DUTCH
SAFETY BOARD

Crash following engine failure

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The Hague, March 2016

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Dutch Safety Board

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NB: This report is published in the Dutch and English languages. If there is a difference in interpretation between the Dutch and English versions, the Dutch text will prevail.

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GENERAL OVERVIEW

Identification number:	2012096
Classification:	Accident
Date, time[1] of occurrence:	15 September 2012, around 19.10 hours
Location of occurrence:	Valkenswaard area
Registration:	ES-YLS
Aircraft type:	Aero Vodochody L-39C
Aircraft category:	Single engine jet
Type of flight:	Formation flight
Phase of operation:	Cruise flight
Damage to aircraft:	Destroyed
Flight crew:	One
Passengers:	One
Injuries:	None
Other damage:	Pollution of a field
Light conditions:	Daylight

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[1] All times in this report are local times unless stated otherwise.

SUMMARY

Being one of seven aircraft of the Breitling Jet Team, the L-39C Albatros jet with registration ES-YLS experienced engine problems during the flight. These problems became so serious that the flight could not be continued. The pilot then shut down the engine and steered the aircraft towards an open area. Here, he and the second occupant left the aircraft with the ejection seats. The aircraft ended up in a field. Both occupants were unharmed. After extensive investigation it was found that the engine problems were primarily caused by a defective low pressure turbine front bearing. Further it turned out that the assessment of the engine oil quality by a laboratory was done without any written references. Finally it was concluded that the L-39C does not have to comply with European safety level requirements.

The long time between the occurrence and the publication of this report was mainly caused by the number, and sometimes long-term technical, examinations carried out for this investigation and the investigator's involvement in other investigations with higher priority.

FACTUAL INFORMATION

History of flight

The Breitling Jet Team consists of seven L-39C Albatros aircraft and performs flight displays at air shows. On 15 September 2012, the team performed a display at Den Helder Airport. After the flight display had ended, the seven aircraft departed from Den Helder Airport in formation at 18.47 hours on their way to Kleine Brogel air base in Belgium.

At approximately 19.10 hours, when the formation was flying over Valkenswaard at an altitude of approximately 3,500 feet and a speed of 550 km/hour, one of the aircraft, ES-YLS, encountered engine problems.

The crew of ES-YLS, consisting of the pilot, seated in the front of the aircraft and the mechanic, seated in the rear, both felt engine vibrations, which became increasingly powerful. After a few seconds, the crew smelled a burning odour. Approximately 20 seconds later, the pilot received a general fault warning. The warning light indicating that the engine vibrations were exceeding the safety threshold engaged, and oil pressure started to drop. The pilot notified the other members of the formation that he was experiencing engine problems. Soon after, he heard an explosion after which engine power started to drop. After having received a notification from one of the other formation pilots that flames were coming out of the aircraft's exhaust, the pilot shut off the fuel supply after which the engine switched off. The pilot then activated the fire extinguisher in order to extinguish any potential engine fires. In view of the fact that the aircraft was now too far from Kleine Brogel air base and there was no other airport in the vicinity, the pilot decided that he and the mechanic would have to evacuate using the ejection seats. He then steered the aircraft to a vacant area. At an altitude of approximately 1,500 feet, the mechanic then ejected from the aircraft followed by the pilot. The aircraft crashed in a potato field and was entirely destroyed. The two occupants landed on the ground near the crashed aircraft.

Once the emergency services had arrived at the scene of the crash, the mechanic was taken to hospital for further examination. After having been examined, he was discharged from hospital.

Figure 1: ES-YLS after the accident. (Photo: National police)

The pilot

The pilot of ES-YLS was a 52-year-old man and had worked as a jet pilot in the French air force from 1980 to 2000. He held a valid Commercial Pilot Licence (CPL) with the following ratings: SEP (land), Pilatus PC7, PA46, Let L39, IR, CRI(A) and FI(A). He also held a valid Class 1 medical certificate, valid until 30 September 2013. The table below provides an overview of his flying experience.

Flying experience in hours	
Total all types	Approx. 8,500
Total on type	Approx. 1,200
Total last 90 days (all types)	Approx. 100

Table 1: The pilot's flying experience.

The aircraft

ES-YLS was a single-engine jet, make and model Aero Vodochody L-39C. This aircraft type is equipped with an Ivchenko AI-25TL turbofan engine. The aircraft has two ejection seats, located behind one another.

The Aero Vodochody L-39C is built in the Czech Republic and was designed to serve as a military training and light attack aircraft. The aircraft can be equipped with weaponry or other military equipment. Under European Union (EU) regulations, such military aircraft can be registered in the civil aviation register and used for civil aviation purposes.

Figure 2: L-39C. (Photo: Aero Vodochody)

ES-YLS

ES-YLS was built in 1985 under number 533638 and made its maiden flight on 2 December 1985. The aircraft was then in service as a training aircraft in a military flight school in the former Soviet Union until July 1995. The aircraft was kept in conserved storage between July 1995 and 2002.

It was subsequently sold to an Estonian company in 2002 and registered into the Estonian aviation register on 7 September 2002 under registration ES-YLS. According to the certificate of registration, the aircraft owner and operator was an Estonian company. From 25 September 2002 the aircraft was based in France and taken into use by the Breitling Jet Team. On 27 November 2002 the owner and operator of ES-YLS changed. A corporate body in Luxembourg became owner and a French aviation company became operator of the aircraft. The Breitling Jet Team is part of this aviation company. The certificate of registration was changed accordingly.

ES-YLS had a valid certificate of airworthiness in the ‘restricted’[2] category, set to expire on 14 December 2012. This restriction implies that its certificate of airworthiness is a national certificate only valid in Estonia. Estonia is a member of the European Aviation Safety Agency (EASA), but other states (EASA and non EASA) are not obliged to recognise such a national certificate.

By the day of the accident, the aircraft had accumulated a total of 1975:30 flight hours.

ES-YLS was maintained through the Breitling Jet Team’s maintenance programme, which had been approved by the Estonian authorities. Maintenance was conducted in France by employees of an Estonian maintenance firm that were permanently stationed in France, in collaboration with the aviation company’s maintenance employees.

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[2] In Estonia, the ‘restricted’ category is applied to - amongst other aircraft types - former military aircraft.

According to the technical administration, both the aircraft and engine were subjected to regular inspections. The last mandatory 50-hour inspection was performed on 12 and 13 September 2012. Maintenance documents show that all mandatory maintenance work was carried out over the course of this inspection, during which no deviations were found. The maintenance log was signed by an Estonian licensed maintenance person of the French aviation company.

The engine, an Ivchenko AI-25TL,[3] was overhauled between 15 January and 24 March 2004, after which the number of air time hours was reset to zero. After this date, the engine was not used again until 30 October 2009. On this date, the engine was installed in ES-YLS. On the date of the accident, the engine had been used for a total of 192:30 hours since having been overhauled.

The weather

The Royal Dutch Meteorological Institute (KNMI) provided the following weather information for the Valkenswaard region at the time of the accident:

Wind	Direction in degrees	Speed in knots
On the ground:	210	3
500 feet:	230	7
2,000 feet:	250	10
5,000 feet:	300	10
Visibility:	More than 10 kilometres	
Cloudiness:	Broken (a cloud density of 5/8 through 7/8) Cloud base at 3,700 feet, top at 4,000 feet	
Turbulence:	None	
Temperature/dew point:	15/12 °C	

Table 2: Overview of weather conditions at the time of the accident.

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[3] Engine number 7082521800215.

INVESTIGATION AND ANALYSIS

Technical investigation

Once the salvage had been completed, the aircraft was subjected to an initial technical investigation in the Netherlands. This investigation was attended by both experts from aircraft manufacturer Aero Vodochody and engine experts. The investigation showed severe burned turbine blades and vanes, indicating they had been exposed to abnormal high exhaust gas temperature. Because of this damage and the pilot's experience of severe vibrations during flight, a bearing failure was believed to be a potential cause of the engine malfunctioning. Determining whether the bearing was actually defective, required further investigation and engine disassembly at an engine overhaul shop.

As the Ukraine, state of manufacturer and design of the engine, initially had not responded to participate into the investigation, the engine was torn down at LOM Praha in the Czech Republic on 20, 21 and 22 March 2013. The engine was disassembled in the presence of air safety investigators from Estonia, the Czech Republic and the Netherlands. The investigation showed that the engine low pressure turbine front bearing, an oil tube and a coupling bolt[4] had failed. The front bearing showed signs of extreme wear, the oil tube was twisted and broken and the coupling bolt was bent and broken into four pieces. These components are located between the engine's low-pressure compressor and low-pressure turbine. Further component examination would be necessary in order to determine the exact nature of their failures.

