Chapter 1

Factors Characterising Performance Of P/M Journal Bearings

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1.0 INTRODUCTION

Mini-size (< 8mm diameter and < 10 mm length) journal bearings are widely used in automobile accessories like instruments, sensors, oil pumps and fuel injection system etc. These products are critical in nature for intensely competitive, small engine motorbikes. Design data from the world leader of the above range of product is a protected one for commercial reasons and technology assistance is not yet available.

Service life of the product is expected to be a typical five years of normal use or a road distance of 100,000 km. Customers seek higher product reliability and (Mean time to repair) MTTR, fuel economy and least cost while it is qualifying for contemporary quality standards. Other design factors like suitability of bearing under harsh environmental condition, feasibility of bearing replacement in service, the influence of speed variation and vibrations on the bearing performance also require serious consideration. Hence design factors need close attention.

The present investigation is devoted to the study of design and manufacturing factors of journal bearings of highly demanding automotive engines. As a precursor, the introductory chapter recaps the background developments and direction of work in this area.

1.1 DEVELOPMENTS IN PRODUCT DESIGN AND FRICTION STUDIES

1.1.1 Design Factors

Bearing clearance, geometric tolerance, material composition, hardness, surface topography are important design factors [1.1]. While service habits of customers need, 'fit-and-forget' designs, that of manufacturers a standardised, finely cut, easy-to-manufacture design. Designers need to provide answer to the demands by effecting continuous design improvements. Associated benefits of design improvements are fuel and oil conservation and easier Homologation process in export approvals. Category and design of the bearing selected for investigation are described below.

1.1.2 Bearing Category and Design

As applied to small sizes, close tolerance conditions, low-maintenance and applications involving high speeds, the wear joints and bearings are journal and bush type because of their inherent advantages. General outcome on design efforts is to select and recommend journal and bush combination. Journal bearings in oscillating movements and slow arcing motions work well, because they have low breakaway and starting
torque characteristics [1.2]. Surface irregularities between the moving journal and bush, as well as frictional quality of materials, play an important role in the bearing performance. Surface irregularities and poor finish increase the interlocking asperities. However, the condition of friction and quantum of wear need in depth analysis for completing the design of suitable journal bearing.

1.2 SMALL JOURNAL BEARINGS IN AUTOMOBILES

Journal bearing consists of a sleeve of bearing material named bush wrapped partially or completely around a shaft referred as Journal. The nomenclature of a hydrodynamic journal bearing is generally as shown in figure 1.1. Here, \((r,\theta,z)\) is the polar co-ordinate system, with \(\theta=0^\circ\), being aligned with the line of centres in the positive direction shown clockwise. In the present study, \(b,j\) are the suffixes used for bush and journal respectively. The bearing dimensions are: \(r_b\), the radius of bush (mm); \(r_j\), the radius of journal (mm); \(b\), the length of the journal in the bearing (mm); \(c\), the radial clearance = \(r_b - r_j\) (mm). Under stable conditions, with the applied load \(F(N)\), the journal operates with a eccentricity \(e\) (mm) in relation to the bush; the operation speed of the journal is \(N(rpm)\). The minimum film thickness occurs along the line of centres at \(\theta = 180^\circ\). With a load acting and presence of a hydrodynamic film of lubricant between the journal and bush, reduces friction. Reynold(1886)[1.4] used a reduced form of the Navier-Stokes equations in association with the Continuity equation to generate a second-order Differential equation for the hydrodynamic pressure in the narrow, converging gap existing between bearing surfaces. Load acting on a journal is carried, by the lubricant pressure generated around the journal resulting in extremely low friction as depicted in figure 1.2 (a) and (b).

1.2.1 Application of Journal Bearings

Service conditions of automotive applications for bearings in the critical function areas of engine and electrical systems were of interest. Few of the journals used in such applications are shown in the figure 1.3 (a) to (g). This work aims at the small size
bearings and area of study focussed on the sub-system of the automobile 4S engine, Viz., the lubrication oil circuit and its elements.

Range of application of journal bearings could be limited only by the imagination. Marine

Figure 1.2 (a) and (b) Lubrication and frictional movement

a) Resistance to movement and higher frictional force caused by asperity interaction between contacting surfaces.
b) Free movement with very minimal metal-to-metal contact. Journal load fully supported by fluid film.

crankshaft support and hydroelectric turbine power plant main bearings lead the pack at 'mega size' side and rotor support bearings in surgical hand tools and indication instruments perform at the 'micro size' end. Some of the current applications for journal bearings in reference to bearing operating requirement are:

▲ High Speed
- machine tool spindles
- turbochargers
- hard disk drives
- hand tools
- textile spindles etc.,

▲ Extremely Low Lube
- surgical hand tools
- semiconductor processing equipment
- liquid oxygen pumps
- flow and gas meters etc.,

▲ Clean Environment (low particulate emissions)
- computer hard disk processing machinery
- LCD panel production machinery
- operation theatre equipment
- pharmaceutical equipment
- semiconductor processing machinery etc.,
Figure 1.3 (a) to (g) Examples of precision journal bearing combinations

- Corrosion Resistance
  - aircraft applications
  - chemical and food processing applications
  - in-line skates
  - photographic equipment etc.,

- System rigidity and accuracy
  - kinematic mounts
  - film coating and processing machinery
  - precision spindles
• heavily loaded structural supports etc.,

**Extreme Temperature**
- liquid oxygen pumps
- ovens and metal processing applications
- kiln applications etc.,

**Vacuum Atmosphere**
- aerospace applications
- pumps
- semiconductor processing equipment etc.,

**Low Torque**
- robotics
- measuring and indication instruments
- clocks etc.,

**Light Weight**
- electronic equipment
- automobile accessories
- hand tools etc.,

**Oscillating Motion**
- in-line skates
- cam supports
- machine tools etc.,

**Contamination and Wear Resistance**
- electric motors
- equipment for medical procedures
- machine tool guides etc.,

The new rules for this class of bearings make them able to run cooler, run faster, run cleaner, run smoother and run longer for less. One of the recent applications by Fritz Faulhaber [1.3] in a micro motor of 1.9 mm body outer diameter, capable of operating from 1~100,000 rpm to meet the demand of medical procedures conducted inside body's major blood vessels, speaks about the usability of journal bearings.

The oil sump in a 4 stroke engine is generally located at the bottom of the crankcase for gravitational advantage and ease of service. Other conveniences are heat sinking and space availability. In the 100 ~ 125 cc class IC engines, pumping of oil in commercially
produced 4S (four stroke) has been traditionally through splash lubrication from the crank shaft features; whereas it was through fuel–oil mixture in the case of mass manufactured 2S (two stroke) till 1970s worldwide. Oil pumping later on changed to the present method of dedicated, speed and load sensitive supply around 1985 in India providing a more reliable oil flow for points of lubrication. The oil pumps are falling under positive displacement category–gerotor type (internal-external gear in engagement, fixed flow), piston type (both load sensitive-flow variable and fixed flow) and swash plate type (load sensitive-flow variable and fixed). The brand new e-generation engines released in India during 2000 does have an electric operated piston type pump; the Engine Control Unit [ECU] shall provide for the speed and load sensitiveness. In versions of oil pumps shown in figures 1.4(a)–(h) flow is generally variable, directly depending on engine speed.

Investigations require confirmatory data from the failed products. Valuable data could be got from the Service Stations of various motorcycles. However, investigator couldn’t get necessary help from the vehicle manufacturers for detailed study.

1.2.2 Wear Studies

Scott (1983) defined wear as the undesired displacement or removal of surface material, although under some circumstances, the initial stages of mild wear may be beneficial for the running-in of elements [G1]. Economic implications of wear cause concern, as some reasonable life is required for the equipment, to cover capital and maintenance costs. Costs associated with the maintenance and the loss in productivity make the continuous wear life improvement, a basic need.

In journal bearings, majority of the wear occurs due to metal-to-metal contact when the lubricating film is partial and this state represents the mixed lubrication condition [1.4]. Journal bearings generally experience mixed lubrication condition during starting and stopping. Factors influencing wear are clearance, geometry, surface topography, loading pattern, speed spectrum, lubricant supply and its contaminant concentration etc., Under mixed lubrication conditions, asperities and the partial fluid film present in the bearing clearance share load [1.5]. The interdisciplinary nature of wear makes it difficult to elucidate and so industry also has sometimes accepted it as inevitable; hence mechanical part replacement technology has dominated its wear control technology in third world countries predominantly depending on borrowed/adopted technology. The insight of factors controlling wear had assisted the international Industry bring improved products. Adtranz (2000) reports the impact of Design for Environment (DFE) and Life
Cycle Assessment (LCA) guidelines on the efforts by designers on new mechanical designs [1.6]. Leading companies of auto-industry started making design approvals based on the applicable LCA guidelines.

