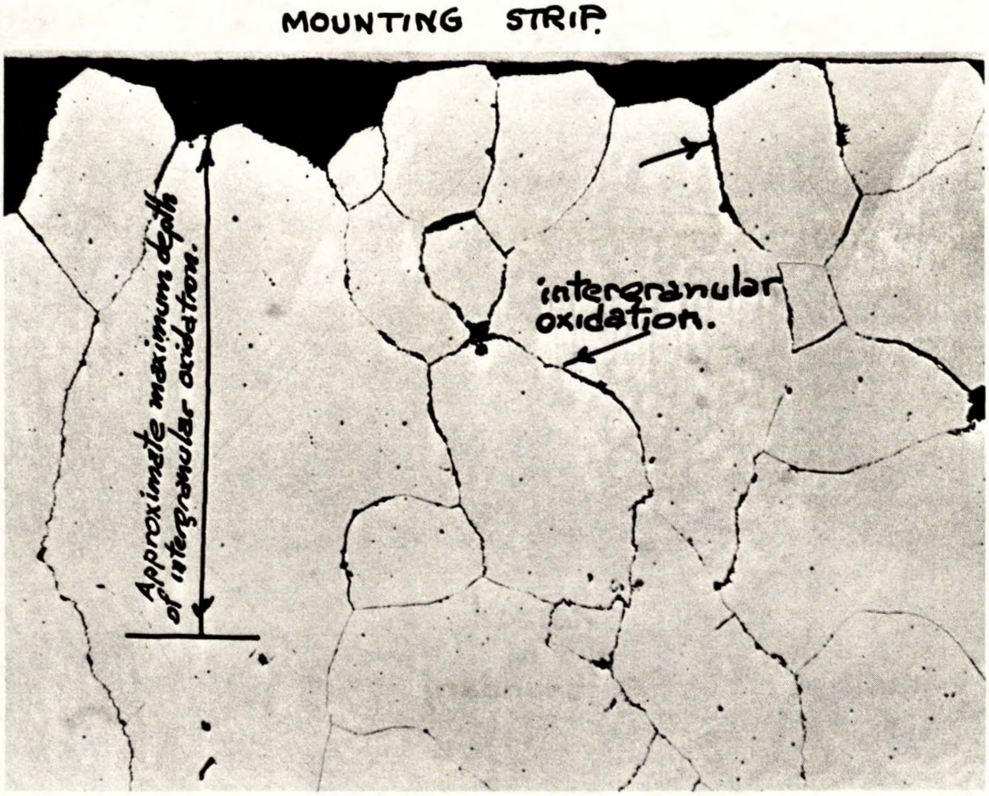
The crack is visible
as the dark line (arrows)

- the remainder of the grains are visible because of precipitate present at grain boundaries which is relief-polished

