'MACHINING TYPE' TURBINE BEARING FAILURES

This article is an Admiralty appreciation of various factors associated with the phenomena of 'machining' or 'wire wool' bearing failures in turbine machinery. Although H.M. ships have not suffered such failures, it has appeared desirable to investigate reports and research in this field due to various opinions which were being freely expressed by certain authorities. In recent months opinion has hardened to some extent, and it appears that there may be good reasons why naval machinery is adequately protected from such failures.

Introduction

General information relating to recently reported failures in service of thrust and journal bearings, and the findings of preliminary laboratory work which has been undertaken with a view to establishing the cause and/or mechanism of failure, are described below. The information so far collected on this subject is by no means complete and insufficient evidence has been acquired by the R.N. to establish definitely either the cause or mechanism of these failures.

A number of relatively rapid failures of turbines have recently been reported in the U.S.N., R.C.N. and U.K. land service, and in the Merchant Navy which are associated with a phenomenon described as 'machining' of the steel thrust collars and bearing journals.

The R.N. is anxious to establish a full understanding of this phenomenon, as it would appear possible that conditions in H.M. ships are such that it might occur, although H.M. ships have not been so affected to date. Preliminary investigations into these failures have resulted in more than one suggestion as to the causes and/or mechanism of failure, but there is wide agreement that inclusions of dirt, probably steel particles, embedded in the bearing material, trigger-off this machining phenomenon under certain suitable conditions. These inclusions may be initially hard or subsequently hardened in some way and eventually lead to the characteristic machining of the collar, normally causing extensive damage and failure. Three factors suspected of giving rise to these 'suitable conditions' are tabulated below.

(*a*) The use of an E.P. lubricating oil together with $\frac{1}{2}$ per cent molybdenum steel shafts or thrust collars

(*b*) The use of high chrome steel journals (i.e. containing 3 per cent or more chromium) with non-E.P. mineral oils

(*c*) Inadequate filtration in some lubricating oil systems which allows the phenomenon to occur with a variety of conditions.

An investigation of the evidence available from turbine thrust bearing failures of all types in merchant ships over the last five or six years (still incomplete, but already covering some 60 or so failures) may be considered to provide some statistical evidence against E.P. oils. It is not known how many of these failures were of the machining type, although some certainly were. Though it is rather conflicting the evidence also indicates the importance of (*c*), above, relating to the possible ingress of dirt or swarf, in that there appeared to be a much higher incidence of failures during the first few months of operational life of new or 'refitted' installations. It may or may not be coincidental that the use of E.P. oils under such circumstances has increased considerably over the same period.

Two rather startling cases which came to light during this investigation were briefly as follows:

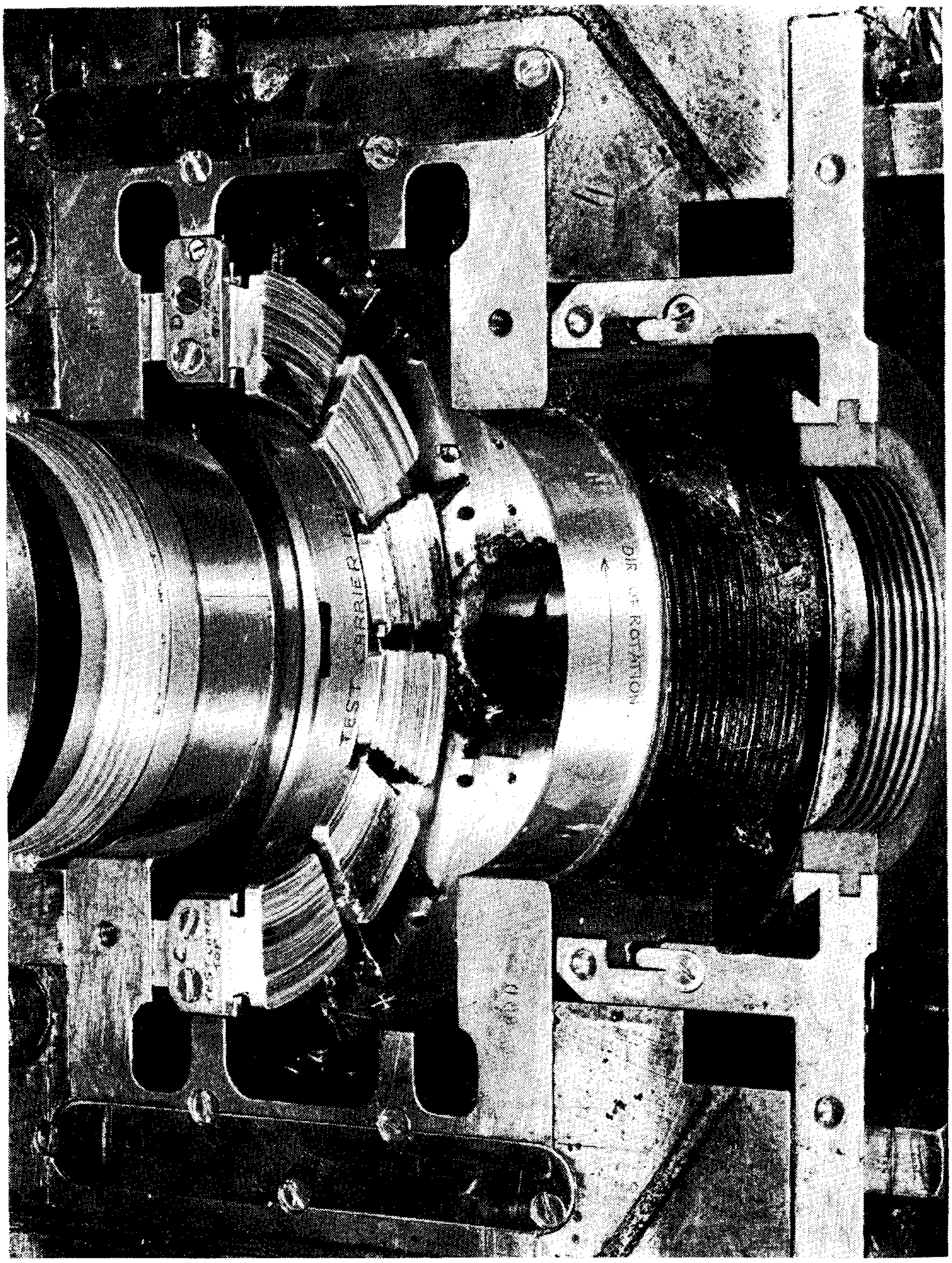

FIG. 1—AN EXAMPLE OF A MACHINING TYPE FAILURE ON A THRUST BEARING TEST RIG SHOWING THE SCABS ON THE WHITEMETAL PADS AND WIRE-WOOL DEBRIS

(Courtesy of the British Ship Research Association)

(*a*) Four practically identical ships were built for the same owner, in pairs in different yards. The builder of one pair ran them in on E.P. oil and had thrust collar failures in both ships; the other builder used conventional double inhibited turbine oil and had no failures. In these cases H.P. collars were of nickel-vanadium steel, and L.P. collars of carbon steel.

(*b*) A fairly old ship which had a history of three thrust failures over 12 years whilst using non-E.P. oil, was refitted and filled with an E.P. oil; five such failures occurred during the following 18 months. Collar material was carbon steel but other details are not known, except that a higher standard of cleanliness appeared to prevent further failures.

A Suggested Mechanism of Failure

Dawson and Fidler, whose paper is one of the few on the subject so far published, are concerned primarily with failures of 3 per cent chromium $\frac{1}{2}$ per cent molybdenum steel journals. They have demonstrated that the failures may be caused by a mild steel particle carried into the bearing by the lubricating oil, being partially embedded in the whitemetal, and finally becoming a nucleus for the build-up of shaft-wear detritus in such a way as to bridge the oil film. The resultant rubbing on the shaft could generate sufficient local heat to cause oil to 'flash', and to release active carbon compounds from the oil which combine with the steel detritus to produce a carburized material (black scab) which is virtually a tipped cutting tool. This leads to rapid machining of deep grooves (e.g. $\frac{1}{8}$ in. in 10 minutes) in the journal. The process appears to be self-propagating under suitable conditions. It is interesting to note that the lubricating oil used was not an E.P. oil and that the material was $\frac{1}{2}$ per cent molybdenum steel, but it seems possible that a similar mechanism operated in the thrust bearing failures in which E.P. oils were involved.

