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EXAMINATION OF FAILED PROPELLER TAP BOLT FROM M. S. 'PRINCE NOVA'

by

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PHYSICAL METALLURGY DIVISION

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SUMMARY OF RESULTS

A broken propeller tap bolt from the M. S. "Prince Nova" was examined and found to contain strong evidence of stress-corrosion cracking. It was surmised that bolt loading stresses and traces of ammonia in sea water or from some other source were the causative factors in producing failure in material that may be highly sensitive to such a combination. The recommendations include changing the bolt material to an alloy less susceptible to this form of failure.

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INTRODUCTION

This Department was requested to ascertain the cause of failure of an aluminum bronze propeller retaining stud by the Board of Steamship Inspection, Department of Transport, Ottawa (letter December 9th, 1965, Reference: 9562-7751, S.M.I.). It was indicated that the bolt submitted for examination was one of several noted failures. Further correspondence with the shipbuilders, Ferguson Industries Limited, Nova Scotia, revealed that on the twin-screw vessel, M. S. "Prince Nova", three retaining bolts were fractured on one blade of one of the variable pitch propellers and that blade was lost after coming into contact with a foreign object. Inspection showed three other bolts with signs of fracture on a blade located on the opposite side of the vessel. The bolt examined in this report is one of the three in this last category.

DESCRIPTION OF FAILED BOLT

A schematic diagram of the bronze bolt is shown in Figure 1, indicating its general features and the main sites of fracture just below the head of the bolt. It should be noted that the central axial hole is intended to accommodate a device for measuring torque during assembly of the blade to the propeller boss, and contained a close-fitting mild steel pin and a screwed end closure. Two pictorial views of the fracture are shown in Figure 2. There was no evidence of corrosion products or discoloration anywhere in the bolt material itself, although the steel pin insert was considerably rusted by the ingress of sea water along the crack path. There were no visible indications of metal deformation near the fracture and the outside surfaces were free from any signs of abuse.

MACRO-EXAMINATION

The bolt was sawn into two parts along its longitudinal axis in such a way as to complete the separation of the bolt-head from the shank. One half thus obtained was ground and crack-tested using a dye penetrant. An illustration of this crack-revealing test is shown in Figure 3 and a close-up detail of the fractured area is shown in Figure 4. Several small cracks, not illustrated, were observed in the threaded part of the shank. These fine transverse cracks appeared to run from the root of the thread at right angles to the bolt axis and were approximately ¼ in. to 3/8 in. long.

After cleaning, the bolt section was ground and macro-etched in order to determine the grain structure contours and, by deduction, the method of manufacture. Fine, strongly aligned grains lay parallel to the bolt axis in all parts of the section. It is concluded, therefore, that the bolt was machined directly from extruded bar.

Clearly, the metal failure in this material is not nearly as localized as might be suggested by Figures 1 and 2. A large network of cracks extend radially from sites in and just below the bolt head, while smaller hairline cracks were observed in the bolt shank. This generally widespread metal failure is of significance in discussing the causes of cracking.

PHYSICAL AND CHEMICAL TESTS

A sample of metal drillings taken from the bolt head were chemically analysed by the Mineral Sciences Division. The results obtained are shown in Table 1. Small tensile test pieces were machined from sound sections of the bolt shank, and were broken to give the tensile properties of the material in the direction of the bolt axis. These results are given in Table 2.

MICROSCOPIC EXAMINATION

Sections parallel to the bolt axis were cut from the main fracture area, polished and examined. The microstructure was revealed as a fine-grained oriented alpha-beta structure containing a small number of very fine spheroidal particles. This duplex constitution is typical of complex Al-Mn bronzes of the 12% Mn type. Of chief interest were the crack paths themselves, since these reflect the mechanism of cracking and, hence, the cause of failure. One area of the large network of fine cracks extending from the primary fracture surface is shown in Figure 5. It will be noted that this field illustrates the tendency for cracks to run at 45 deg to the extrusion direction and bolt axis, and suggests the intergranular type of crack path shown in more detail in Figure 6. The cracks appear to run intergranularly along alpha-beta boundaries, with some evidence of transgranular cracking in the beta phase. Close examination of the outside surface of the bolt both near and remote from the source of crack paths failed to reveal any products of corrosion action, pitting or de-aluminization.

