EASA
European Aviation Safety Agency

Report EASA.2012.07

Research Project:

HELMGOP II
Helicopter Main Gearbox Loss of Oil Performance Optimisation

Appendix A

An agency of the European Union

APPENDIX A – LITERATURE REVIEW OF HELICOPTER MGB LUBRICATION

A.1 Function of a Helicopter Main Gearbox

In all helicopter designs, turboshaft engines drive the rotors to generate lift and therefore flight. This is made possible with the use of a Main Gearbox (MGB) that converts the engine power from high speed and low torque to low speed and high torque, which is necessary to drive the main rotor and tail rotor systems. To achieve this, the MGB uses a number of reduction gear modules in its design (Figure A.1). The MGB is also responsible for driving other critical accessories on the helicopter such as the electrical generators, hydraulic pumps and oil lubrication pumps via the accessory drive modules. These components are essential for powering the aircraft electronics and flight control system as well as to support the proper functioning of the MGB.

Given the directional change between the axes of rotation for the engine and the main rotor, helicopter MGBs typically incorporate a spiral bevel gear system as part of their designs. In addition they also utilise the epicyclic gear systems to attain maximum torque conversion in a compact size, as both weight and space are premium entities for a rotorcraft. During operation, the high input speeds and high output torque of modern compact MGBs generate a huge amount of frictional heat at the gears and bearings. They therefore require an effective lubrication system to minimise physical wear and to maintain the reliability of the gears and bearings.

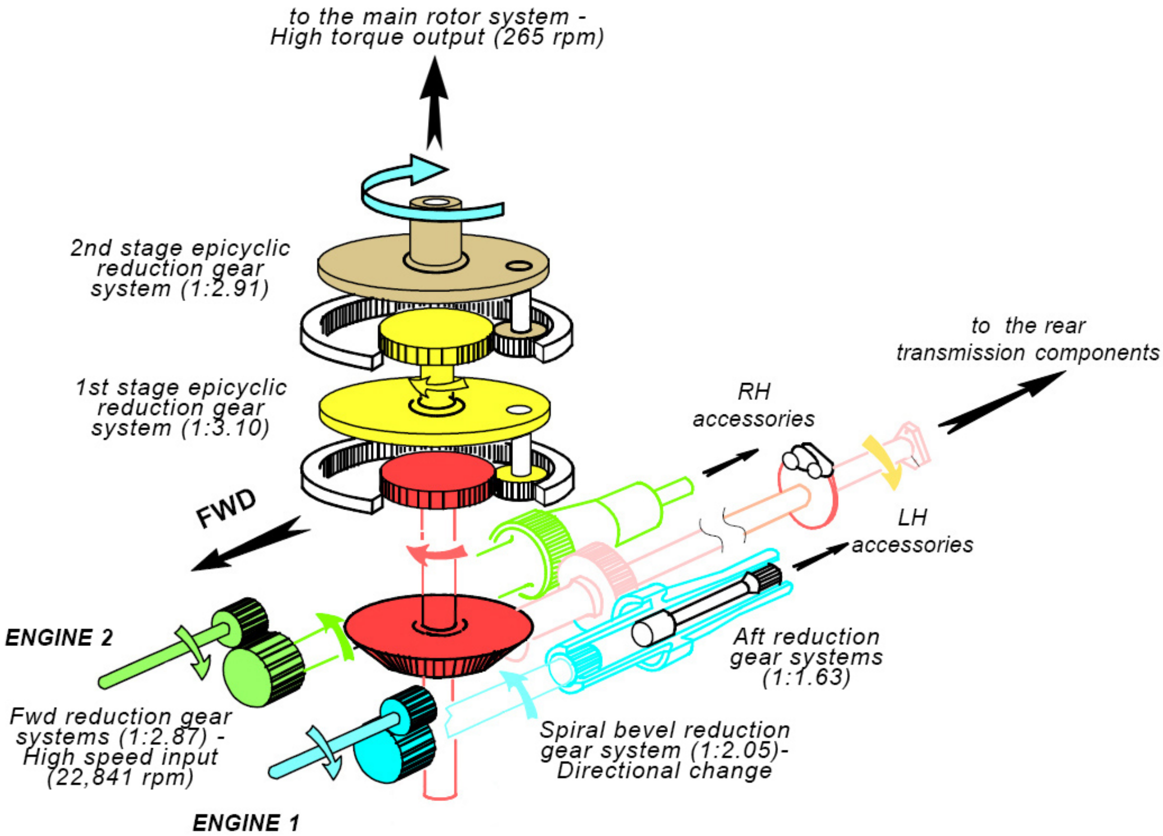


Figure A.1 Category “A” Helicopter MGB Drive Schematic (Source: Helicopter Manufacturer)

A.2 Lubrication of a Helicopter Main Gearbox

The high power densities of modern helicopter MGBs demand high levels of lubrication and cooling that often involve forced oil lubrication. For the example of a Category “A” helicopter MGB with pitch diameters and rotational speeds of the high speed input pinion and the 2nd stage epicyclic sun gear as depicted in Table A.1, the computed pitch line velocities are approximately 84 m^{s-1} and 9 ms^{-1} as shown in Equations A.1 and A.2 respectively.

Category “A” Helicopter MGB Input Pinion		
Description	**Value**	**Units**
Rotational Speed (N_1)	22,841	rpm
Pitch Diameter (D_1)	0.07	m
Pitch Line Velocity (V_1)	83.72	ms^{-1}
Category “A” Helicopter MGB Second Stage Epicyclic Sun Gear		
Description	**Value**	**Units**
Rotational Speed (N_2)	772	rpm
Pitch Diameter (D_1)	0.23	m
Pitch Line Velocity (V_2)	9.30	ms^{-1}

Table A.1 Pitch Line Velocities of Category “A” Helicopter MGB
(Source: Author)

$$v_{input} = \frac{D_1}{2} * \frac{2\pi N_1}{60} = \frac{0.07}{2} * \frac{2\pi * 22{,}841}{60} = 83.72\, ms^{-1} \qquad \text{Equation A.1}$$

$$v_{1st\ Sun} = \frac{D_2}{2} * \frac{2\pi N_2}{60} = \frac{0.23}{2} * \frac{2\pi * 772}{60} = 9.30\, ms^{-1} \qquad \text{Equation A.2}$$

From Figure A.2, the mode of lubrication best suited for the computed pitch line velocities of the category “A” helicopter MGB is forced oil circulation lubrication. On the physical helicopter, this involves the use of an external oil cooler (heat exchanger), oil filter and a MGB driven pump. The constant volume pump circulates the lubrication oil through the oil cooler and the oil filter before providing an oil supply of 1.5 to 1.7 bars at around 80°C into the MGB. Upon entering the MGB, the oil then circulates through the internal passages within the casing and into the oil nozzle jets directed at critical gear meshes and bearings. Such a lubrication system is necessary to lubricate and cool a MGB with a maximum continuous power rating of above 1000 kW.

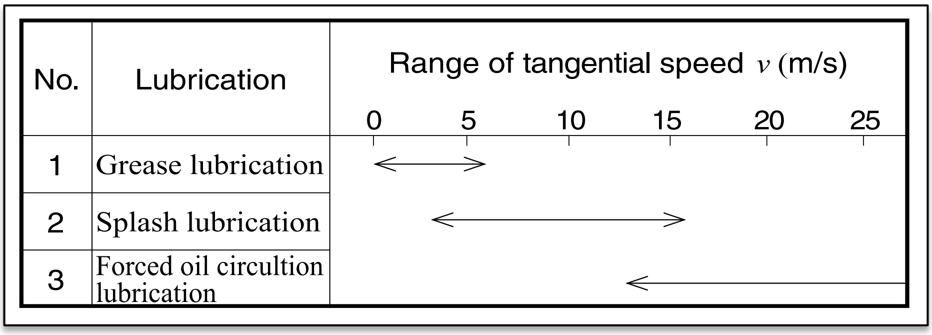


Figure A.2 Type of Lubrication for Range of Tangential Speeds (Pitch Line Velocities)
(Source: KHK “Practical Information on Gears”)

A.3 Criticality of Helicopter Main Gearbox Lubrication

Owing to its physical weight and size, the MGB is not designed with redundancy in mind. Instead, it remains as one of the critical load paths between the power generating engines and the rotor systems that sustain flight in a helicopter. The integrity of the MGB for safe and proper operation is heavily dependent on its lubrication system due to the high rotational speeds and torque loads involved. A loss of MGB lubrication results in higher levels of friction generated at the gear meshes and bearing roller elements and therefore elevated component surface temperatures. Higher surface temperatures adversely affect the components' surface hardness and their ability to transmit the high loads within the gearbox. In addition, thermal expansion due to the higher temperatures causes stresses in the gearbox components, which eventually bring about mechanical failures of the gearbox.

The criticality of the MGB lubrication system is evident in the list of accidents and serious incidents between 1983 and 2013 as shown in Table A.2. This list is an updated version of the compiled list mentioned in a research report by the European Aviation Safety Agency (EASA) on Helicopter Main Gearbox Loss of Oil Optimisation [1]. Of the 14 listed cases, a total of 10 cases were related to the loss of effective lubrication as a result of severe oil leaks, restricted oil flow, debris in oil or oil pump failures. Amongst these cases, the most recent incident was on 12 Mar 09, which involved a Cougar Helicopters' Sikorsky S-92A on a flight to the Hibernia oil production platform in Canada. The helicopter had suffered an inflight total loss of MGB oil lubrication that led to the failure of the MGB before it ditched into the waters near St John's, Newfoundland and Labrador. In this incident, one passenger suffered serious injuries while the remaining seventeen passengers died of drowning. According to the investigation report by the Transportation Safety Board of Canada (TSB) [2], the causal factor behind the loss of MGB oil lubrication was the fracture of the titanium studs that secure the oil filter bowl. Figure A.3 illustrates the location of the oil filter bowl assembly on port side of the MGB, while Figure A.4 provides images of the incident oil filter bowl and the attachment stud involved.

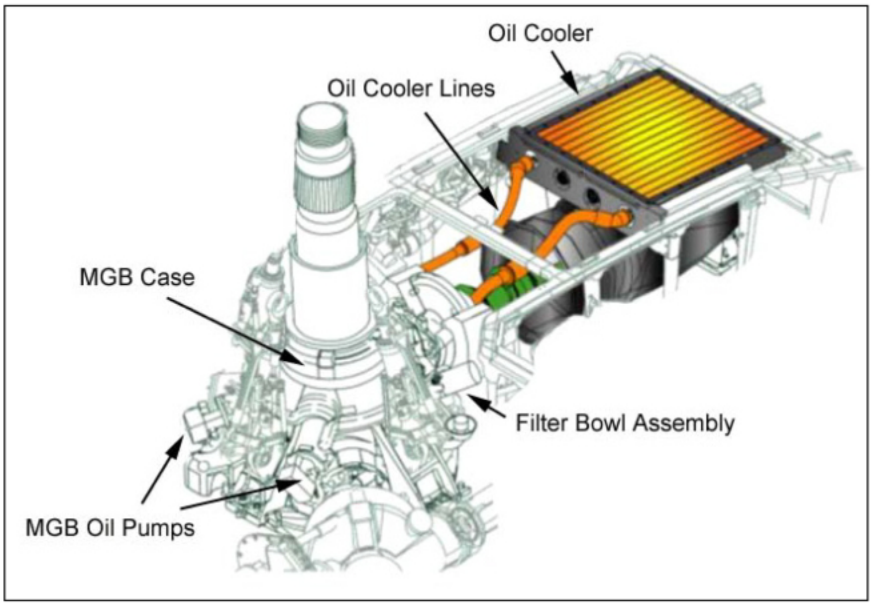


Figure A.3 S-92A MGB Oil Lubrication System
(Source: TSB Aviation Investigation Report A09A0016)

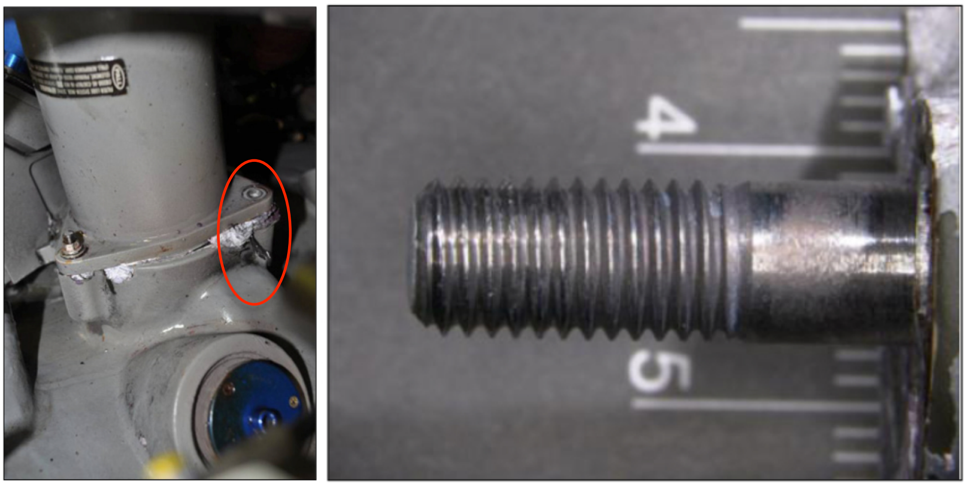


Figure A.4 Incident Oil Filter Bowl with Fractured Studs (Left) and
Image of Damaged Stud (Right) (Source: TSB Aviation Investigation Report A09A0016)

The attachment studs for the oil filter bowl assembly were made of titanium alloy for its corrosion resistant and lightweight features. They were anodised to provide improved resistance to corrosion and were successfully employed to secure the MGB oil filter bowls in other Sikorsky helicopters such as the CH-53 Sea Stallion. Unfortunately, the alloy is prone to an adhesive wear process called titanium galling, in which material is removed from the surface due to sliding contact or fretting. In the incident, 2 of the 3 attachment studs had fractured due to overload failure resulting from fatigue cracks. Tests on new attachment studs and nuts showed that titanium galling was evident on the threaded portions after 13 to 17 removal and installation cycles.

