MAIN PROPULSION PRIMARY GEAR WHEEL FAILURES IN TYPE 42 AND TYPE 21 SHIPS

BY

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This article is based on the research work carried out by Lieutenant Boggust, supervised by Lieutenant-Commander Botten, at the Royal Naval Engineering College, Manadon, as part of the Advanced Marine Engineering M.Sc. Course that was completed in July 1978. Comments on the findings are given by Messrs. David Brown Gear Industries Limited and by the Ship Department.

Introduction

The type 42 destroyers and the Type 21 frigates are twin-shafted ships, each shaft being driven by either a Rolls-Royce Olympus or a Rolls-Royce Tyne gas turbine in a COGOG arrangement. Unidirectional drive to the propeller shaft is through a double-reduction, dual-tandem, double-helical gearbox, as shown diagramatically in FIG. 1.

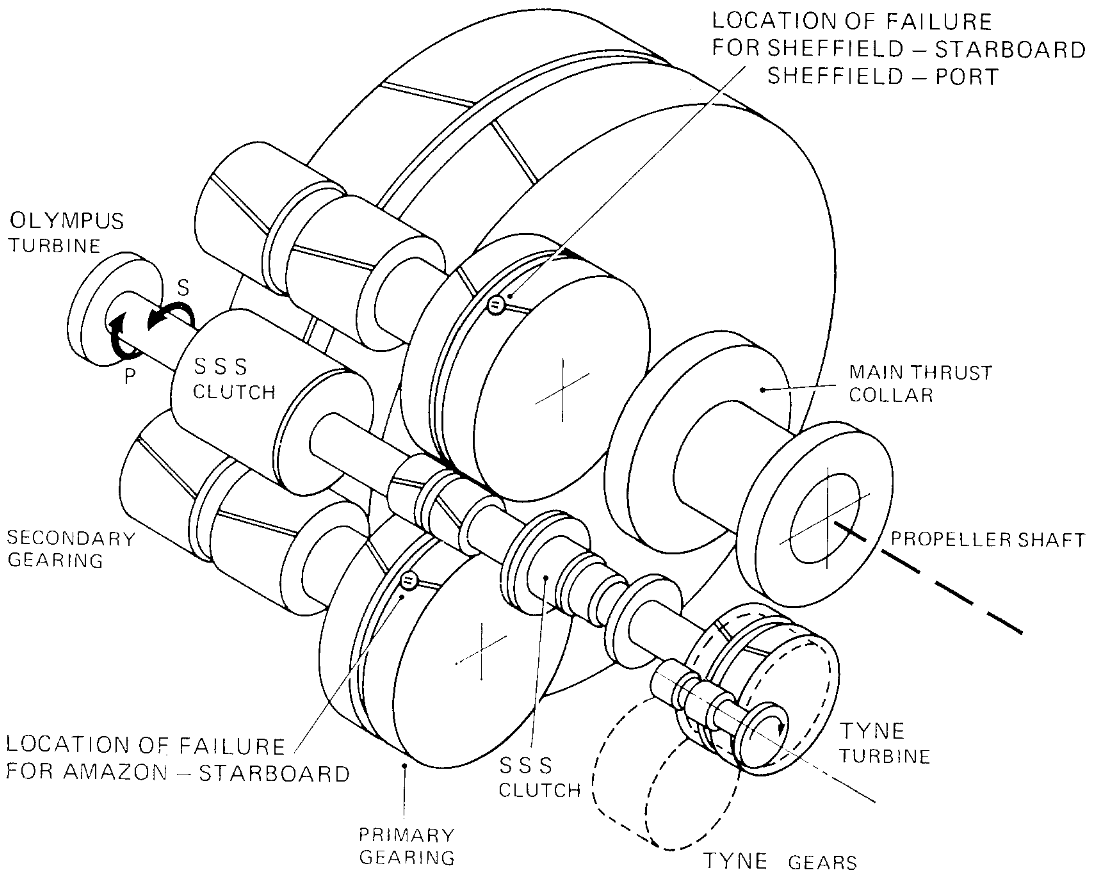

FIG. 1—SCHEMATIC DIAGRAM OF TYPE 42 DESTROYER STARBOARD GEARING. PORT GEARING ARRANGED OPPOSITE HAND, WITH IDLER WHEEL FITTED IN TYNE GEARS SHOWN DOTTED

