# A CRACKING TALE OF CPP BLADES AND HOW THEIR HEALTH IS BEING RESTORED

BY

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## Introduction

'Rather like a very large tail wagging a very small dog', said one Type 21 MEO having suffered a CPP blade failure. Anyone who has been present in a ship at the time of such a catastrophe will testify to its having been a memorable although somewhat alarming experience. Thankfully the likelihood of a fractured blade puncturing the hull of a warship has been assessed as very low; the combination of bending moment, centrifugal force, wake, and the ship's speed would almost certainly ensure that the blade would be thrown clear. However the out-of-balance force of a 'four-and-a-bit' bladed, ex five-bladed hub rotating in the mid-speed range is in the order of 50 kN, which is sufficient to cause significant damage to a shafting system if left unattended.

Six such failures have occurred in COGOG ships since 1978, the last of which was in early 1984. Following a brief description of blade design and manufacture, this article explains how the failure investigation was mounted, the results and conclusions reached, and how the reliability of CP propeller blades is being improved as a result.

## The Blades

The design of the propeller blades for the Type 21 frigate and Type 42 destroyers was novel in two important respects: they were the first major controllable pitch propeller blades to be designed by the Ministry of Defence; and a different material, Superston 70, had been proposed by the manufacturer. Superston 70 is a manganese aluminium bronze, the chemical composition and mechanical properties of which are shown in TABLE I. The

TABLE I—*Material Specification and Mechanical Properties of Manganese Aluminium Bronze*

| *Material* | *% Mass* |
|---|---|
| Manganese | 14.5 |
| Aluminium | 7.75 |
| Iron | 3.0 |
| Nickel | 2.5 |
| Copper | balance |
| UTS | 725 MPa |
| Young's Modulus | 117 GPa |

supposed advantages of this alloy over nickel aluminium bronze, which had been used in propellers for some years, were its higher ultimate tensile strength and the potential ability to achieve a higher quality casting. The lower fatigue resistance was not thought to impose a significant restriction on its use as a naval propeller material.

The design was constrained by the need for blades to pass each other as they developed reverse thrust. This resulted in a shorter chord length and less available blade area for a given diameter than would have been the case for an equivalent fixed pitch propeller, and the problem was compounded by relatively high rotational speeds and restrictions on diameter. The method used for calculating stresses within a propeller blade is well established[1] and is based on the theory of thin shells. Inevitably, as with any engineering design, compromises were necessary: the hydrodynamic requirements of width and thickness can clash with the requirement to provide adequate strength, and load distributions carefully selected to delay cavitation could themselves be affected by elastic deformation causing changes to blade geometry.

The determination of the maximum permissible stress for a particular propeller is dependent upon its operational role and the wake, which affect the stress cycling within the blade as the propeller rotates at constant speed, as do the material properties. The specified stresses in merchant ships, for instance, where operation is almost always at or near the maximum rating, tend to be lower than those for a warship where full power is used less frequently.

The maximum nominal stress for the Type 21 and Type 42 blades was set at 112 MPa (7½ tsi) which, although only approximately one fifth of the ultimate tensile strength of Superston 70, was nevertheless some 30% higher than had previously been employed with other materials. Blade form was then arranged to give the best possible shape without this stress being exceeded, and the design was such that an effectively constant stress was obtained out to about 80% of the radius, after which it decreased towards the tip. The form of the propeller blade, together with the Agouti arrangements, are shown in FIG. 1.

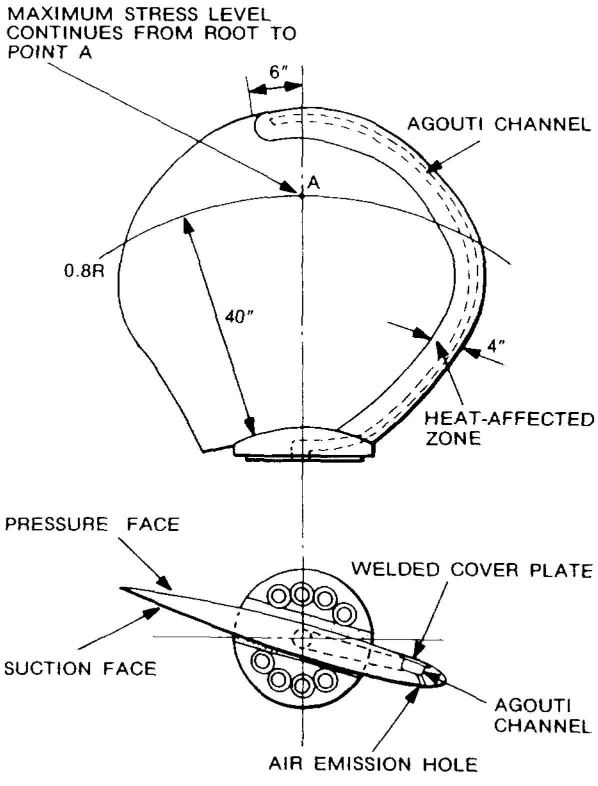


FIG. 1—CPP BLADE: MAJOR FEATURES

Manufacture was undertaken by Stone Manganese Marine Engineering, Ltd. (SMME), and at this time the complete process, including casting, was undertaken by the one firm. In 1981 however, Vickers, plc., acquired the manufacturing part of the organization, re-naming it Stone-Vickers. Their Birkenhead factory became SMM Propellers, Ltd., and retained the foundry at Charlton. Many, although not all of the blades now produced by Stone Vickers are still cast by SMM Propellers Foundries at Charlton.