Figure A.5 New Tail Take-off Pinion Gear (Left) and Incident Pinion Gear (Right)
(Source: TSB Aviation Investigation Report A09A0016)

The total loss of MGB oil pressure resulted in an increase rate of frictional heat generation due to the continued gearbox operation without lubrication. This brought about the plastic failure of the tail take-off pinion gear teeth (Figure A.5) and eventually the loss of tail rotor control. According to the onboard data recorder, the MGB had operated for an approximately 11 mins upon the loss of total oil pressure. Following this incident, Sikorsky introduced a new two-piece MGB oil filter bowl, which is now secured using six replaceable nuts and bolt fasteners. Replacement to the new oil filter bowl assembly became mandatory in Oct 2010.

S/N	Date	Aircraft	Register Code	Country	Reference / Report	Description	Injuries / Fatalities
01	22 Oct 12	Eurocopter EC225 LP	G-CHCN	UK	AAIB – UK Report S6/2012	Failure of drive of MGB oil pumps (Failed bevel gear vertical shaft at a welded joint – Non oil-system failure. Ditching followed erroneous warning on emergency lubrication system that was activated successfully)	No injury to 2 crew and 17 passengers
02	10 May 12	Eurocopter EC225 LP	G-REWD	UK	AAIB – UK Report S2/2012		No injury to 2 crew and 10 passengers. 2 passengers with minor injury
03	01 Apr 09	Aerospatiale AS332 L2	G-REDL	UK	AAIB – UK Report 2/2011	Loss of MGB oil due to MGB case rupture (Failed 2nd stage epicyclic planet gear - Non oil-system failure)	16 fatalities (2 crew and 14 passengers)
04	12 Mar 09	Sikorsky S-92A	C-GZCH	Canada	TSB – Canada A09A0016	Total loss of MGB oil due to fracture of oil filter bowl fixing titanium studs	1 passenger with serious injury. 2 crew and 15 passengers drowned
05	02 Jul 08	Sikorsky S-92A	VH-LOH	Australia	TSB – Canada A09A0016. P70	Total loss of MGB oil due to fracture of oil filter bowl fixing titanium studs	No injury to 2 crew and 14 passengers
06	04 Feb 08	Schweizer 269D-1	G-TAMA	UK	AAIB – UK EW/C2008/02/04	Seizure of MGB pinion outer bearing due to oil starvation	No injury to 1 crew (Post maintenance flight)
07	Jan 08	Sikorsky S-92A		Sarawak-Malaysia	TSB – Canada A09A0016. P70	MGB input module overheating that led to slow oil leak	No injury to crew and passengers
08	Apr 05	Sikorsky S-92A		Norway	TSB – Canada A09A0016. P70	Failure of drive of MGB oil pump	No injury to crew and passengers
09	08 Mar 04	Schweizer 269C-1	C-FZQF	Canada	TSB – Canada A04Q0026	Normal flow of MGB oil obstructed due to incorrect positioning of input quill bearing housing	No injury to 1 crew (Ground test)
10	06 Aug 03	Enstrom F-28F	G-BXXW	UK	AAIB – UK EW/C2003/08/03	Failure of MGB rear bearing due to inadequate lubrication	No injury to 1 crew and 2 passengers
11	16 Dec 02	Sikorsky S-61N	C-FHHD	Canada	TSB – Canada A02P0320	The plain bearing in the main gearbox cover for the number 1 input pinion failed, lost lubrication, and disintegrated	Minor injury to 2 crew and 1 passenger
12	08 Nov 01	Eurocopter SA315B	C-GXYM	Canada	TSB – Canada A01P0282	The input freewheel unit (IFWU) and drive shaft assembly failed because of the wear on the internal parts caused by the repeated heavy lift operations and because of the contamination suspended and trapped in the lubricating oil between the unit's rotating parts	1 fatality (pilot) (Logging operation)
13	16 Oct 00	Aerospatiale AS335-F2	N355DU	USA	NTSB – USA MIA01FA006	Failed MGB oil pump	1 fatality (pilot) (Post maintenance flight)
14	11 Mar 83	Sikorsky S-61N	G-ASNL	UK	AAIB – UK EW/C815	Loss of MGB oil due to MGB case rupture (Failed spur gear at input stage - Non oil system failure)	No injury to 2 crew and 15 passengers

Table A.2 Accidents and Incidents Involving Helicopters MGB Lubrication Systems (Source: [1])

The criticality of the helicopter MGB lubrication system is echoed in an article published on Air International News (AIN) Online[1] in Jan 2013 [3], where the MGB is still being described as the "*Achilles Heel*" of modern helicopters. The MGB remains the weakest link in the rotor drivetrain system despite numerous improvements to the design of the gearbox components and the regulatory requirements or airworthiness directives over the decades. Notable design improvements include the use nitriding surface-hardening process for the bearing raceways, gear surfaces and rotor shafts.

At the airworthiness front, a latest revision to EASA regulatory requirement CS 29-2C[2], in the form of a certification memorandum was made in Nov 2013 with respect to section CS 29-297(c): lubrication system failure on the helicopter main gearbox. The memorandum aims to clarify the safety agency's stance on the additional tests that demonstrate the capability of the helicopter to sustain operation for 30 mins (for Category "A" rotorcraft) in the event of failures leading to the loss of lubrication pressure to the MGB primary oil system. In particular, the phase "unless such failures are extremely remote", which is related to the additional tests and is subjected to ambiguity, should not be interpreted as a form of waiver for additional tests when considering extremely remote failures to the primary oil system. Instead, the compliance approach should assume a failure in the primary oil system that leads to a rapid loss of lubrication pressure and to rely on an auxiliary oil system or the robustness of the MGB components to sustain operation for 30 mins. The auxiliary oil system should be independent of the primary oil system in order to avoid common failure points that may lead to loss of lubrication pressure. It may not be pressurised like the primary oil system.

The trigger for the certification memorandum was the crash of a Cougar Helicopters' Sikorsky S-92A helicopter on 12 Mar 2009. The investigation by the TSB revealed several safety issues, one of which was that a Category "A" helicopter certified under the "extremely remote" criteria might not able to sustain operation of 30 mins after the loss of lubrication pressure to the MGB primary oil system. TSB assessed that the present operating environments of helicopters demand a rotorcraft that can sustain operation in excess of 30 mins following a loss of lubrication pressure to the primary oil system. It also argued that the current aerospace industry have both the technology and financial resources to achieve it.

The Transport Canada Civil Aviation (TCCA), EASA and the Federal Aviation Administration (FAA) have since conducted a joint review of the current regulatory requirement CS 29-2C related to the certification of the helicopter main gearboxes, and have made several recommendations on it. EASA will lead the group in making changes to the requirement based on these recommendations in 2014. In the meantime, the certification memorandum serves as the design guidelines for helicopter manufacturers with respect to the

---

[1] A publication of The Convention News Company, Inc. The website features articles from the AIN monthly publications that catered for a more technically oriented pilot and aviation industry audience.

[2] Certification of Transport Category Rotorcraft

additional tests on the main gearboxes. The memorandum is also part of the common harmonised text agreed by the three aviation safety agencies.

A.4 Helicopter Main Gear Box Secondary (Emergency) Oil System

Owing to the regulatory requirement for the helicopter MGB to sustain 30 mins of operation following the loss of lubrication pressure from the primary oil system, the manufacturers of modern helicopters have come up with various designs for the secondary or emergency oil lubrication system. Such systems either provide an external means of emergency lubrication to the critical gears and bearings within the MGB or utilise new manufacturing methods for improved MGB operation upon the loss of the primary lubrication pressure. They can be classified into two broad categories: Active and Passive Secondary (emergency) Oil systems. Table A.3 summarises the characteristics of the secondary oil systems incorporated in modern helicopters by the various rotorcraft manufacturers.

An active secondary oil system can comprise of an independent lubricant system such as the one deployed on the EC225 helicopter (Figure A.6). In this design, a glycol and water mixture is housed in a separate tank with a capacity of 11-litres. It is mixed with the pressurised bleed air from the aircraft left engine in a distributor before being sprayed onto the components within the MGB. A pump driven by an electric motor delivers the glycol lubricant into the distributor. The manufacturer, Airbus Helicopters, claims that the emergency lubrication system has achieved 52 mins of sustained MGB operation upon the loss of the primary oil lubrication pressure during certification trials.

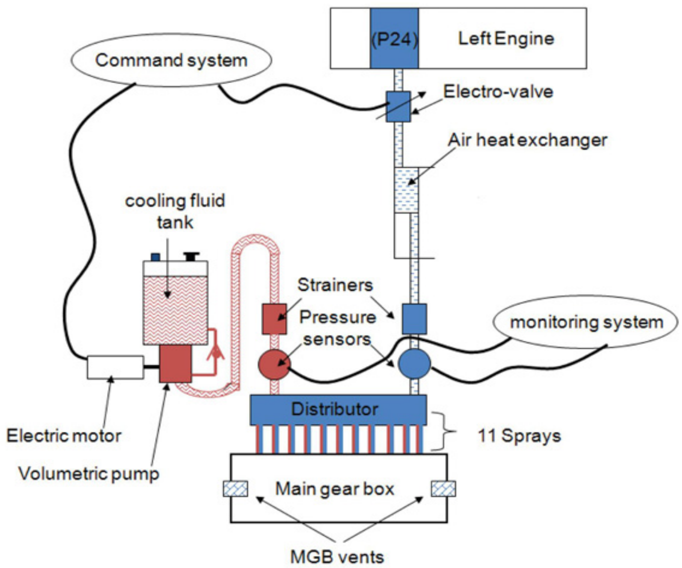


Figure A.6 Schematic of EC225 Emergency Lubrication System
(Source: http://www.ec225news.com/site/en/hc/Hums-2_44.html dated 27 May 14)

Manufacturer	Airbus Helicopters	Sikorsky Helicopters	Bell Helicopter		AgustaWestland	Boeing
Manufacturer Logo	AIRBUS HELICOPTERS	Sikorsky A United Technologies Company	Bell Helicopter A Textron Company		AgustaWestland A Finmeccanica Company	BOEING
Helicopter Model	EC225 Super Puma	S-92A (With proposed new MGB)	BH-525 Relentless	Patent #US 20120247874 A1 filed on 22 Mar 12	AW189	AH-64D Apache
Helicopter Photo						
Photo Credit	www.turbosquid.com		Bell Helicopter	NA	AgustaWestland	Boeing
Classification	Large Twin Engine	Medium Twin Engine	Medium Twin Engine	NA	Medium Twin Engine	Medium Twin Engine
Weight	11 Tons	12 Tons	8.7 Tons		8 Tons	6.8 Tons
Crew	19 Passengers	19 Passengers	16 Passengers		18 Passengers	2 Passengers
Secondary (Emergency) Oil System Description	Independent mixture of glycol (11-litres) and left engine bleed air sprayed through 11 nozzles into MGB. Glycol supplied via elector motor driven pump	Double oil filter bowl and a redundant oil scavenge and emergency lubrication system. Automatic bypass switch if leaks occur in oil cooling system.	Emergency pump driven by MGB. Heat exchanger and oil routing integral with MGB casing. Super finishing of gears to minimise friction. Use of heat tolerant materials	Reserve housing integral with MGB casing to retain lubrication oil. Pressurised supply line to reserve housing. Metering jet to provide oil to MGB components at a controlled rate.	Emergency pump driven by MGB. Super-finishing of MGB gears and special coatings for low friction at gear and bearing contacts with residual oil. High “hot-hardness” of gears and bearings against thermal distortions. Heat removal from MGB hot spots by conduction and convection.	Oil saturated felt wicking devices inside bevel gears and around helical gears. Bearings employ silver-plated steel races to aid in lubrication during MGB start-up and in an emergency
Emergency Lubrication Duration	52 mins	To be tested in 2013	At least 30 mins	At least 30 mins	50 mins	At least 30 mins
Category	Active + Independent	Active	Passive	Passive	Passive	Passive
MGB Reliability Improvement	High	Medium	Medium	Medium	Medium	Medium
Source(s)	EC225news.com + (AIN) Online, 01 Nov 11	(AIN) Online, 01 Nov 11 and 01 Jan 13	(AIN) Online, 01 Jan 13	Patent #US 20120247874 A1	(AIN) Online, 17 Jun 13	AH-64D TM 1-1520-238-T-4

Table A.3 A Summary of Secondary (Emergency) Oil System Designs (Source: Author)

In comparison, a passive secondary oil system relies on the advances in manufacturing techniques to improve the durability of the existing MGB components when operating under a “loss of oil” condition. One example is the AW189 MGB designed by AgustaWestland. Low contact friction at the gears and bearing is achieved through the combination of residual lubrication oil and gears with super-finished surfaces or special low friction coatings. Gears and bearings are designed and manufactured to attain high “hot-hardness” properties in order to handle the high loads with minimum thermal distortions. The gearbox casing facilitates heat dissipation through conduction and convection at the hot spots caused by the contact friction. Thermal gradient across the MGB is minimised through designing for uniform thermal expansion of the MGB components. The AW189 MGB is certified for sustained operation of up to 50 mins following the loss of the primary oil system.