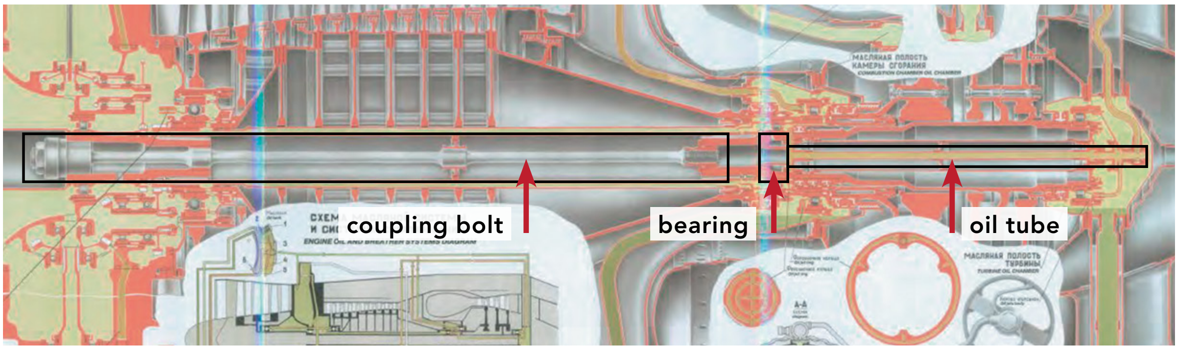

Figure 3: The engine diagram with the three above-mentioned components. (Photo: Book of Charts and Diagrams AI-25TL)

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[4] The coupling bolt keeps the low-pressure turbine at a fixed distance from the low-pressure compressor.

Figure 4: The failed front bearing. (Photo: NLR)

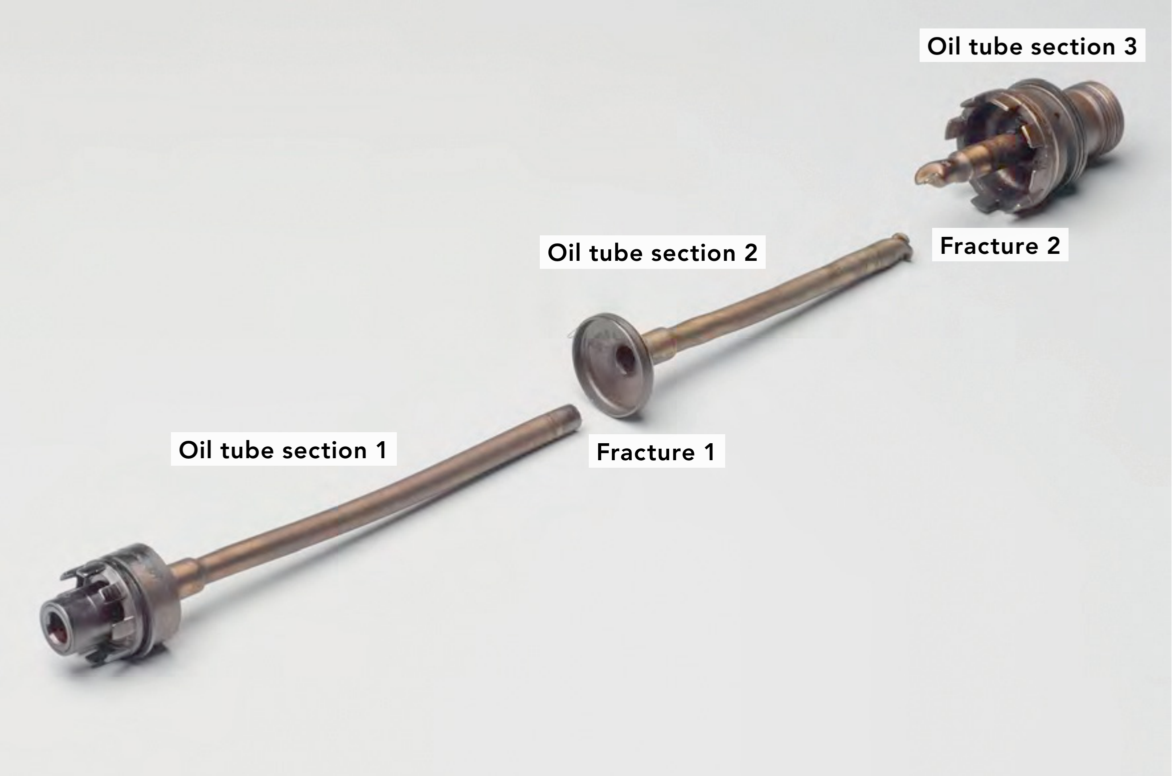

Figure 5: The twisted and broken oil tube. (Photo: NLR)

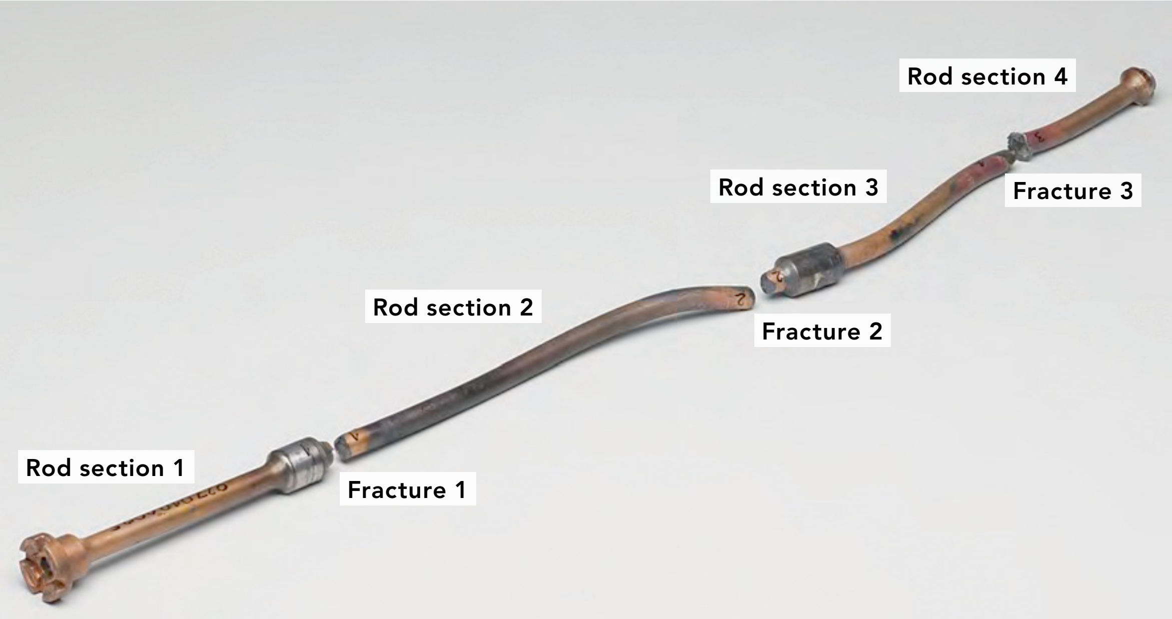

Figure 6: The bent and broken coupling bolt. (Photo: NLR)

On request of the Dutch Safety Board (DSB), the National Aerospace Laboratory (NLR) conducted a detailed metallurgical investigation of these components. This investigation was based on the following key questions:

- Can the root cause of the engine failure and the sequence of events be determined on the basis of the damage of the front bearing, oil tube and coupling bolt?
- Could be verified whether an improved (new) type of bearing had been installed?

The NLR investigation report[5] was presented to the DSB and its findings can be summed up as follows:

- Cracks in the bearing inner ring base material, removed material at the inner raceway, wear particles in the oil and vibrations, noticed just prior to the crash, point to the bearing as the root cause of the crash. The wear and vibrations of the bearing most likely led to more stress on the coupling bolt and reversed bending in section 2 of the coupling bolt. Failure of the coupling bolt caused rotation between the oil tube ends, leading to torsion and tensile overload at fracture 2 and 1 of the tube, respectively. The cracks in the inner ring base material, the removed material at the inner raceway and wear particles in the oil, indicate that a slowly degrading process preceded the single event.
- The makings on the bearing and the measured chemical composition of the bearing parts indicate that a new version of the bearing was installed.

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[5] Failure analysis of several gas turbine engine components, Aero L-39C Albatros aircraft, NLR CR-2013-263-V2, April 2014.

Laboratory oil analyses

Mechanics of the French aviation company discovered a hydraulic leak at the level of the pump drain during maintenance on 6 August 2012. They then replaced the hydraulic pump and performed an engine run-up after which they noticed an abnormal colouring of the engine oil. Because this colouring could have been caused by an internal leak of the first hydraulic pump, they took an oil sample to confirm this leak and replaced the engine oil with new oil on 8 August 2012. No flights were flown between 2 and 12 August 2012. On 22 August 2012 the oil sample was sent for analysis to the laboratory that the aviation company uses for regular oil analyses. After the maintenance performed on 6 August 2012, the engine status was monitored by checking the engine magnetic plug of the overheat and chip detector[6] after every flight. In addition, it was decided to verify the engine oil filter during the next 50 hours inspection, an additional operation not scheduled in the engine manufacturer maintenance program.

According to the laboratory report of the oil sample analysis, sent to the aviation company on 28 August 2012, the status of the engine parts (indicated by 'components'[7]) was classified as 'normal' (1 on a scale of 1 through 5). The status of the oil (indicated by 'fluid') was classified as 'danger' (5 on a scale of 1 through 5).[8] The summery of the oil status was also classified as 'danger'. The report also stated: *"We note abnormal fouling of the oil - we advise you to run a preventive inspection of the unit - check the operating temperature - drain and rinse out if possible – lubricant. The properties measured are regular."* The report does not mention whether hydraulic fluid was found in the oil sample.

When asked for additional clarification, the laboratory stated that in case of ES-YLS, only the gravimetric membrane showed some deposits and that it was advised to change the oil. The pollution could have been caused by a deviant engine operating temperature. All measured elements of the oil showed regular values. The classification of the oil was estimated by the analyst without any written reference. The judgment of the fluid status was only based on the fact that the oil must be clear. The laboratory considered that when the oil shows some deposits on the gravimetric membrane, it is classified as 5 (danger).