Although all stages of blade manufacture are important to the final performance of the propeller, the initial casting is perhaps the most critical. Considerable effort has been exerted over the years to improve the quality of this process[2] by controlling the gas content of the liquid alloy, paying greater attention to the avoidance of gas absorption from the mould, and by using improved types of running system. The amount of metal to be removed from the surface of the casting, especially in the critical root fillet area of the pressure face, is also important if the severity of remaining defects is to be minimized.

The process of metal removal starts by drilling the pressure face to depths which indicate the material to be machined off to give the correct pitch, and the suction face is similarly drilled to give the specified suction thickness. Craft skills are still very important here as the propeller surface is ground by hand. An open channel is cast into the blade where the Agouti space will run and, following dressing, a cover plate is welded in as shown in FIG. 2.

Checking the geometry and balance of the blade is time-consuming and can result in costly repair and even rejection. The leading and trailing edges are dressed to fit edge gauges, the tolerance for the former being 0.2 mm, and the pressure face pitch angles are checked and recorded. The blade is mounted in a special rig and metal ground from the suction surface to achieve the final static balance. The balancing process is designed to ensure that the completed propeller assembly will not cause excessive vibration and checks that blades are interchangeable. The blades are therefore tested individually and the mass adjusted to achieve a balance moment within a specified tolerance band.

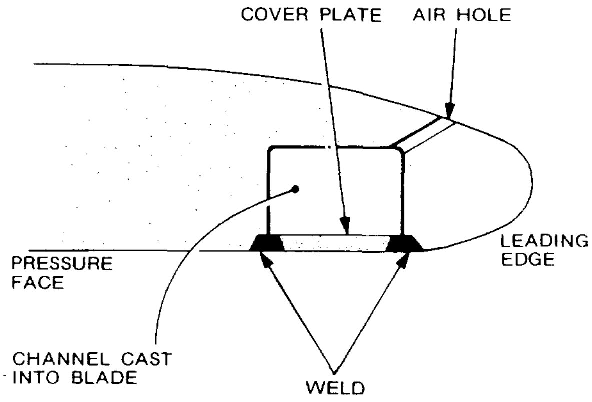


FIG. 2—CROSS-SECTION OF CPP BLADE, SHOWING AGOUTI CHANNEL

The unbalance tolerance is dependent upon the number of blades, the blade mass as a fraction of the total propeller mass, and the maximum propeller speed; it is expressed in Kg m $\text{tonne}^{-1}$ and reflects the permissible offset in centre of gravity in the radial direction.

## History

The first failure occurred in October 1978 when a blade broke away from the starboard propeller of a Type 21 frigate which at the time was running at 90 PCL. Investigations, which are described more fully below, were carried out to determine the cause of the fracture, and almost four trouble-free years followed. In July 1982, however, another Type 21 frigate experienced a blade failure whilst under way. Investigations were again put in hand, the urgency of which was increased by a failure on the other propeller of the same ship some six months later, and another in a Type 42 destroyer in February 1983.

Two further failures, again in Type 21 ships, followed at approximately six-monthly intervals to give an alarming linearity to the frequency of defect occurrence.

Repair can be undertaken either afloat or with the ship docked, and both methods were successfully employed, with refinements being made to the procedures as time progressed. The choice of which method to adopt was largely dependent upon the facilities and support which were available at the time; the times for repair were not significantly different whichever method was used.

## Investigation

ME112 is the specialist section within the Directorate of Marine Engineering which has design and production responsibility for CPP systems, although the hydrodynamic aspects of the propeller and its design are handled by the department of the Chief Naval Architect (CNA) and ARE Haslar. With ME112 being the point of contact between the Sea Systems Controllerate and the blade manufacturer it was natural for them to take the co-ordinating role in the investigation and the search for a solution. Much of the actual investigative work however was undertaken by other agencies, such as ARE (Dockyard Laboratory) Portsmouth, ARE Haslar, and the manufacturers themselves.