Another type of passive secondary oil system comes in the form of a recent patent filed by Bell Helicopter (Figure A.7) in 2012. It involves the introduction of a reserve housing that is integral with the MGB housing to retain a certain volume of the primary lubrication oil. The supply of lubrication oil to the reserve housing comes from a pressurised oil line. An overflow tube prevents the reserve housing volume from exceeding a pre-determined amount. Delivery of the reserve lubrication oil is through metering jet that allows a controlled flow rate to the gearbox components, even if the supply line ceases.

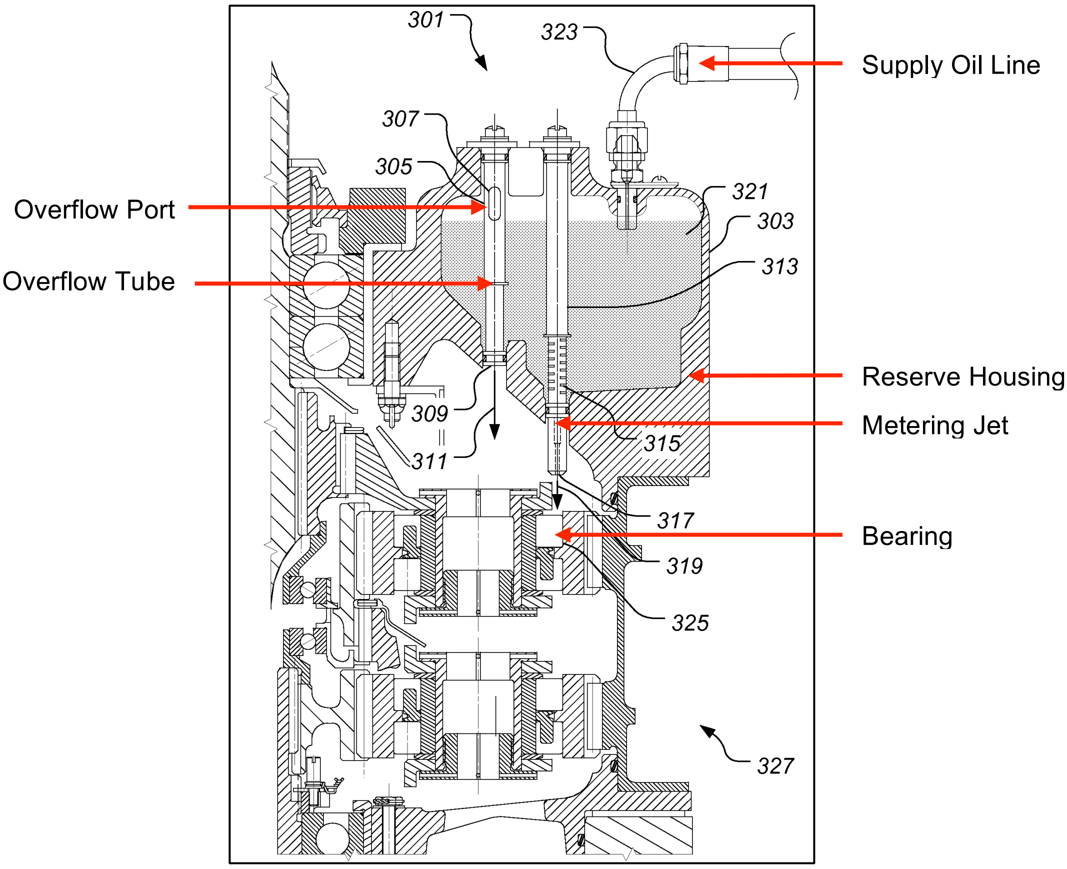


Figure A.7 Schematic for Bell Patent #US 20120247874 A1: Reserve Housing for Lubrication Oil
(Source: http://www.google.com/patents/US20120247874 dated 27 May 14)

Comparing the various secondary oil lubrication systems developed by the different rotorcraft manufacturers, the expected enhancement to the reliability of the MGB during a loss of primary oil lubrication system can be broadly classified as high or medium. In particular, the active and independent secondary oil lubrication system by Airbus Helicopters that utilises a separate mixture of glycol and pressurised air offers the highest reliability improvement. This is attributed to the independent lubrication system that remains intact to sustain MGB operation when there is a total loss of the primary oil system due to severe leaks or pump failure. Relative to this design, the other systems have a lower level of reliability improvement, as they are dependent on the controlled degradation of the MGB gears and bearings. This is achieved using surface polishing and heat treatment techniques or through the release of residual oil trapped in a reserve housing or saturated in felt wicks.

Even though the levels of improvement to the reliability of the MGB varies, it is still important to note that all systems are capable of sustaining at least 30 mins of MGB operation upon the loss of the primary oil lubrication system. What differs would be the extent of the damage to the MGB internal components following a period of emergency operation in the absence of normal oil lubrication. The various systems also incur different levels of design and manufacturing complexities, maintenance requirements and system implementation weight, sizes and costs to the helicopter program.

A.5 Thioether Vapour Mist Phase Reaction Lubrication (VMPL)

From the discussions on the different design of MGB secondary (emergency) oil lubrication systems, it is evident that an active and independent secondary oil lubrication system offers the highest level of reliability improvement to the helicopter MGB. Unfortunately, the weight of an active emergency oil system that comprises an external pump, pipelines and an oil tank, adversely affects the payload capability of a helicopter. Furthermore, the typical hydrocarbon lubricants thermally degrade at elevated temperatures above 280°C (Table A.4). With the introduction of new high power density MGBs, emergency operation close to these elevated temperatures will become more probable. For these reasons, an alternative method of gearbox lubrication that is lightweight and can provide lubrication at elevated temperatures has been the focus of researchers in the aerospace industry.

Base Oil	Thermal Decomposition Temperature
High-quality hydrocarbons	280-320°C
Di-Esters	275°C
Polyolesters	315°C
Polyglycols	220°C
Phosphate Esters (triaryl phosphates)	420°C
Silicones	315-370°C
Silicates	345-450°C
Polyphenol Ethers	440-485°C
Perfluoropolyalkyl Ethers (PFPAE)	360-390°C

Table A.4 Thermal Decomposition of Lubrication Oils (Source: http://www.machinerylubrication.com/Read/29371/high-temperature-lubricant dated 06 Jun 14)

The Vapour Mist Phase Reaction Lubrication (VMPL) method using an organic polyphenol ether known as thioether had seen promising results through experiments conducted by NASA and the US Army Research Laboratory [4] and [5]. VMPL differs from other vapour and mist lubrication techniques such as vapour lubrication and regular oil-mist lubrication, in terms of its delivery means as well as its thermal decomposition and chemical reaction properties. In vapour lubrication, a lightweight hydrocarbon gas such as acetylene is delivered in gaseous form to the mechanical wear surfaces operating at sufficiently high temperatures. The high temperature decomposes the gas to form lubricious graphite layer that provides lubrication to the wear surfaces. In regular oil-mist lubrication, hydrocarbon oil is delivered as a mist in an air stream to the mechanical wear surfaces at normal operating temperature, where it coagulates to form a lubricious film. No chemical decomposition or reaction occurs between the oil film and the metal surfaces. In VMPL, an organic liquid is vaporised or delivered as a mist in an air stream to the mechanical wear surfaces that operate at sufficiently high temperatures that the liquid react with the metal surfaces to generate a lubricious deposit layer that is capable of effective lubrication.

The earlier studies on VMPL [6] had used an organic liquid compound, pure aryl phosphate ester (Figure A.8), which reacts chemically with the metal surfaces at high temperatures to form a lubricious iron-phosphorous type film. Other studies of VMPL on metallic and ceramic substrates [7] and [8] had revealed the requirement for a transition metal, such as iron, to be present in the metal surfaces in order to produce the iron-phosphorous type film successfully. This film, which comprises iron polyphosphate (ferric pyrophosphate) (Figure A.9) and other compounds such as biphenyls and complex phosphate esters [9] and [10], is able to lubricate the metal surfaces at temperatures greater than 300°C, but with a drawback. Extended and continuous VMPL lubrication of bearings and gears using phosphate ester will result in excessive wear on the metal surfaces due to the constant chemical reaction between the phosphate ester compound and the iron in the metal surfaces. It was also found that the iron-phosphorous film grows with time through a diffusion-reaction mechanism that eventually leads to lubrication failure.

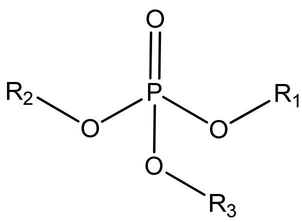


Figure A.8 Structure of Tri-Aryl Phosphate Ester (R_1 to R_3 denotes an aryl group)
(Source: http://www.mdpi.com/2075-4442/1/4/132 dated 07 Jun 14)

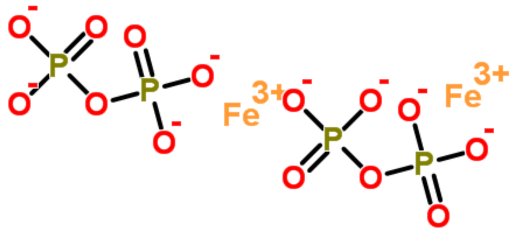


Figure A.9 Iron Polyphosphate Compound (Ferric Pyrophosphate) from Chemical Reaction of Phosphate Esters with Iron
(Source: http://www.chemspider.com dated 07 Jun 14)

Given the disadvantage of ary phosphate ester to serve as a lubricant in VMPL, researchers turned to non-phosphorous organic liquids to eliminate the problem of excessive wear at the metal surfaces. The experiments by Morales and Handschuh [4] and [5] using polyphenyl thioethers have shown the formation of a polymeric film that provides lubrication to the metal surfaces with minimal wear. Polyphenyl thioethers are derivatives of polyphenyl ethers in which one or more of the oxygen atoms in the polyphenyl ethers molecules are replaced with sulphur atoms (Figure A.10).

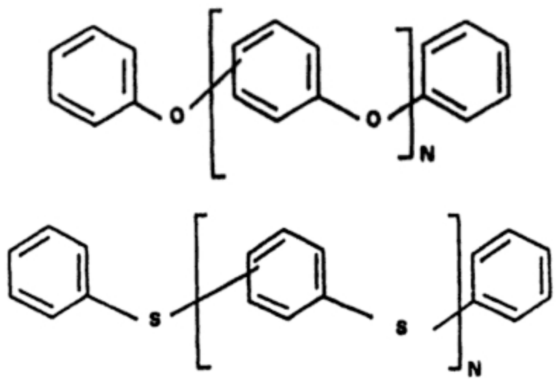


Figure A.10 Structures of Polyphenyl Ether (Left) and Polyphenyl Thioether (Right) (Source: Synthetic Lubricants and High-Performance Functional Fluids, Revised and Expanded, Leslie R. Rudnick, Ronald L. Shubkin, 1999, Page 244)

Polyphenyl Ethers (PPEs) are viscous, light yellow liquids that have outstanding resistance to thermal degradation, oxidation, radiation, hydrolysis and chemical attacks, and are compatible with most metals and elastomers employed in high temperature applications. Because these compounds are non-halogenated, they are non-toxic and require no special precautions when being handled [11].