Early in 1977, failures of teeth by breakage or cracking were discovered on the after helix of the primary gear wheels of H.M.S. *Sheffield* and of H.M.S. *Amazon*, Type 42 and 21 respectively. The location of the failures is given in FIG. 1.

The failed primary gear wheels were designed to GMES specification[1] and the appropriate Class Marine Engineering Specification. They were manufactured from nitrided EN40B (722M24)[2] and the meshing pinions from case-carburized EN36A.

As a result of the failures, extensive investigations into their cause were undertaken by the gear manufacturers and by MOD(N), but their reports[3, 4] failed to conclude a mechanism for failure.

The aim of this investigation at the Royal Naval Engineering College was to conclude a mechanism for failure.

Direction of Investigation

A close analysis of the previous investigations into these primary gear wheel failures revealed areas which warranted further study:

Precise Location of Failure

The earlier investigations had shown a difference of opinion over the location of the initiation of the bending fatigue failure—whether this had been at the tooth flank surface or sub-surface.

Pitting of the Primary Gear Wheels

Tooth profile traces of the after helices were seen to be rougher than the forward helices by their more jagged appearance. The parameters of tooth flank roughness, lubrication, and tooth contact stress have been shown to be related to the surface-initiated gear failure phenomenon of pitting.[5, 6]

The Effect of Inclusions on Fatigue Performance

The fatigue performance of the steel of the failed primary gear was low when compared with previously documented tests of EN40B in the nitrided condition.[7] The effect of inclusion size is known to be at least one factor which can lower the fatigue performance of a steel,[7] and the distribution of the inclusions within the gear wheel steel had been expressed by a previous investigation of the failure as a cause for concern.[4]

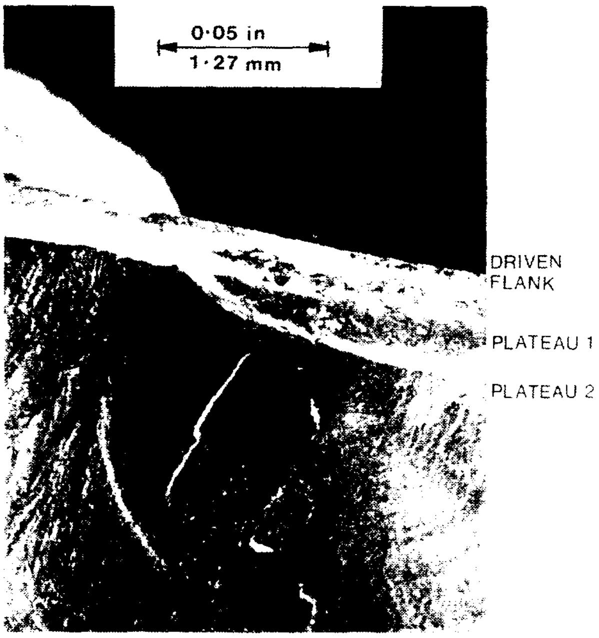

FIG. 2—VIEW OF TOOTH FRACTURE FACE SHOWING ORIGIN OF FATIGUE FRACTURE

Investigation

The investigation was split into three distinct though related areas as follows:

(*a*) Scanning electron and optical microscopy of a failed gear tooth and other failed test specimens.

(*b*) Disc testing under gear contact conditions experienced by the gear mesh to assess the surface fatigue or pitting characteristics of EN40B.

(*c*) Rotating bend fatigue tests of nitrided EN40B.