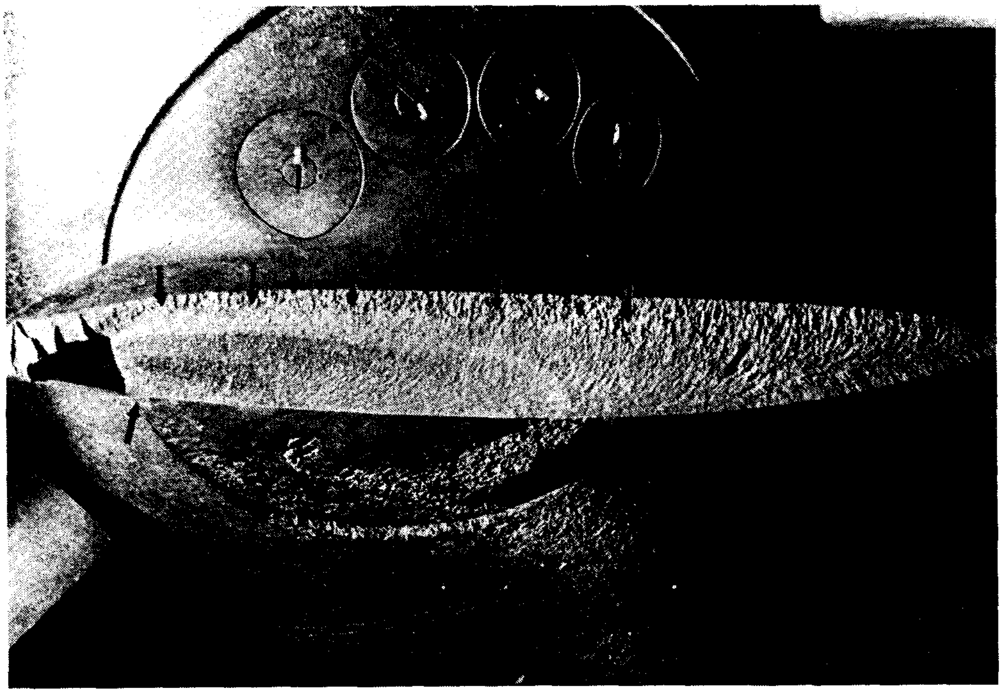


FIG. 3—FRACTURE CHARACTERISTICS OF FIRST FAILURE

A photograph of the stub of the first failed blade is shown in FIG. 3, and indicates the area over which a fatigue crack had propagated before final loss occurred by fast fracture. The axial markings present also indicated that crack initiation had occurred at the Agouti channel cover plate weld which was furthest from the leading edge. Detailed metallurgical examinations[3,4] concluded that the blade had failed by the initiation and propagation of a corrosion fatigue crack from a defective weld repair, the extent of which is shown in FIG. 4. The repair itself had been necessary because the Agouti channel had been cast with a greater than designed cross-sectional area and was further from the leading edge than intended.

Further blade stressing calculations indicated that, because of the increase in ship displacement since the propeller design was completed, the actual

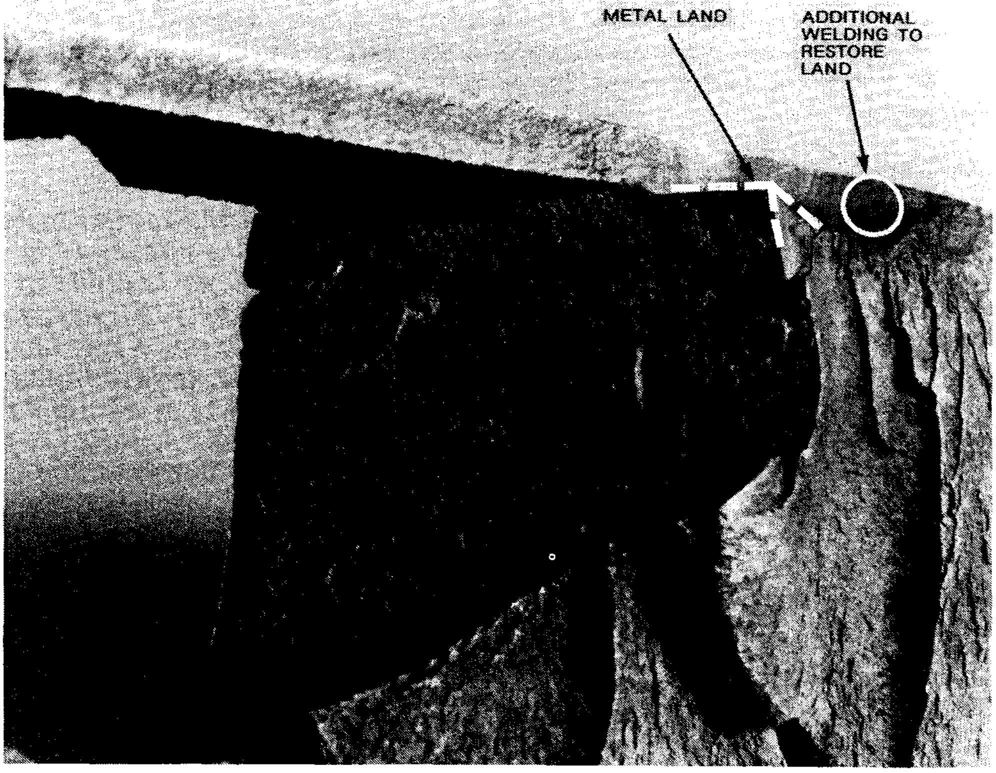


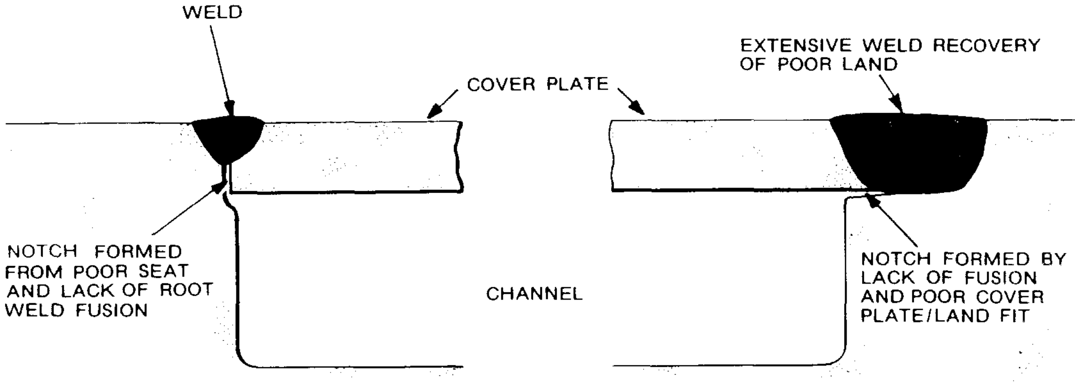
FIG. 4—EXTENT OF WELDING UNDERTAKEN TO RESTORE AGOUTI CHANNEL LAND PROFILE

stress in the region of failure was 120 MPa with a fluctuation of ± 48 MPa. This was still within the quoted fatigue limit for $10^7$ cycles, but there was a lack of strictly relevant corrosion fatigue data in the cast and welded form, particularly when considering the added influence of post-weld heat treatment. Work was arranged to study the material's air fatigue behaviour in more detail, using specimens machined from the failed blade. The analysis[5] included predictions of failure using the stress intensity approach, which estimates crack growth from a specified defect in a given stress field. These predictions were correlated with ship running data from build to the time of failure and were used to estimate the size of surface defect which would warrant rejection of a blade.