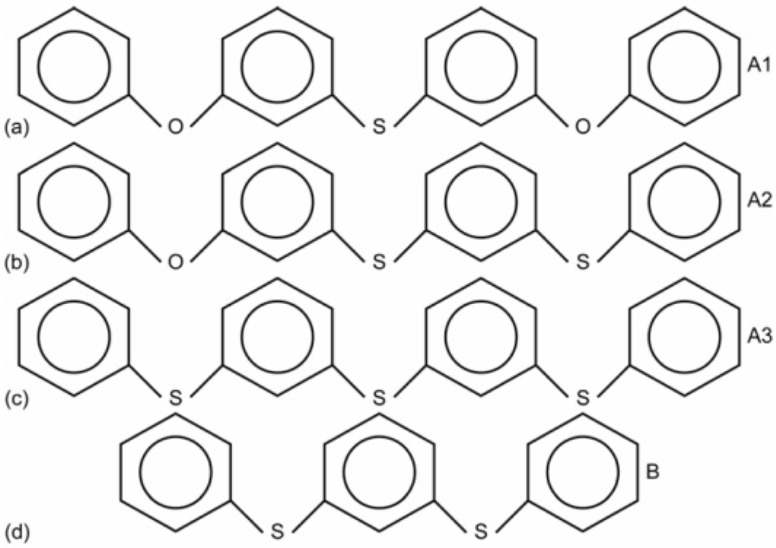
The history of PPEs started in 1906 when a German research chemist, F. Ullmann, created diphenyl ether. He wanted to produce a chemical compound that could remain as a liquid at low temperatures by substituting an oxygen atom between two benzene rings. Ullmann was successful in creating a class of PPEs comprising two to ten benzene rings connected by ether linkages. Unfortunately, the compounds had no immediate usage at that time. It was only until the beginning of the 21st century that PPEs were used as lubricants in complex machinery, aircraft, space vehicles and communication equipment that operate in extreme environments [12].

PPEs can remain in their liquid state at low temperatures due to their flexible molecule structure, a physical characteristic given the location of the oxygen atoms amongst the benzene rings. The benzene rings of these compounds possess high resonance energy, which accounts for their high boiling points and strong resistance to thermal degradation and oxidation. The thermal stability of PPEs coupled with their properties of low vapour pressure led to their first major use as high temperature lubricants in the engines of the SR-71 supersonic strategic reconnaissance aircraft. At altitudes above 60,000 feet and with operating bearing surface temperatures of 316°C, a 5-ring polyphenyl ether (5P4E) could provide lubrication unmatched by no other lubricants [12].

When compared to other hydrocarbon fluid lubricants, PPEs also possess high surface tension. Upon application to a surface, the PPE molecules are more attracted to one another than the surface, and readily form a stationary field of microscopic droplets instead of a continuous film. The droplets are densely packed and tend to stay where they have been applied. The high surface tension of PPEs, together with its high thermal stability and low vapour pressures made them useful in satellites, where the lubricated surfaces are close to other surfaces such as solar cells and heat dissipaters that must be kept clean. Other usage of PPEs include lubricants for switch contacts and moving parts of nuclear reactors, lubricants for pin-in socket connectors subjected to constant microscopic vibration (fretting), fluid for high-vacuum diffusion pumps and optical fluids and gels for advanced diode lasers [11].

Owing to the high costs of raw materials and a complex manufacturing process, the price of PPEs is high. This meant that the applications for PPEs are currently restricted to extreme environments where no other hydrocarbon fluid lubricants can be used or when the criticality of the application justifies the high cost. In this regard, the criticality of lubrication for a helicopter MGB may justify the usage of such compounds as an emergency (secondary) oil lubricant.

The PPE lubricant used in the experiment by Morales and Handschuh is a commercial blend of four chemicals comprising one 3-ring phenyl compound and three 4-ring phenyl compounds (Figure A.11). According to [11], this blend is commonly known as a C-Ether family (3 and 4-ring oxy/thioethers) and goes by the commercial trade name of MCS-293™[3] (Figure A.12). Figure A.13 compares the physical properties of the C-Ether family of chemicals to that of other PPEs.



Thioether Compounds for VPML		
S/N	**Chemical Name**	**Molecular Weight**
(a)	1,1-Thiobis [3-phenoxybenzene]	370
(b)	1-Phenoxy-3-[[3-(phenylthio) benzene] thio] benzene	386
(c)	1,1-Thiobis [3-(phenylthio) benzene]	402
(d)	1,3-Bis (phenylthio) benzene	294

Figure A.11 Molecular Structures of Thioether Compounds for VMPL (Source: [5])

[3] A product of Santolubes Limited Liability Company (LLC), USA

Chemical Names for Polyphenyl Ethers (PPEs)

Common and trade name	Chemical name
Six-ring polyphenyl ether (6P5E) Trade name: OS-138™	*Bis*[*m*-(*m*-phenoxyphenoxy) phenyl] ether
Five-ring polyphenyl ether (5P4E) Trade name: OS-124™	*m*-*Bis*(*m*-phenoxyphenoxy)-benzene
Four-ring polyphenyl ether (4P3E) Trade name: MCS-210™	*Bis*(*m*-phenoxyphenyl) ether
Three- and four-ring oxy- and thioethers Trade name: MCS-293™	Thiobis[phenoxybenzene] and *Bis*(phenyl mercapto) benzene
Three-ring polyphenyl ether (3P2E) Trade name: MCS-2167™	*m*-Diphenoxybenzene
Two-ring polyphenyl ether (2P1E) Trade names: Monsanto or Dow DPO	Diphenyl oxide, phenyl ether, phenoxybenzene, or diphenyl ether

Figure A.12 Chemical and Trade Names for Polyphenyl Ethers (PPEs) (Source: [11])

Properties of Base Stocks

Property	C-Ether	PPE [5P4E]	PPE (2PIE)
Viscosity, cSt			
At 37.8°C	25.2	363	100
At 98.9°C	4.1	13.1	7.8
At 260°C	0.81	1.2	
Thermal decomposition, °C	367	453	ca. 310
Autoignition temperature, °C	504	559	435
Pour point, °C	−29	+5	−59
Evaporative loss, % (204°C, 6.5 h)	10	<1	12
Surface tension, dyn/cm at 24°C	50	50	ca. 30
Isotherm secant bulk modulus, psi at 37.8°C	340,000 (0–7500 psi)	390,000 (0–6000 psi)	

Figure A.13 Physical Properties of PPEs (Source: [11])

In his earlier research on the C-Ether family of compounds [13] and [14], Morales have found that although thioether liquids have high thermal resistance up to 390°C, simple pin-on-disk (tribometer) tests at 25°C showed that they break down easily under boundary lubrication conditions[4], to form a polymeric type material. He subsequently demonstrated the polymeric forming ability under both dynamic boundary lubrication conditions as well as static conditions using an electrochemical cell. The promising results of the polymeric type material that is potentially lubricious led to his use of thioether as a VMPL liquid. Table A.5 summarises the differences between VMPL, vapour and oil mist lubrication techniques that have been discussed. Importantly, the inert properties of thioether allow it to be employed in a high temperature environment with no risk of reaction with the metal surfaces or any degradation to its lubrication capability. Once again, its application as an emergency lubricant during an MGB oil loss situation allows its unique physical properties to be utilised.

VMPL, Vapour and Oil-Mist Lubrication Techniques				
Properties	**Vapour Lubrication**	**Regular Oil-Mist Lubrication**	**VMPL using Phosphates Ester**	**VMPL using Thioether**
Lubricant	Acetylene	Hydrocarbon Oil	Phosphate Ester	Thioether
Delivery State	Vapour	Mist	Vapour or Mist	Vapour or Mist
Delivery Medium	Nil	Air	Air	Air
Operating Temperature of Wear Surfaces	Very High	Normal	Very High	Very High
Thermal Decomposition of Lubricant	Yes	No	No	No
Chemical Reaction of Lubricant with Metal Surfaces	No	No	Yes	No
Lubricious Layer	Graphite	Oil Film	Iron Phosphorous Film	Thioether Polymeric Film (droplets)

Table A.5 VMPL vs Vapour and Oil-Mist lubrication Techniques (Source: Author)

In the experiments by NASA and the US Army Research Laboratory [4] and [5], a pair of case-carburised and ground AISI 9310 spur gears of aerospace grade (ANSI-AGMA 2000-A88 Class 11) were tested in a test rig (Figures A.14 and A.15) using thioether VMPL. The spur gears were measured as having a specific hardness of Rockwell C 58-62. The thioether VMPL system was designed to generate a fine mist of thioether lubricant using pressurised air as the delivery medium. The regulated flow rates for the thioether lubricant and the pressurised air were 15 mL/hr and 400 L/hr respectively. Figure A.16 depicts the schematic of the spur gears test rig. The pressurised air was tapped from a shop air supply at 8.3 bars (120 psi). The air was first filtered and its pressure regulated before it was introduced to the thioether lubricant in a mister. Thioether mist was directed at both the gears as well as the gear mesh through

[4] Conditions that prevent the formation of a complete lubrication film between two contacting metal surfaces in bearings and gears, such as routine starting and stopping of machinery.

three lubrication jets (Figure A.17). A thermocouple was placed near the position where the gear mesh disengages to record the temperature of the fling-off lubricant. The spur gears were driven at a test speed of 10,000 rpm and with a normal tooth force of 516N. Peak contact pressure at the pitch point was computed to be 1.2 GPa (175 kpsi).

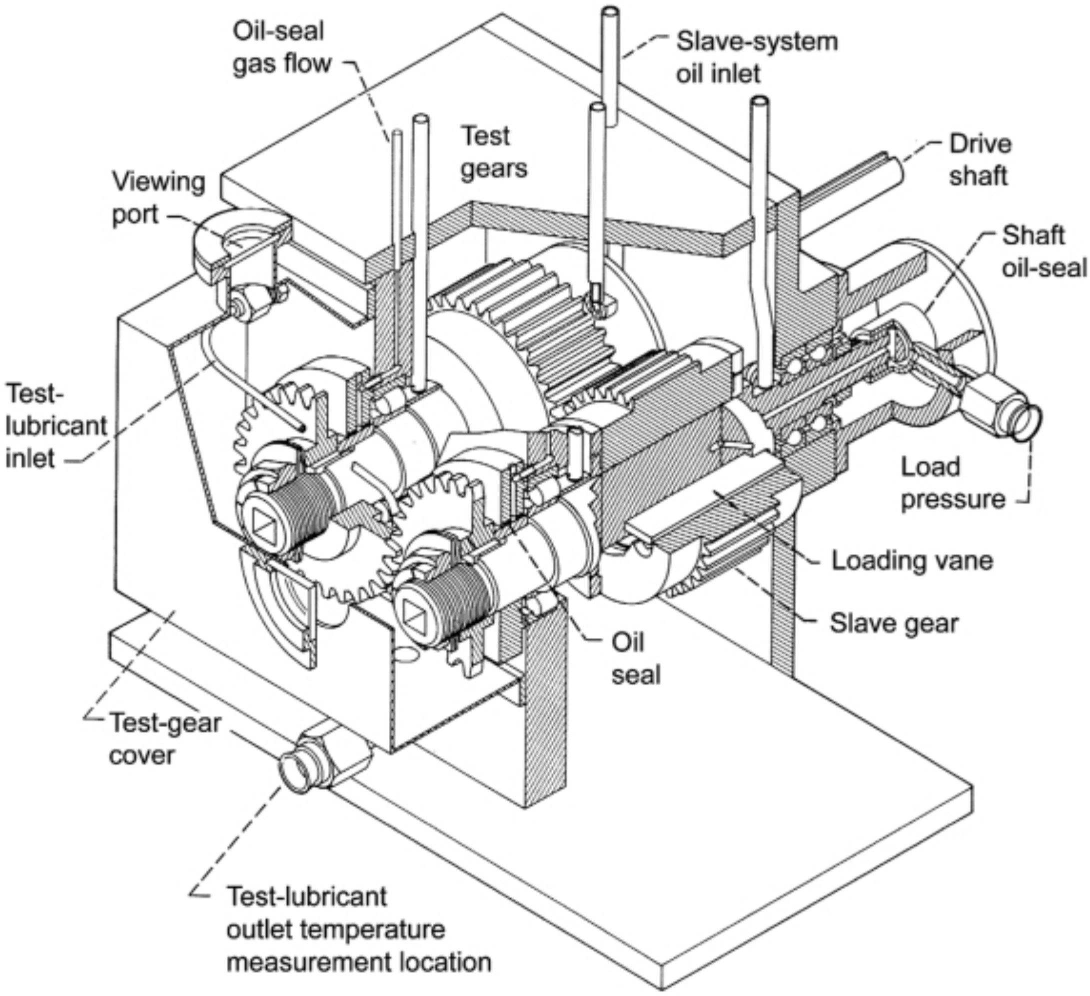


Figure A.14 Cutaway Figure of Spur Gears Test Rig (Source: [5])