The macroscopic dark spots usually found on field run (FR) surfaces are a form of surface damage named as “hot spotting” in reports by Jang and Khonsari [1.7] based on their analysis for Thermo Elastic Instability (TEI). Continued studies on FR surfaces into seizure conditions of journal bearings have been providing wealth of data towards design improvements.
1.2.3 Journal Bearing and Wear

Hardness of material surfaces in contact is an important parameter in predicting the behaviour of the bearing elements. The journal bearings face abrasive wears which can be dealt with as, two body and three body abrasive wear, the third body being, abrasive contaminants coming between the journal and bush. Such journal bearings come under the realm of lubricated, tribo-mechanical components in which, closed three body abrasive wear due to abrasive contaminants in the fluid can occur on the internal critical surfaces that are separated by a fluid film. Hardness ratio of the wear joint is more important in deciding wear life in three-body system, than the individual hardness. In the case of a rough, hard surface, mating with a relatively soft, smooth one, the coefficient of friction depends on the surface roughness and normal pressure. The effect of friction will be very large, especially at high pressures. With these various avenues being wide open, the scope of this work is to be defined.

Quoting Ford Motor Company data, David [1.8] concludes that the decisions made during the design process affect 70% of the manufacturing cost and investment. Where relative motion takes place between surfaces, wear can never be eliminated, but designers may attempt to reduce it to a significantly low level.

1.2.4 Superimposed Wear Mechanisms and Material Interactions

Wear shows up in the form of wear debris and in changes of material and shape of the tribologically stressed surface, with material loss being amount of wear, its inverse called wear resistance. When stresses work collectively on the elements of the tribological system, both physical and chemical processes occur. These take the form of energetic and material interactions between base surface and mating surface. When influenced by intermediate material and ambient medium in real cases of wear, the main wear mechanisms like adhesion, abrasion, tribochemical reactions as shown in figure 1.5 are reported. Surface destruction rarely occurs independently but tend to be superimposed on each other [1.9].

1.2.4.1 Adhesion

When base surface and mating surface are in the direct contact, considerable stress is generated in regions of micro-contact that are enhanced by the tangential relative movements of contact surfaces. These stresses cause plastic deformation of the roughness peaks. This can
lead to destruction of the adsorption or reaction layers adhering to the surfaces between which only van der Waals forces act at a distance of less than 10 nm. Metallic and covalent bonds form between the unprotected surfaces. Such adhesive interactions are particularly marked between “pure” surfaces.

1.2.4.2 Abrasion

When a hard body penetrates into the softer layer of the base surface, the relative movements create furrows. The hard body may be a mineral particle, a micro-roughness on the mating surface or loose debris. Different material pairings or surface roughnesses are possible causes of abrasive wear.

1.2.4.3 Surface destruction

Frequent mechanical cycling in the surface regions of a material leads to surface destruction or fatigue wear. Alternating stress causes changes in microstructure, crack formation and growth, which may lead to debris formation when several cracks run together.

1.2.4.4 Tribochemical reactions

Tribo-oxidation is a chemical reaction between base surface with components of the intermediate material and / or the ambient medium as a result of tribological stress. This results primarily in changes to the external boundary layer. Wear may reduce when the reaction layers prevent direct metallic contact between surfaces. However, when the reaction layer gets detached and forms into loose debris, the amount of wear may even increase since abrasion and adhesion wear modes come into play.

1.2.4.5 Co-efficient of friction and wear mechanism

As the potential for wear and friction depends on the intensity of contact between surfaces, the prior evaluation of steady state finish during the design stage will be beneficial. Heat generated during rubbing contact depends on the load, speed, and the co-efficient of friction [1.10]. The co-efficient of friction (COF, f) will depend on the material composition of the surfaces, surface finish, service temperature, and the effectiveness of lubrication. Heat generated by friction with dissipation by various means attaining thermal equilibrium, will result in some temperature rise of the surface above that of the environment.

Thus, for rubbing contacts at high specific loads or high velocities, the bearing materials are required to have high thermal conductivity, low friction co-efficient, and ability to accept high surface temperatures. When the part material has conductivity limitations, it is preferable that the thickness is very small.
In dry condition, however, the cohesion and mixture of wear particles cannot be attained, because water mist by capillary condensation is not easy to generate. The scaled films formed in dry condition cannot prevent metal-to-metal contact over a wide load range. Adhesive friction and wear becomes predominant and the friction coefficient and wear rate are generally higher than those in lubricating condition.

1.2.5 Wear Control Efforts

Wear being a process of surface destruction in rubbing solids, which results in reduced dimensions of the journal/bush in the direction perpendicular to rubbing. Dynamic torque for the performance of intended action too changes significantly. Designer has two concerns, one to establish whether significant wear will occur and second to take steps to reduce the wear rate to acceptable levels within the constraints imposed on design. In order to propose methods of quantifying wear, the mechanism of occurrence and factors which influence need to be understood.

1.3 WEAR PHASES

Diverse changes occurring in the contact give rise to various types of wear. Specific type of wear is not defined by a single term; it is rather described by several characteristics. Removal of solid material from rubbing surfaces have been dealt at length by Burwell (1957), Kragelskii (1965), Engel (1976), Rigney and Glaeser (1978,1981), Scott (1975, 1979), Rigney (1981), Bhushan et al (1985), Loomis (1985), Suh (1986), Zum Ghar (1987), Hutchings (1992), Bayer (1994), Rabinowicz (1995) et al., [1.11] have modelled the phenomenon. Character of the interface medium help distinguish dry wear, boundary-lubrication wear and abrasive wear. Hamrock (1994)[1.4] shows wear rate in the various lubrication regimes as determined by operating load as in Figure 1.6. In this context, wear rate is defined by volume of material removed (mm$^3$) per unit load (N) per unit sliding distance (m) and relative load represented by the journal operating load. In the hydrodynamic and elastohydrodynamic regimes, there is little wear owing to reduced asperity contact. In the boundary lubrication regime, the degree of asperity interaction and wear rate increase with load.
Hamrock [1.4] also clearly demarcates the transition from boundary lubrication to an unlubricated condition as the point marked by a drastic change in wear rate. As the relative load is increased in the unlubricated regime, wear rate increases until scoring takes place to generally end in seizure. Deformation of the surface layer differentiates wears during elastic contact, plastic contact and during micro cutting. Hence, three characteristics should be used for the description of a specific type of wear, for example, fatigue wear at boundary friction during elastic contact. Wear rate itself, not being constant, is a complex function of time; hence, added further are three phases under a condition of constant rubbing, like the running-in period, the period of steady state wear and the period of severe wear.

1.3.1 Running-in Phase

Running-in is a phase widely understood and followed by the new motor vehicle buyers on the fear of permanently damaging engine and other substrates. The asperities on rubbing surfaces change their shape and the material becomes work-hardened; as a result of these two processes, the conditions bringing about the elastic contact. Ensuring elastic contact at rubbing surfaces is essential because it provides for minimum wear rate and a stable magnitude of frictional force. However, running-in is characterised, as a rule, by more intensive wear of rubbing surfaces and by higher heat generation, which are accompanied by changes both in surface geometry and in the physical and mechanical properties of bearing surfaces. In the process of running-in, asperities that survived till then are intensively destroyed and new asperities differing from the original ones in shape and dimensions are formed. Thus a stable surface roughness proper to the rubbing conditions develops which need not have much bearing on the original surface roughness as seen in figure 1.7.

The molecular-mechanical theory of friction reveals a close relation between the parameters characterising frictional interaction and that of the surface geometry. As stable surface roughness of a solid depends on the strength of bonds due to contact molecular interactions, elastic properties of the material, specific normal load etc., the same can be found...
by analytical estimations based on variables. Combined with matching surface treatment methods and pre-selected surface topography, design shall ensure shorter running-in period minimising wear.