Between 12 August and 9 September 2012, ten flights were flown with a total flight time of 7:10 hours. No anomalies were noted in the flight documents.

The aviation company stated that, since the AI-25TL maintenance manual does not specify the actions that must be taken when abnormalities are found after laboratory oil analysis, they applied the recommendations that the laboratory made. The engine oil was already replaced on 8 August 2012, a 50-hours engine inspection was carried out on 12 and 13 September 2012; the operating temperature was checked by the pilots during the flights and was found normal. In addition, the mechanics checked the engine magnetic plug every day when the aircraft was used and it was found normal.

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[6] A magnetic plug in the engine's turbine section on which metal particles from the engine oil are deposited.

[7] Components are all moving parts of the engine that are lubricated by engine oil.

[8] The status can be classified as normal, attention or danger where 1 and 2 are classified as 'normal', 3 and 4 as 'attention' and 5 is classified as 'danger'.

According to the aviation company, the engine magnetic plug was also checked before the accident flight on 15 September 2012 and was found normal, i.e. no metal particles were found on the magnetic plug.

An engine oil sample that had been taken on 13 September 2012, as part of the 50-hours engine inspection, was sent to the laboratory on 17 September 2012, two days after the accident. The results were sent to the aviation company the next day on 18 September 2012. The laboratory still found an abnormal fouling of the oil. Compared to the results of the 8 August 2012 oil sample, the percentage of the concentration of the chemicals phosphorus, lead, sulphur and cadmium was similar and the ferrometry[9] values were higher. The value of large particles was increased from 21.8 to 8.6 and of small particles from 0 to 3.5. The scale behaviour for the engine and the oil was classified as similar to the scale behaviour of the 8 August 2012 oil sample, respectively 1 and 5. The following remark was made by the laboratory: *"We still note abnormal fouling of the oil. We note additive parameters:*[10] *in line with expected amounts."*

When asked for clarification, the laboratory answered that *"the wear of components is assessed by several tests:*

Spectrometry for metallic particles between 1 and 5µ,
Ferrometry and gravimetric membrane for metallic particles up to 250µ.

Both laboratory tests (22/8 and 13/9) showed very low values and there were no particles. Consequently, the component status had been evaluated to normal (value: 1).

Although the increase of the CPU[11] *appears to be very high, the CPU value (=2) in August, as the CPU value (=12) in September, are completely correct because the values are very low. No alert thresholds are set for the CPU parameter because each component has its own wear characteristics. It is necessary to take into account the results regarding the values found in spectrometry, ferrometry and gravimetric membrane tests."*

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[9] The number of metal particles per unit.

[10] Sulphur is used as an additive in many extreme pressure oils and metal-working fluids. The sulphur amount of 585 mg/kg in both oil samples, was assessed as normal.

[11] CPU stands for the French abbreviation "Concentration en Particules d'Usure" (Concentration of wear particles).

August 2012

6 August: *Maintenance, hydraulic leak, change of hydraulic pump*

8 August: *Oil sample 1 taken*

22 August: *Oil sample 1 sent to laboratory*

28 August: *Analysis oil sample 1 sent to company*

> *"We note abnormal fouling of the oil - We advise you to run a preventive inspection of the unit - check the operating temperature - drain and rinse out if possible - lubricant the properties measured are regular"*

September 2012

13 September: *Oil sample 2 taken*

15 September: ***Crash***

17 September: *Oil sample 2 sent to laboratory*

18 September: *Analyses oil sample 2 sent to company*

> *"We still note abnormal fouling of oil - we note additivation parameters: in line with expected amounts"*

Figure 7: Time line of important events.

Maintenance Manual

The relevant AI-25TL Maintenance manual describes amongst other things the operation and maintenance of the engine. Relevant text of the manual will be discussed.

Page 30b describes in which cases the LOW OIL PRESS light becomes illuminated. One of the cases described is when chips appear in the oil and/or the oil temperature rises above a value of 202 (+5/-2) °C in the oil scavenge line of the turbine front and rear bearing voids (signals from one or two overheat and chip detectors).

The maintenance manual also describes the situations when the engine must be withdrawn from service:

- In case metal particles are detected on the magnet of the overheat and chip detector and these particles have characteristics indicating that they have been inserted into the engine in the course of its manufacture, repair or operation, the overheat and chip detector, oil filter and the magnetic plug must be flushed. Subsequently, engine operation can be continued. After a period of 10 to 15 engine hours, an inspection of the overheat and chip detector, oil filter and the magnetic plug must take place. If the check reveals the presence of particles of the above-described nature for a second time, the engine must be withdrawn from service.
- If no metal particles are revealed in the overheat and chip detector, there are no dark-brown deposits of oil decomposition products in the magnet region, and no coke particles are detected in the oil drained from the overheat and chip detector chamber, but the fusible insert reveals fusion traces or it cannot be removed from the coil interior, the engine must be withdrawn from service.
- If the metal particles are a lustrous scale of different size and shape, found in the detector, or if there are deposits of dark-brown oil decomposition products on the overheat and chip detector in the magnet area, and coke particles are revealed in the oil drained from the filter chamber of the overheat and chip detector, the engine must also be withdrawn from service.

The maintenance manual does not specify how to handle anomalies regarding the engine and oil characteristics from an oil analysis. Over the course of the investigation, it became clear that, for instance, the Thai Air Force opted to draw up its own maintenance requirements for engine oil analysis as the engine manufacturer's manual did not provide useful reference. The maintenance does describe the actions that must be taken in the case metal particles are detected on the magnet of the overheat and chip detector. In that case, attention must be paid to the nature and condition of the particles. The actions to be taken depend on the size, shape and colour of the particles.

Analyses

It can be analyzed that the relevant events started when the aviation company had been faced with a failure of the hydraulic pump. After maintenance work to solve this problem, an oil sample was sent to the laboratory to confirm the leakage of hydraulic fluid into the engine oil as a result of the failed hydraulic pump. Although the findings of the maintenance personnel indicated the presence of hydraulic fluid in the engine oil, the laboratory report does not mention this presence. However, it appeared that deposits were found on the gravimetric membrane indicating that the engine oil was contaminated. This resulted in a 'danger' classification of the fluid status. In the absence of any written reference, this classification was only based on the personal opinion of laboratory personnel. In addition, the maintenance manual does not describe the measures to be taken after such a laboratory result. Only measures to be taken in the case metal particles are found in the engine oil are described.

The laboratory did only pay attention to amount of particles but did not pay attention to the nature and condition of the particles that were present in the oil samples. Although this is not described in the maintenance manual and the amount of particles was very low according to the laboratory, a qualitative analysis of the oil samples in addition to the quantitative analysis, could have been also valuable. This would be an extra check on the engine condition.

Based on the 'danger' classification of the fluid status, the aviation company followed the advice of the laboratory and took additional measures. Because it was not possible for the aviation company to rate the classification at its true value, the aviation company was of the opinion that the measures taken were adequate and that no additional corrective measures had to be taken. This was confirmed by the fact that during and after flights (before the accident flight), no abnormalities were found. Checking the overheat and chip detector after every flight, no particles were found on the magnet so there was no reason for further inspection of the engine. There was also no cause to withdraw the engine from service as none of the signs as described in the maintenance manual, appeared during the operation of the aircraft.

Illumination of the LOW OIL PRESS annunciation during flight could have been an indication that metal particles appeared in the oil and/or the oil temperature raised above a value of 202 (+5/-2) °C in the oil scavenge line of the turbine front and rear bearing voids. The absence of the illumination of this warning was also no reason for the aviation company to take more measures.

All these circumstances made it explicable, from the point of view of the aviation company, that despite the 'danger' classification (which is the highest ranking) of the oil status, it was not decided to further investigate the possible cause of the pollution of the oil or to change the engine.

The oil analysis results of the 13 September 2012 sample turned out that the measures taken in respect to the engine oil had not been sufficient, the pollution of the engine oil was still present. A possible evolution in engine wear could have been noticed, although the values of the particles were very low and did not lead to further examination. Furthermore the laboratory results became available after the crash and could not be used anymore by the operator to take additional measures.

According to the engine maintenance manual the methodology of laboratory oil analysis for metal impurities detection is not described. The laboratory stated that, for the status of the fluid, no written quantified criteria are used. this is evaluated based on the condition of the fluid. This could lead to different status assessments in the case of roughly the same findings in pollution of oil samples.

The DSB is of the opinion that objective standards in the assessments of oil samples are necessary to assure that safe engine operation depends on validated references.

Although the aviation company's reaction on the oil analysis is explicable, the DSB has objections to the continuation of flight operations with ES-YLS without further investigation of the cause of the pollution. Although, due to the lack of a clear reference, the term 'danger' could not be valued, this qualification could have been reason for a further assessment of the problem to guarantee a safe operation

Additional laboratory investigation

In July 2014, the DSB requested a chemical laboratory of the Dutch Ministry of Defence to examine two oil samples that were taken from ES-YLS during the initial technical investigation after the crash had occurred. The goal of the examination was to determine the nature of the pollution and also the presence of hydraulic oil in the samples originating from the engine oil filter and the engine oil tank. This following the opinion of the engine manufacturer that hydraulic fluid could have infiltrated into the oil system.