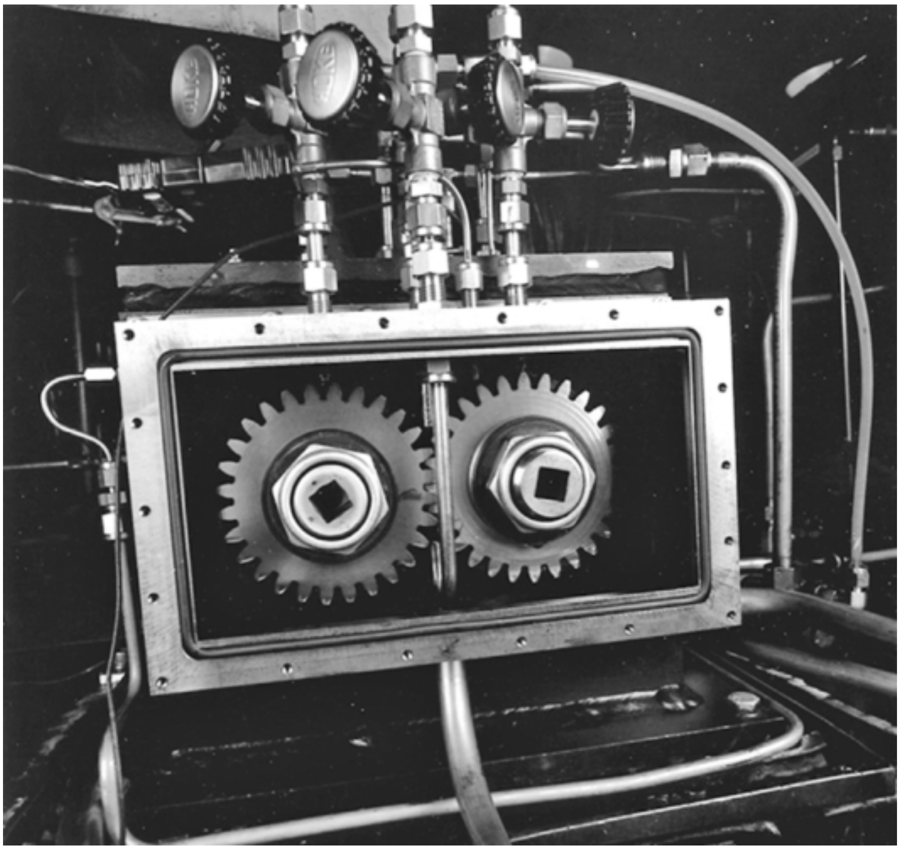


Figure A.15 Photograph of Spur Gears Test Rig Setup (Source: [5])

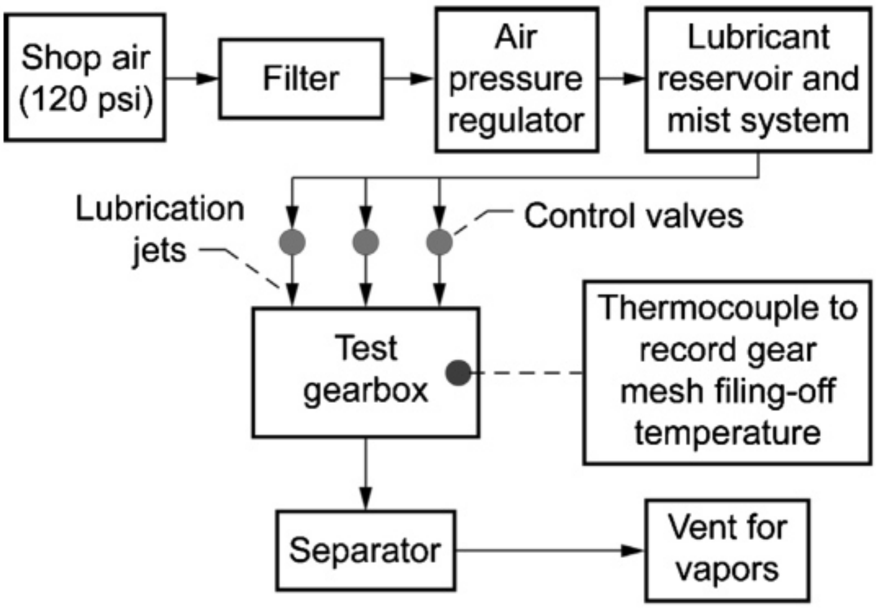


Figure A.16 Schematic of Spur Gears Test Rig

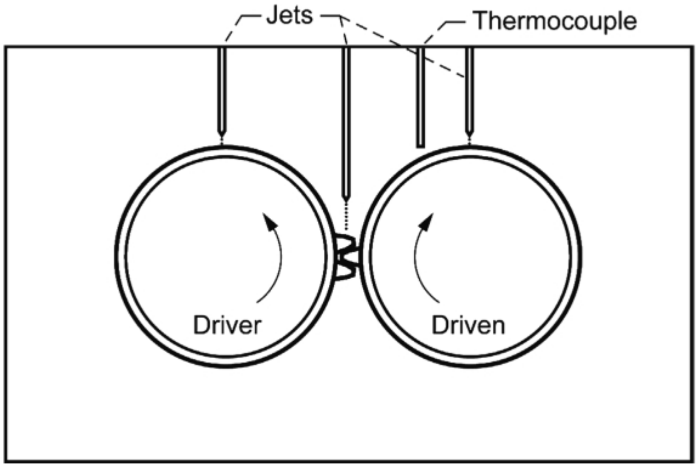


Figure A.17 Lubrication Jets and Thermocouple Positions in Spur Gears Test Rig (Source: [5])

In total, the spur gears test rig was operated over six sessions with an accumulated duration of 35.3 hours or 21.2 million shaft revolutions at the stated test speed and tooth force. The temperature rise at the thermocouple[5] as well as the vibration signature of the test rig on each session took on similar trends as shown in Figure A.18. It can be observed that the temperature reading levels off at around 107°C in the early phase of the test rig operation and remained constant thereafter with the use of thioether VMPL. In comparison, the temperature of the gears was fluctuating and has reached 205°C when phosphate ester was used as the VMPL lubricant. The gear teeth surface profile before and after the test revealed very little mechanical wear on the tooth surface as shown in Figure A.19. The results of a low and stabilised operating temperature of the spur gears as well as the minimum change in tooth profile over 35.3 hours of operation point towards the promising use of thioether as a VMPL lubricant [5].

[5] The fling-off temperature of the lubricant, which is lower than the surface temperature of the spur gears.

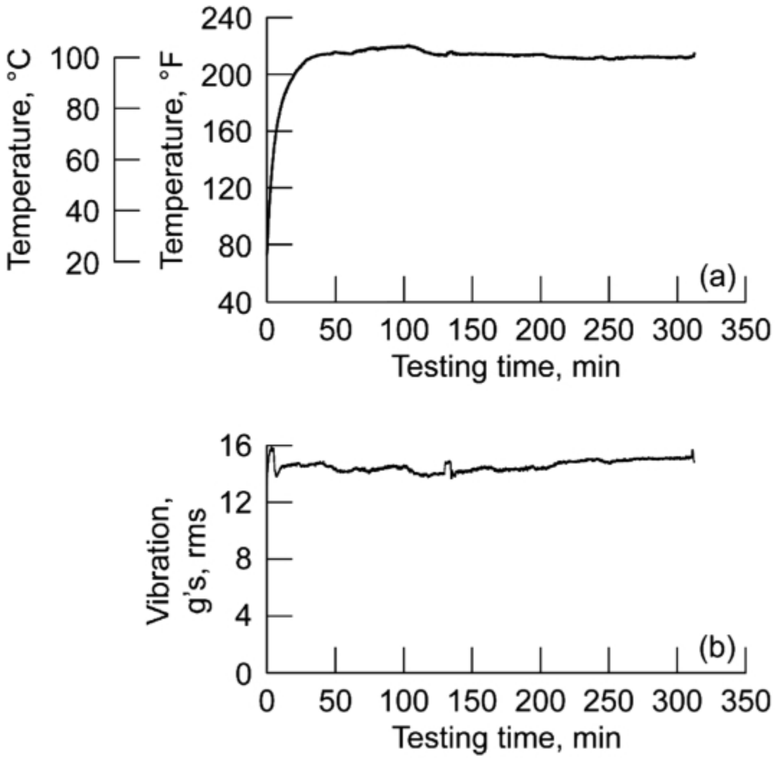


Figure A.18 Temperature and Vibration Signatures with Time (Source: [5])

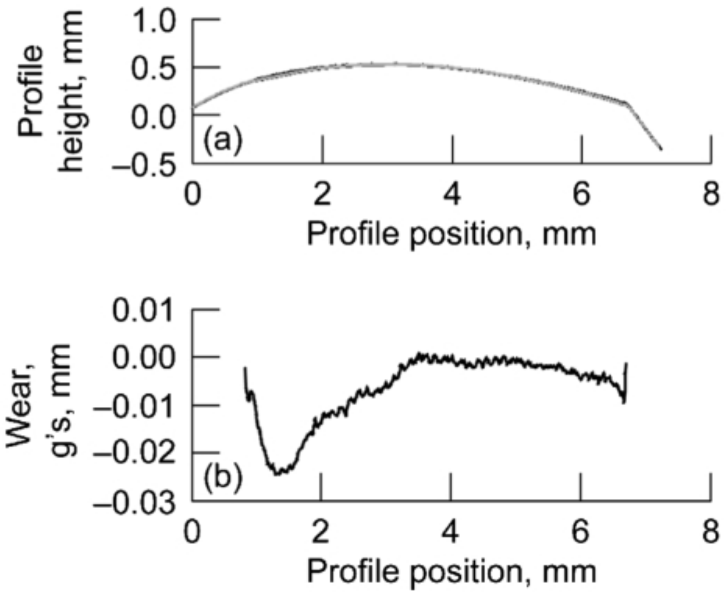


Figure A.19 Surface Profile Measurement Before and After Tests (Source: [5])

It is important to note that besides the minimal mechanical wear on the gear tooth surface, there were also no traces of coking on the gears. This was unlike another experiment that used synthetic paraffinic gear oil as a VMPL lubricant. In that experiment, there was severe wear on the gear tooth surface and coke had formed due to the thermal decomposition of the paraffinic gear oil under the high temperature and pressure conditions of the meshing surfaces [15].

The experiment on paraffinic gear oil VMPL also explored the temperature rise of the gears under three different oil-off lubricating conditions: dry-surfaces[6], oil-off with mist lubrication and oil-off without mist lubrication (Figure A.20). Under dry-surfaces condition, the rate of temperature rise was high in the very early stage of operation and the test was terminated when the gears reached around 225°C. The rates of temperature rise were lower for both the oil-off conditions, even though the test under oil-off with no mist lubrication eventually reached a temperature close to 225°C after 50 mins of operation. Under the oil-off with mist lubrication, the temperature of the gears was observed to be higher than that of the oil-off without mist lubrication during the early stage of operation, before dipping lower and ratcheting up and down in the later stages The maximum contact pressure of the gears during the experiment was 1.32 GPa (192 kpsi) and paraffinic gear oil VMPL was delivered at a flow rate of 0.68 mL/hr (3 x 10^{-6} GPM) [15]. These temperature graphs served as a useful source of information on the relative rise in temperature of the spur gears under different lubricating conditions.