1.3.2 Steady State Wear
Steady state wear follows the period of running-in during which wear rate is at a minimum. Asperities break away as a result of numerous load cycles on a single friction bond. Archard [1.15] postulated formation of hemispherical wear particles, while Rabinowicz [1.11] applied the ratio of surface energy to the material hardness for determining the size of wear particle. Though the theories referred above could achieve consistent experimental results, it was considered that they do not account for the basic metallurgical conditions of materials but depend on arbitrary assumptions. Seifert and Westcott (1972,1974)[1.22] and Suh et.al.,[1.11, 1.39] demonstrated the generation of thin flake shaped particles in their Delamination theory of wear against the earlier assumption of spherical particles based on the Adhesive Wear theory. Kayaba and Kato [1.12] too modelled this breaking away in their Slip-tonque and Wedge model. The surface roughness is modified by plastic deformation in this steady state. Lim [1.13] models this phase into four distinct conditions based on the contact pressure and sliding velocity combinations. The wear volume data and the surface topographic studies shall confirm on-set of this mode of steady state wear. Scott [1.11] confirms the findings of Suh, Westcott and others that bulk material hardness itself is not the controlling factor on wear and also that the Delamination theory satisfies the thermodynamic requirements of frictional and wear behaviour of metals.

1.3.3 Severe Wear
The polished surface obtained in the steady state wear has been accounted for by a shear mix layer of short crystalline order of almost super ductile material spreading over the wear-interface by Westcott et.al., (1974,1975) [1.14, 1.22]. Repeated rubbing causes the shear mix layer to become fatigued and the rubbing wear particles flake off leading the asperity junctions to the mode of severe wear. In this mode, formation of plate-like debris was reported by Bates et.al (1974) [1.22]. Scuffing, Abrasive, Fretting, Cavitation, Rippling, Scoring and Contact Fatigue modes of wear have been widely researched by many to support the failure in the phase of Severe wear. Lim et.al., [1.13] propose three distinct phases for the severe wear too, based on the contact pressures and sliding velocities. They postulate that at the sufficiently high asperity contact
pressures and sliding speeds, the asperity interface temperatures reach the melting points leading to severe wear phase.

Classification of wear particles based on the morphology was analysed by many researchers [1.5]. Apart from this, based on the dimensions, surface appearance and the colour of wear particles, an attempt has been made [1.14] to identify different wear regimes in sliding steel surfaces. Table 1.1 gives details of the various wear regimes.

<table>
<thead>
<tr>
<th>Regime</th>
<th>Particle description</th>
<th>Size of particles, ( \mu m )</th>
<th>Description of mating surface</th>
<th>Wear rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Free metal particles</td>
<td>5</td>
<td>The surface of mating members may vary between polished and very rough. One surface can be polished while the opposing one remains as generated.</td>
<td>Negligible</td>
</tr>
<tr>
<td>2</td>
<td>Free metal particles</td>
<td>15</td>
<td>Stable, smooth shear mixed layer with a few grooves depending on the nature of particles in the oil</td>
<td>Low</td>
</tr>
<tr>
<td>3</td>
<td>Free metal particles</td>
<td>150</td>
<td>Ploughed with evidence of plastic flow and surface cracking.</td>
<td>High</td>
</tr>
<tr>
<td>4</td>
<td>Red oxide particles appearing as cluster or individually</td>
<td>150</td>
<td>Ploughed with areas of oxide on the surface.</td>
<td>High</td>
</tr>
<tr>
<td>5</td>
<td>Black oxide particles appearing as cluster or individually</td>
<td>150</td>
<td>Ploughed with areas of oxide on the surface.</td>
<td>High</td>
</tr>
<tr>
<td>6</td>
<td>Free metal particles</td>
<td>1000</td>
<td>Severely ploughed gross plastic flow</td>
<td>Catastrophic</td>
</tr>
</tbody>
</table>

Regimes 1 and 2 indicate normal wear conditions corresponding to hydrodynamic and boundary lubrication. Evidence of higher regimes indicates that some parameters have changed unfavourably leading to excessive wear. Wear mode diagrams illustrating the prevailing wear mechanisms for different combinations of load, speed and hardness are reported in literature [1.15]. The explanations discussed in the preceding sections lead to the conclusion that wear theories are still open for discussion and further work is necessary to generate more information.
1.3.4 Quantification of Wear

In general, the two most important forms of sliding wear, Viz., adhesive and abrasive obey a Holm-Archard [1.16] relationship of the type

$$v = \frac{(1000 \xi F I)}{(H_{vb})}$$

where

- \(v\) = wear volume, mm\(^3\)
- \(F\) = load, N
- \(\xi\) = wear coefficient
- \(I\) = relative sliding distance between bearing surface, m
- \(H_{vb}\) = hardness of bush, MPa

The other forms of wear, Viz., corrosive and surface fracture wear do not obey this equation, but in many cases they can be assigned equivalent wear coefficient, \(\xi\) based on typical observed wear rates. Typical wear coefficient values for metal-on-metal sliding systems are shown in Table 1.2. This table also gives coefficient for ceramic sliding on ceramic materials [1.16,1.17].

<table>
<thead>
<tr>
<th>Types of Wear</th>
<th>Wear coefficient (\xi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>metal-on-metal</td>
</tr>
<tr>
<td>Adhesive wear</td>
<td></td>
</tr>
<tr>
<td>Severe galling</td>
<td>(10^{-3})</td>
</tr>
<tr>
<td>Moderate wear</td>
<td>(10^{-5})</td>
</tr>
<tr>
<td>Burnishing</td>
<td>(10^{-7})</td>
</tr>
<tr>
<td>Abrasive wear</td>
<td></td>
</tr>
<tr>
<td>Severe abrasion</td>
<td>(10^{-2})</td>
</tr>
<tr>
<td>Polishing</td>
<td>(10^{-5})</td>
</tr>
<tr>
<td>Corrosive wear</td>
<td></td>
</tr>
<tr>
<td>Severe corrosive</td>
<td>(10^{-2})</td>
</tr>
<tr>
<td>Solid lubrication</td>
<td>(10^{-5})</td>
</tr>
<tr>
<td>Surface fracture wear</td>
<td></td>
</tr>
<tr>
<td>Brittle fracture</td>
<td>(10^{-4})</td>
</tr>
<tr>
<td>Surface fatigue</td>
<td>(10^{-8})</td>
</tr>
</tbody>
</table>

From equation given above and Table 1.2, it can be inferred that for a sliding device in which a specified load must be moved a specified distance, there are two ways of minimising the wear, viz, to use hard materials or to achieve a low wear coefficient. The hardness range which is available in practical bearing materials is roughly 2.5 orders of magnitude whereas the wear coefficient can cover a range of 6 ~7 orders of magnitude. Hence, changes in bearing materials that reduce the wear coefficient are more likely to reduce the wear volume than are changes in hardness. For any commercially successful
sliding system, a wear coefficient of $10^{-7}$ or less is necessary and accordingly the material combination need to be selected. Of late, specific wear rate, $k_s$ is also used to make a comparative study of wear characteristics of bearing materials [1.18], [1.15]. Specific wear rate, $k_s$ (mm$^3$ N$^{-1}$ m$^{-1}$), is defined as the wear volume, $v$ (mm$^3$) per unit journal load, $F$ (N) per unit sliding distance, $l$ (m). It can be seen that a burnishing wear coefficient $\xi = 10^{-7}$ corresponds to a specific wear rate, $k_b = 6.67 \times 10^{-7}$ mm$^3$ N$^{-1}$ m$^{-1}$ for sintered steel bushes with hardness $H_{vb}=150$ MPa, sliding on steel journals [1.19].

1.3.5 Factors Influencing Wear

Through continuous efforts, problem of wear is being steadily researched; tribo-systems are affected by a multitude of parameters, the majority of which may be difficult to control, to measure or even to identify. It is practical to divide these parameters into three groups; design, material and environment are listed in Table 1.3 [1.17]. Controlling of the above parameters leads to good control over the wear. The following paragraphs deal with the major parameters that influence wear of journal bearings.

<table>
<thead>
<tr>
<th>TABLE 1.3 TRIBO SYSTEMS – PARAMETER GROUPS [1.17]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design</strong></td>
</tr>
<tr>
<td>Shape of the tribo surfaces.</td>
</tr>
<tr>
<td>Area of nominal contact</td>
</tr>
<tr>
<td>Mode of mechanical contact</td>
</tr>
<tr>
<td>Spectrum of applied forces</td>
</tr>
<tr>
<td>Spectrum of relative velocities of contacting surface.</td>
</tr>
<tr>
<td><strong>Material</strong></td>
</tr>
<tr>
<td>Material / properties; mechanical, chemical, physical etc.</td>
</tr>
<tr>
<td>State of phase; gas, liquid, solid.</td>
</tr>
<tr>
<td>Material combinations</td>
</tr>
<tr>
<td>Friction and wear inducted alterations</td>
</tr>
<tr>
<td><strong>Environment</strong></td>
</tr>
<tr>
<td>Chemical properties; chemical, potential aggressiveness etc.</td>
</tr>
<tr>
<td>Physical properties; temperature, pressure etc.</td>
</tr>
<tr>
<td>Mechanical properties; friction coefficient, viscosity etc.</td>
</tr>
</tbody>
</table>

Under boundary lubrication conditions, there is evidence to suggest that radial clearance, contact angle and contact pressure have only marginal effect on wear. Experimental investigations by Halling [1.20] showed that the radial wear of bush was the greatest for large clearance bearings and it increase with an increase in number of starts and stops. Further, he has also demonstrated that the friction and wear characteristics of bearings are likely to be enhanced with improvement in surface finish.
of the journal. Due to relative sliding, wear results in an increase in radial clearance and thus it impairs the performance of the bearings.