The report of the Dutch Ministry of Defence[12] contained among other things the following findings. In particular the elements iron, lead and magnesium were present in an increased concentration. The concentration of these elements in the oil filter were higher than the amount of these elements in the oil tank. The pollution in the oil from the filter contained a high number of particles with a high concentration of aluminium and/or silicon. The pollution in the oil from the tank was more fine and also contained a striking amount of aluminium and silicon. After consultation with the chemical laboratory, the DSB concludes that the increased concentration of the mentioned metals could not be explained other than increased wear of some components of the engine. It remains unclear if this is a cause or a result of the engine failure. The amount of silicon is in line with the laboratory finding that sludge was present on the gravimetric membrane. The presence of hydraulic oil could not be established in both samples.

The DSB compared the results of the two mentioned oil analyses of ES-YLS with the results of three other oil analyses of another L-39C aircraft equipped with the same type of engine and with an oil analysis of ES-YLS of June 2011. No significant differences in the values of the elements present in the oil samples were found.

Engine manufacturer

The engine manufacturer is of the opinion that the destruction of the low pressure turbine front bearing was initially caused by its long-time operation in degraded lubrication and cooling conditions after hydraulic liquid got into the oil system. It was stated that the operator could have detected the infiltration of hydraulic liquid into the air engine oil system at an early stage through the absence of engine oil consumption, an increase of its level in the engine oil tank, as well as by the decrease of hydraulic liquid volume in the aircraft hydraulic system during it pre-flight preparation.

The DSB analysed the maintenance documentation and could not find any abnormalities with regard to oil consumption or hydraulic liquid. Therefore, the above-mentioned statement of the engine manufacturer could not be confirmed, but cannot be ruled out either.

As a measure to maintain a reliable operation of all AI-25TL engines on L-39 aircraft in the European Union, the engine manufacturer considers it to be expedient to implement a system of support for the operation of these engines with the participation of the designer (SE “IVCHENKO-PROGRESS”).

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[12] Onderzoek olie Albatros L-39 straaljager, Koninklijke Marine, november 2014.

Based on the NLR report, the results of both laboratory oil analyses and further investigation, it can be concluded that the bearing failure was possibly caused by:

- hydraulic fluid entering the engine oil system, or
- abnormal fouling of the engine oil, caused by deposits.

Both scenarios could have deteriorated the lubricating and cooling properties of the engine oil. It could however not be established which scenario is the most likely.

European legislation

Regulation (EC) No 216/2008 sets out general requirements for aircraft, organisations and individuals working in the aviation industry. These requirements are designed to ensure a high, uniform standard in the aviation industry in order to protect the safety of European citizens at all times. This is achieved through collective safety regulations and measures ensuring that all products, individuals and organisations within the community meet these requirements.

According to the regulation, these collective requirements should not necessarily apply to all aircraft; in particular aircraft that are of simple design or operate mainly on a local basis, and those that are home-built or particularly rare or only exist in a small number should generally be exempted. Such aircraft should therefore remain under the regulatory control of the Member States, without any obligation under this Regulation on other Member States to recognize such national arrangements.[13]

Annex II to Article 4(4.) of the Regulation (EC) No 216/2008 specifies the various aircraft exempted from these rules. Amongst other aircraft types, the list mentions:

(d) aircraft that have been in the service of military forces, unless the aircraft is of a type for which a design standard has been adopted by the Agency;

In view of the fact that the EASA has not adopted a design standard for the Aero Vodochody L-39C - an aircraft type that is and has been used by military forces in various countries - this aircraft was exempted from Regulation (EC) No 216/2008 by the Estonian aviation authority. As a result, this aircraft does not have to comply with European requirements for civil aviation aircraft. Amongst other consequences, this means owners are free to maintain aircraft and engines as they see fit, and may opt to apply manufacturer manuals as guidelines for their maintenance work. As a consequence, lower standards for maintenance and airworthiness may exist, resulting in an undetermined safety level.

The L-39 is originally a military aircraft which had been in use, but also still is in use by military forces. Furthermore, the aircraft does not have a simple design and is, registered as civil aircraft, used for commercial operations. That is why this aircraft does not meet the definition which is intended by the exemption of Regulation (EC) No 216/2008: aircraft that are of simple design or operate mainly on a local basis, and those that are home-built or particularly rare or only exist in a small number That is the reason that it is

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[13] Regulation (EC) No 216/2008, introduction (5).

unclear to the DSB why the Estonian aviation authorities exempted L-39C from Regulation (EC) No. 216/2008.

Oversight

The certificate of airworthiness for ES-YLS was restricted to only Estonian airspace. That is why the Dutch Civil Aviation Authority (CAA) issued a permission based of article 3.8 and 3.21 of the Dutch Aviation Act, to fly in Dutch airspace to all aircraft in the Breitling Jet Team for the duration of their stay in the Netherlands. According to Regulation of 17 February 2004/Nr.IVW/DL/03.520960 (Beleidsregel ontheffingen luchtwaardigheid), this permission was issued after having received the relevant certificate of registration, the certificate of airworthiness and the insurance policy. The explanatory memorandum of this Regulation states that the restrictions imposed on the flight to compensate for the lower safety level, are important. However, no restrictions to the flights of the Breitling Jet Team were laid down. The only mentioned conditions were:

1. *The aircraft is operated and maintained in accordance with the requirements as stipulated in the relevant "Certificate of Airworthiness."*
2. *A copy of this exemption is carried on board of the relevant aircraft.*

According to the Dutch CAA, a sufficient safety level is guaranteed by these conditions. It is unclear to the DSB in which way the lower safety level of the aircraft was compensated because no restrictions were imposed by the Dutch CAA to the flights of the Breitling Jet Team in Dutch airspace. Since 2013 the Dutch CAA does not grant permissions to former military aircraft anymore.[14]

Oversight is conducted by the country in which the aircraft has been registered. In the case of ES-YLS, this is Estonia. As regards annual renewal of the certificate of airworthiness, Estonian inspectors of the CAA assess the aircraft and check whether the aircraft meets the relevant requirements and has been maintained according to the applicable standards. When the aircraft is declared airworthy, a new certificate of airworthiness will be issued by the Estonian authorities. The oversight of aircraft that are registered in Estonia and stationed abroad is limited. It cannot be proven that this limited oversight played a role in causing the accident.

Estonia is one of the few European countries that allows Aero Vodochody L-39C aircraft to be registered in the civil aviation register. As a result, a large number of these aircraft - stationed in various European countries - are registered in the Estonian aviation register.

In the Netherlands, this type of aircraft is also used for various purposes, including flights in aid of the Ministry of Defence. Monitoring by the Estonian authorities is mainly carried out on a remote basis and is often limited in scope. Actual inspections are limited to those necessary for renewal of the certificate of airworthiness. Random assessments do not take place. The lack of adequate oversight in combination with the lack of

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[14] From 2013 the Dutch CAA implemented a more stringent exemption policy emphasized on the technical issues of the application. This stringent policy is laid down in the 'Normenkader ontheffingen luchtwaardigheid'. This code describes the conditions for the special occasions and the status of airworthiness. The code leaves no room for issuing exemptions to former military aircraft.

airworthiness requirements similar to those applied to civil aviation aircraft, may result in potentially unsafe operations. As in this event, adequate reference and thresholds for oil sample requirements were missing, allowing for room to continue operation.

The DSB has conducted several prior investigations into incidents with aircraft that were not subject to EU airworthiness requirements and had been registered abroad and stationed in the Netherlands, such as the Yak-52 aircraft. Amongst other conclusions, these investigations showed that the monitoring of such aircraft in the Netherlands by foreign aviation authorities is limited in scope. Monitoring by the Dutch aviation authorities - who are not primarily responsible - is also limited. In the case of the Yak-52 aircraft, requests from the relevant aircraft users resulted in new legislation allowing for these aircraft to be registered in the Dutch aviation register. As a result, the aircraft can now be monitored by the Dutch aviation authorities. This does not apply to aircraft subject to exemption from EU regulation 216/2008 that have been registered in other countries. This aircraft category is generally not subject to any operational constraints.

The DSB hereby expresses its concern as to the limited scope of monitoring to which these aircraft are subjected and, especially those that have been registered in another country.

According to the certificate of registration, ES-YLS was owned by a legal person in Luxembourg and operated by a French aviation company.

According to the Estonian Aviation Act, valid on the accident day, an aircraft must meet the following requirements in order to be registered in the Estonian aviation register:

1. The aircraft owner or operator must be a citizen of or legal entity in Estonia;
2. All military equipment must have been removed from the aircraft.

When ES-YLS was registered in the Estonian aviation register in September 2002, legislation valid on that date required that the owner or possessor must be a citizen of, or legal entity of Estonia, this was the case. In November 2002 the owner and operator of the aircraft changed. Although the requirement laid down in the legislation was not met anymore, the change was approved by the Estonian CAA.

CONCLUSION

The accident was the result of an engine malfunction caused by a failure of the low pressure turbine front bearing. The bearing failure was probably caused by hydraulic fluid entering the engine oil system or abnormal fouling of the engine oil caused by deposits.

For engine maintenance procedures the qualitative assessment of the particles in the engine oil, as described in the engine maintenance manual, did not take place. Such an additional assessment should have given a better picture of the oil status.