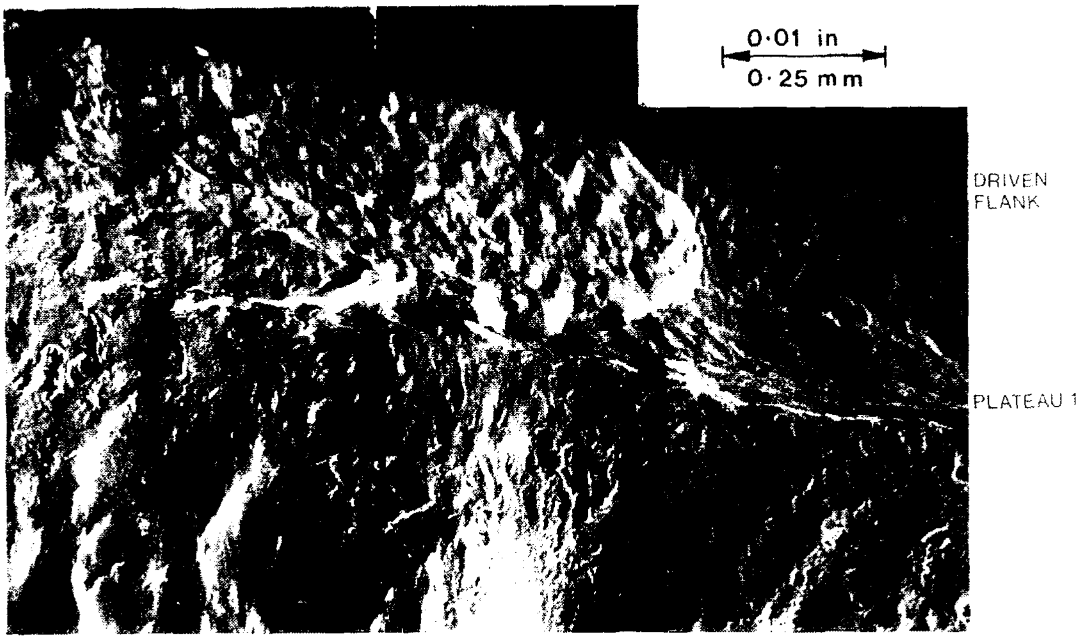

FIG. 3—VIEW OF PLATEAU No. 1 SHOWING CRACK ON FRACTURE FACE

FIG. 4—CRACKING, SPALLING, AND PITTING ON SURFACE OF DRIVEN FLANK OF TOOTH

Results and Discussion

Examination of Gear Tooth Failure

The scanning electron microscope was employed to assess the salient features of the fracture of a failed tooth from H.M.S. *Sheffield's* No. 1 starboard gearbox. The fracture surface of this specimen was viewed looking parallel to the surface of the driven flank of the tooth. The area shown in FIG. 2 illustrates the origin of the bending fatigue failure which appears to emanate from the lower of the two planes or plateaux designated plateau No. 1 and plateau No. 2 as shown, these plateaux being parallel to the driven flank of the tooth. The lower plateau was seen to contain probable sites of inclusions, and the upper plateau ran into a crack on the fracture surface (FIG. 3) which appeared on the surface of the driven flank of the tooth in an area of shallow pits and spalls (FIG. 4).

FIG. 5—SECTION OF TOOTH SHOWING CRACKING BETWEEN DRIVEN FLANK AND FRACTURE FACE

This failed tooth was sectioned, and under the optical microscope it was seen that two cracks existed: one originating from the driven flank and one from plateau No. 1 (FIG. 5). Also, a group of three inclusions was found at or adjacent to the fracture surface at a depth of 0·04 in (1·02 mm) from the driven flank, the largest of which was 0·01 in (0·25 mm) in length.