intergranular oxidation

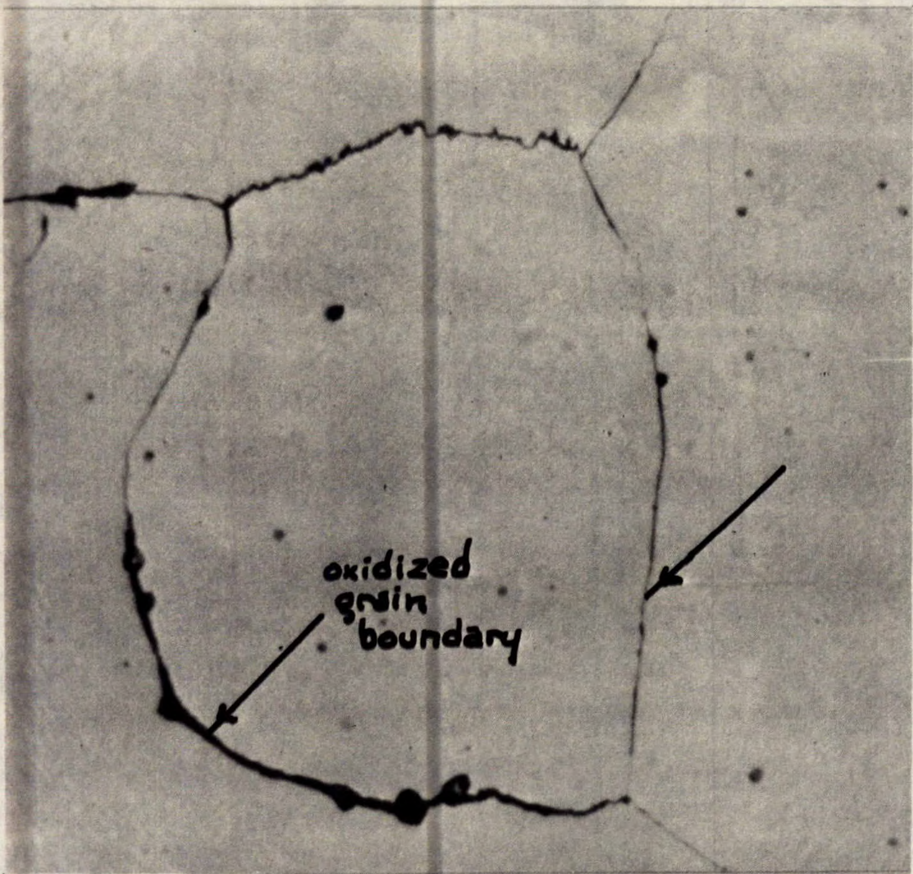
X10 as-polished

Figure 7. Section in Region Marked, "Thin Section", Figure 5. The path of a crack formed by impact is illustrated (arrows). The extent of corrosion pitting and intergranular oxidation (cavitation + corrosion) in this area after 4 years' service is illustrated.



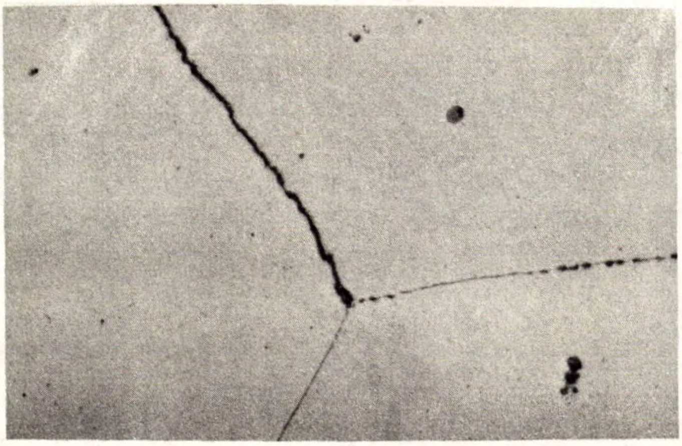
X100 as-polished

Figure 8. <u>Surface Adjacent to Mounting Strip as in Figure 7, but at Higher Magnification - "Thin Section" (Figure 5).</u> The depth of intergranular oxidation (grain boundary corrosion attack) is approximately 0.03 in. This area illustrated contains the most severe corrosion observed i.e., corrosion has possibly been accelerated on this surface by cavitation close to the tip of the blade.

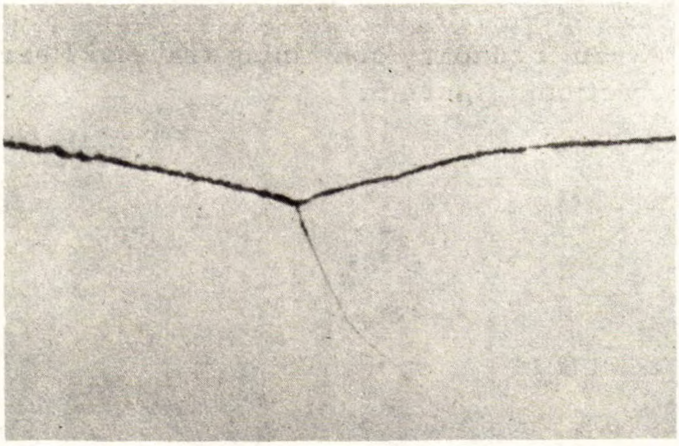


X500 as-polished

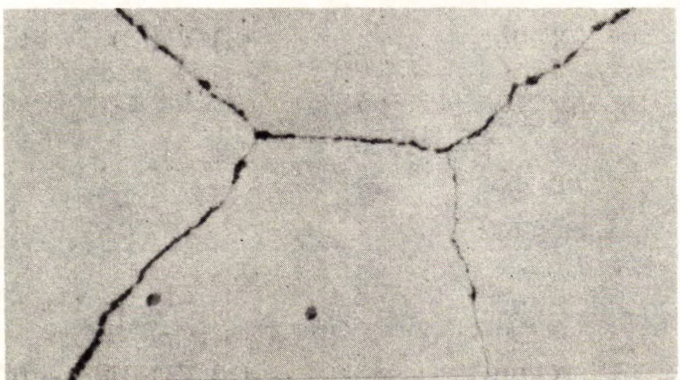
Figure 9. "Thin Section" Area Intergranular Oxidation Observed in Area of Cavitation and Corrosion for a depth of 0.03 in.