The oil status was especially assessed on the status of the magnetic plug of the overheat and chip detector and on quantitative parameters for particles, for which no written procedures and references existed in the laboratory that performed the analyses, nor with the operator. As such, the outcome of the analyses could not be valued for this engine. The classification of the fluid status was only based on the fact that the oil must be clear.

The aviation company took measures, as advised by the laboratory and continued the flight operation with ES-YLS. The Dutch Safety Board is of the opinion that the operator did not take full opportunity to establish that a normal engine operation was guaranteed.

This Aero Vodochody L-39C does not have to comply with European safety level requirements for civil aviation aircraft. As a consequence different standards and practises for maintenance and airworthiness may be applied. This is undesirable according to the Dutch Safety Board.

The lack of adequate oversight in combination with the lack of airworthiness requirements similar to those applied to civil aviation aircraft, may result in potentially unsafe operations.

RECOMMENDATION

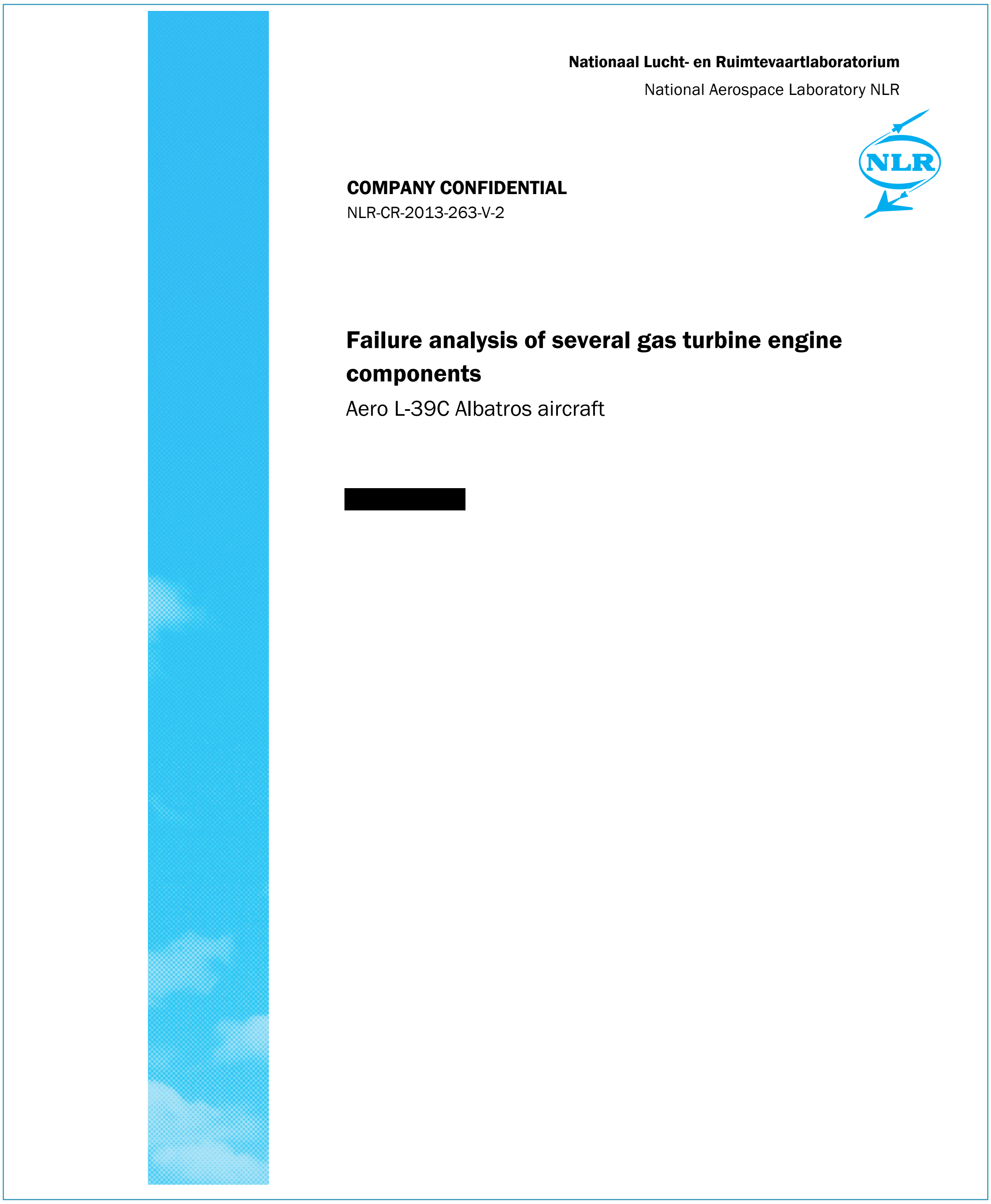
This investigation revealed that some type of aircraft could be exempted from the common rules of Regulation (EC) No 216/2008 although these aircraft don't meet the definition as mentioned in the preamble of the Regulation: aircraft that are of simple design or operate mainly on a local basis, and those that are home-built or particularly rare or only exist in a small number. The Dutch Safety Board is of the opinion that this is undesirable because the aim to ensure a high and uniform level of protection of the European citizen at all times in civil aviation, is accomplished insufficiently.

That is the reason why the Dutch Safety Board makes the following recommendation to the European Aviation Safety Agency (EASA):

Limit the possibility to exempt aircraft from the common rules of Regulation (EC) No 216/2008 to those category of aircraft as mentioned in the preamble of the Regulation under (5).

APPENDIX A

NLR REPORT



Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

COMPANY CONFIDENTIAL
NLR-CR-2013-263-V-2

Failure analysis of several gas turbine engine components
Aero L-39C Albatros aircraft

[redacted]

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UNCLASSIFIED

Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

Executive summary

Failure analysis of several gas turbine engine components

Aero L-39C Albatros aircraft

Report no.
NLR-CR-2013-263-V-2

Author(s)
[redacted]

Report classification
COMPANY CONFIDENTIAL

Date
April 2014

Knowledge area(s)
Vliegtuigmateriaal- en schadeonderzoek

Descriptor(s)
failure analys
gas turbine
bearing
shaft
fatigue

Problem area
On September the 15th 2012, an Aero L-39C Albatros aircraft crashed near Valkenswaard due to an engine failure. Several failed components were discovered upon disassembly and inspection of the engine. The Dutch Safety Board requested the National Aerospace Laboratory (NLR) to investigate the possible cause of failures for an oil tube and a coupling bolt. A shaft roller bearing also failed, and the Dutch Safety Board asked to verify whether an old or a new version of the shaft bearing was installed.

Description of work
All parts were inspected visually, with low power binocular and photographed. Fracture surfaces were removed from the coupling bolt and oil tube for fractography in the scanning electron microscope (SEM). Cross-sections of the inner ring and outer ring with the cage and cylinders were made to observe the microstructure. The raceways have been examined in the SEM. A cross-section of the oil tube was also made. The chemical compositions of the bearing and oil tube components were measured with energy dispersive analysis of X-rays (EDX) in the SEM.

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Results and conclusions

Fracture 1 and 2 in the coupling bolt are located in the radii. The fracture surfaces of the fractures 1 and 2 show fatigue crack initiation and propagation and different oxide thicknesses. The fatigue cracks and oxide skin on the fracture surfaces of the coupling bolt needed some time to grow. Fracture 3 in the coupling bolt shows a classic ductile “cup and cone”-failure in the middle of the section. It is clear that rotation between the oil tube ends has occurred and that most of the rotation ended up in section 2. Fracture 2 is caused by overload in torsion. Torsion of section 2 results in shortening of this section. Since the disk did not rotate, the torsion in section 2 results in uniaxial tensile load in section 1. Necking of the tube and the tube wall at multiple locations in circumferential direction of fracture 1 indicates that it failed in tensile overload. It is expected that the rotation of the oil tube end closest to the coupling bolt occurred due to the failure of the coupling bolt. The markings on the bearing and the measured chemical composition of the bearing parts indicate that the new version of the bearing was installed. The cracks in the bearing inner ring base material, the worn out material at the inner raceway, wear particles in the oil and the vibrations just prior to the crash, point to the failure of the bearing as the root cause of the crash. The wear and vibrations of the bearing probably lead to more stress on the coupling bolt and reversed bending in section 2 of the coupling bolt. Failure of the coupling bolt caused rotation between the oil tube ends leading to torsion and tensile overload at the fractures 2 and 1 of the tube, respectively.

Applicability

It is recommended to review the maintenance history of the shaft bearing and the assembly procedure. The results of this investigation can be used to prevent failures in the future and therefore increase safety of air transport.

Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

COMPANY CONFIDENTIAL
NLR-CR-2013-263-V-2

Failure analysis of several gas turbine engine components

Aero L-39C Albatros aircraft

[redacted]

Customer	Onderzoeksraad voor Veiligheid
Contract number	0010/2013/010
Owner	Onderzoeksraad voor Veiligheid
Division NLR	Aerospace Vehicles
Distribution	Limited
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Approved by:

Author	Reviewer	Managing department
[redacted]	[redacted]	[redacted]
Date: 30-04 '14	Date: 30/4/'14	Date: 30/4/'14

COMPANY CONFIDENTIAL

Summary

On September the 15th 2012, an Aero L-39C Albatros aircraft crashed near Valkenswaard due to an engine failure. Several failed components were discovered upon disassembly and inspection of the engine. The Dutch Safety Board requested the National Aerospace Laboratory (NLR) to investigate the possible cause of failures for an oil tube and a coupling bolt. A shaft roller bearing also failed and the Dutch Safety Board asked to verify whether an old or a new version of the shaft bearing was installed.