Microhardness traverses were undertaken through the nitrided case in the area of the bending fatigue initiation and it was found that there was a sharp rise in hardness to over 800VPN at a depth of plateau No. 1. This rise in microhardness was very localized and at about 0·032 in (0·81 mm) back from the fracture face its value had fallen back almost to the tooth tip value which had been taken as a datum. FIG. 6 gives the results of these traverses. The rise in microhardness was caused by the presence of a stress raiser which in this case could have been an inclusion.

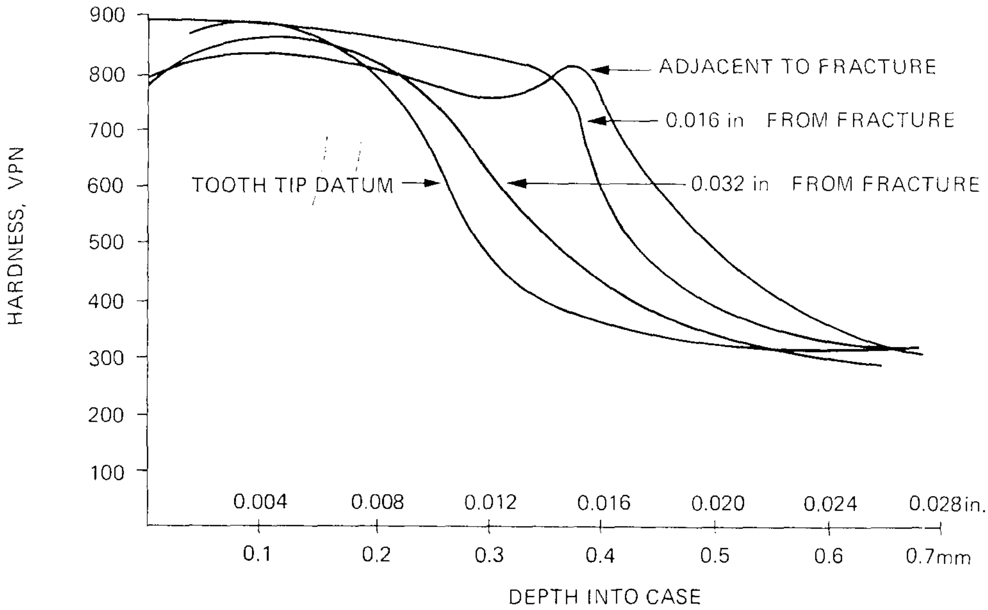

FIG. 6—MICROHARDNESS TRAVERSES (100 g) OF NITRIDED CASE ADJACENT TO FRACTURE SURFACE

The evidence from the microscopical observations of the failed tooth was that subsurface cracking had occurred parallel to the surface of the driven flank of the tooth at depths of plateau 1 (0·015 in; 0·38 mm) and plateau 2 (0·026 in; 0·66 mm) and that their initiation was possibly due to inclusions. A surface crack on the driven flank of the tooth had also been observed although no indication of its initiation could be ascertained.

Disc Testing

Surface cracking or pitting of the surface of the driven flank of gear teeth has been observed using Disc Tests (References 5, 6, 7, 9, 10, 11, 12, 13, 14, 15, 16, 17, and 18.)

These tests can simulate gear contact conditions taking into account surface roughness, oil film thickness, and contact stresses at the driven flank of gear teeth. Previous researchers had not undertaken tests of nitrided discs which took into account all the forementioned parameters. An assessment of the surface cracking characteristics of a nitrided EN40B, carburized EN36A combination was carried out on the disc-testing rig at the National Gas Turbine Establishment at Cobham. The contact stress used was calculated as the maximum that the gear wheels were likely to experience in service, the oil film thickness used was calculated as the minimum likely to be experienced, and the surface roughness was taken from talysurf measurements of the gear wheels. Comprehensive details of how these conditions were derived are given in the author's thesis.[19] After running 7·5 × 10^6 cycles, a shallow pit with a surface crack extending from it was observed; at 8·4 × 10^6 cycles, the crack had extended axially to 0·072 in (1·83 mm) and was sharply defined; and by 1·76 × 10^7 cycles, the axial growth had ceased. Fig. 7 shows the extent of the crack after 1·76 × 10^7 cycles. It was concluded that, as the crack had ceased to grow axially, it could possibly be propagating into the body of the disc by the hydraulic pressure of the oil trapped in the crack when it is sealed by the rolling action as it passes through the zone of Hertzian contact.