In general, surface roughness has got a significant influence on the wear rate [1.21]. When the journal is harder than the bush and is also rough, the hard asperities plough the soft bush resulting in a greater wear in the bush. However, the surface finish of the hard journal improves during the initial period and this is called the running in or polishing as mentioned in section 1.3.1 resulting in a reduced and steady wear rate. Such polishing effect is not common to all bearing material pairs, examples being steel journals in contact with either aluminium-tin or zinc-aluminium bushes [1.22]. The reason may be explained in terms of electrochemical interaction between the non-ferrous alloys and steel. The polished journal surface finally gets roughened due to continuous metal transfer, leading to ‘wear particle’ formation and hence severe wear. Such a sequence of changes in roughness of journals is noticed at any speed and load [1.23]. The roughness effect on wear is sometimes studied taking it as one of the parameters in a composite group [1.24].

Studies by Poon et.al [1.25] have shown that extremely smooth surfaces may be tribologically unacceptable as significant wear and high friction occur in such cases. The reasons for such strong adhesion with very smooth surface are being investigated. The presence of abrasive particles in the lubricant results in abrasive wear of the material but the roughness of mating members is unaltered in some cases like white metal bushes whereas it is increased considerably in the case of bronze bushes [1.26]. Wear data generated can have a significant bearing on the nature of test set up employed. Habig et.al. [1.27] have shown that results of six bearing material tested on three different test set ups in three places, were not identical. This aspect has to be noted by the designers.

Sometime ago it was considered axiomatic that a sliding system should consist of one soft and one hard material. This is an excellent practice for lubricated bearings, where a hard steel journal and a soft bush metal are used to an advantage. But this system operates well only if a good lubricant were available, otherwise wear of the soft metal would become excessive. The use of soft material for the bush is of advantage in a bearing only where abrasive particles might be carried out by the lubricant, which could be trapped in the soft metal or if the deformation of the soft metal can help in aligning the
bearing surfaces so that the hydrodynamic action is restored. In situations where these factors are not of importance, it may be preferable to use two hard surfaces. The following classification of materials gives a list in the order of decreasing wear resistance but increasing desirability as regards cost of materials and their processing:

- Diamond
- Boron carbide
- Silicon carbide, aluminium oxide
- Tungsten and/or Titanium carbide
- Nitrided steel
- Carburised steel

To this list, Sursulf and Tufftride treated steels are two important additions under nitrided steels. Marappan et.al. [1.18] have established that Sursulf treated plain carbon steel bearings have performance characteristics similar to that of conventional bearings. When the wear situation is one of abrasive action, consideration of hardness is the foremost. The surfaces that are to resist abrasive wear must be harder than the contaminant particles. The most common contaminant in lubricants is silica. This has a hardness, which is almost as high as that attainable in metals, and thus there is limited number of choices available for resisting abrasion by silica.

Apart from above factors, metallurgy of materials also plays an important role in the wear behaviour of sliding components. Factors like microstructure, presence of interstitial compounds, their size, shape and distribution, chemical composition etc., have a strong influence on wear rates. Moreover, the wear situation becomes complex in the presence of journal/housing mis-alignments, geometric errors of mating members, dynamic loads etc., On account of the complexity of factors, a comprehensive set of experimental investigations aimed at determining conditions favouring minimum specific wear rate will assist the designer in rationally selecting the operating parameters.

1.3.6 Bearing Materials

Experience and research has indicated that the most important characteristics of a bearing material are [1.28], [1.29]:

- Compatibility to provide anti-weld and anti-score properties.
- Conformability provided by the modulus of elasticity to compensate for misalignment and geometric errors.
Embeddability indicating softness of material to absorb foreign particles in application and help reduce wear and scoring.

Compressive and fatigue strength combination to match the type and magnitude of loads in preventing extrusion, mushrooming, cracks and brittle fracture.

Corrosion resistance, a property generally required to readily resist the attack of organic acids and peroxides formed by the oxidation of lubricating oils.

Heat conductance to help stabilise at lower temperatures during application.

Cost, ease of fabrication and availability being the prime needs for mass production applications.

Use of powder metal parts in automobiles have significantly increased in the last decade owing to their superiority in meeting many of the above factors.

1.3.6.1 P/M bearing applications

The powder metal (P/M) process can offer numerous combinations of materials to meet specific applications. As they are available in various types and grades to meet a wide range of requirements. Common materials available include iron, copper, tin, zinc, carbon, nickel and stainless steel. These metal powders can be blended to produce a variety of alloys, brass and bronze to precisely meet the requirements. Powder metal parts have proven acceptable wear resistance and long life [1.30]. The near-net shape and tight tolerance achieved through P/M at high volume manufacturability offers substantial cost saving compared to other processes. Self-lubricating property through oil retention gives smoother actuation and self damping properties which silences many operations.

1.3.7 Friction and Wear

Bowden and Tabor [1.31] proposed that such a friction between surfaces is sufficient to shear the welded junctions formed by adhesion bonds between contacting asperities. While McFarlane and Tabor [1.32] later on explained the growth of junctions, reasoned that most of the load is taken by the asperities on the interface and then the interfacial friction is controlled by the growth of the real contact areas. Providing further incremental improvement to the asperity model of Bowden and Tabor, Challen and Oxley [1.33] proposed the wave model, wave removal model and the chip formation models. As per
this wave model, with the plastic deformation setting in after initial run-in, the softer material will resist "break-off" and that is substantiated by the decreased wear per unit mm.

As the wear progresses, there is a transition of wear, causing higher friction co-efficient suggested by Double Chord Model due to Challen and Oxley [1.34] and debris formation due to cutting action of the hard asperities along the traversed surface. As discussed by Syles and Poon [1.35], the over all friction force in a precision journal bearing can be attributed to the combined effects of adhesion, deformation and plowing; under moderate contact pressures, the plowing component is large under the conditions of such increased wear rates applicable to the second region.

1.3.8 Accelerated Wear Tests
Field collected samples of journal bearings show differing patterns of wear characterising their application. Collecting samples, associating with the conditions of application and isolating non-conformities has been difficult. Accelerated Wear Test (AWT) has been topic of interest, for patterns of wear could be simulated under controlled conditions. Few of the accelerated wear experiments reported are attributed to Rabinowicz [1.36], [1.37] and Bhushan [1.38] where, the effects of time, speed, pressure and contaminant concentration were studied. The test results were reported to be consistent with the known wear data. Earlier, Suh et.al., [1.39] too studied component wear due to fluid particulate contamination to report that, an AWT could produce abrasive and accelerated fatigue wear on surfaces with predictable correlation.

1.4 BEARING PRESSURE DISTRIBUTION
Mass manufacturing practices in the automobile field depends very much on the process capability analysis and sampling techniques for quality assurance. Several different indices have been developed because [1.40]

1) no single index can be universally applied to all processes, and
2) no given process can be completely described by a single index.

Process capability is defined as the least variability of a quality characteristic that a process is capable of maintaining when in a state of statistical control under a given set of conditions [1.41].

The finishing practices in bearing part manufacturing consisting of heat treatment, grinding, coining and shrink fitting assembly sometimes tend to oscillate to their limit of
manufacturing standards. The associated cylindricity, surface topographic and alignment errors may affect directly the performance characteristics. Hence, it was felt that the cumulative effect of these variations in bearing geometry on the operating oil film thickness and the consequent pressure distribution in the circumference of the journal bearing also need investigation.

1.4.1 Geometric Errors

Parts under manufacturing face dimensional variability because of setting, process and measurement practices. Owing to the machine condition, process shift and tooling conditions, further variations in form also creep in. Such variability reflected on the bearing parts as circularity and cylindricity have significant effect on bearing performance [1.42]. Cylindricity error is generally arrived both experimentally as well as theoretically. The press fit load developed between the bush and body during assembly can be estimated using Lame’s equations [1.43]. Geometric errors like barrelling, bell mouthing, circumferential undulations, cylindricity, surface roughness factor etc., are to be covered to take into account the manufacturing reality.