X500 (a) as-polished

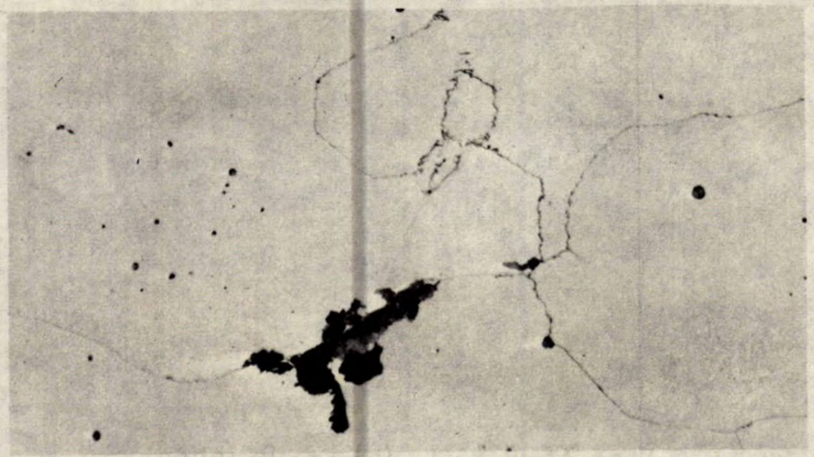


X500 (b) as-polished



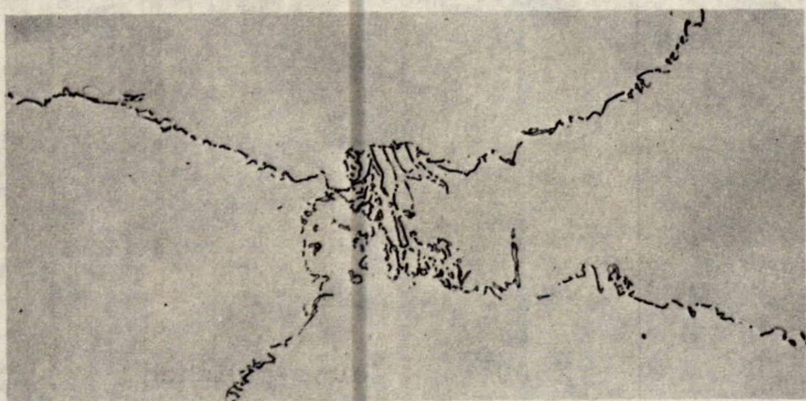
X500 (c) as-polished

Figure 10 (a, b and c). Intergranular Oxidation, Thin Section, 0.02 in. from Surface. Photomicrographs illustrate the limit of penetration of intergranular oxidation - (cavitation-corrosion).



X100 - Villella's etchant

Figure 11. Grain Boundary containing trace of Pearlite Thick Section, Figure 5.