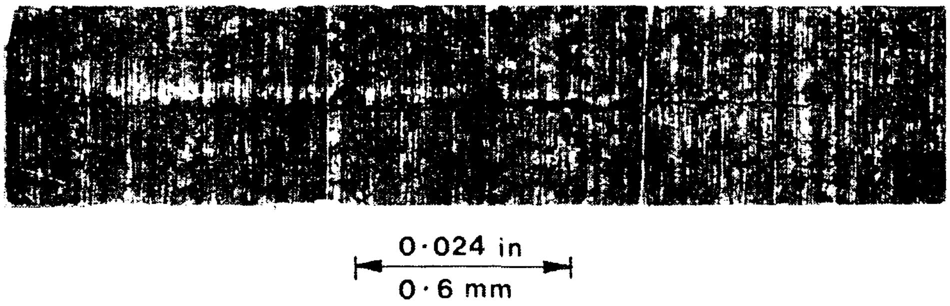

Fig. 7—Nitrided disc track after 1·76×10^6 cycles (replica micrograph)

The associated spalling or pitting of the disc track surface bore a marked similarity to the flank of the failed gear tooth (Fig. 4). The test also showed that it was possible to initiate surface cracking on the driven flank of the tooth under a simulated service condition.

The Effect of Inclusions on Fatigue Performance

Rotating bend fatigue tests were carried out on nine specimens cut from H.M.S. *Amazon*'s failed primary wheel and nitrided as per the original gear. A S–N curve could not clearly be derived due to the small number of specimens although all specimens failed even at the lowest stress applied (25·5 tons.in^{-2}) which gave a highly unsatisfactory fatigue ratio of under 0·44.

Initiation of the fatigue failures was at the case/core interface of the specimens and was generally caused by an inclusion, typically 0·01 to 0·014 in (0·25 to 0·36 mm) in size.

Scanning electron microscopy of the fracture surfaces was carried out and inclusions on the surfaces were analysed by the Energy Dispersive Analysis of X-rays (EDAX) attachment. Analysis of the inclusions which initiated the fatigue failure all showed a heavy concentration of aluminium and other constituents (calcium, magnesium, and silicon) were detected. Fig. 8 shows an example of one of these inclusions, and Fig. 9 gives the dispersion of aluminium which can be seen to be associated with the inclusion. These inclusions containing aluminium were detected in other regions of the fracture surfaces, and manganese sulphide inclusions, mainly in the form of stringers, were also detected and