1.4.2 Dimensional Stability and Clearance Variation

Hardened bearing components are also found dimensionally unstable when measured to the levels of their precision class. More accurate and practicable methods are necessary to predict the growth over the long term and effect corrections in material/heat treatment combination. Dimensional stability needs to be seen as an important parameter for providing extended bearing performance. Growth of journal or shrinkage of bush will result in loss of clearance. Both the above factors influence the bearing pressure distribution. Staffen [1.44] suggested Dilatometer technique to measure dimensional stability with a well-controlled furnace, where the test temperature and resultant change in length can be registered. JMA (Johnson-Mehl-Avrami) kinetics is reported to be making it feasible to begin “design” materials and their heat treatment to give maximum stability to bearings for specific applications. Staffen [1.44] reported experimental and numerical results for carbon chromium steel. The standard dilatometer test sample is of 8 mm length and 3 mm diameter. The temperature and the sample length measurements are done at lower pressures to control decarburisation between room and 1300°C. Phase transformations at 140, 280, 320 and 370°C corresponding to epsilon carbide formation, the retained austenite decomposition in the first two and cementite precipitation in the last two respectively are charted in this test. The JMA Model offers the mathematical description of how the phase transformation
progresses with time and temperature during tempering. With the retained austenite content and tempering temperature, journal dimensional growth is predicted. The model predictions and the results obtained by dilatometer test are reported to be with reasonable level of correlation. The model is able to predict dimensional change years ahead and could replace a serious of time-consuming experiments. Figure 1.8 shows the data as closely applicable to the journals. In analysing data of random variables, Convolution is one of the techniques.

1.4.3 Convolution of n Variables
Reference to variability in manufacturing process and its influence on the geometric errors and basic dimensions has been already made. Statistical tools to deduce requisite key parameters help systematic analysis and enriching of design data base. Numerical convolution of variables is employed in the present investigation in analysing journal and bush diameters measured ideally varying in a random fashion, in the bearing manufacturing line. If X and Y are two independent random variables defined by the probability density functions f(x) and g(y) then the density function Z(Z = X+Y) is understood as convolution of X and Y [1.45]. The density function Z can be derived by analytical evaluation of the integral. As the analytical evaluation is complex, numerical integral formulae are used.

1.4.3.1 Numerical Convolution
In order to obtain the distribution characteristics of the variable Z, which is defined as the sum of two variables, i.e., Z = X+Y, the method of numerical convolution could be applied as follows. As variables X and Y are normally distributed i.e., the random variable X can be defined by N(μx, σx) and the random variable Y can be defined by N(μy, σy) where μx, μy are the mean values and σx, σy are the standard deviations of the variables X and Y [1.46]. The cumulative distribution function (CDF) of the variable X is denoted by F and the probability density function (PDF) of variable Y denoted by G can be given by

![Figure 1.8 Dimensional stability of shafts-Staffen's Test](image)

Predictions compared with measured long-term stability data
Grade : hardened and tempered at 220°C for 4 hours
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\[ F(t-z) = P(X \leq t-z) = \frac{1}{\sigma_x \sqrt{2\pi}} \int_{-\infty}^{t-z} e^{\frac{1}{2} \left( \frac{x-\mu_x}{\sigma_x} \right)^2} \, dx \quad \ldots \quad \text{eqn. 1.1} \]

\[ G(z) = \frac{1}{\sigma_z} \sqrt{2\pi} e^{\frac{-1}{2} \left( \frac{z-\mu_y}{\sigma_y} \right)^2} \quad \ldots \ldots \quad \text{eqn. 1.2} \]

where \( t-z, Z \) are the values of random variables of \( X \) and \( Y \). The CDF of the variable \( Z=X+Y \) is denoted by \( H \) and can be obtained from the convolution of \( X \) and \( Y \)

\[ H(t) = P(Z \leq t) = \int_{-\infty}^{t} F(t-z)g(z)dz \quad \ldots \ldots \quad \text{eqn. 1.3} \]

1.4.4 Clearance Analysis

Bearing clearance is estimated by both measured values and by interpretation of design specifications. Majority of the random phenomenon observed in practice, appear to follow Gaussian distribution [1.47]. In order to establish the distribution characteristics, profile height data of a given surface obtained from surface roughness tester is segregated into different cells and the total numbers of entries for every cell is determined. The plot made on normal probability paper yields dispersion effects, mean, standard deviation etc., [1.48]. A plot of cumulative probability versus asperity profile heights is made on a normal probability paper. When the point could be approximated to a straight line, the same confirms the Gaussian nature of distribution of profile heights. Further a 95% confidence limits accounting for dispersion effects due to statistical noise can also be obtained.

The profile height value corresponding to 50% cumulative probability gives the mean, \( \mu \). The standard deviation, \( \sigma \) is estimated by obtaining the profile height values where the fitted straight line intersects the 93.3% and 6.7% probability values. The difference between the values is divided by three to yield the standard deviation, \( \sigma \) as indicated in...
the figure 1.9. For any statistical estimate, a confidence interval is accounted by knowing the degree of uncertainty associated with the estimate. Confidence intervals for the mean and the standard deviation shall also be obtained from the band of confidence limit curves.

1.4.4.1 Clearance analysis by numerical convolution
In the present work numerical convolution is employed for bearing clearance, which is contributed by the bush and journal diameters varying randomly. Clearance in the bearing results from the difference in dimensions of bush and journal diameters. The salient features of numerical convolution is as applicable to the sum of two variables is described in reference [1.46].

1.4.4.2 Estimation of clearance by surefit and normal law [1.48]
From the measured dimensions, clearance values can also be calculated using Surefit law (Arithmatic law) and Normal law based on piece part errors and are compared with that of design clearances. The Surefit law applied to a dimensional loop or chain where
there are n dimensions such as $U_1 \pm u_1, U_2 \pm u_2, \ldots U_n \pm u_n$, the resultant dimension will be $U_T \pm u_t$. Where,

$$
U_T = \sum_{i=1}^{n} \pm U_i \quad \text{eqn. 1.4}
$$

$$
u_t = \sum_{i=1}^{n} \pm u_i \quad \text{eqn. 1.5}
$$

The $\pm$ in the equation 1.4 above corresponds to algebraic value of the dimensions in the dimensional change based on the assumed sign convention. Similarly, by normal law, the resulted dimension $U_T \pm u_t$ can be estimated using the under mentioned equations when the dimensions follow normal distribution characteristics. Where,

$$
U_T = \sum_{i=1}^{n} \pm U_i \quad \text{eqn. 1.6}
$$

$$
u_t = \sqrt{\sum_{i=1}^{n} \pm u_i^2} \quad \text{eqn. 1.7}
$$

The maximum and minimum clearances calculated on the above formulations can also be compared. The Gaussian nature of the dimensional spread can be verified using the probability chart method discussed above.

1.4.5 Selective Assembly

A method followed in automobile industry to achieve high precision fit by using relatively low precision parts is shown pictorially in figure 1.10, by tuning the assembly process. Accuracy of bearing fit is achieved by marking and pairing off the parts to be assembled. As shown in the figure parts falling within a much wider dispersion of a specified dimension shall be utilized by the selective assembly process, while blind

Figure 1.10 Distribution of actual dimensions of single parts about a mean value (Tipping)
Source: Manufacturing Assembly Hand Book by Biunolotter [G32]
automatic assembly will need high precision parts. Corresponding groups of the mating parts, yielding the optimum fit are assembled. The advantages of selective assembly are arising in two aspects:

(i) Economical Manufacturing tolerances are decided, and
(ii) High precision assembly is achieved with reduced waste.

The disadvantage is, being left with surplus parts to be mated due to the cases of undesired dimensional distributions. X D Fang and Y Zhang [1.49] propose an algorithm to minimize surplus parts by grouping the mating parts based on Probability Indices method.

1.5 SEIZURE

Wear joints experience various modes of failure. The bearings can experience seizure mode of failure too. In the process of improvement of journal bearings, investigative study of seizure becomes important. Such seizure condition is generally associated with uncontrolled rise in temperature of the wear interfaces and the ensuing dimensional variations of parts. The resulting working clearance change quickly reaches the point when the normal functioning of the parts becomes impossible. This development, based on other factors leads to seizure of affected wear joints. The condition of sudden stalling of the engine leads to very high rate of deceleration of the road speed, which often may cause vehicle toppling. Early studies have focused on the following [1.50],[1.51],[1.52],[1.53],[1.54]

❖ Heating during running-in
❖ Starvation effect due to non-supply of oil
❖ Susceptibility to seizure
❖ Catastrophic failure

1.6 LUBRICATION

Lubricants have helped designers to control friction and wear. The UK governmental committee which coined the word "Tribology" in 1966 went ahead to project a minimum saving of 1% of GNP with improved use of lubrication and wear control technology then. The continuous increases of energy and petroleum costs have increased that potential for savings. Statistics show the inverse relationship between oil consumption and industrial growth as far as India goes, on account of higher oil consumption per unit production. With the import of petroleum products slated to cross 150 million MT by
2007, the population of two wheelers crossing 30 million in the year 2000 and the country emerging as the largest consumer of 2T oil (two wheeler lubricating oil) at approximately 22.4% of World consumption [1.55], the need for analysis needn't be re-emphasised.