Following on this work the same Company has been able to initiate a similar phenomenon at will using non-E.P. oils in a test rig, which incorporates a small lubricated whitemetal pad running against a rotating steel disc at various loads. Machining can be triggered off by the insertion of a mild steel pin through the whitemetal pad in such a way as to protrude through the lubricating oil film. Work on this rig has also shown that the use of certain E.P. oils may actually prevent failures with a range of different steels, including the one containing 3 per cent chrome and $\frac{1}{2}$ per cent molybdenum. No detrimental E.P. additive effect was found by these workers. The rig has also shown that it is difficult to produce failures with plain carbon steels, as used in many turbines, and this correlates with the low incidence of failures in actual service with this type of steel using any type of oil.

Metallurgically, this mechanism is very interesting, and, perhaps, even surprising. It involves local frictional heating, sufficient to raise at least the tip temperature of the steel fragments to 800 degrees C. or more, and to flash a sufficient quantity of lubricating oil to carburize them while in an oil flow with sufficient heat-transfer capacity to produce the quenching stage which gives the 'hardened' steel cutting edge. The susceptibility of air- or oil-hardening alloy steels is therefore likely to be greater than that of plain carbon steels and this is, of course, what has been found. Cavitation due to bubble collapse, or contamination could explain high temperatures of this order.

If, as seems likely, the formation of a carbide or a hardened cutting edge depends on the establishment of high temperatures, the combination of speed with load or pressure is probably an important parameter. Lower speeds and/or loads may therefore partially explain the absence of failure in some installations, in particular older installations, and the higher incidence of failures in some newer, higher temperature designs. On the other hand U.S. authorities tend to regard lower operating powers as more likely to produce such failures. It might, however, be surmised that high powers and high loads produce thinner oil films, with a greater risk of bridging.

The heat generated in the black scab through machining the collar or journal is known frequently to melt the surrounding whitemetal. This generation of heat, combined with the quenching effect of the oil, may also crack and break up the scab, so that it is washed away with the oil. Both these factors may contribute to some 'complete' failures of bearings, where most of the 'evidence' is lost.

The Steel Factor

Most of these types of failure have occurred in marine service, with E.P. oils and $\frac{1}{2}$ per cent molybdenum steel, or, in land service, in turbine and generator journal bearings, generator hydrogen seals and a gas-turbine compressor with non-E.P. oils and 3 per cent chromium steels. However, there appear to have been many exceptions to the rule, particularly in the marine application. A limited survey of merchant ship thrust failures pointed to a high incidence when using E.P. oils, but, as previously stated, the Admiralty draws no firm conclusions from this rather incomplete evidence.

It is quite clear, however, that suspicion is directed towards $\frac{1}{2}$ per cent molybdenum steel on the marine side and to steels containing 3 per cent or more of chromium on the land side. More theories have been advanced in relation to the latter than to the former, including suggestions about their scuffing tendency and wettability; but it is doubtful if any other is as valid as that related to their quench-hardening characteristics.

Nevertheless, different organizations appear to be trying out varying palliatives related to these suggestions, such as sleeves of reputably less susceptible materials, and various surface treatments, such as phosphating, electro-plating, and metal-spraying, and the use of hardened collars. It is clear that the normal wear process may eventually remove the thin surface treatments and the danger of machining could recur.

A survey of a limited number of materials used in turbine rotors and in thrust collars within the R.N., and in certain merchant ships, indicates that a significant factor might be the hardness of the steel concerned. Most R.N. steels are somewhat harder than those used in mercantile practice, and this might partially explain R.N. immunity from those failures.

The Oil Factor

It is, of course, impossible to completely separate any of the factors mentioned. However, certain organizations in the U.K. and in the U.S.A. have directed strong suspicion towards E.P. additives, particularly those containing chlorine, and some evidence to support this suspicion has been advanced. This relies heavily on the statistical analysis previously mentioned of all thrust bearing failures, although circumstantial evidence exists from certain laboratory trials. The Admiralty believes that it has so far been impossible to reproduce this phenomenon at will on a thrust bearing rig with either E.P. or non-E.P. oils in natural conditions. The use of a pin inserted through a pad is so far the only successful approximation. The recent reluctance of the U.S.N. and U.K. Mercentile Authorities to use chlorine-containing E.P. additives, with or without the presence of molybdenum steel, is openly admitted to be based only on this inconclusive type of evidence. It is perhaps arguable that the mechanism by which chlorine containing additives operate in cutting oils could be similar to their operation in E.P. oils. The relationship with the observed machining phenomenon would still need to be established.