DISCUSSION

The basic design of the bolt, and the mechanical properties of the material used appear adequate for propeller tap bolt application. Although the chemical specifications for the material, Cunial II, were unobtainable, the analysis and name suggests that the alloy belongs to a family of propeller alloys developed by Lips Propeller Works, Drunen, Holland, containing between 11 and 27 wt % Al+Mn+Zn and between 5 and 10% Fe+Ni. These materials reputedly possess higher strength and corrosion resistance than manganese bronze (60:40 Cu-Zn) alloys.

The brittle nature of the failure, and the multibranch cracking associated with it, are clearly identified characteristics of stress corrosion cracking, and it is instructive to consider how the stress system in the bolt, and a corrosive agent with access to the bolt shank, together combined to produce cracking. The loaded bolt contained tensile and torsional stresses, which compounded to give high stress concentration in the radiused part of the shank just below the bolt head, and at the bottom of screw threads. The corrosive agent, apparently having access to the whole of the shank surface, has produced cracks normal to the tensile stress axis of the bolt at both of these regions of high tensile stress concentration. It is probable, therefore, that the loading stress, as opposed to any residual, internal stresses in the bolt, has contributed to the failure. It should be noted that the designer has taken all possible steps to reduce stress concentrations in the bolt, by the provision of ample radii, and "waisting" the shank between the head and the threads. In addition, provision has been made for some form of measuring device to be inserted in the bolt so that it is not tightened excessively during assembly, which would, of course, raise the stresses in the bolt. It is presumed that these precautions were taken during assembly, and that the propellers were not put into service with excessive stresses in the bolts, which would, of course, make them much more vulnerable to stress corrosion attack.

The large number of branching cracks around the site of failure suggests the presence of an extremely active corrosion component, since the propagation of the primary crack path would have reduced the high state of stress in the area of failure.

It will be noted that the larger cracks, i.e., those first produced, tend to run normal to the bolt axis, while a larger number of smaller branch cracks are seen to lie at about 45 deg to the bolt axis. This may be related to the change in the vectors of the stress system in material adjacent to the primary crack path after initial failure. The nature and action of the corrosion component presents some problems in interpretation since it appears to have been generally active both at the bolt head and lower down in the screwed portion of the bolt, yet has produced no evidence of chemical attack on fracture surfaces or on uncracked portions of the shank. In addition, it appears from a drawing of the propeller assembly that the air space around the shank of the bolt was protected from exposure to sea water by the seating between the bolt head and the propeller hub. Thus, the seepage of sea water into the air space would have resulted in a virtually closed environment of sea water and air. Alternatively, there exists the possibility that seepage could have occurred through the end closure, although the good condition of the steel pin insert, and the indications that cracks moved in from the bolt surface suggest that this was not so. Finally, it must be considered that no seepage of sea water occurred at all, and that the corrosive agent was present in the air space after dry-dock fitting of the propeller.

Various reviews and papers on stress-corrosion cracking of copper alloys [1-3] indicate that the most aggressive corrosion agent capable of producing stress-cracking (in environments where mercury is known to be absent) is ammonia and that in alpha-beta alloys of the type discussed here, the crack path is usually intergranular with respect to the alpha grains and occasionally transcrystalline in the beta phase [2]. The minimum concentration of ammonia necessary to cause stress-cracking is known to be very low, and it has been suggested that an ample source of ammonia in marine atmospheres and sea water may be the decaying animal and vegetable matter found in marine environs.

Thus, while it is not possible to prove the point, the evidence indicates strongly that failure occurred as a result of the simultaneous action of tensile stress and an aqueous source of ammonia vapour or the NH_4^+ ion. Consideration of the stress system has been given, and the source of ammonia may have been sea water seeping under the bolt head, or it may have been trapped in the system during assembly of the components.

It remains to discuss the ways of overcoming this problem of stress-corrosion cracking. The first important metallurgical point is that alpha-beta alloys of the Cu-Mn-Al type are known to be susceptible to stress-corrosion cracking in sea water so that a greater measure of safety would be obtained by changing the bolt material to an alloy offering more resistance to this failure mechanism. There is but little guiding information available in this regard, but it is generally true that resistance to stress-corrosion cracking increases with increase in copper content, so that a high tensile nickel-aluminum bronze, containing no aluminum-rich beta, may prove satisfactory in this application. Apart from changing the bolt material, there are two practical points worth considering that deal directly with the stress and corrosion environment of the tap bolt. The first of these is that, while it has been argued that failure occurred because of bolt loading stresses, the presence of any residual, fabrication stresses in the bolt material would undoubtedly have decreased the resistance to stress-corrosion cracking. Internal stresses, if they were present, could be removed by an appropriate stress-relieving anneal. Similar treatments are known to reduce the occurrence of stress-corrosion cracking in alpha and alpha-beta copper-zinc alloys.