1.6.1 Lubricants

It is commonly understood that the final purpose of any lubricant is to preserve the geometric shape of the parts. They serve other secondary purposes of heat sinking, corrosion protection, control of maintenance costs through extension of lubrication intervals and down time, higher speeds of operation and hence higher productivity, local scavenging at the wear interfaces, modification of noise-vibration-harshness (NVH) property etc. Newer issues arising out of environmental understanding, laws and stipulations need to be taken into effect for lubricant selection. For whole of the service life, engine lubricant is exposed to the most hostile environment and gets replaced at the verge of chemical and thermal breakdown. Used up lube-oil contains potentially harmful breakdown products and need careful handling to avoid risks. Traces of metals from the lubrication system and the subjects formed by prolonged exposure to fuel, shall cause dermatological problems. The disposal on ground will affect water table, affect the microorganisms and disrupt the delicate food chain. Hence, the responsibilities of design engineers include selection of an environmentally least loading lubricant. The selection of viscosity depends upon its steady state operating temperature influenced by the sump and engine. A lubricant with lower viscosity has to be selected for ensuring its supply at low temperature and cold start of the engine [1.56]. Similarly, needs for higher temperature operation and high load conditions demand different viscosity characteristic.

The major categories of lubricants generally considered can be grouped as [1.56], [1.57], [1.58]

- solid lubricants
- powders
- bonded dry films
- semi solids
- greases
- pastes and
- oils.
1.6.2 Oils
Apart from serving the typical tribological purposes, liquid lubricants also serve some secondary characteristics as stated below:

- They can be drawn between moving parts by hydraulic action to maintain a lubricant film under a range of operating conditions.
- They have heat-sink capacity to cool the contacting points.
- Ability to form mixtures with chemicals to provide corrosion resistance, detergency or surface-activation.
- Providing special electrical properties like easy conduction for power and static charge.
- Scavenging wear particles from point of potential damage.

In order for a lubricant to be effective, it must be viscous enough but should be as fluid as possible to meet the above and to avoid excessive power loss in the engine due to viscous drag.

More than 90% of the lube-oil consumption all over the world are mineral oils. The estimated 140 billion tons of earth's reserve are expected to last up to 2040 AD and being consumed at the daily rate of 2.4 billion liters as petrol, 1.3 billion liters as other fuels, 1.20 million litres as other oils by 1994 data [1.59]. Basic petroleum oil family has limitations in terms of performance, due to operating temperature range, viscosity index, oxidation resistance, thermal stability etc., for the new age products. However, these basic formulations have gone through a series of improvements by gradings and additive mixtures. Additives based on solid lubricants like Molybdenum di-sulphide and teflon are few among them. Synthetic oils come handy with improved thermal and oxidation stability, viscosity behaviour and flash point. Table 1.4 and Table 1.5 indexed in Appendix X.1 compares important properties various groups of oils. The life and performance dependency of the journal bearing on properties and characterisation of fluid film has been discussed to a greater extent by Vijayaraghavan (1989) et.al., [G.14] in full THD Model, Elrod, Roelands and Jones [1.60]. It is not uncommon, in the operation of journal bearings, for the viscosity within the film to be different by a factor of 50.

1.6.2.1 Oil properties
Effect of temperature on viscosity is generally a factor needing attention in design of precision bearings. Minimum nominal film thickness in dynamically loaded journal bearings, such as crankshaft bearings, oil and fuel pump bearings, is in the same order
of magnitude as surface roughness, causing mixed lubrication conditions to occur. The thermal effects in hydrodynamic lubrication are important due to the strong dependence of viscosity on temperature. The modern automotive lubricants are multi grade oils, containing polymeric additives at treat rates up to 20 percent and making lubricants mildly visco elastic and slightly shear thinning [1.61]. The cumulative effect of transverse and longitudinal roughness on temperature and on the viscosity-pressure relationship has been dealt by Chao Zhang and H S Cheng [1.62] in detail. Lube oil should also be stable under thermal and oxidation stresses and have the expected volatility. The reality in the engine needs investigation owing to the fact that the particle contamination is dynamic and shall vary with user practice. The demand for the lube oil flow to help check wear as intended by the bearing designer, too changes because of the operating conditions like load, speed and system wear condition etc., Hence, the lube oil properties themselves need a finer matching with the journal bearing design in particular.

1.6.2.2 Viscosity-temperature effects

Journal bearings generally have a continuous flow of oil supply. This helps faster equalisation of temperature through the mass of oil. Vijayaraghavan (1998) and Roelands (1966) postulate that within the conventional temperature range and at moderate pressures, for mineral oils, a rule of thumb is a pressure increase of 20 atmospheres would roughly have the same effect on viscosity as a temperature decrease of 1° C[1.60]. Roelands Model attempted characterisation between samples of viscosity profile of a lubricant as seen in figure 1.11 to deduce the “slope index” and “pressure index”. Further works like the JFO (Jakobsson-Floberg-Olsson) model helped Elrod and Vijayaraghavan (1995) propose the Full THD Model. This model takes into consideration of cavitation effects in a thermohydrodynamic analysis accounting for oil flow and side leakage in the realm of viscous dissipation and heat flow through entire bearing clearance, power loss and heat transport within the

Figure 1.11 Viscosities of lubricating oils at atmospheric pressure.
Source: Hamrock
journal-bush set of bearing assembly. By solving the two-dimensional Reynolds and Energy equations Dean ET al. [1.29], [1.63] too emphasise the viscosity-temperature relationship and eccentricity ratio on load carrying capacity.

1.6.3 Oil Change

Contamination is main cause of lube oil change in the small four stroke internal combustion engines. Lubrication system is designed for flood lubrication of elements like cam chain, tappets, main bearings, connecting rod end bearings, sprockets, clutch assembly etc., Figures 1.12, 1.13 and 1.14 give views of typical small IC engines. Figure 1.12 shows a two stroke single cylinder automobile engine where the lubricating oil is metered and delivered to the points of requirement based on the engine speed and load. Precision metering of quantity of oil provides improved lubrication. In such types lubrication oil replenishing provides the continuity in lubrication. Figure 1.14 shows the overall view of a four-stroke engine employing re-circulating type of oil lubrication. Figure 1.13 shows the block diagram of such a four-stroke engine. Oil is metered with incorporation of restrictors as required. Oil gets re-circulated after filtration. Oil change in such applications is recommended based on application of the automobile.

Wear particle count contributed by the metallic and non-metallic elements continues to increase till the oil change is effected. These contaminants were generally believed to exert significant influence on the viscosity of the lubricating oil. Problem of contaminants, other than the wear particles, is significant too. Starting 1980s, developments have taken place to reduce the frequency of oil change in engines. An example is a car needing an oil change per 1,500 km in 1970 needs one per 20,000 km [1.64] and, in a truck it has been improved from 10,000 km in 1980 to 60,000 km in 1997 [1.65]. Oil aging is computed on-board using data, such as crankshaft revolutions, oil temperature, engine...
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speed, number of cold starts, load hauled etc., to reduce the number of oil changes. Significant improvements in maintenance and lube-oil conservation methods have been reported. Simultaneous research on ambitious designs of bearing joints in automobile engines which never need a oil change in its life-time in the fill-for-life engines are being conducted.