The Bearing-Metal Factor

Most of the failures reported have been associated with whitemetal bearings and no one appears to have taken any interest in their composition. It is generally believed to be of no consequence. However, it may be worth reporting that not all failures have been so associated. One case, at least, involved a leaded-bronze bearing which was probably much harder than whitemetal, although still softer than the steel with which it operated.

The Cleanliness Factor

It is thought most significant that R.N. filtration standards of between 30 and

40 microns for main machinery using felt filters are probably unique. U.S.N. cleanliness standards are much closer to U.K. merchant ship practice—approximately 70-80 microns. Some companies have explained the prevention of this type of failure by the introduction of fine filtration at the inlet to the affected thrust bearing. While this matter still needs further elucidation by a survey of actual filtration standards, it is generally acknowledged to be of great importance.

Most authorities describe the primary cause of machining as a ferrous particle which forms a carbide and builds itself up in the machining operation. The possibility of a carbide particle itself entering the bearing cannot be discounted. This carbide particle could emanate from any of the cast iron constituents in some lubrication systems. These would normally be grey cast iron, but certain portions could have been locally chilled to form white cast iron during manufacture. White cast iron would be the most abundant source of carbide—or cementite in fact. Present practice of employing chilled cast iron shot for shot blasting operations is known to have resulted in some shot being left inside a turbine and gearing installation. This is, of course, also white cast iron, and could very well be the source of a carbide chip.

The Design Factor

The fact that apparently similar failures have been reported in different designs of thrust bearings and journal bearings has perhaps tended to focus attention on materials rather than on design. This may or may not be valid, but the R.N. experience reported below, together with that of some turbine manufacturers who have been almost free from such failures may be significant.

Reports have been made of alterations in the amount and manner of oil supply to affected bearings, which have, together with other modifications to physical conditions, combined to prevent machining failures. Current R.N. opinion is that the common factors between immune and affected designs, in addition to consideration of materials, oils, and cleanliness standards, should be carefully established.

Among other characteristics noted are the apparent prevalence of failures of this type in H.P. rather than L.P. turbine thrust bearings, and the differences in pivot positions of various designs of pad. Alterations in oil recirculation arrangements may have prevented some failures. Many authorities have found it beneficial to provide a separate pressurized oil supply to H.P. thrust bearings, which is, in fact, usual R.N. practice.

R.N. Experience

The R.N. has, over the last 10 years, had in service a large number of main and auxiliary turbines with rotors of 3 per cent chrome $\frac{1}{2}$ per cent molybdenum steel. The majority of the main turbines are a particular company's design. There have been a number of instances where journals have been scored by chilled cast iron shot and other foreign matter, but in no case has the damage gone beyond that caused directly by the original particle. The self-propagating feature of the 3 per cent chrome failures has been completely absent.

The oils used have been OM-100 and various 'experimental' supplies of OEP-90 or OEP-69 containing many different E.P. additives. For the last two years, a particular formulation of E.P. oil (OEP-69) has been employed and its continuing use is envisaged for the present. This formulation has given no trouble, despite a chlorine content of 2·1 per cent, and OEP-90, containing the same additive, gave no trouble during the four years' ship trials which preceded the introduction of OEP-69. These are considered to have constituted a thorough 'screen' of the oil.

The fact that, until recently, R.N. experience with main propulsion turbines has mainly been with one manufacturer's design, perhaps points to the important role the 'design' aspect may play in the initiation of these failures, an aspect which has been ignored until quite recently. The quantity of oil flow and its pressure has been shown by several authorities to be critical in the adequate performance of bearings. R.N. designs incorporate a separate pressurized oil supply to H.P. thrust bearings.

The R.N. is naturally concerned, however, to establish the mechanism of the failures reported by other turbine users, as soon as possible, in view of the similarity of R.N. materials and oils with those involved in certain failures.

The R.N. has experienced in recent years a fair number of unexplained thrust and journal bearing failures in new designs of turbo-driven auxiliaries. None of these has been identified as a machining failure, but this possibility cannot be completely discounted, although wire wool has never been reported, if it is agreed that 'evidence' can be lost in the case of a catastrophic failure.