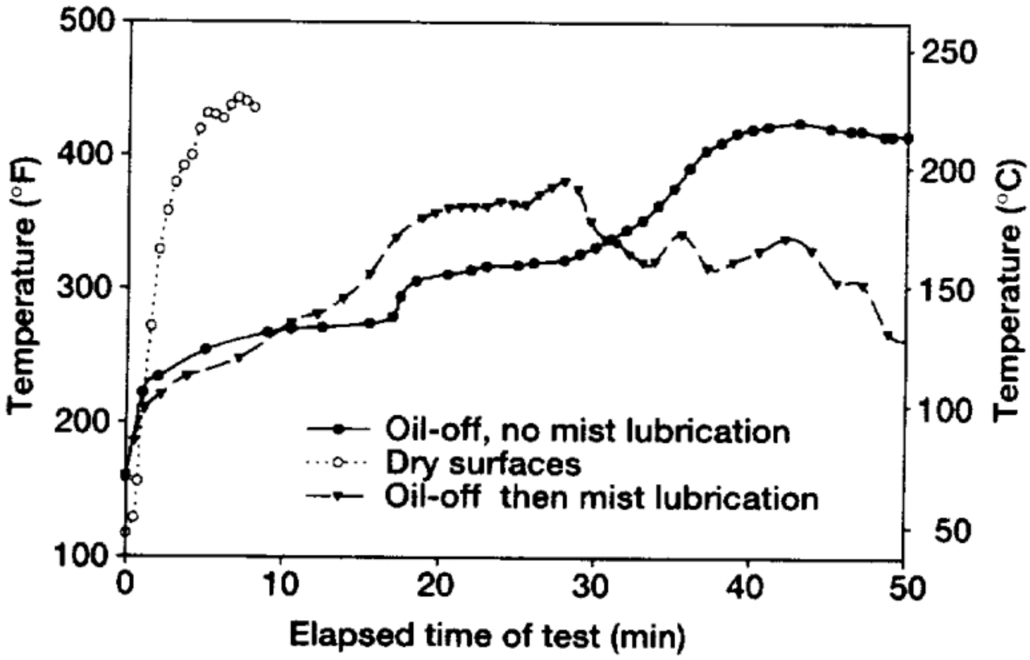


Figure A.20 Temperature Rise under Oil-Off Lubricating Conditions (Source: [15])

[6] Gears surfaces were wetted with lubricant prior to installation on the test rig

A.6 Main Gearbox Defects with Inadequate Lubrication

The primary functions of a gear lubricant are to minimise friction between the metal contact surfaces, dissipate heat, control wear, remove contaminants and to protect the gears against rust and corrosion. To control the wear of the gear surfaces, the lubricant has to provide extreme pressure protection against fatigue, scoring and wear damage during boundary lubrication conditions [16].

Pitting is a common form of surface fatigue damage on gears that occurs when cyclic contact (Hertzian) stresses exceed the endurance limit of the gear material. In a typical pinion and wheel gear mesh, there exist compressive stresses at the surface as well as unidirectional and bi-directional shear stresses at the sub-surface of a gear tooth as shown in Figure A.21. The magnitudes of the principal and shear stresses (normalized to the maximum contact stress, S_{cm}) vary with depth from the tooth surface (normalized to the width of the contact patch, b) and are depicted in Figure A.22. The compressive stresses are highest at the gear tooth surface and they taper to less than 20% of the maximum contact stress at depths below 2.25b. Importantly, the sub-surface shear stress peaks at a magnitude of 30% of the maximum contact stress at a depth of 0.39b, and plays a significant role in surface fatigue damage by initiating cracks beneath the gear tooth surface. [17].

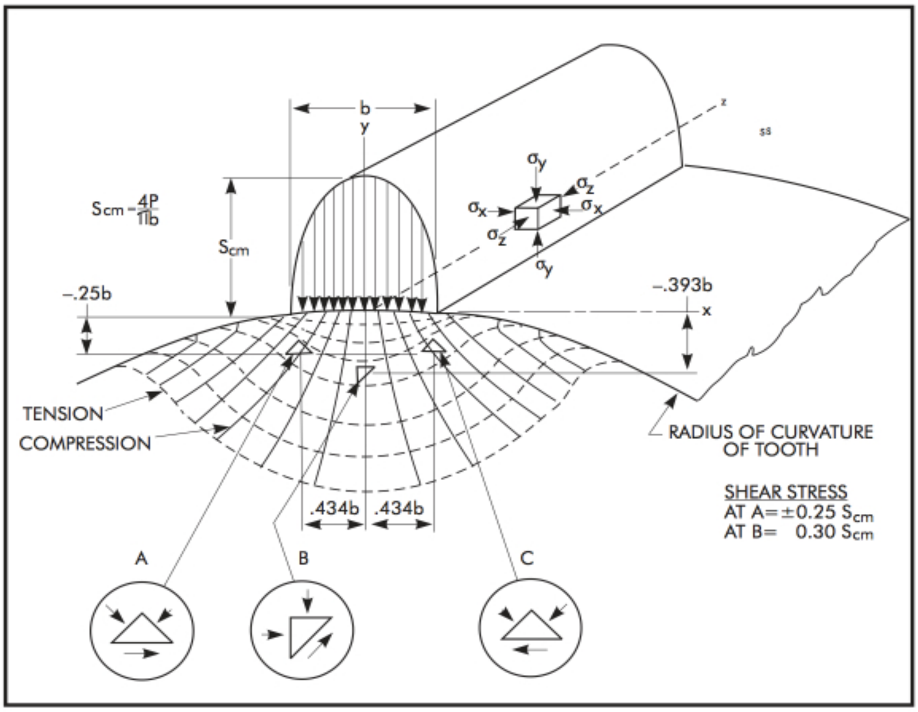


Figure A.21 Hertzian Stresses on a Gear Tooth (Source: [17])

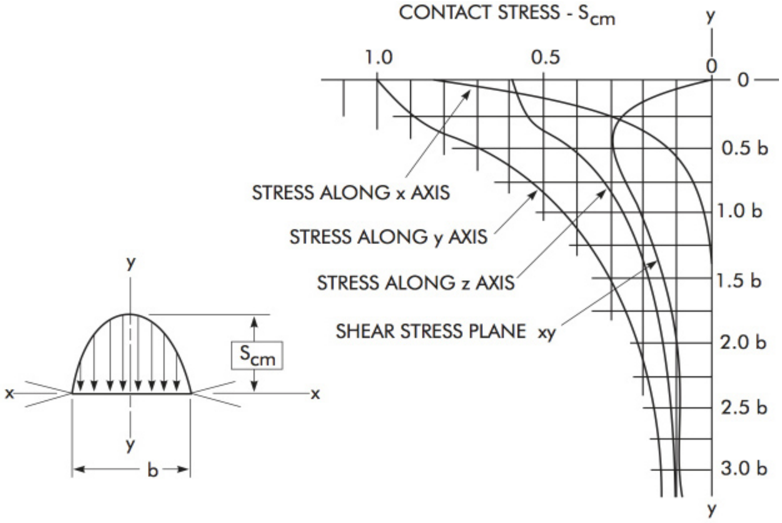


Figure A.22 Variation of Stresses Below Tooth Surface (Source: [17])

Pitting is also the most common causes of failures in anti-friction bearings, which experiences rolling/sliding under high loads. Pitting begins with small surface or sub-surface cracks that grow under repeating loading. When the cracks reach the tooth surface, a small amount of the gear material is lost thus forming a pit [16].

Pitting can be further classified into initial pitting and progressive pitting (Figure A.23). Initial pitting, which is also known as corrective pitting, is caused by localized areas of high stresses due to uneven gear tooth surfaces. It can develop fast and reach a maximum level before it diminishes with severity as the tooth surfaces get polished through operation. It usually occurs at the gear tooth pitchline or just below it in the dedendum region. Progressive or destructive pitting arises from surface overload conditions that are not alleviated by initial pitting and occurs at the dedendum regions of the gear tooth [17].

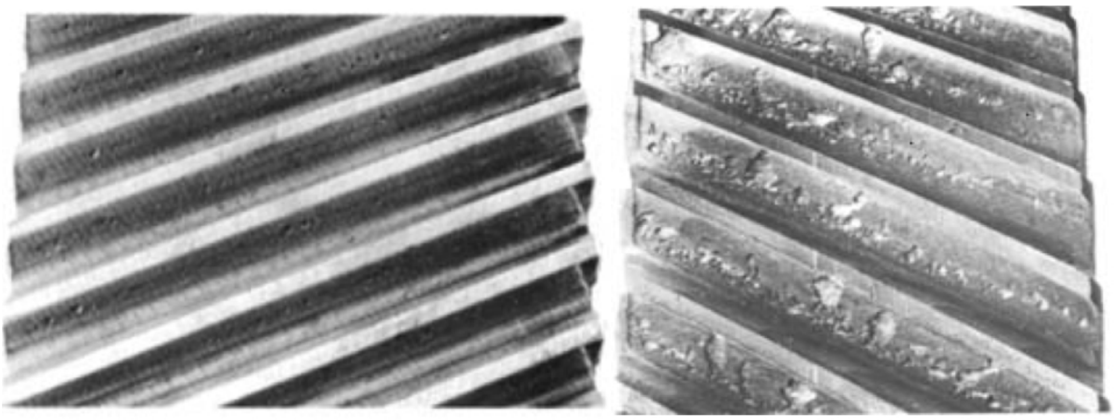


Figure A.23 Images of Initial Piting (Left) and Progresive Pitting (Right) (Source: [17])

A different type of pitting, known as micro pitting, involves the formation of smaller craters at the tooth surface as compared to macro pitting. It results from rolling and sliding contact fatigue, from repeated normal and tangential loads in a boundary or mixed-film lubrication regime [16] (Figure A.24).

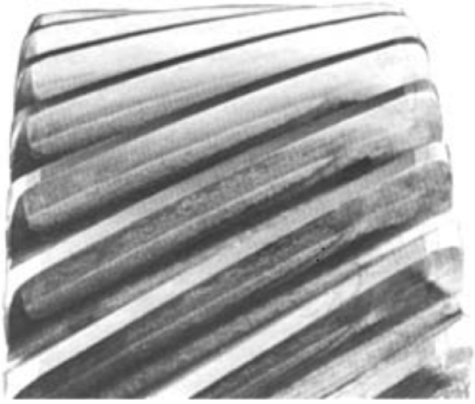
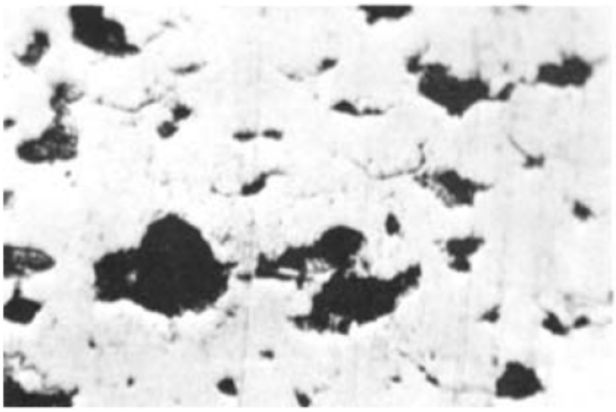
 

Figure A.24 Images of Micro Pitting (Left) and its Surface Zoomed 430 times (Right) (Source: [16])

Extensive destructive pitting eventually leads to spalling, whereby large and massive areas of gear surface material break off from the gear tooth. In surface hardened gears, which are employed in helicopter MGBs, spalling defects appear as a loss of a single or several large areas of material. Often, the bottom of the spall appears to run along the case-core interface [17] (Figure A.25).

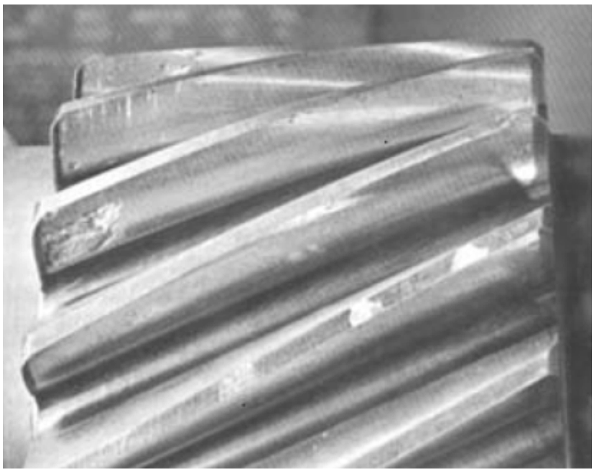
 

Figure A.25 Images of Spalling on Case-Hardened Gears (Sources: [17] and [18])

Scoring or scuffing is the welding and rapid removal of material from the gear tooth surface as a result of the lubricating oil film and high temperature metal-to-metal contact in the tooth mesh zone. After welding occurs, the sliding forces tear the metal from the surface to produce a small cavity in one surface and a projection on the other. This defect is microscopic in nature and develops rapidly (Figure A.26). Scoring occurs frequently in localized areas on the gear tooth where high contact pressure pressures or sliding velocities (and hence contact temperatures) exists in the presence of marginal lubrication [17].

Figure A.26 Image of Scoring defect on Gear Tooth (Source: [17])

Wear is a general term describing the loss of material from the contacting surface of a gear tooth. It can be classified into two categories: Abrasive and Adhesive. Abrasive wear, also known as cutting wear, occurs when hard particles such as metal wear particles, sand and scales slide and roll under pressure across the tooth surface. Examples of abrasive wear include polishing and scratching. Adhesive wear occurs when teeth contact at random asperities and form a strong bond. The junction area grows until a material particle is transferred across the contact interface. Subsequent contacts may cause the material particle to fracture away from the surface, forming a wear particle (Figure A.27). One example of adhesive wear is scoring [17].