All parts were inspected visually, with low power binocular and photographed. Fracture surfaces were removed from the coupling bolt and oil tube for fractography in the scanning electron microscope (SEM). Cross-sections of the inner ring and outer ring with the cage and cylinders were made to observe the microstructure and the raceways in the SEM. A cross-section of the oil tube was also made. The chemical compositions of the bearing and oil tube components were measured with energy dispersive analysis of X-rays (EDX) in the SEM.

The fractures 1 and 2 in the coupling bolt are located in the radii. The fracture surfaces of the fractures 1 and 2 show fatigue crack initiation and propagation and different oxide thicknesses. The fatigue cracks and oxide skin on the fracture surfaces of the coupling bolt needed some time to grow. Fracture 3 in the coupling bolt shows a classic ductile “cup and cone”-failure in the middle of the section. It is clear that rotation between the oil tube ends has occurred and that most of the rotation ended up in section 2. Fracture 2 is caused by overload in torsion. Torsion of section 2 results in shortening of this section. Since the disk did not rotate, the torsion in section 2 results in uniaxial tensile load in section 1. Necking of the tube and the tube wall at multiple locations in circumferential direction of fracture 1 indicates that it failed in tensile overload. It is expected that the rotation of the oil tube end closest to the coupling bolt occurred due to the failure of the coupling bolt. The markings on the bearing and the measured chemical composition of the bearing parts indicate that the new version of the bearing was installed. Cracks in the bearing inner ring base material, worn out material at the inner raceway and wear particles in the oil indicate that the sequence of events started with the failure of the bearing.

Cracks in the inner ring base material, worn out material, wear particles in the oil and vibrations; noticed just prior to the crash, point to the bearing as the root cause of the crash. The wear and vibrations of the bearing most likely led to more stress on the coupling bolt and reversed bending in section 2 of the coupling bolt. Failure of the coupling bolt caused rotation between the oil tube ends leading to torsion and tensile overload at fracture 2 and 1 of the tube, respectively.

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Contents

Abbreviations

EDX	Energy Dispersive analysis of X-rays
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
NLR	National Aerospace Laboratory
SEM	Scanning Electron Microscope

1 Introduction

On September the 15th 2012, an Aero L-39C Albatros aircraft crashed near Valkenswaard, in The Netherlands, due to an engine failure. Several failed components were discovered upon disassembly and inspection of the engine. The Dutch Safety Board requested the National Aerospace Laboratory (NLR) to investigate the possible cause of failures for an oil tube and a coupling bolt. A shaft roller bearing also failed and the Dutch Safety Board asked to verify whether an old or a new version of the shaft bearing was installed.

2 Description of the components

A technical drawing of the engine and the oil system is given in Appendix A. The upper yellow oval indicates the position of the oil tube. The middle yellow oval indicates the position of the bearing and the lower yellow oval gives the location of the coupling bolt in the N1 shaft. The coupling bolt connects the low pressure compressor (LPC) to the low pressure turbine (LPT). LPC and LPT are connected with torsion shaft splines (splines are sliding) and the coupling bolt set the position of LPT. (LPC is supported by ball bearings and therefore has a fixed position. The LPT is supported by roller bearings and thus can expand axially.)

3 Experimental set-up

All parts were inspected visually, with low power binocular and photographed. Fracture surfaces were removed from the coupling bolt and oil tube for fractography in the scanning electron microscope (SEM). Cross-sections of the inner ring and outer ring with the cage and cylinders of the roller bearing were made to observe the microstructure and the raceways in the SEM. A cross-section of the oil tube was also made. The chemical compositions of the bearing and oil tube components were measured with energy dispersive analysis of X-rays (EDX) in the SEM.

4 Results

4.1 Bearing

4.1.1 Visual inspection

Fig. 1 shows the various parts of the bearing as received. The cage is still inside the outer ring and is smeared for about 160°. The outer raceway and the cage are very dirty and black. Several connections between the rings of the cage are not present anymore as well as some of the cylinders (see Fig. 2). Flat sides are present on all cylinders, while the remainder of the rolling surface appears undamaged. This can indicate a sudden event. The cylinders under the smeared cage are still present and the contours can be vaguely observed. 7 cylinders are received separately, while 8 empty positions can be counted on the cage. Two cutting saw markings are present on the outside of the outer ring and with a black marker the code “5-3211OR” is written on the outside of the outer ring. This corresponds to the markings that are found on the side of the outer ring:

Deep markings:	57	PI
Shallow markings:	5-3211[]Ƥ	4┌∏3
Vague markings:	800 or X00	H O

Fig. 2 shows that the cage is also smeared out on the inner ring. In the centre of the inner raceway, where no cage material is present, the surface is black and several small steps can be observed.

4.1.2 Cross-sections

Fig. 3 shows the cross-section of the inner- and outer ring of the bearing. The chemical composition of the bearing components were measured with EDX in the SEM (see Table 1). The chemical composition of the inner ring, outer ring and the rollers is similar and is also similar to the specified material EI 347 Sh, which is similar to 8KH4V9F2-SH [1].

An optical microscopy (OM) image of the cross-section of the outer raceway shows no apparent damage to the raceway (see Fig. 4). The inner raceway does show material removal from the original raceway surface (see Fig. 4 and Fig. 5). This corresponds to the visual inspection of the inner ring. Fig. 5 show an SEM image of the raceway surface with the smeared out cage material. EDX measurements and the microstructure of the smeared out cage material indicate that the smeared out cage material consists of about 50 percent of ring material and is actually a solidified mix of cage and ring material (see Fig. 5 and Table 2). Vertical cracks are present in the inner ring material where the ring material is worn out. Phases of iron-chromium oxides are present on the surface and around the cracks (see Fig. 6, Fig. 7 and Table 2). Fig. 8 shows SEM images of the black surface of the inner raceway where the ring material is worn out. Cracks are present in the surface layer in axial and the circumferential direction. Flakes of the surface layer are almost broken off exposing the (oxidized) surface below.

4.2 Coupling bolt

4.2.1 Visual inspection

Fig. 9 shows a photograph of the four sections of the coupling bolt. The coupling bolt failed at three locations. Each fracture has two fracture surfaces and they are denoted as {A,B}, where A is the fracture number and B the section number. The following observations have been made for each fracture surface:

{1,1} The fracture surface show possible signs of fatigue
{1,2} The fracture surface show beach marks and discoloration (see Fig. 10)

{2,2} The fracture surface is destroyed due to smearing
{2,3} The fracture surface may contain signs of fatigue

{3,3} The fracture surface shows a lot of plastic deformation
{3,4} The fracture surface is destroyed due to smearing

Fracture 3 is located in the middle of that coupling bolt section and shows a lot of necking with a classical cup and cone configuration. This indicates ductile fracture and therefore overload. Fractures 1 and 2 show possible signs of fatigue and both fracture locations are at a point of stress concentration (in the radius). Fig. 10 shows higher magnification images of fracture surface {1,2}. Beach marks and discoloration can be clearly observed. Coupling bolt section 2 (see Fig. 9) shows a dark discoloration, which is absent in all the other sections.

4.2.2 Fractography

Fig. 11 shows a fatigue crack initiation point in fracture 1. Striations at short crack length are not visible, because a thick oxide layer is present at that part of the fracture surface. At larger crack lengths beach marks or large striations can be observed (see Fig. 12a and b). More plasticity can be observed between these larger striations and at even larger crack lengths dimples can be observed (see Fig. 12c). No thick oxide layer is present on the dimpled area (see Fig. 12c).

4.3 Oil tube

4.3.1 Visual inspection

Fig. 13 shows a photograph of the sections of the oil tube and Fig. 14 higher magnification images of the fractures in the oil tube. Fracture 2, between tube sections 2 and 3, shows a high twist (see Fig. 14b). Fracture 1, between tube section 1 and 2, originally lies within tube section 2 and is not twisted (see Fig. 14a). The darker colour of tube 1 shows the length of tube section 1 that was inside tube 2. All sections of the tube show some distortion, but especially tube section 2.

4.3.2 Fractography

Fig. 15 shows the fractograph of fracture surface {1,1}. The fracture surface is not very clean and a lot of deposit is present (see Fig. 16). Therefore it is difficult to detect characteristic fractographic features. Fig. 16 does show small steps, which can be a sign of fatigue. Some fine lines were observed, but due to their appearance and orientation they are not regarded as fatigue striations.

4.3.3 Cross-section

The outer tube is welded to the disk on one end and is brazed to the tube at the other end. Brazing material has penetrated between the outer tube and the tube. Excess brazing material on the outside was removed by grinding. The brazing did not alter the microstructure at the braze compared to the microstructure further along the tube (compare Fig. 19 with Fig. 20). Table 3 gives the chemical composition of the oil tube parts. The tube and the outer tube are both made of austenitic steel (CrNiMn steel).

Necking of the tube wall can be observed on both sides, followed by some widening at the fracture surface. This is known as a “cup” configuration in ductile failure. It indicates that at these locations of the circular fracture surface the wall failed ductile (see Fig. 15 for the intersection locations of the tube wall with the plane of the cross-section). Cracking of the brazing material occurred on the right side due to the necking of the tube.
Side view photographs of tube section 1 just below fracture surface {1,1} also shows tube necking on both sides, however more on the left side than the right side (see Fig. 21). The left side of Fig. 21 corresponds to the left side in Fig. 18.