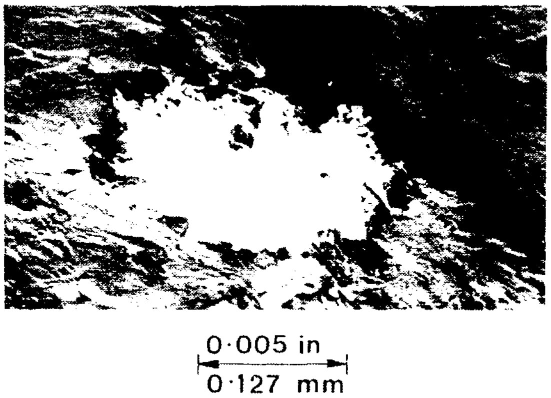

FIG. 8—INCLUSION AT INITIATION OF FATIGUE FAILURE

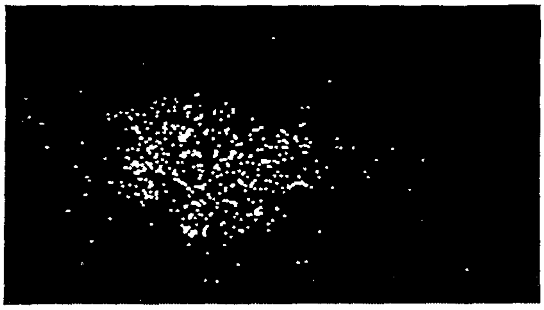

FIG. 9—ALUMINIUM SPOT MAP OF INCLUSION IN FIG. 8

FIG. 10—LARGE INCLUSION IN FRACTURE SURFACE

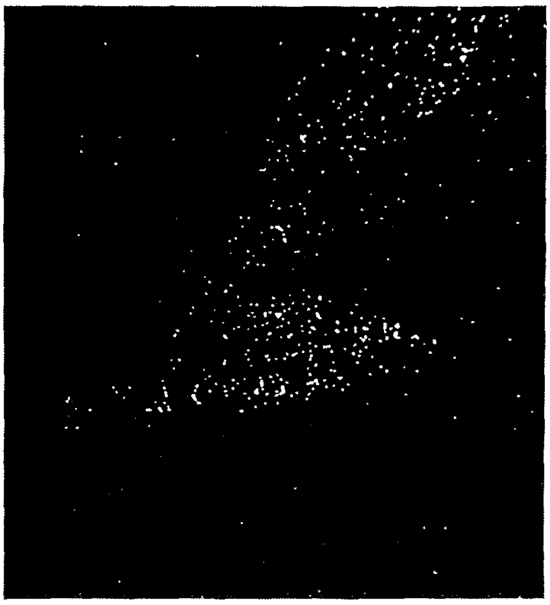

FIG. 11—ALUMINIUM SPOT MAP OF INCLUSION IN FIG. 10

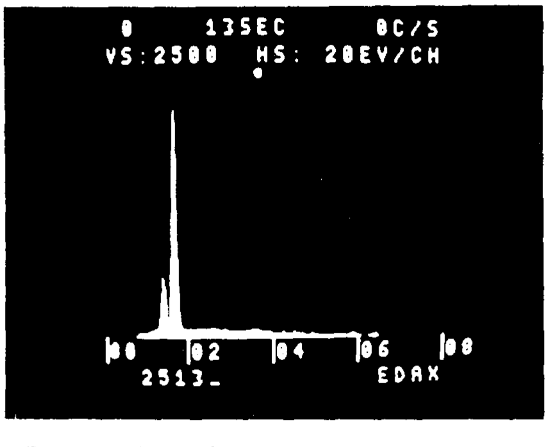

FIG. 12—'EDAX' QUALITATIVE ANALYSIS OF THE CORE REGION OF INCLUSION IN FIG. 10 SHOWING ALUMINIUM AND SILICON PEAKS

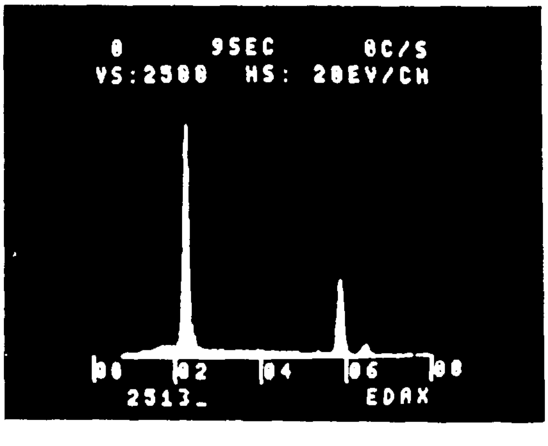

FIG. 13—'EDAX' QUALITATIVE ANALYSIS OF THE PERIPHERY OF INCLUSION IN FIG. 10 SHOWING SULPHUR AND MANGANESE PEAKS

analysed. In some cases, aluminium bearing inclusions and manganese sulphide inclusions were found in close proximity to each other.