Discussion

The marine thrust-bearing failures, often associated with $\frac{1}{2}$ per cent molybdenum steel and E.P. oils, and the industrial journal bearing failures, usually associated with 3 per cent chromium steel and non-E.P. oils, have been considered together in this report, because both have been characterized as machining type failures, and it appears likely that a common mechanism (probably that proposed by Dawson and Fidler) is, at least partly, responsible for both. However, the evidence is conflicting and it is possible that further investigation may indicate that a distinction should be drawn (i.e. some factors, at present unidentified, may apply to one type and not to the other).

The statistically high incidence of failures in new and refitted marine installations, run-in with E.P. oils, appears, at first sight, to be significant; as also does some experimental rig work reported during 1963 to the R.N. However, other work mentioned in this report appears conflicting and it must be concluded that the significance of the use of E.P. or non-E.P. oils is not yet clear, but it may become apparent in relation to the distinctive factors, mentioned above, if and when these are completely determined. Rightly or wrongly, there is now considerable suspicion of E.P. additives, particularly of those containing chlorine, on both sides of the Atlantic, but the R.N. cannot endorse these suspicions, based on naval experience over the last six years.

Summary of Current R.N. Views

The present R.N. appreciation of this problem can be summarized as follows:

(*a*) The R.N. is aware of the incidence of a machining type of failure, which is normally identified by the extensive production of wire wool from the face of a thrust collar or bearing journal.

(*b*) It is considered that however prudent might appear the recent actions by other authorities to discourage the use of E.P. oils, particularly those containing chlorine additives, the evidence so far advanced to support such action is at best very conflicting and unsubstantiated. Suspicion still attaches, however, to the use of chlorine-containing oils.

(*c*) Little reliance is placed on the existing very limited statistical analysis of all merchant ship thrust failures, whether or not of this particular type. The R.N. advocates a further very complete survey of all associated factors (see next paragraphs).

(*d*) The R.N. is now leaning in new designs towards the use of a hardened material for all thrust collars and journals. It is reasonable to suppose that this action provides a further safeguard against machining failures.

(*e*) The need for a repeatable rig test which reproduces the phenomenon is great, and is regarded by most as an essential part of investigations into these failures.

(*f*) The temporary expedient of phosphating thrust collars appears to be beneficial, at least for short periods.

(*g*) The special conditions which apparently obtain where these failures have occurred are under consideration. The most notable facts which emerge at present are:

(*i*) Standards of filtration probably play a significant part in the incidence or otherwise of these failures.

(*ii*) The fact that mainly H.P. turbine thrust rather than L.P. thrust bearings are affected might attract attention to molybdenum steel or temperature considerations.

(*iii*) The triggering of this type of failure by the formation or trapping of a carbide, originating as an inclusion of ferrous dirt, or cast iron shot, is generally accepted. It is thought that this carbide becomes embedded in the bearing white metal and is responsible for subsequent machining of thrust collars or journals. The conditions under which the carbide can be formed from a piece of steel require both a reducing atmosphere and temperatures of about 800 degrees C. It is not known how the carbide is formed in this instance as it appears unlikely that these conditions obtain. Cavitation bubble collapse conditions and/or cavitation due to the presence of contaminants or entrained air *might* cause temperatures of this order, or otherwise cause failure.

(*iv*) Inadequate oil supply, or oil pressure, or interruptions in oil supply might be instrumental in inducing machining failures.

(*v*) The advent of carbide as a carbide chip from a source of cast iron either in the system or the 'shot' from shot-blasting is recognized as a possibility. More cast iron is used in the Merchant Service in sets of gears, heat exchanger casings, oil system piping, and isolating valves, than in the R.N. This might provide a valuable clue in these investigations, but it is known that the carbide chip (in fact a particle of cementite) would be much more likely to emanate from the white cast iron of chilled cast iron shot, than from the cast iron in the system, in those ships so designed.

Interim Conclusions

Since there are good indications that current R.N. turbine thrust and journal bearings might well be immune in present conditions, the Admiralty is interested in directing attention mainly to a detailed survey of design variables relating to thrust and journal bearings of all merchant and R.N. ships and land-based turbines, which have exhibited known machining type failures. No convenient means of carrying out this survey has yet been found.

The importance of high standards of cleanliness and filtration, and of certain aspects of bearing and installation design, might thus be stressed with greater authority.

The Admiralty cannot at present endorse the suspicions of some authorities which are directed exclusively at the use of E.P. lubricating oils. In fact, H.M. ships are at present continuing to use OEP-69 containing approximately two per cent of chlorine in its additive constituents.