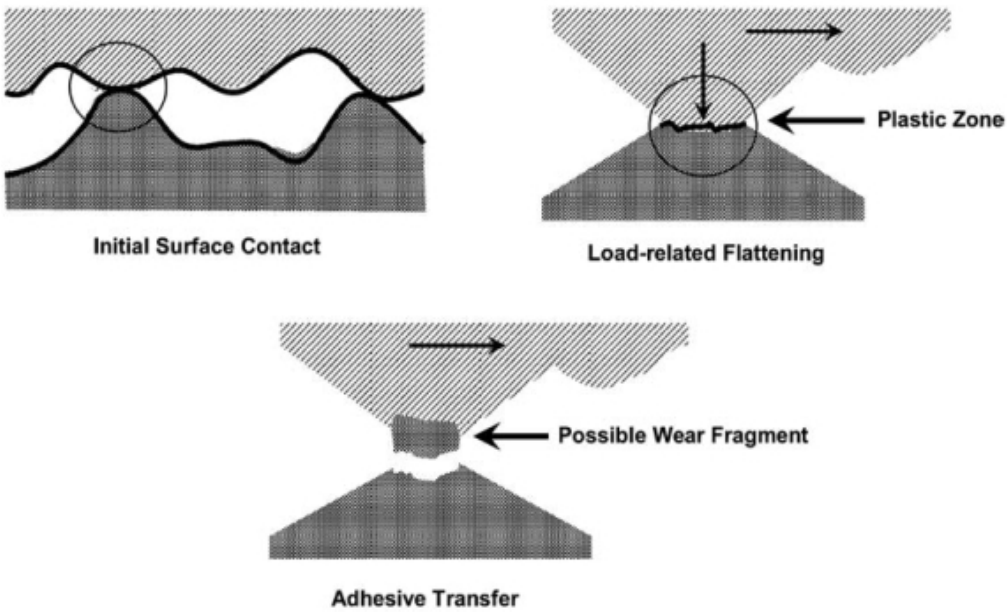


Figure A.27 Schematic of Adhesive Wear (Source: [16])

In tribology, the lubricating environment is defined by several key parameters: the level of friction, lubricant viscosity, the rotating equipment speed and load. The Stribeck Curves (Figure A.28) graphically depict the relationships between the coefficient of friction (μ), and the lubricant oil film thickness to the lubricant viscosity (Z), equipment rotational speed (N) and equipment load or pressure (P). In these curves, three distinct lubrication regimes exist [16].

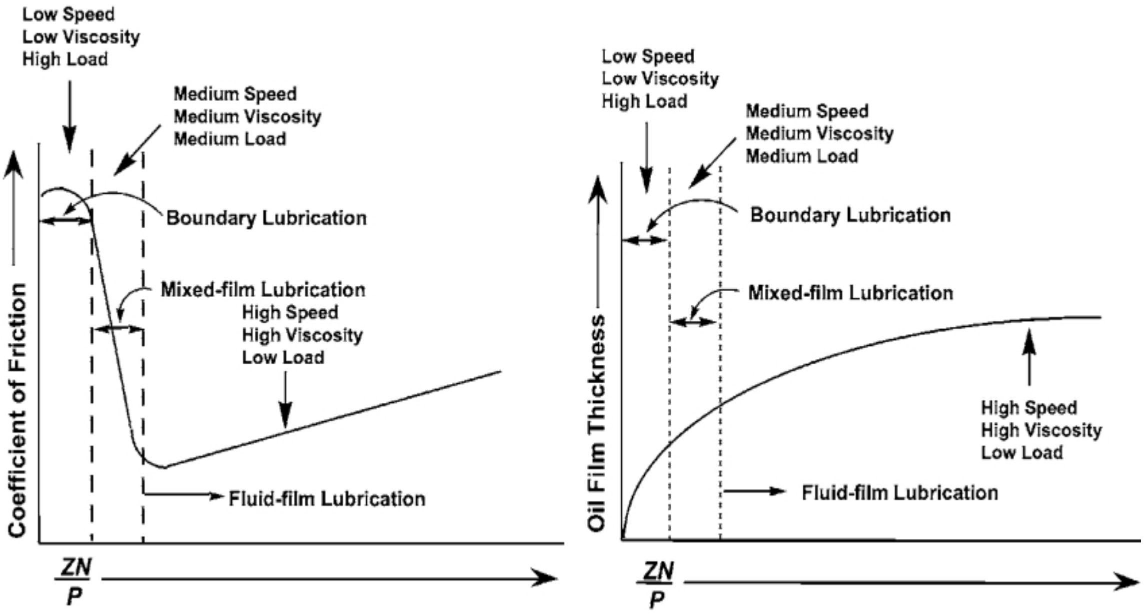


Figure A.28 Relationships between Coefficient of Friction and Lubricant Oil-Film Thickness with Lubricant Viscosity, Equipment Speed and Load (Source: [16])

The ratio of ZN/P has a direct relationship with the lubricant oil-film thickness and an inverse relationship with the coefficient of friction. The implies that high lubricant viscosity and rotational speed together with low equipment load supports the formation of a thick lubricant oil-film and the equipment operates with a low level of friction. Conversely, a low lubricant viscosity and rotational speed at high equipment load generates a thin lubricant oil-film and equipment operation involves a high level of friction. Depending on the ratio of ZN/P, the lubrication environment can be classified into three regimes: Boundary, Mixed-Film and Fluid-Film. The increase in the coefficient of friction when transiting from a mixed-film to fluid-film lubrication regime is attributed to a rise in viscous drag as the lubricant viscosity increases [16].

Boundary lubrication is one extreme representation of the lubrication environment spectrum. In this regime, high operational loads, coupled with very low rotational speeds produced extreme pressures that lead to the lack of effective lubrication, where maximum metal-to-metal contact occurs between the gear or bearing surfaces. The lubricant oil-film thickness lies in the range of 0 to 2 microns [16].

Fluid-film lubrication, also known as hydrodynamic lubrication, is the most desirable regime. In this regime, the low operational loads and high speeds generate a lubricant oil-film thickness between 2 to 100 microns. Effective lubrication exists as the sliding and the rolling surfaces are separated by a lubricant film several times the thickness of the surface roughness asperities. This lubrication regime is evident in thrust bearings and journal bearings operation. Mixed-film lubrication is a regime that lies between the boundary and fluid-film extremes and have characteristics of both regimes [16].

Although highly desirable, fluid-film lubrication seldom operates in gear systems because of the gear design as well as the requirement for efficient power transmission. Keeping gear surfaces apart to achieve hydrodynamic lubrication will lower the efficiency of a gear system, because the effective transfer of power requires the teeth in a gear set to mesh with one another. This produces boundary or mixed-film lubrication when the gears are static or moving slowly. It is interesting to note that when the rotational speed of the gears is high, the oil lubricant is drawn into the contact region and when subjected to high pressure (especially in heavily loaded gears), its viscosity increases to that of semisolid grease. The semisolid grease-like nature of the oil lubricant is capable of effective lubrication, which minimises metal-to-metal contact between the gear surfaces. This is a form of hydrodynamic lubrication is called Elasto-Hydrodynamic lubrication (EHD) (Figure A.29). The EHD oil-film thickness of up to 5 microns is at least two to three times the composite surface roughness. It is extremely rigid and causes elastic deformation of the metal surfaces in the contact zone. The ability of the lubricant to form an EHD oil film depends on its viscosity and the nature of the base fluid. EHD also exists in roller element bearings subjected to high contact pressures [16].

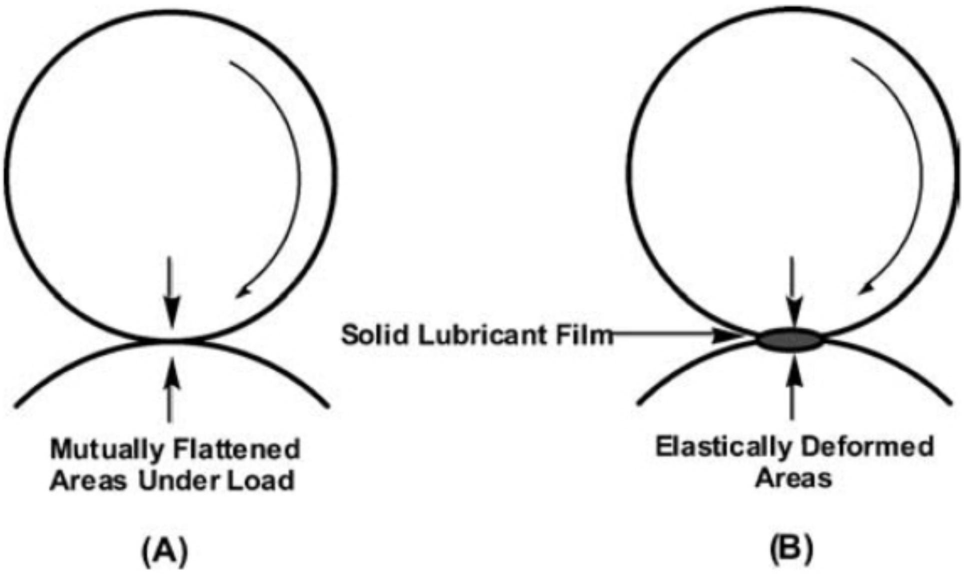


Figure A.29 Formation of Elasto-Hydrodynamic Lubrication (EHD) (Source: [16])

Gear lubricants are designed to support operations in all three types of lubrication regimes. Boundary lubrication occurs when the gears start from rest or coming to a stop. At low speeds, gears are subjected to mixed-film lubrication and during at high speeds, EHD exists. As the lubricant oil-film during boundary lubrication conditions is negligible, protection against metal-to-metal contact can only be achieved with the use of extreme-pressure (EP) additives. These are thermally organo-sulfur and organo-phosphorous compounds that form protective chemical films on the gear surfaces. In mixed-film lubrication conditions, there exist zones of metal-to-metal contact as well as zones where an adequate lubricant oil-film separates the metal surfaces. Wear between the contact surfaces asperities can be minimised with the use of Anti-Wear (AW) additives, which are derivatives of dialkyl dithiophosphoric acid and dialkyl dithiocarbamic acids. They worked in the same manner as EP by forming protective chemical films on the gear surfaces, except that this is achieved at a lower temperature as compared to the EP additives. During hydrodynamic lubrication conditions, EHD can be achieved under high loads using lubricant base fluids comprising alkyl aromatics or naphthenics [16].

In a modern helicopter MGB, the routine start-up and shut down of the aircraft engines coupled with the requirement to convert high speed low input torque to low speed high output torque, meant that the internal gears and bearings will experience all three types lubrication regimes. One recommended category of oil lubricant that is suitable for reliable helicopter gearbox operation is the NATO O-155[7]. It is a type of mineral oil with EP additives, which is designed for heavily loaded gear mechanisms. Under normal conditions, this category of oil lubricants together with the primary oil system ensure the protection of the gear surfaces against fatigue, scoring and wear damage especially during boundary lubrication conditions. Any failure to the constituents of the primary oil system that results in inadequate or a complete loss of lubrication would trigger the onset of gear defects, which can progress to destructive wear on the gear surfaces and eventually a MGB failure.

When lubrication is marginal or absent, the type of defects that gears are subjected to is dependent on the operational loads of the gear system. Figure A.30 summarises the effects of torque and rotational speeds on the various types of gear defects. The shaded region denotes the different combinations of torque and speed that support durable and reliable gear mesh operation. The zones beyond the shaded regions denote the probable failure modes that can be expected for a particular combination of torque and speed.