This association was also detected when specimens, prepared for optical microscopy, were analysed (FIGS. 10, 11, 12, and 13). The aluminium bearing inclusions are indicative of slag inclusions from the original cast and they could act as stress raisers.

FIG. 14—SULPHUR PRINT OF H.M.S. 'SHEFFIELD' NO. 1 PRIMARY WHEEL (TAKEN AXIALLY)

Other Significant Results

To assess the inclusion distribution between the forward and after helices, a sulphur print was taken from the rim of the failed port wheel of H.M.S. *Sheffield* (FIG. 14). This shows that the concentration of sulphides (and, in fact, aluminium bearing inclusions by their association with sulphides) had a tendency towards the forward helix. As cracking and tooth breakage had always occurred on the after helix, some other mode of failure must have existed although the presence of slag inclusions had a contributory effect.

Failure Mechanism

The following failure model of the tooth specimen from No. 1 starboard primary wheel of H.M.S. *Sheffield* was deduced. (see FIG. 15).

A surface fatigue crack initiated by the asperity interaction between the contacting primary teeth propagated into the driven flank away from the pitch point and curved towards the plane of maximum shear stress in the nitrided case. At the same time, inclusion-initiated fatigue cracking developed parallel to the tooth flank at depths of 0·015 in (0·38 mm) and 0·026 in (0·66 mm) by the shear stress induced at tooth contact. These cracks are indicative of rolling contact fatigue mechanisms. The surface crack and the crack at a depth of maximum shear stress propagated until a crack formed between them. The hydraulic action of tooth contact caused the cracks to propagate rapidly and a large pit was formed. Bending fatigue failure then followed caused by the stress-raising influence of the pit.

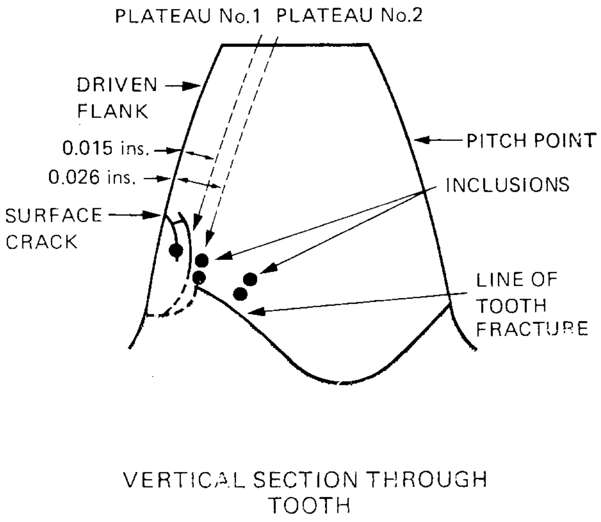

FIG. 15—MODEL OF TOOTH FRACTURE OF H.M.S. 'SHEFFIELD' NO. 1 STARBOARD PRIMARY WHEEL TOOTH (NOT TO SCALE)

Conclusions

Failure of the No. 1 starboard primary wheel of H.M.S. *Sheffield* was due to bending fatigue, initiated by rolling-contact fatigue mechanisms and exacerbated by the stress-raising effect of slag inclusions within the steel of the primary wheel.

The controlling influence for the location of the rolling contact fatigue, surface crack initiation sites (as determined by disc testing) was the greater roughness of the primary wheel after helix.

The fatigue performance of the steel of the primary wheel (as determined by rotating bend tests) was rendered inadequate by the presence of slag inclusions.

Acknowledgements

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Comment by David Brown Gear Industries Limited

Having had available for examination not only this article but also the M.Sc. thesis report on which it is based, we congratulate Lieutenant Boggust on an excellent piece of work. The investigation into the metallurgical aspects and into those immediately surrounding was thorough and painstaking. The effort was, however, concentrated on to only one aspect of the several that were considered by D.B.G.I. during the investigations that were carried out there. In particular, the question of the location of the failure has been considered as distinguishing between surface and sub-surface initiation. Whilst this is of great academic interest, its importance to the design is small compared with the question of why the failures all occurred on the after helix.