The second point deals with the complete exclusion of sea water and sources of ammonia from the bolt shank. This might be achieved by using a gasket under the bolt head and by packing the bolt hole with grease. Since some engineering lubricants contain a stabilizing additive of ammines (sources of ammonia) these should be specifically avoided.

CONCLUSIONS AND RECOMMENDATIONS

The records show that the tap bolt examined was one of a number that showed the same type of failure in this installation. This suggests that the failure was generic to the material, the stress history or the environment, and was not an isolated incidence caused by abuse, neglect, etc. Metallographic examination of the tap bolt submitted indicated that it failed by the mechanism of stress-corrosion cracking. It has been surmised that under the tensile operating stresses, a source of ammonia, either sea water or some other substance, was present in sufficient quantity to induce intergranular cracking in the material at regions of high stress concentration.

With regard to the future performance of similar tap bolts of this material, it is recommended that all tap bolts be replaced and that one or all of the following suggestions be adopted:

1. New bolts be made from an alloy having a higher copper content and at least the same yield strength as Cunial II, e.g., an aluminum bronze containing iron and nickel.

2. Steps be taken to exclude sea water and any possible source of ammonia from the bolt shank.

3. To eliminate the possibility of using material containing internal stresses, bolts should be given a stress-relief anneal before use.

4. The use of ferrous bolts should be considered, bearing in mind possible corrosion problems associated with the use of dissimilar materials.

REFERENCES

1. "The Stress Cracking of Brass", A.R. Bailey, Metallurgical Reviews 6(21), 101-142 (1961).

2. "Copper, Metal and Alloys", A. Butts, Amer. Chem. Soc., Monograph No. 122, Rheinhold Publishers, New York (1954).

3. "Stress Corrosion Cracking in Marine Service", B.F. Peters, et alia, Materials Protection 4(5), 24-38 (1965).

RT/sg

TABLE 1

Chemical Analysis of Bolt Material (%)

Cu	Mn	Al	Fe	Ni	Zn
73.74	11.70	6.58	1.35	1.97	4.72

TABLE 2

Tensile Properties of Bolt Material

	UTS (kpsi)	0.2% YS (kpsi)	El. % in 4D
	96.6	54.6	20
	94.6	54.2	28
	93.8	53.1	16
Average	95	54	21

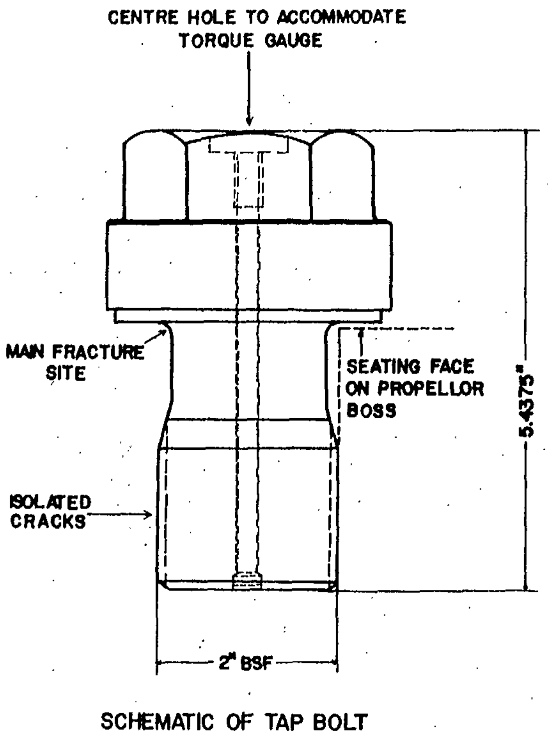


Figure 1. Engineering sketch of bolt showing failure centre.