Fig. 22 shows SEM images of the cross-section of fracture surface {1,2}. Fig. 23 shows that a deposit is present on the inside of the tube at exactly the failure and brazing location. Fig. 23 also shows SEM images of the deposit and it can be observed that two different layers of deposit are present. The chemical composition of the two different deposits are given in Table 4. It largely consists of carbon oxides, but elements of Pb and Cd are also detected.

5 Discussion

5.1 Bearing

The old version of the bearing is: 6-32110Б1Т (Russian name), 6-3211B1T. The old version is made of material: ШХ-15 (Russian name), ShCh-15. The new version of the bearing is: 5-32110Р (Russian name), 5-32110R and is made of material: ЗИ-347 Ш (Russian name), EI-347 Sh. The markings on the bearing correspond to the new bearing type. The chemical composition of the bearing parts also correspond to the new bearing type. It is therefore concluded that the correct bearing was installed. Further failure analysis of the bearing was outside the scope of this investigation.

The bearing is heavily damaged; the cylinders all have a flat facet, the case is broken and the cage is highly deformed/smeared out on one side. A black deposit is present on most inner surfaces of the bearing except the smeared out cage. It is therefore expected that the flattening of the cylinders and fracture of the cage occurred first in a single event, followed by the deposit of the black material, which is probably soot, and finally smearing of the cage at the moment of impact during the crash. However, the cracks in the inner ring base material, the worn out material at the inner raceway and wear particles in the oil indicate that a slowly degrading process preceded the single event. The lack of damage to the rolling surface (except the flat facet) could indicate that the bearing did not rotate anymore between the single event and the crash. It is expected that lack of rotation cannot stay unnoticed and should therefore have occurred just prior or during the crash.

5.2 Coupling bolt

Fracture surface {1,2} of the coupling bolt clearly shows crack initiation and propagation from opposite sites. In the middle a band of discoloration can be observed, due to a thin oxide layer. At the crack initiation points the oxide layer is thicker and hence the discoloration is not present. Crack growth from opposite sides is characteristic for reversed bending. The fatigue failure occurred in both radii of that section (fracture 1 and 2). The origin of the reversed bending and the black discoloration on the outside of the section in between fractures 1 and 2 is at this point unclear. Since the stresses and the crack propagation rates are also unknown, the time to failure cannot be calculated. However, the relative small overload areas and the thick oxide layer at the initiation points indicate that the stresses were low and crack propagation took some time.

5.3 Oil tube

Although some microscopic steps were observed on fracture surface {1,1}, no other clear signs of fatigue were detected. No brazing material was found on the outside of section 1 near fracture 1. The cross-section does show brazing material on the outside of the tube at fracture 1. It is therefore concluded that fracture occurred at the end of the brazing zone. Uneven penetration of the brazing material can explain the larger steps observed on fracture surface {1,1} (see Fig. 21b)

Fig. 14b clearly shows that Fracture 2 is due to torsion and the amount of rotation between the disk in section 2 and the tube end in section 3 is estimated to be >90°. No clear rotation is observed in section 1, which means that the disk did not rotated considerably. Fig. 24 shows scratches in the circumferential direction and flattening of the outer edge of the disk, which can indicate that the disk was tightly locked in the shaft. Rotation is also prohibited at the tube end at section 1. It is therefore clear that rotation between the tube ends has occurred and that most of the rotation ended up in section 2. Torsion of section 2 results in shortening of this section. Since the disk does not rotate, the torsion in section 2 results in uniaxial tensile load in section 1. The cross-sections show necking of the cell wall at one side of the tube. Fig. 21a and b show necking of the tube on both sides for other locations around the fracture surface (see Fig. 15 for locations). It is therefore concluded that the tube also failed due to overload at fracture 1.

5.4 Overall failure scenarios

On September the 13th 2012, two days before the crash, oil samples were taken. However, the samples were received at the laboratory on September the 18th. Therefore, the results of the analysis were only available after the crash [2]. The oil samples show an uncommon increase in large and small wear particles. This indicates that one of the rotating parts in the oil system, like gear wheels or bearings, is deteriorating. No other rotating parts with excessive wear damage were found, except for the failed bearing. The failed bearing was from the new type. The fact that there is a new type can indicate that in the past there were problems with the old bearing as well. According to the pilot report, the crash started with vibration, which increased to very heavy vibration [3]. The cracks in the bearing inner ring base material, the worn out material at the inner raceway and wear particles in the oil indicate that the sequence of events started with the failure of the roller bearing. The inner raceway shows steps that can be caused by fatigue. The following sequence of events or failure scenario is most likely:

1. Wear of the bearing lead to vibrations during flight.
2. The wear and vibrations of the bearing lead to more stress on the coupling bolt and reversed bending in section 2 of the coupling bolt.
3. Excessive wear of the bearing leads to higher vibrations just prior to the crash.

4. Large cracks in the coupling bolt and failure of the bearing parts lead to heavy vibrations.
5. Failure of the coupling bolt occurs.
6. At the same time, failure of the coupling bolt caused rotation between the oil tube ends leading to torsion and tensile overload at fracture 2 and 1 of the tube, respectively.
7. Failure of the coupling bolt and ignition of the oil from the tube in the N1 shaft at the LPT caused the reported explosion felt by the pilot.
8. The fire in the N1 shaft leads to soot deposition on the bearing
9. Impact of the engine with the ground caused smearing of the case

It is expected that the deposition on the inside of the oil tube has nothing to do with failure. The presence of Pb and Cd in the oil was measured one month before the crash. The deposition is only present where the disk and small tube section is brazed to the oil tube. It is expected that heat from the engine dissipates through the disk to the oil tube and causes deposition of the Pb and Cd at the hotter parts of the tube. The thin tube sections have a low heat input and are cooled by the oil.

6 Conclusions

Coupling bolt:

- Fracture 1 and 2 in the coupling bolt are located in the radii. The fracture surfaces of fracture 1 and 2 show fatigue crack initiation and propagation and different oxide thicknesses. Fracture 3 in the coupling bolt shows a classic ductile “cup and cone”-failure in the middle of the section.
- The fatigue cracks and oxide skin on the fracture surfaces of the coupling bolt needed some time to grow.

Oil tube:

- It is clear that rotation between the oil tube ends has occurred and that most of the rotation ended up in section 2. Fracture 2 is caused by overload in torsion.
- Torsion of section 2 results in shortening of this section. Since the disk did not rotate, the torsion in section 2 results in uniaxial tensile load in section 1. Necking of the tube and the tube wall at multiple locations in circumferential direction of fracture 1 indicates that it failed in tensile overload.
- It is expected that the rotation of the oil tube end closest to the coupling bolt occurred due to the failure of the coupling bolt.

Roller bearing:

- The markings on the bearing and the measured chemical composition of the bearing parts indicate that the new version of the bearing was installed. The cracks in the bearing inner ring base material, the worn out material at the inner raceway and wear particles in the oil indicate that the sequence of events started with the failure of the roller bearing.

Root cause of failures:

- Cracks in the bearing inner ring base material, worn out material at the inner raceway, wear particles in the oil and vibrations; noticed just prior to the crash, point to the bearing as the root cause of the crash. The wear and vibrations of the bearing most likely led to more stress on the coupling bolt and reversed bending in section 2 of the coupling bolt. Failure of the coupling bolt caused rotation between the oil tube ends leading to torsion and tensile overload at fracture 2 and 1 of the tube, respectively.

References

[1] L.Ya. Konter, V.L. Zakharova. *Effect of cooling method during hardening of a thermally stable bearing steel on its properties and bearing life*. Material Science and Heat Treatment 26 (11) (1984) 789-793.

[2] IESPM - Condition monitoring report oil, plane: ES-YLS, report date: 18-09-2012, sample number: 120918-1003, sampling date: 13-09-2012.

[3] English translation of the pilot report by P. Marchand per email: ES-YLS: first report, 16 September 2012 19:29.