X500 (a) Vilella's etchant

X500 (b) Vilella's etchant

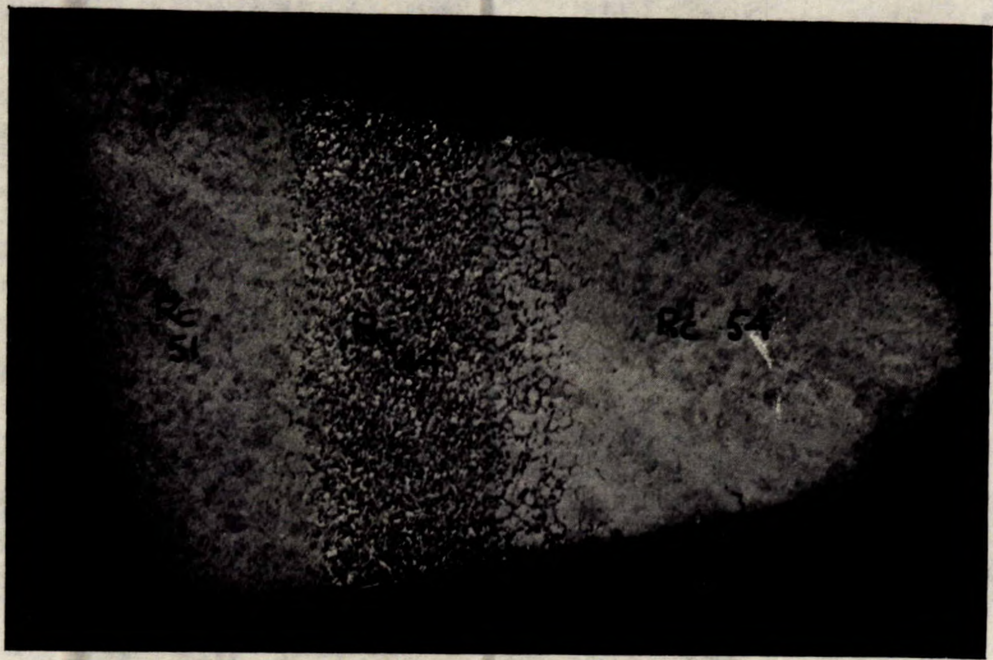
Figure 12 (a and b). Grain Boundary Thick Section. Traces of pearlite were observed in the thick section region but were not seen in the "thin section" and hub samples.

Two pieces of foreign (ferritic) steel were observed to be wedged in a crack adjacent to the main fracture (arrow figure 1). The appearance of the two ferritic steel fragments are shown in Figure 13.

X5 approx.

Figure 13. Fragments of Foreign Ferritic Steel which were Wedged in a Crack Adjacent to the Broken Stub. (see Figure 1). This metal was foreign to the propeller casting showing that the object struck by the propeller contained both wood and ferritic steel.

Figure 14 illustrates the microstructure of the smaller fragments shown at the top of Figure 13.



X5 etched 2% nital

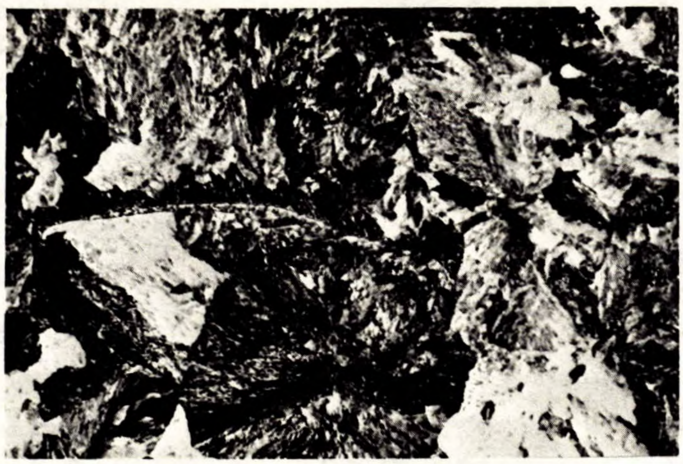
Figure 14. Foreign Steel Fragment Removed From Crack (Rockwell C as shown). The metal is ferritic and magnetic whereas the casting is austenitic and non magnetic. This fragment of steel has been hardened and has a carbon content and microstructure resembling that present in a hardened steel wedge or axe-head.

X500 (a) R_c (51) Nital

tempered martensite

X500 (b) R_c (54) Nital

tempered martensite



X500 (c) R_c (44) Nital

fine pearlite

Figure 15 (a, b and c). Hardened Steel Fragment (Figure 14). The hardened areas are illustrated (a) and (b). An area of fine pearlite (R_c44) is illustrated (c).

MECHANICAL TESTS

Bend Tests

Two bend samples 8 in. x 1-1/2 in. x 1/2 in. were cut from an area of one propeller tip showing minimum secondary damage. One sample sustained a 140° degree bend showing excellent ductility at BHN 165 (R_B85) hardness. This sample bent 140°, flat side down, over a 1 in. diameter radius - the sample showed some 1/4 in. edge cracks at 140° but did not break. The second bend sample contained a crack due to service damage, which reduced the section by 30%, but still withstood a 70° bend prior to rupture. Both bars work-hardened and showed the "rippled" surface pattern similar to that observed due to work-hardening of Hadfield's austenitic manganese steel. The fractures were tough, coarse-grained columnar and fibrous.

Bend tests indicated that the metal was tough and ductile but that final rupture, after extensive deformation, was intergranular.