More rigorous cleaning procedures and dye penetrant crack detection routines in the Agouti channel area were introduced for in-service blades as a result of the investigations, and in particular those blades which had been subjected to repair concessions during manufacture were identified. Two blades in a Type 42 destroyer were soon rejected because of crack-like features, and subsequent examination showed them to be corrosion fatigue cracks associated with defects within the Agouti channel welding. FIG. 5 shows the type of defect which could result in failure by the resulting cracks running into the blade material.

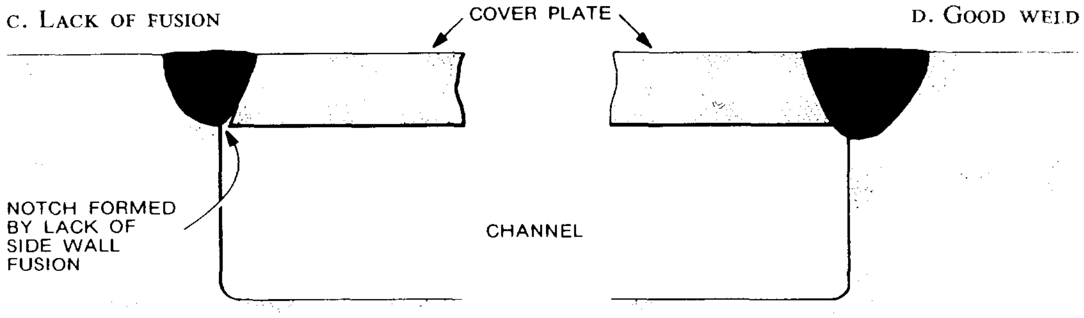
After several years without a catastrophic failure, the second such instance (in July 1982) was both unexpected and alarming. From an inspection of the fracture surface, shown in FIG. 6, it was evident that the nature of the defect was entirely different from that previously experienced, although as before it had been caused by a fatigue mechanism.

Metallurgical examination[6] revealed that the defect was a filamentary oxide entrapment near to or actually breaking the free surface of the pressure face,



A. Lack of penetration

B. Poor cover plate/land geometry



C. Lack of fusion

D. Good weld

Fig. 5—Examples of Agouti channel cover plate weld, illustrating typical defects

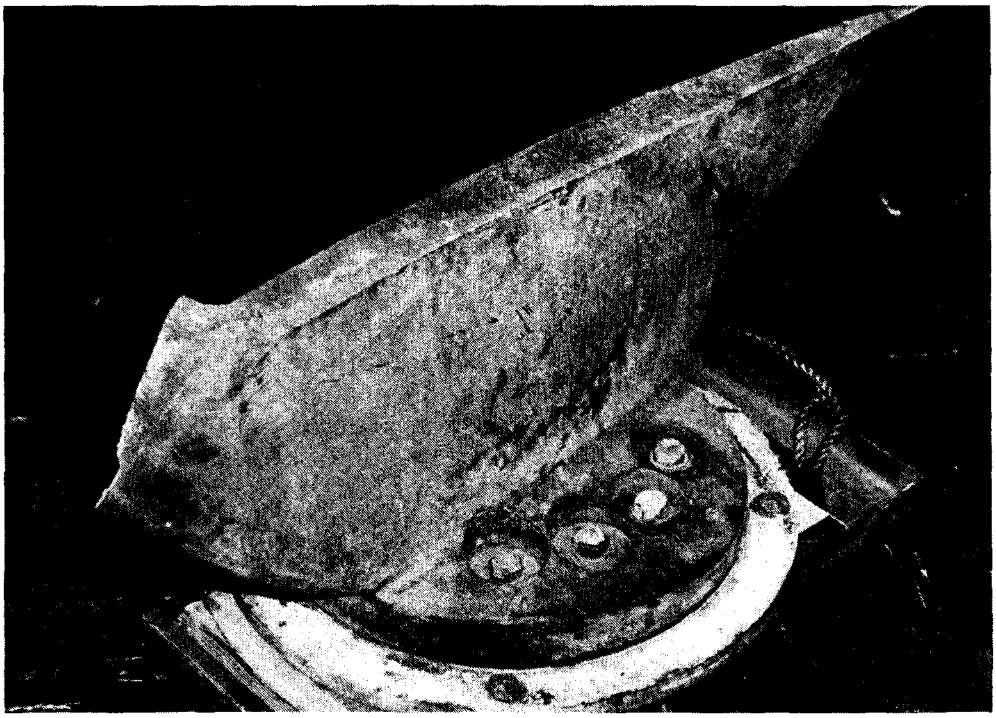


Fig. 6—Fracture characteristics of second failure

introduced when the blade was cast. An extension of dye penetrant testing to the entire lower half of the blade surface was recommended, but a similar failure of another blade in the same ship highlighted the measure of the task confronting those responsible for determining NDE methods for obtaining the required assessment of blade integrity both at the production stage and after the blades had entered service. The specific problem was that the latent defects could be within the blade and might only be manifest at the surface during the fracture process. Furthermore, it was felt that the fatigue characteristics of Superston 70 were still not fully appreciated and further fracture mechanics studies were set up[7] to provide more detailed acceptance and rejection criteria for the blades in terms of the defects that could be tolerated.