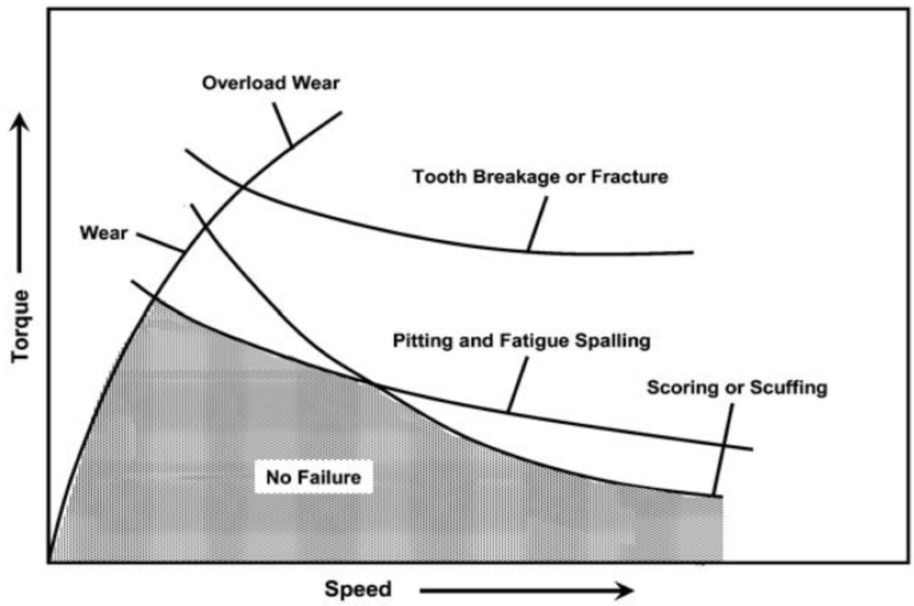


Figure A.30 Torque-Speed Combinations for Gear Defects (Source: [16])

For a helicopter MGB, the input drive pinions and gears are subjected to high

[7] Equivalent specifications to the British DEF STAN 91-112 Grade M, the US MIL-PRF-6086E and the Joint Service Designation OEP-70.

speeds at lower torque values, while their output epicyclic counterparts are subjected to very high torque values at low speeds. This implies that the gears in the input reduction module are susceptible to scoring while those in the output epicyclic reduction module are prone to pitting, spalling and abrasive wear when subjected to marginal or no lubrication. This information is useful when inspecting gears for damage after operating in these lubricating conditions.

The primary functions of a bearing lubricant are similar to that of a gear lubricant and the three regimes of lubricating conditions are also applicable to the roller element bearings (Figure A.31). In addition, the use of EP additives in the lubricant oil is necessary for minimising metal-to-metal contact between the rolling elements and the raceway as well as between the ends of rollers and the inner race rib when operating in the boundary lubrication regime (Figure A.32). Very high pressure and temperature at the contact zones can lead to chemical reactions between the additives and the metallic surfaces. From these reactions, a thin boundary layer in the nanometer range is formed, which is capable of effective lubrication by separating the metal surfaces and is comparable in effect to EHD full lubrication (Figure A.33) [19].

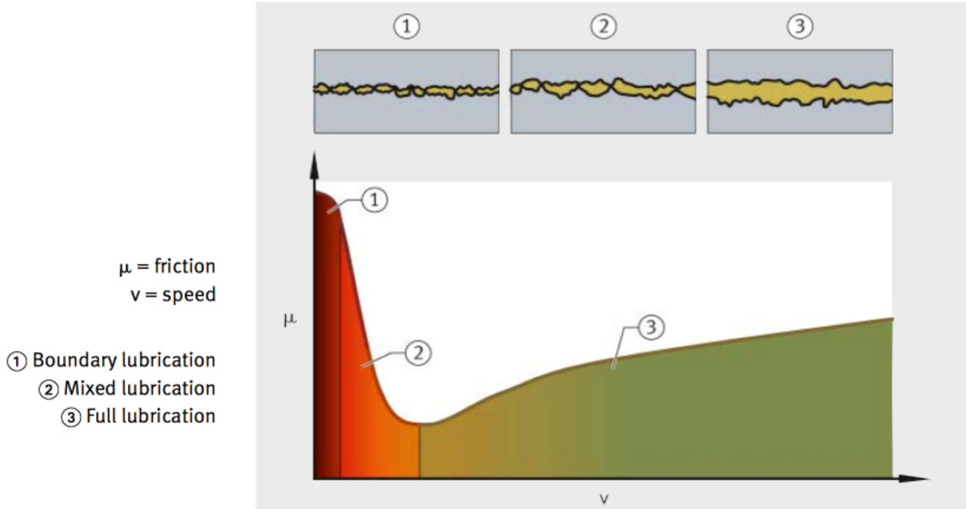


Figure A.31 Stribeck Curve for Roller Element Bearings (Source: [19])

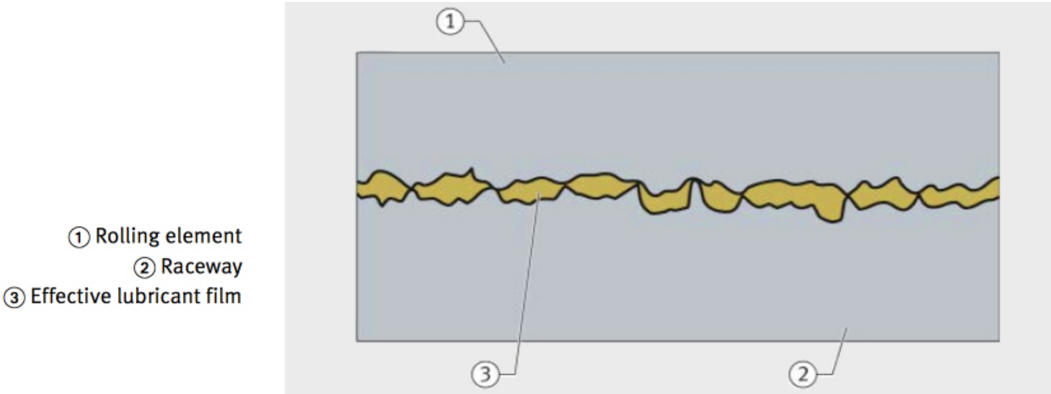


Figure A.32 Boundary Lubrication of Bearings (Source: [19])

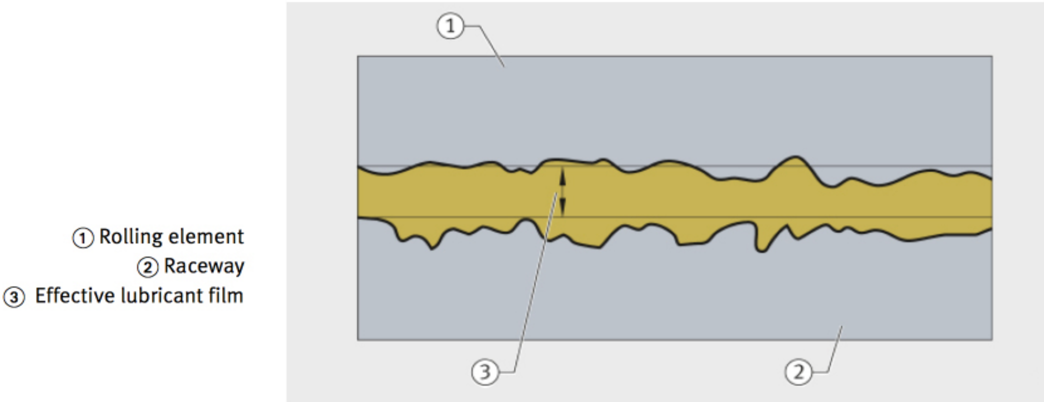


Figure A.33 Full Lubrication of Bearings (Source: [19])

When lubrication to the roller element bearings become marginal or inadequate, a wide range of damage conditions exists as the lubricant oil-film is insufficient to separate the rolling and sliding contact surfaces during operation. The damages may be classified into 4 progressive levels and range from light heat discoloration to total bearing lockup with extreme metal flow [20].

At the initial Level 1, discoloration is observed on the bearing races and rollers. This is the result of metal-to-metal contact that leads to excessive bearing temperature (Figure A.34). At Level 2, scoring and peeling (or micro-spalling) occurs due to insufficient or complete lack of lubricant between the contact surfaces (Figures A.35 and A.36). As the damage progresses to Level 3, localised high temperatures will result in scoring at the ends of the rollers (Figure A.37). Lastly, at Level 4, bearing seizure or lock up ensues from the localised high heat that produces metal flow in the bearings and alters the geometry and material properties of the original bearing. At this stage of damage, there will be a skewing of rollers, a destruction of the bearing cage and metal transfer within the bearing (Figure A.38) [20]. The progressive levels of damage provide useful information regarding the extent of inadequate or loss of lubrication within a given bearing.

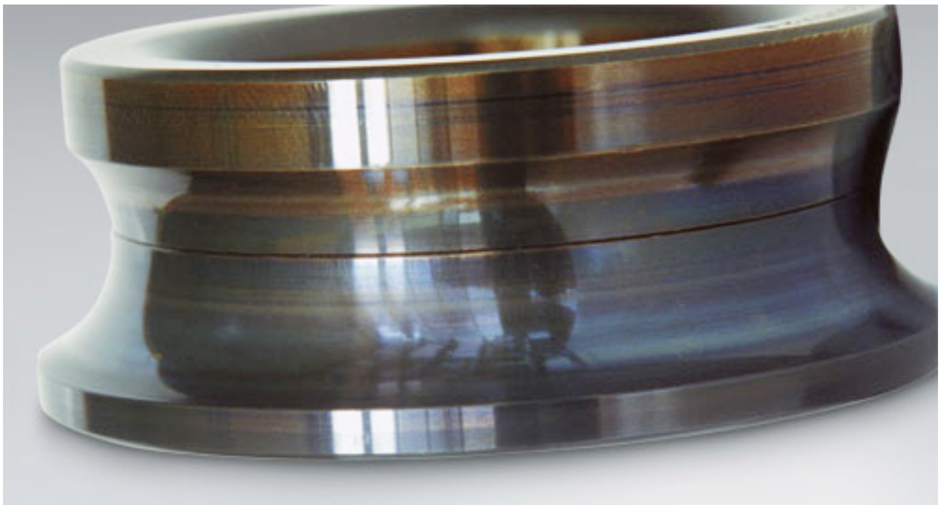


Figure A.34 Discoloration of Bearing Race From Excessive Bearing Temperature (Source: [21])

Figure A.35 Scoring of Bearing Inner Ring (Left) and Roller Ends (Right)
(Source: [21])

Figure A.36 Peeling of Bearing Inner Race (Left) and Roller Ends (Right)
(Source: [21])

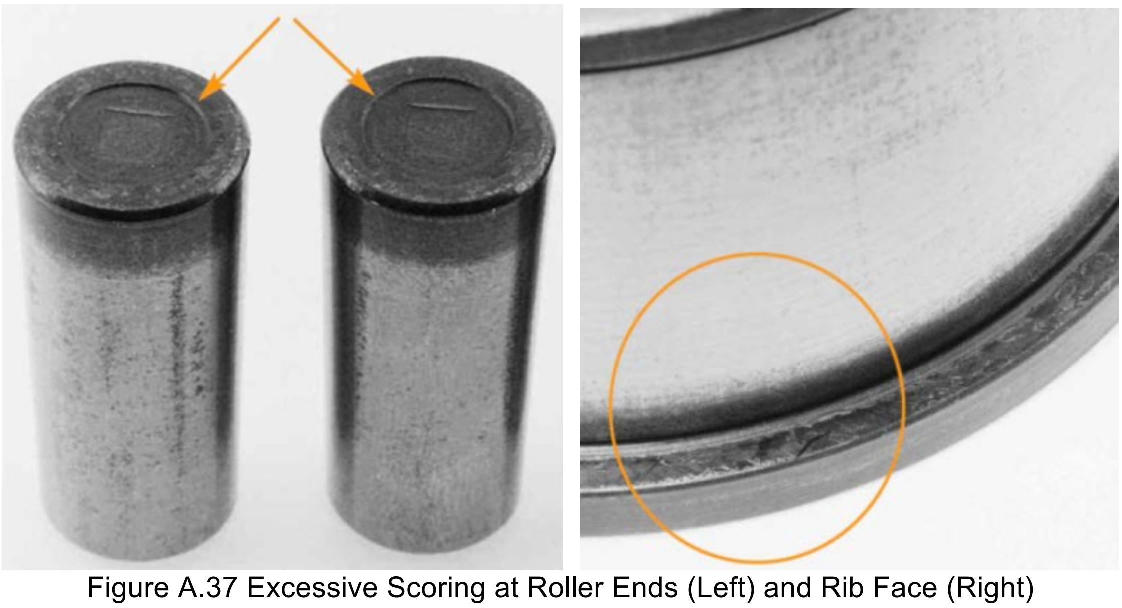


Figure A.37 Excessive Scoring at Roller Ends (Left) and Rib Face (Right)
(Source: [20])

Figure A.38 Plastic Flow of Metal, Rib Deformation and Cage Expansion (Left) and Bearing Seizure (Right) (Source: [20]

Intentionally left blank

EASA

European Aviation Safety Agency

European Aviation Safety Agency

Postal address
Postfach 10 12 53
50452 Cologne
Germany

Visiting address
Ottoplatz 1
50679 Cologne
Germany

Tel. +49 221 89990 - 000
Fax +49 221 89990 - 999
Mail info@easa.europa.eu
Web www.easa.europa.eu