The metal resisted crack propagation - so that Charpy V notch bars gave room temperature values of the order of 100 ft-lb. Several Charpy bars containing secondary cracks over 1/3 of their cross section were broken and gave results in excess of 30 ft-lb. The NDT temperature of metal from the hub was considerably below -90°F. (-70°C was lowest test temperature).

Charpy V Notch Impact Tests

Charpy V notch impact bars were machined from the blade-tip and hub areas and were broken at +80°F, +20°F, 0°F, -20°F and -40°F. The results are listed in Table 2.

TABLE 2

Charpy V Notch Impact Test Results (Triplicate and Average)

Test Temperature (°F)	Blade ft-lb	Blade Description of Fracture	Hub ft-lb	Hub Description of Fracture
+ 80°F	44, 36(Av. 40)	coarse, columnar*	102, 114, 108	intergranular
+ 20°F	22, 58, 40(Av. 40)	coarse, interdendritic*	86, 142, 100	intergranular
0°F	36, 30, 36(Av. 34)	" " " *	103, 142, 108	intergranular
- 20°F	30, - , 21(Av. 24)	" " " *	88, 76, 76	
- 40°F	24, 14, 8(Av. 15)	flat, intergranular	120, 60, 70	intergranular
-100°F	———		76, 56, 40	intergranular
-320°F	———		22, 22, 14 22, 32, 36	intergranular

*Evidence of work-hardening during impact and Brinell hardness Test. Hardness of metal tested was 165-170 BHN (RB 85).

Tensile Tests

Two tensile bars were cut from uncracked hub metal and were broken. The results are listed in Table 3.

TABLE 3

Tensile Tests

Sample No. and Location	UTS kpsi	0.2% PS* kpsi	Elongation (%) 4D	Av. and Max. RA (%) (approx)	Hardness (BHN-3000 kg)
Bar No. 1 (Hub)**	76.0	40.2	29.0	35.7;46.3	170
Bar No. 2 (Hub)**	74.5	38.3	33.0	49.2;51.9	170

*No yield point. Work hardens to extent where tensile fracture is oval and surface is dimpled.

**Broke outside 2 in. gauge.

Drop Weight Tests

Eight bars 5 in. x 3/4 in. x 2 in. were beaded notched and were subjected to drop weight tests to estimate the nil ductility temperature. The bars were cut from hub metal. The NDT temperature determined by drop weight testing with a 264 ft-lb blow, 200 lb hammer and 1/8 in. deflection was lower than -90°F.

DISCUSSION

The appearance of the fracture and the fact that blade tips bent 45° before rupture, tensile, impact and NDT properties indicate that the propeller casting was sound tough and adequate for normal service. The contents of the covering letter, the presence of foreign steel particles, wood fragments, and extensive deformation indicate that this casting was severely overloaded by impacting an object prior to failure.

The presence of numerous secondary intergranular cracks is not unexpected since this metal ultimately ruptures along grain boundaries rather than across grains when subjected to breaking loads.

The hardness, BHN 165-170, and microstructure appeared normal. The microstructure was mainly austenite with a minimum quantity of carbide and pearlite at grain boundaries due to the necessity of air-quenching the casting rather than liquid-quenching during heat treatment.

The Charpy V notch, drop weight and tensile ductility results indicate that the casting was adequate with respect to mechanical properties and resistance to cavitation-corrosion.

An incidental examination of surface metal in an area most effected by cavitation and corrosion showed that after 4 years of service (1962-1966) intergranular oxidation was present for a depth of approximately 0.03 in. on the affected surface 2 in. from the blade tip. No evidence of corrosion (pitting, or intergranular oxidation) was observed in the root or hub area.

The macrostructure and fracture showed that this casting was chill-cast and was well-fed in the section examined.

CONCLUSIONS

1. Failure was due to impact overload of a magnitude sufficient to embed steel and wood in cracks adjacent to the main fracture.

2. The appearance of the fracture, extent of deformation without fracture and mechanical properties indicate that the casting was superior with respect to low temperature toughness.

3. The hardness and microstructure were satisfactory, although traces of grain boundary constitutents (carbide and pearlite) were observed in some areas.

4. Corrosion in 4 years appears to have been limited to a depth of approximately 0.03 in. maximum in local areas affected by cavitation and intergranular oxidation.

5. The impact transition temperature and NDT temperatures were very low.

6. Foreign particles of wood and hardened ferritic steel were found embedded in the surface of the austenitic casting.

DEP:DAM:lc