The need for such criteria was borne out by the next failure[8] which was shown to be directly attributable to poor standards of preparation and welding of the Agouti channel cover plate in the area of the boss. The situation was now critical, and much of the evidence indicated inadequacies in the manufacturing process. In conjunction with the other investigations, work was therefore started to draw up an inspection and acceptance standard for blade production.

## NDE Techniques

To apply an acceptance criterion, the defects first of all have to be located. Several methods are available (see Appendix, pp. 383–385). Each has its own advantages in particular circumstances and, because a combination of circumstances could occur in one blade, the complementary use of the various techniques is likely to be necessary.

### *Surface Defects*

The methods of determining surface defects are a simple visual inspection which can be enhanced by dye penetrant, and the eddy current technique which measures abnormalities in the magnetic field when a current is passed through the specimen. Extreme caution must be exercised, especially in the visual methods, because a crack may be closed by the sheer weight of a blade and hence be more difficult to detect.

### *Subsurface Defects*

The eddy current technique will detect defects just beneath the surface but the more reliable methods for finding subsurface defects are normally radiography and ultrasonics.

X-rays, gamma radiation, and neutron sources can all be used for the radiographic detection of defects and the technique essentially measures the energy loss of the radiation as it passes through the specimen. Since defects are less dense than the surrounding material the energy loss is less and detection is therefore possible. As shown in the Appendix the orientation of the defect is important to the success of its detection, with defects in line with the radiation being the easiest to find. The particular radiation used depends on the thickness of the specimen. An iridium source is adequate for 75% of the blade area but for the critical zones—the highly stressed regions of the blade, including the root—the thickness is such that a cobalt 60 gamma ray source has to be used. This source has to be accompanied by the most stringent precautions to avoid a radiation health hazard and also requires very long exposure times for the thicknesses in CPP blade roots. If a cobalt source were used in a dock bottom the after half of the ship and an area of equivalent diameter around the propellers would have to be evacuated for the 8–12 hours required for each 100 inches square shot. This is clearly impracticable and cobalt can only be used if the blade is brought to a purpose-built radiography centre such as that in Portsmouth Dockyard. Iridium carries its own, lesser, restrictions which because of the number of shots required to cover the whole of each of the ten blades render it extremely inconvenient if not impracticable to use during a routine docking.

Defects which are approximately parallel to the specimen surface are theoretically best determined by ultrasonics; a crack causes a discontinuity which enables the sound wave to be reflected back to the surface and receiver, as shown in the Appendix. The curved surface of a propeller blade makes the technique much more difficult to apply, particularly as the curve varies in two directions; and great care is called for in the interpretation of results. Unfortunately there is little practical experience of the use of ultrasonics on copper-based alloys with the geometry of propeller blades. Some work was done at the Pixash Lane ND testing centre before its closure in 1984 but tests on full size blades indicated large areas of signal attenuation in the most important thick sections at the root of the blades, so that in practice ultrasonics do not provide a useful method for flaw detection in the critical areas of CP propellers.

## The Standard

From the early investigation work it was clear that there were two fundamental deficiencies in the quality of blade manufacture:

(*a*) *Agouti Channel* The origins of four out of the six failures were in deficiencies in the construction of the Agouti channel, either in the casting of the cover plate 'land' (see FIG. 5), or in poor welding.

(*b*) *Casting* The remaining two failures had been shown to be a result of subsurface casting defects of the 'filamentary oxide' type.

The combination of defects from these two sources, the blade service stress, and the material properties of Superston 70 was lethal. It was therefore essential to consider these aspects in detail in any new standard. It had already been established that radiography and dye penetrant were the only two practical methods of NDE for CPP blades and the standard had to utilize them at the appropriate stages in the manufacturing process, whether it be in new production or in repair, to look for incipient defects of the type now known to be the potential source of failure.

By this stage in the investigation a large number of spares and blades awaiting repair had been radiographed at Portsmouth using iridium and cobalt and the technique was well established. With one notable exception all blades were found to have defects in the Agouti channel weld areas in varying degrees, but only one was found to have a casting defect and this was not thought to be critical. Hence it was clear that this, and any other area of welding—basic casting repair for example—were the most important areas to concentrate on in the new standard. As far as new manufacture was concerned the emphasis could be largely on achieving freedom from critical defects, with the manufacturer responsible for developing his own production techniques. With repair, however, these techniques required further practical work by Devonport Dockyard repair centre in conjunction with CNA.

The exception to the general experience of radiographical results described above was that of a set removed from *Amazon* for examination. These blades proved to be much higher quality than most others and almost entirely free from Agouti weld defects. They were also the oldest set of CPP blades at sea and this led to a study of the age of blades which had either failed at sea or which had been removed following discovery of cracks during dye penetrant checks. This appeared to indicate that four to five years was the critical age for CPP blades and led to some optimism that those older than this may not possess critically sized defects. This conclusion owes less to basic metallurgical and crack growth theory than engineers' statistical instinct!