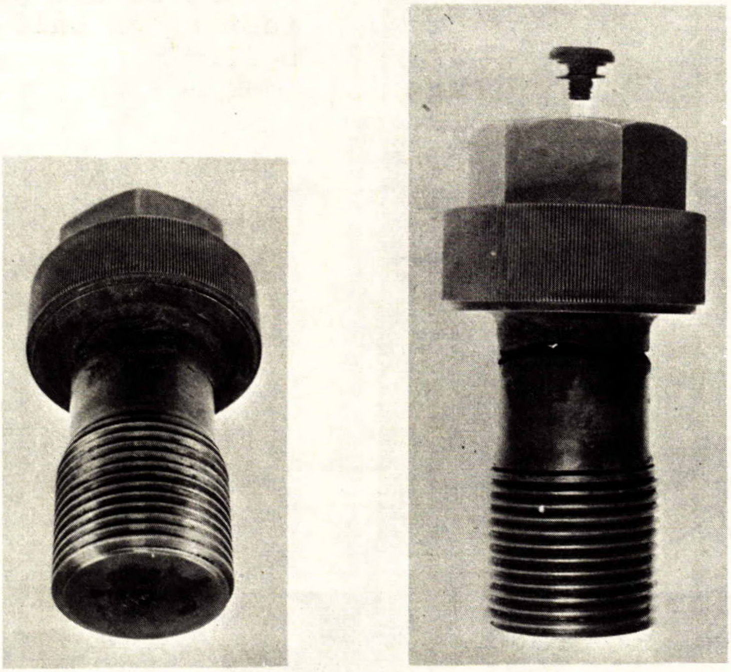


Figure 2. Two views of failed bolt.

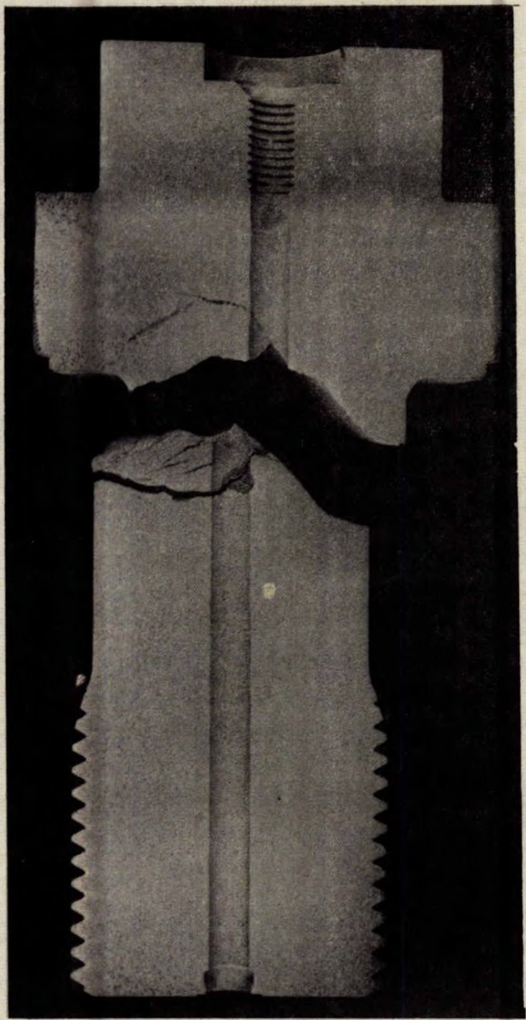


Figure 3. Illustration of the result of dye penetrant crack testing on half section of bolt.