When the problem was notified to D.B.G.I., a theoretical investigation was initiated. The first steps in this were the analysis of the meshing conditions and the stresses resulting using standard computer programs. These programs have all been developed since the gears were designed (in 1968) and using them it became apparent that the GMES specification in use at that time was optimistic with respect to the load carrying capacity of nitrided gears. This first investigation also showed that failure was more likely (by a margin of 20 per cent. on load) at the forward end of the forward helix than at the actual failure point. Because of the statistical nature of the factors involved in gear tooth failures, this discrepancy was not considered important initially when only one broken gear had been reported. However, when three failures at roughly the same location had been observed, it was realized that there must be some definite cause. The phenomenon which actually transfers the failure location in gears is misalignment. In this case, however, it is impossible to conceive of body displacements and/or rotations which would have the desired effect. Geometric and metallurgical differences between the helices were considered and rejected; the differences were either deemed insignificant or, as in the aspect of slag inclusions, effective in the wrong direction. (It is interesting to note that Lieutenant Boggust's article confirms this latter point.) Thermal distortions were examined and discarded as a possible source. The remaining possibility, that of their being an axial load which unbalances the torque between the helices, was never completely rejected nor was it substantiated.

Lieutenant Boggust's explanation that the relatively small differences in surface finish are the cause is contrary to current thinking and is not supported by the last NAVGRA evidence. We feel that the evidence put forward in the article, which is based on the testing of only one disc, is not conclusive.

One further point is that, whilst acknowledging the desirability of a cleaner steel, the effect of the slag inclusion has, we believe, been over emphasized. This material conformed to DGS 6019 specification with respect to freedom from defects and there is no conclusive evidence that the fatigue properties were reduced below the levels normally to be expected. In fact, Wohler tests carried out on cleaner steel gave much the same endurance limit as did those taken from the failed wheel, the observed limit being approximately that predicted by the techniques used for the gear analysis described earlier.

Comment by Ship Department

These totally unexpected gear failures severely shook the confidence of the Ship Department and the gear manufacturers in the adequacy of the nitrided gear material (EN40B). It had been used in this application because it offered advantages in cost, production timescales, and freedom from risk of scuffing. Considerable effort has been expended to explain these failures and although, in retrospect, it is possible to conclude that these gears had insufficient margins to accept the heavy and frequent overloads to which gas turbine ships are subjected, we still lack a generally accepted explanation of the mechanism of failure on which to base a criterion for future designs. Lieutenant Boggust has contributed significantly to the search for such understanding and the Ship Department would reiterate the congratulations offered by D.B.G.I.

Although he has succeeded in opening up a number of interesting possibilities, we agree with D.B.G.I. that the work he has done is not sufficient to justify the firm conclusion that differences in surface finish determined the position of the failures.

The failure mechanism of nitrided gears, whereby a crack propagates from just below the pitch line, is not anticipated by either of the traditional gear loading criteria: the K factor, which assesses the risk of pitting; and the Root Bending Stress, which measures the risk of root fracture. In these circumstances, nitrided materials cannot be used with confidence. Fortunately the Royal Navy has substantial experience with two alternative case hardened gear steels the failure mode of which can be adequately predicted—EN36A carburized and hardened, and EN24T induction hardened. It has therefore been decided to fit retrospectively replacement primary gear trains in the Y205 gearboxes with wheels made from EN36A. This material would also be used for primary wheels of the remaining gearboxes for new construction.

Further work is clearly required to establish or refute Lieutenant Boggust's important claim regarding surface finish and also to investigate, in service, the load distribution between the two helices as proposed by D.B.G.I. It is hoped to proceed on both of these issues so that heavily loaded nitrided gears may once again be used with confidence. The ready availability of adequate alternative steels has, however, reduced the priority of this work.