It was the manufacturing standard that was produced first, in late 1983, and was put to work in the contract with Stone-Vickers for the CPP blades for Type 22 09–12. In broad terms it listed the inspection procedures (radiography, dye penetrant, and visual) and standards to be achieved at each step in the manufacturing process—the casting in the fettled state (in order to avoid nugatory work on any with basic gross defects), and the as-finished blade after all welding and heat treatment had been completed. The standards to be achieved represented the combination of the best MOD(N) knowledge of copper-based alloy castings included in existing DGS specifications together with the results of the metallurgical analysis carried out by ARE(DL) (Portsmouth) on specimens from failed blades. The contract referred to above had already been let, leaving no scope for any changes to the basic design stress or material. The opportunity was also taken to introduce, for the first time, a surface finish specification for all areas of the blade in order to reduce the tendency to suction face erosion resulting from oxide inclusions and porosity. This kind of defect had been a feature of CPP blades for some years and was believed to be a prime cause of cavitation.

The document produced represented a radical tightening of standards, and required considerable effort by the two foundries supplying blades for this contract and by Stone-Vickers themselves. No blades in the contract have been rejected from considerations of strength, but several have fallen foul of the surface finish specification. This is a tribute to the efforts of the manufacturer in improving the Agouti channel cover plate weld quality.

A repair standard followed in late 1984 as did an in-service inspection procedure. The latter, however, presents considerable difficulties. As already mentioned, the most valuable means of examining blades, radiography, is not practicable on ships in service unless the blades are removed. The only remaining practical techniques are those using dye penetrant and the naked eye. Both are already part of the standard preventative maintenance procedures but have the disadvantages that they require careful cleaning of the blades and can only be carried out whilst the ship is in dry dock. The in-service procedure attempts to give operators and maintainers a 'go/no go' guide to the acceptable defects in each area of the blade. Efforts are being directed by CNA to find an underwater cleaning method which will not destroy the evidence and also an underwater ultrasonics device to find sub-surface defects. Application of the guide has had mixed results to date. More than one potential blade failure has been detected and the blade changed, following dry dock inspection, but one of the six failures had been inspected ten days before the event and given a clean bill of health, thus emphasizing the need to find a means of detecting sub-surface defects without having to take the blades off the hub.

## Blade Replacement

The two fundamental conclusions from the failures and the ensuing investigation are:

(*a*) Blade design stress level must not exceed 83.5 MPA (5½ tsi) in any future designs.

(*b*) The blade material must in future be nickel aluminium bronze, as in all fixed pitch propellers (see TABLE II for properties).

TABLE II—*Material Specification and Mechanical Properties of Nickel Aluminium Bronze*

| *Material* | *%Mass* |
|---|---|
| Manganese | 1.25% |
| Aluminium | 9.5% |
| Nickel | 4.5% |
| Iron | 5.0% |
| Manganese | 1.25% |
| Copper | balance |
| UTS | 680 MPa |
| Young's Modulus | 124 GPa |

Three ship designs are at risk—Type 21, Type 42, and Type 22, in descending order of design stress level. The latter are still building and development of the role and displacement of these ships had already dictated that the propeller design be re-examined. These two facts led to this class being the first to undergo a propeller blade re-design, and thus taking advantage of the revised specifications. Type 22—12 onwards will benefit from this design—the Type 22 design 'C'—and a procurement programme for back-fitting the whole class is under way. A further advantage of this course of action is that the discarded Type 22 blades are suitable for use on Type 21, thus saving additional procurement costs. The same is not possible with the Type 42 without significant loss of performance, and a further re-design exercise is under way for this class.

## Other Developments

### *Agouti Channel*

The Agouti channel design has been a recurring problem in CPP blades and several important steps have been taken to try and improve this feature. The biggest step, regrettably unsuccessful, was an attempt in new designs to 'core in' the Agouti tube within the casting out to O.6R, in order to take the welded portion out of the most highly stressed region of the blade. Three attempts were made with the prototype design 'C' blades and the development has been shelved for the time being to allow full investigation of reasons for the failure and possible alternatives. The method chosen for the production design 'C' blades is a combination of NC machining and drilling. The channel is placed on the suction face in order to put the welded cover plate into compression rather than tension (as in current designs), drilled out to O.4R, and the remainder NC machined thus allowing very close control of the channel cross-section shape and weld preparation.

### *Surface Finish*

Poor surface finish of the suction surface of CPP blades has been a characteristic of CPP blades for some years. Weld repair of the areas of porosity and oxide inclusion which give rise to the erosion and pitting evident in service is very difficult because of the absence of sound base metal with which to achieve good fusion in areas of porosity. A metal spray repair process has been developed by CNA in conjunction with YARD at Bristol and is being applied experimentally to blades undergoing repair at Stone-Vickers. ARE(DL)(Portsmouth), at the same time, have been examining the use of epoxy filling of non-critical surface defects in ships in service.

### *Inspection Standards*

The existing standard has now been used in the current Type 22 CPP blade contract for over a year and is being updated to reflect the experience gained by the manufacturer and MOD(N).

### *Operational Considerations*

The CPP blade failures have occurred during the time since single shaft running has become an established mode of economical operation. For a given shaft speed the propeller stress is higher when operating in this fashion because of the increased torque, and to achieve the desired ship's speed the propeller is required to operate for longer periods at higher powers than in conventional two-shaft operation. Assumptions are made in warship propeller design about the relationship between maximum design stress and operating profile which allow a far higher maximum value to be used than in merchant design practice. The existing assumptions are no longer correct because the propeller operational profile has changed with the advent of prolonged single shaft running and careful consideration is currently being given to the allowable torque limits when operating in this mode in order to protect the propeller blade life in the COGOG ships.