Figure 1.13 Lubrication flow through a small automobile engine
1. Lube oil pressure sensor
2. Oil pump drive sprocket
3. Lube oil pump
4. By pass valve
5. Flow restrictor
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1.7 BEARINGS UNDER STUDY

The steel on sintered steel bearing selected for the investigation is shown in figure 1.15. Journal for the bearing is precision machined and ground to the required specification. The bush is manufactured by powder metallurgy process and the same is shrunk fitted in to the aluminium housing which also serves as the body for the oil pump used in a 100 cc motorcycle engine. The bearing has plain cylindrical construction with the journal having freedom to float in the axial direction. The 11 mm diameter portion of the bush is assembled in to the crankcase of the said engine and thus having retention in both ends. Material and geometry related data related to bearings referred in the study are listed in Table 1.6. Applicable manufacturing process and analysis pertaining to them are briefly discussed in the forthcoming chapter as and when required. As one of the bush finishing operations need wider understanding, the same is referred here.
1.7.1 Cylindricity of Bearings

Hydrodynamic action of journal bearings is created by the wedge action of the lubricating film. Film thickness along the circumferential and axial direction are directly influenced by the cylindricity of bearing elements, barrel/bell-mouthing on the bush. Boedo [1.66] emphasised the relevance of bearing geometry for the significant enhancement of its performance. Geometry influences the flow of lubricating fluid; which in turn aids the transmission of heat and thus influences the life of the bearing surfaces. Combined elasticity of the bearing elements that was analysed by Boedo and elasticity introduced by the film thickness needs special modelling for its applicability in the bearings under investigation. Bartz [1.67] analysed this, using the Dowson and Higginson equation; but lack of viscosity pressure co-efficient under the elastohydrodynamic contacts couldn't be included. At elemental level, the permitted cylindricity causes clearance variations, which in-turn affects the wear life of bearing. Pressure distribution along the axial and circumferential directions is under the direct influence of cylindricity. It is essential that the axially floating bearing be analysed for cylindricity effects. Attempt needs to be made to conduct the experimental and theoretical analysis of this important parameter.

The shrink fitting of bush and housing can be analysed with Lame's equation. For calculations purpose, bush and the housing can be assumed to be two cylinders shrunk.
one into the other, though the latter has a complex external shape. The shrink fit pressure can be arrived as

\[ P_s = \frac{\delta}{d_c \left( \frac{\alpha_i^2 + \alpha_j^2}{E_b (\alpha_i^2 - \alpha_j^2)} + \frac{\alpha_o^2}{E_h (\alpha_o^2 - \alpha_i^2)} \right) \mu_b + \mu_h} \]  
......... eqn. 1.8

where,

- \( d_i \) = inner diameter of bush
- \( d_c \) = core diameter after assembly
- \( d_o \) = outer diameter after assembly
- \( \mu_b \) = Poisson's ratio of bush material
- \( \mu_h \) = Poisson's ratio of housing material
- \( \delta_{\text{max}} \) = maximum interference
- \( \delta_{\text{min}} \) = minimum interference
- \( E_b \) = Young's modulus of bush material
- \( E_h \) = Young's modulus of housing material.

With modelling, the bush-housing interface can be analysed for cylindricity effects using appropriate analysis tools.

1.7.1.1 Bush burnishing

Of the various surface-finishing operations done on small bores, burnishing is best suited for mass production. Though ball burnishing is comparatively easy, carbide torpedo burnishing was preferred in the bush manufacturing on account of tool life and enhanced size stability. Burnishing is generally used to obtain dimensional accuracy compensating for warpage and to improve surface finish. Local densifications, closure of porous surface on account of surface flow are associated effects. Size of burnishing tool is decided generally by extensive trials, starting form the finished size of the bore. Slight plastic deformation occurs on the surface asperities and the forces required are quite moderate. Tool is swiftly pushed through the work piece surface. P/M parts are suitable for dry working. Equipments used are hydraulic or pneumatic driven based on the loads involved.

1.7.2 Surface Texture and Wear

Although in the past it has not been regarded as a branch of metrology under quality engineering, the specification of surface texture in some form or the other is the need for the design engineer to specify the product life and cost of production. With the more
exact demands of modern engineering products, the control of surface finish together with dimensional accuracy has become more important. As applied to the journal bearings, the reasons for specifying and controlling the surface topography are:

- To reduce the initial wear of parts in contact.
- To improve the fatigue resistance (surface irregularities are the seat of fatigue fracture)
- To allow the fine geometric and dimensional tolerances to be held.
- To reduce frictional wear and the dynamic torque.
- To reduce corrosion by minimizing the number and depth of crevices, where corrosion proceeds at a high rate.

The following parameters and abbreviations are used for our analysis of the test specimens:

- Centre line average ($R_a$).
- Root mean square (RMS).
- Maximum peak to valley height in the sample ($R_t$, $R_{max}$).
- Average of five highest peaks and five deepest valleys ($R_z$).

1.7.3 Surface Characterisation

An analysis of surface topography changes of specimens subjected to wear can be expected to provide quantitative information related to wear characteristics. The general problem of profile characterisation is extensively discussed by Thomas et.al., [1.68]. Nowicki [1.69] recommends a set of statistically independent surface roughness parameters for various applications including wear study. These parameters can be readily computed using digitised profile height data of the contacting surfaces provided by roughness measuring equipment, profilometer based on the methodology outlined in the section.

1.7.4 Filters of Lubrication Oil Circuit

Filters used in lubrication circuits are playing an important role in all facets of tribological performance of engines. Figure 1.16 shows placement of such a filter in a motorcycle engine crankcase. Filtration in a typical lube oil circuit is done in two stages. First level of strainers is in the suction line of lube-oil system and the second filter is generally incorporated in the return oil path. The strainers are critical to the performance of the "journal bearing". It is a gaze, insert moulded in a frame as in figure 1.17 and fitted between two rigid frames of engine assembly.
1.7.5 Lubrication Oil Circuit

Oil pump is mounted near the oil sump. Suction ports are generally integrated in walls of the crankcase housing by drilling through the thickness. The primary suction gaze, at the entry to oil circuit shown in figure 1.17 provides filtration. Oil passes through the control orifices to branch off to the parts of the engine as seen in figure 1.14. The oil, after running through the crevices of the lube oil circuit and that of operating components of the engine, return back to the sump with the contaminants collected enroute.

1.7.6 Failures and Materials Selection

In the application under study, the conventionally used materials are steels (free cutting low carbon, low carbon nickel chromium case hardening alloy, carbon steel etc.), journals operating on powder steel, bronze, and aluminium alloy bushings. Material selection, mechanical design, manufacture and application of these bearing sets are based on design made elsewhere in the world and more decided by the non-documented field data. Performance records show “early wear” as the most encountered problem and hence the associated failures of host products are sources of concern. Parts are subject to significant abrasive wear caused by contaminant particles getting into the lubrication system, resulting in failures. Product specific failures encountered are, failure of lube oil pump causing reduced or no lube oil supply, causing engine over heating and occasional engine seizure. Such seizures have also resulted in abrupt vehicle movement stoppage, causing road accidents. In case of indication instruments, the products stop working, making driver depend on his intuition to drive the automobile till its next earliest service. Above modes of product failure are, potentially very risky, from the viewpoint of safety of vehicle and passengers. The practice of vehicle users resorting to self
prescribed lubrication methods without refill of lube oil in designed circuit cause starvation and aggravated bearing failure.

1.7.7 Operating Pressure

Four stroke pumps are generally specified for fixed lubrication, but flow dependant on engine speed. It is based on an assumption that, wear rate of engine and its parts are primarily dependent on the speed of operation. To cater for the load variation, flow rate (volume/time at a given speed) is limited at the minimum side and left open at the maximum side. Though, this design methodology initially suits engine designer from the cost considerations, longevity requirements placed on the engine, as a whole requires developments. In getting to the specifics of pressure-volume requirements of lubricating oil, block oil pressure and flow at the normal operating temperatures of engine may need in-depth analysis. Oil pump bearings under present investigation have the availability of continuous oil flow at 0.08 to 0.12 MPa under normal conditions.

1.7.8 Contaminants in Lubrication Oil

In order to substantiate the numerical solutions and laboratory simulations, field run (FR) bearings and oils need analysis. Once the contaminants are analysed, tests are to be developed to evaluate the bearings in specific application conditions. Ronen.A, Malkin.S and Loewy.K [1.70] studied dynamically loaded hydrodynamic bearing with clean oil and contaminant in the oil and found that the wear due to contaminant in the oil is nearly 20 times more; the wear rate measured as form weight loss with respect to time was found to be linear in nature. Field oil evaluation has been found useful. "Spectro Chemical Analysis" as a tool to the sampling analysis was evolved around 1912 to detect wear source, contaminants and additives in PPM by weight. Wear metals contributed by parts of engine consists of iron (from rings, shafts, gears, valve train etc) chromium (from rings, liners etc) Nickel (from bearings, valve guides etc) Aluminium (from piston, bushings etc) and so on. Contaminants can be classified as silicon dioxide, grease with aluminium or barium metallic soaps etc. Additives added to oils, fuels and coolants for selective automotive application added to this list. 1970s saw emergence of another oil analysis line-ferrography as a means of microscopic examination of particles from fluids. It has further evolved into direct reading ferrograph and the analytical ferrograph system. The direct reading ferrograph measures the concentration of wear particles by subjecting samples to a powerful, magnetic gradient field and separating the particles by order of size. It is used to obtain numerical base line values for normal wear. When sudden increase in direct readings occur, analytical ferrography allows visual
analysis of the wear particle. That is feasible with the three power bichromatic microscope, capable of magnifying up to 1000X under polarised direct and reflected light conditions [1.71]. Advancement in the field of particle analysis gives faster data in wear type and debris shape analysis.