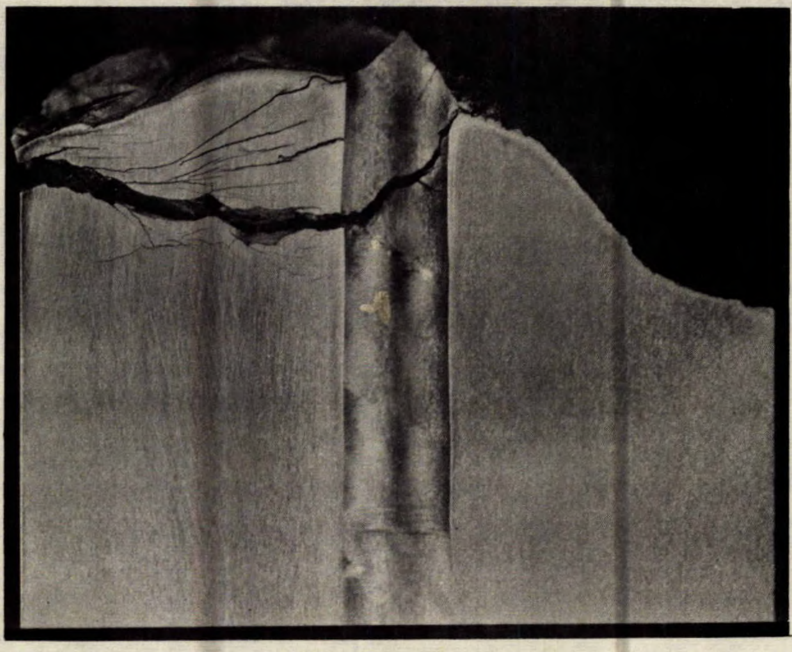
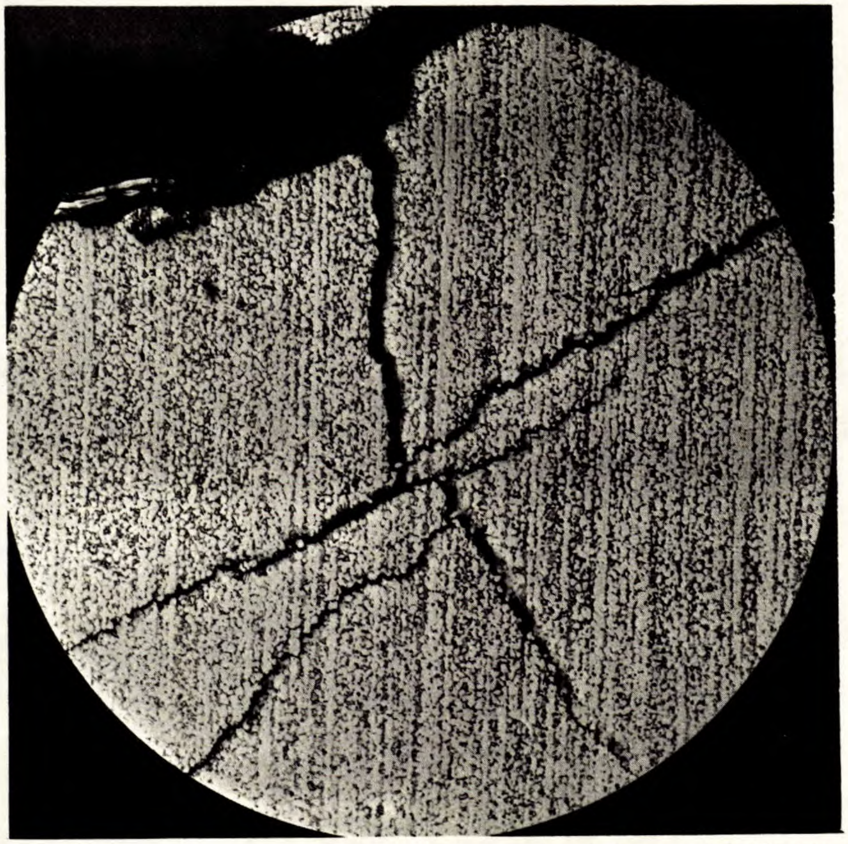
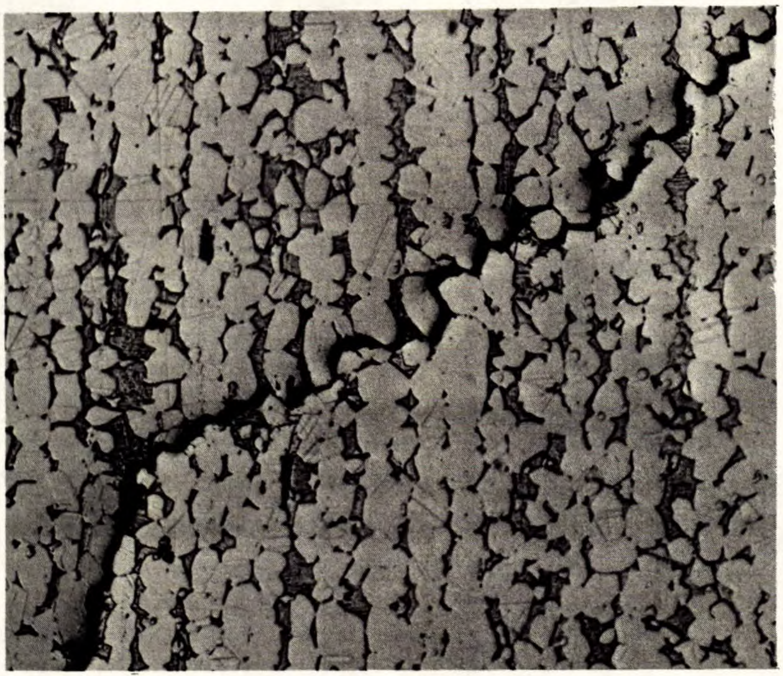


Figure 4. Macro-photograph of area near primary crack showing extensive secondary cracking.



X100
Etched
$FeCl_3$

Figure 5. Secondary crack system extending in from primary fracture surface (typical of the multi-path cracking in stress corrosion embrittlement).



Etched $FeCl_3$
X500

Figure 6. Detail of intergranular crack path.