## Conclusions

CPP blades have failed in service because the established manufacturing standards, based on commercial practice, were insufficient for the increased design stress levels that had been chosen as a result of the constraints imposed on CPP blade geometry and the published properties of Superston 70. Steps have now been been taken to change the design specification, following careful re-assessment of the properties of propeller alloys, by lowering the maximum allowable design stress and selecting nickel aluminium bronze for all future CPP propellers. Manufacturing standards have been significantly tightened and have a direct relationship with the known properties of the alloy concerned and with the propeller duty. However, it will be 1988 or 1989 before the blades currently under manufacture at Stone-Vickers are in service in the later Type 22s and 1988 before the first of the displaced Type 22 blades is fitted to a Type 21 as the type 22 back-fit programme begins. For those ships in service the protection against failure is careful and painstaking inspection of the critical areas whenever the opportunity permits, aided in the near future, it is hoped, by improved NDE and cleaning techniques to allow the defects to be discovered before they reach the blade surface. There has been no failure at sea since February 1984 and there are some grounds for guarded optimism that in-service inspection is achieving its objective, added to which the normal attrition rate for CPP blades ensures that there is a continuing dilution of the 'at-risk' blades with those repaired and quality assured.

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# APPENDIX—NDE TECHNIQUES

## Radiography

Radiography (FIG. 7) can be used for the detection of defects that give rise to voids in the specimen and others which are in line with the radiation beam. Examples of these (FIG. 8) are:

(*a*) Lack of weld fusion arising from poor penetration, lack of inter-run or side wall fusion (though the latter would be probably require angle beam radiography).

(*b*) Cracks (though tight cracks at large angles to the beam may not be seen).

(*c*) Slag—non-metallic or metallic inclusions (e.g. tungsten or copper, dependent on the weld process).

(*d*) Porosity, wormholes (or piping), elongated cavities.

Such features as surface imperfections or plate laminations will not be seen, as they create no voids. The minimum detectable defect size depends on the source used, the material, and the thickness and geometry of the blade.

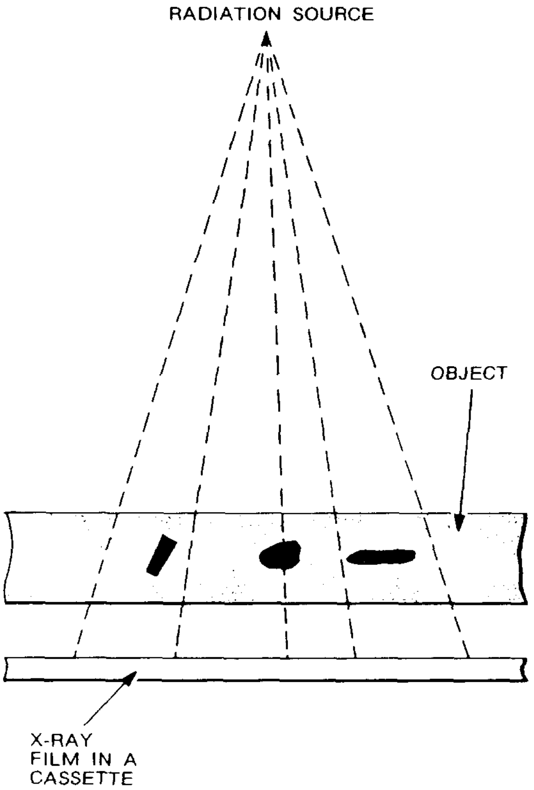

FIG. 7—PRINCIPLES OF RADIOGRAPHIC CRACK DETECTION

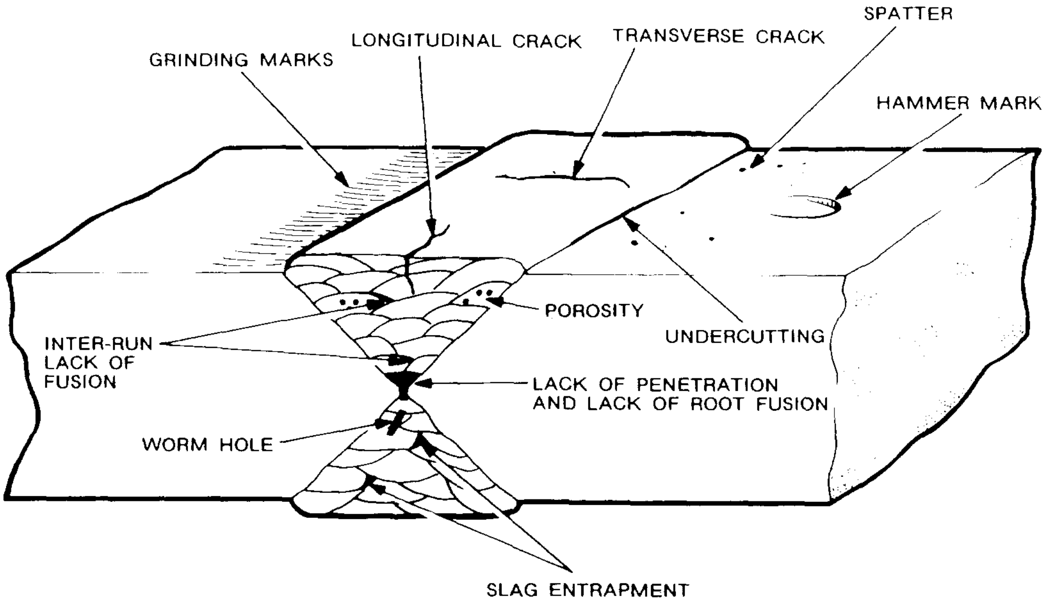

FIG. 8—TYPICAL WELDING DEFECTS

**Ultrasonics**

This technique is suitable for the examination of welds and is capable of detecting a variety of flaws provided they exhibit sufficient area in a plane at right angles to the beam (FIGS. 9, 10 AND 11). A variety of angled probes may therefore be required to achieve positive identification of a defect. The limit of defect detectability is set by the operating frequency which is normally in the range 2 to 6 MHz, the smallest crack size then being approximately 0.5 mm. Gross areas of such phenomena as porosity or oxide entrapment act as signal attenuators and render defect interpretation impossible.