1.8 PROBLEM ANALYSIS
The multiplicity of options and application conditions need design validation. Bearing design validation at the fundamental level has been taken through three levels in this investigation. With the materials and few design factors ranked, the selected material mixes were fabricated into required shape and to the matching design specifications. These bearings are taken through second round of specific design validation in the series of tests in order to reduce duration. These tests, conducted for times shorter than end – of – life, were resorted to and acknowledged [1.72] by Bayer (1976), Bhushan and Martin (1988), Yust and Bayer (1988) as valid models for material and processing parameter evaluation. At third stage, a DoE structured in this investigation for wear data collection at intermediate intervals provided data for prediction of end-of-life. With these simulations, and by analysis of the field run journal bearings, attempt has been made to ascertain "acceleration factor" between the simulation and actual use.

1.8.1 Need for Variable Spectra Simulation Rig
Useful performance of the sub-systems of the automobile engine starts with the first cranking of the engine. Once the engine comes alive, crankshaft driven lube oil system gets activated. Though there are advanced engine lubrication system designs, where there are arrangements to supply the lube oil circuit by external means at the start still the system gets self sustaining, the conventional engines are fed by engine driven mechanical oil pumps only. That means a small delay, typically 3 to 10 seconds in the start of lube oil flow. Another direction of thought was the simulation of a more realistic engine condition wherein the speed variation, as experienced by the bearing assembly is to be repeated. The precision bearings used in the indication instruments, sensors and oil pumps of the automobiles are providing safety, operation related information and feedback to the driver and the other control systems; this puts a demand on the reliability of such information. Condition monitoring of these precision bearings is nearly impossible because of the design of host products, their multiplicity and inaccessibility in the structure of the automobile, in particular. Hence design validation process assumes more significance. As application related design factors need in depth study and
development before product release, the validation process needs appropriate simulation rig. At the new product development stage, individual parameters are generally tested with standard test equipment. Industry practices generally are targeted towards approval of the product in toto and automobile applications particularly rely upon vehicle field-testing. Such an initiative, apart from being prohibitive in cost, the time consumed is very high; hence, the same is un-acceptable to the concerned agencies. Researchers in journal bearings field have designed and developed special tailor made rigs to evaluate the developmental works [1.5], [1.18]. Accordingly, development of the variable spectra rig is considered in this work.

1.8.2 Significance of Ferrographic Studies

Ferrographic Wear Particle Analysis [1.72], [1.73] has gained significant edge over other conventional investigative methodology due to latest advancements and their continuous improvements as mentioned in section 1.7.8. Wear particles from used oil provides a wealth of information. All parts of the engine continuously generate wear particles. Concentration of these wear particles increase continuously until the lubricating oil is changed, following which, their concentration reduces to near zero. Build-up of smaller sized particles in the system starts as soon as the automobile engine starts working. When abnormal wear begins, there is no sharp instantaneous increase in these small particles present in the system. Build-up of large particles (typically bigger than 10\(\mu m\)) dramatically increases when abnormal wear begins. Also, wear particles caused by specific wear modes have distinctive characteristics, which reveals the type of wear mechanism at work. Wear quantification, predominant wear mode qualification and associated wear contribution are the results of signature analysis.

1.8.3 Current Practice and Development of Accelerated Wear Test

Present industry practice for the testing and validation of the oil pumps are as follows:

- Free rotation check
- Leakage test
- Oil flow test
- Oil flow under selected environmental condition
- Dynamic torque test of journal
- Vibration durability test
- 1000 h durability test
- Outlet block pressure test and
- Vehicle endurance test.
Hand in hand with the ferrographic development, tests with dust mixed oil has been adopted.

Researchers on metal removal by wear suggested simulation of field conditions in laboratory to contain costs and to reduce product development time. Early work has been referred in section 1.3.8. Simulation of real life condition of journal bearing could be based on keeping all the factors like lubricant oil flow, oil type, temperature, bearing construction etc., constant, but by varying the speed of operation of the bearing. Applied journal load, errors of alignment etc., have been accounted in such tests by matching mounting and driving to suit product application. Market conditions too require satisfaction of such an elaborate product approval procedure.

1.8.4 Significance of Design of Experiments (DoE)

The DoE classical approach is handy for studying comprehensively about effect of clearance, surface roughness, material properties, assembly errors, third body particles, thermal effects etc., It is desirable to reduce the cost and time of product development without sacrificing any of the effects on product performance.

Robust design, which draws on many ideas from statistical experimental design, was developed and validated by Dr Taguchi. The fundamental principle of robust design is to improve the quality of product and process development by minimising the sensitivity of performance of the product to various causes of variation [1.74].

1.8.4.1 Taguchi methodology

Dr. Taguchi of Nippon Telephones and Telegraph Company, Japan has developed the method based on "ORTHOGONAL ARRAY" experiments which give much reduced "variance" for the experiment with "optimum settings" of control parameters [1.75]. "Orthogonal Arrays" (OA) provide a set of well balanced (minimum) experiments and Dr. Taguchi’s Signal-to-Noise ratios (S/N), which are log functions of desired output, serve as objective functions for optimisation, help in data analysis and prediction of optimum results.

1.8.4.2 Eight steps in Taguchi methodology

The method is applicable over a wide range of engineering fields that include processes that manufacture raw materials, sub-systems, products. Taguchi proposed a standard eight step procedure for applying his method for optimising any process.

Step 1 Identify the main function side effects and failure more

Step 2 Identify the noise factors testing conditions, and quality characteristics
Step 3 Identify the objective function to be optimized
Step 4 Identify the control factors and their levels
Step 5 Select the orthogonal array matrix experiment
Step 6 Conduct the matrix experiment
Step 7 Analyse the data predict the optimum levels and performance
Step 8 Perform the verification experiment and plan the future action

1.9 CONCLUDING REMARKS
Journal bearings used in automotive accessories including oil pumps are crucial for the trouble free functioning of the whole engine. These bearings are generally referred to as full-film bearings implying that the load bearing surfaces of the bush and journal are supported by a thick film of lubricant. Operation of bearings under such condition is made possible with appropriate selection of load, speed, lubricant viscosity and clearance.

It is necessary that the magnitude of wear should be minimum for a bearing. The market trend necessitating the design and development of ‘fit and forget’ designs also need to be considered. Small size bearings to be dealt with in this investigation have closer performance requirements, apart from the anticipated overall reliability in performance. Inadequate maintenance conditions of automobile engine were considered to be primarily causing presence of abrasive contaminants in the lubricating oils. The contaminants flowing into the bearing clearances are of serious concern. Cylindricity errors and inadvertent process mean shift in respect of bush introduced in the manufacturing process is likely to affect the performance of the bearings.

In a like manner, non-conformity between the bearing dimension of mass produced parts in the manufacturing line and that of the design specification will result in significant clearance variation which in turn will affect the wear characteristics of the bearings.

Testing practices for product validation and manufacturing line are found rudimentary and time consuming. Significance of field performance parameters like variations in speed, engine vibration and oil condition, line pressure variations, etc., are not found accounted in the present testing procedures. Owing to the above reasons, the industry
needs significant improvements for improved product deliverance, in terms of cost and time frame.

Any improvements in design need designer's attention on many factors like:

❖ Load variation
❖ Operating speed variations
❖ Roughness of mating members
❖ Clearance
❖ Materials of construction
❖ Part density, etc.

So, a study is therefore called for to determine the conditions, which will facilitate in determining optimum conditions favouring minimum specific wear rate. By establishing correlation between the experimentally obtained data and that from the field, it would assist the designer in rationally selecting the design parameters to minimise wear and thus improve the performance of bearings. To validate the data obtained, correlation with field run bearings and study on seizure failure of the bearings are also required.

Factors influencing wear performance of a typical automotive journal bearing application have been covered; the thesis aims at providing insight into factors related to the design and manufacture and to suggest a method for shorter test duration for product validation.

This research programme, thus has the following essential objectives:

i) Study of bearing manufacturing practices to analyse geometric errors.
ii) Determination of conditions favouring minimum wear.
iii) Development of a new test practice of shorter test duration.
iv) Identification of application specific design inputs.
v) Establishing correlation between test practices and field data.