Radiography and ultrasonic testing are to a certain extent complementary because of their preferential ability to detect defects in orientations 90° apart. However, both require great operator skill for correct interpretation, and the shortcomings of ultrasonics *vis-à-vis* porosity and oxide entrapment render it impracticable for the critical areas of propellers.

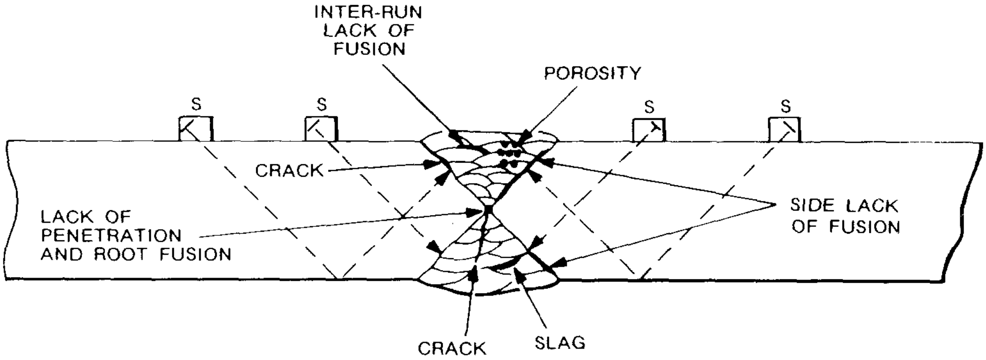

FIG. 9—ULTRASONIC CRACK DETECTION ON A BUTT WELD
*s: shear wave probe or angled probe*

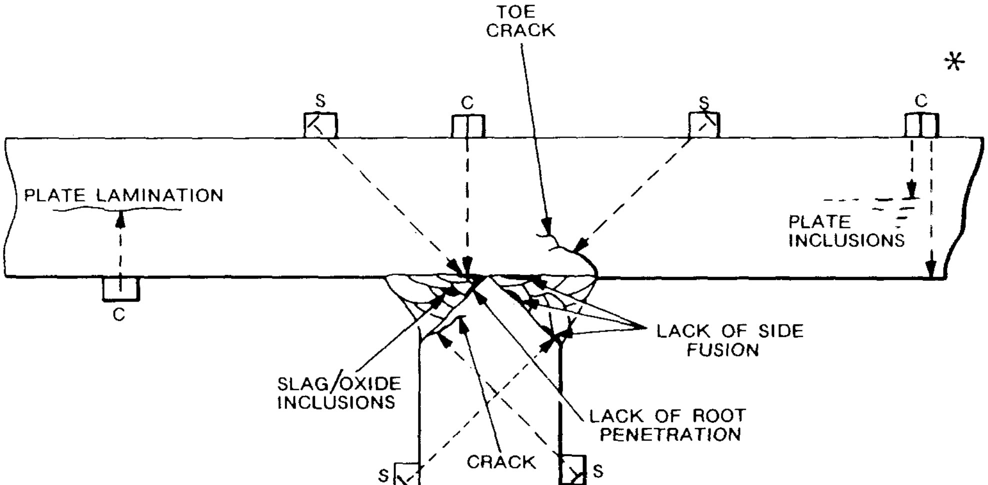

FIG. 10—ULTRASONIC CRACK DETECTION ON A FILLET WELD
s: shear wave probe or angled probe
c: compressional wave probe or vertical probe

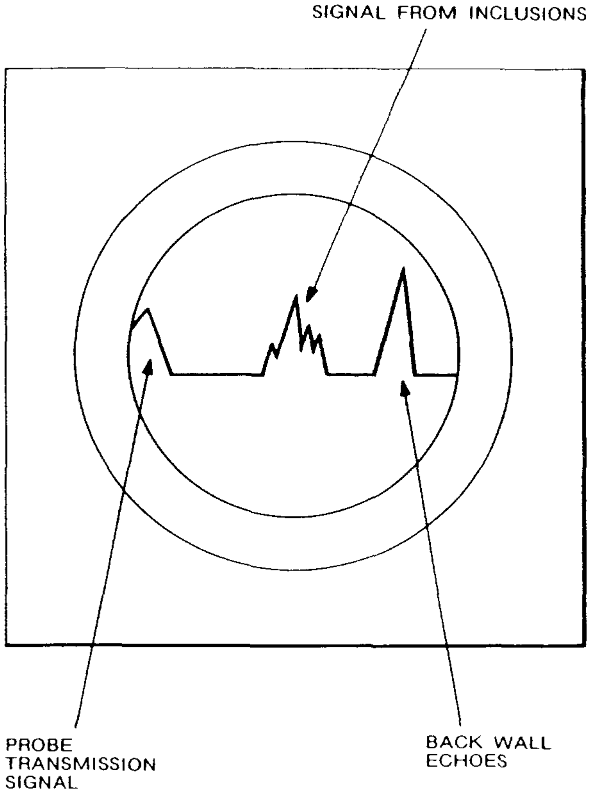

FIG. 11
TYPICAL OSCILLOSCOPE TRACE FOR ULTRASONIC INDICATION OF INCLUSIONS IN PLATE (* IN FIG. 10)

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