Table 1 Chemical composition (wt%) of the bearing components

element	C	Si	V	Cr	Fe	W	Al	Mn	Cu
Spec. 8KH4V9F2-SH	0.7-	0.4	1.4-	4-	Bal.	8.5-		0.4	
(EI 347 Sh)	0.8	max	1.7	4.6		9.5		max	
outer ring		0.2	1.5	3.9	85.0	9.4			
inner ring		0.3	1.7	4.0	84.7	9.3			
roller		0.2	1.7	3.8	85.0	9.1			
cage					2.8		9.3	1.8	86.1

Table 2 Chemical composition (at%) of the bearing inner ring phases

element	Al	O	Cr	Fe	Co	Cu	W
solidified case material	9.48		2.67	50.26	0.78	34.86	1.95
solidified case material (wt%)	4.39		2.39	48.39	0.79	37.86	6.17
phase 1		34.97	29.47	31.91	0.48	1.41	1.76

Table 3 Chemical composition (wt%) of the oil tube parts

element	Si	Ti	Cr	Mn	Fe	Co	Ni	Cu
inner tube	0.1	0.9	16.9	1.6	70.4		10.1	
Disk/outer tube	0.3	0.6	16.8	2.3	70.3		9.8	
Braze material	0.3		0.9	22.4	7.7	5.3	28.9	34.5
Needles braze material			29.5	19.6	30.5	13.5	5.8	1.3

Table 4 Chemical composition (wt%) of the phases found on the inside of the tube

element	C	O	Na	Mg	Al	Si	P	S	Pb	Cd	Cu
Deposition 1	68.1	23.3	0.7	0.4	0.4	0.2	0.3	1.4	3.3	0.9	0.9
Deposition 2	58.3	29.6			0.4			1.5	7.2	3.0	

Fig. 1 Overview of the failed bearing components

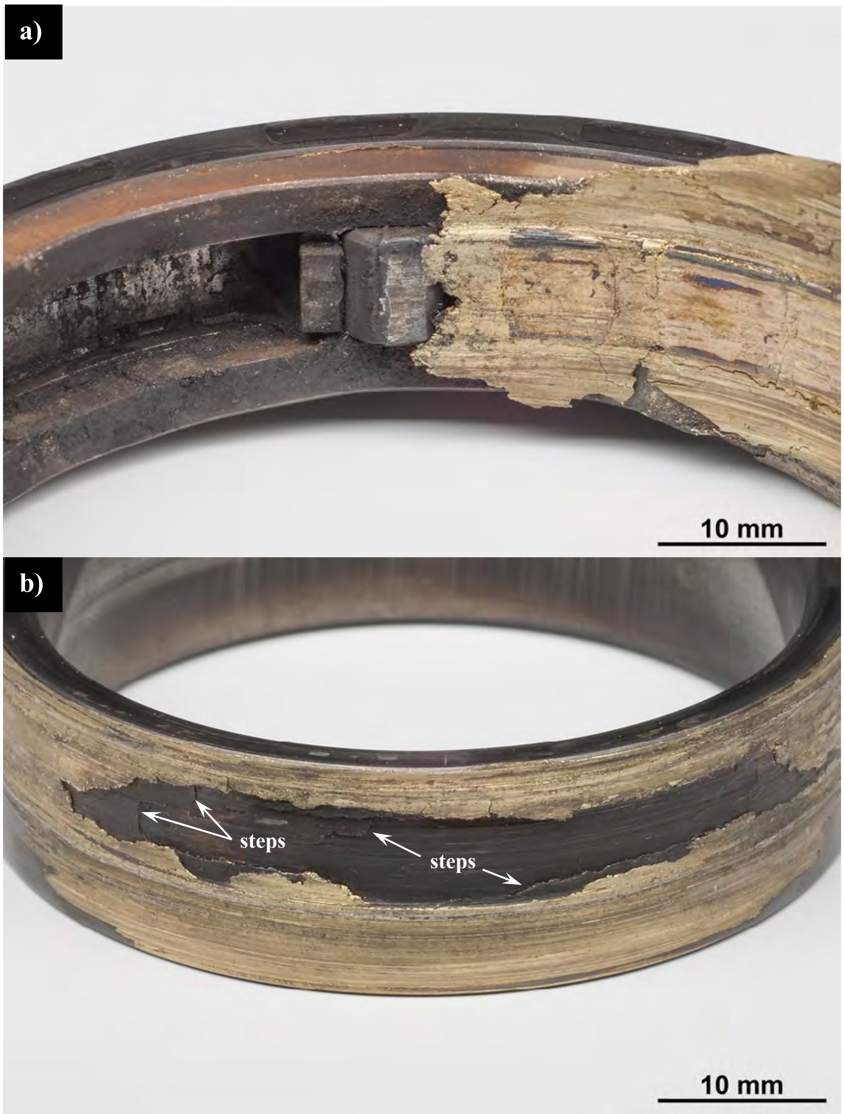


Fig. 2 Photographs of the a) outer ring with (smeared) cage and rollers and b) inner ring with smeared cage

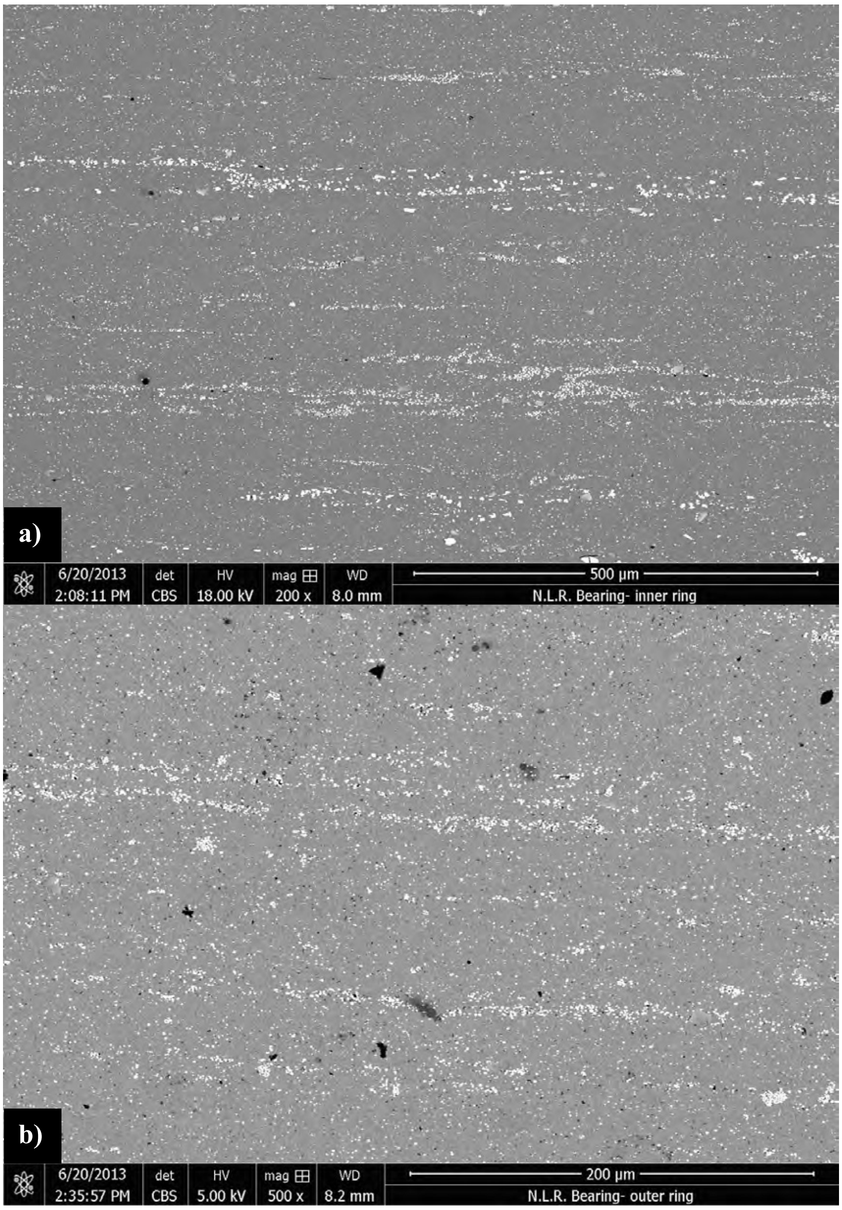


Fig. 3 Microstructure of the a) inner and b) outer ring of the bearing

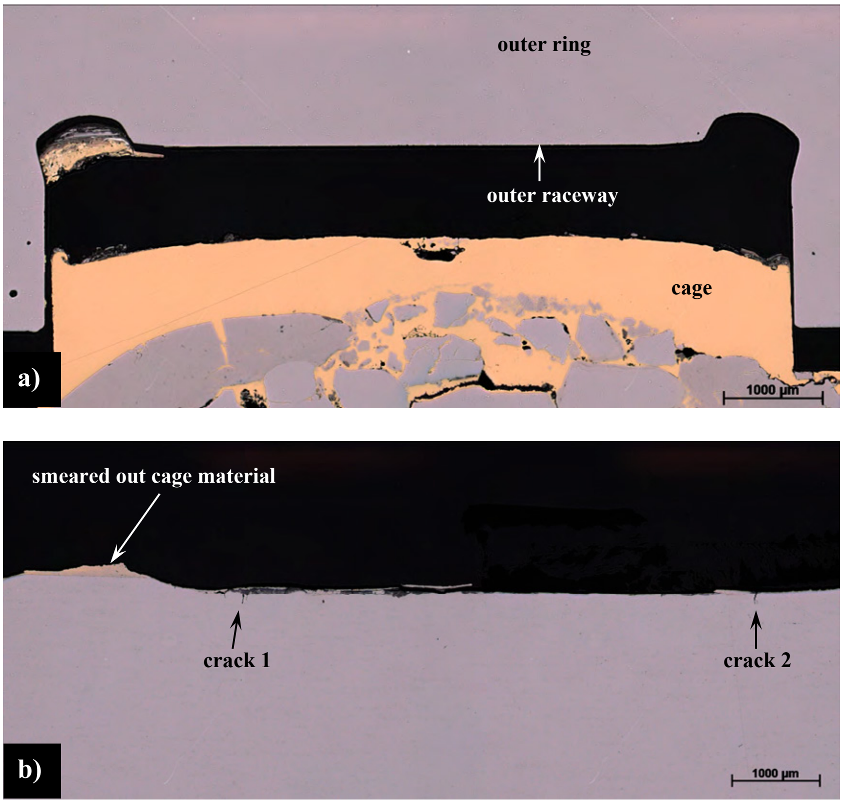


Fig. 4 Optical microscopy image of the cross-sections of the bearing a) outer ring and b) inner ring

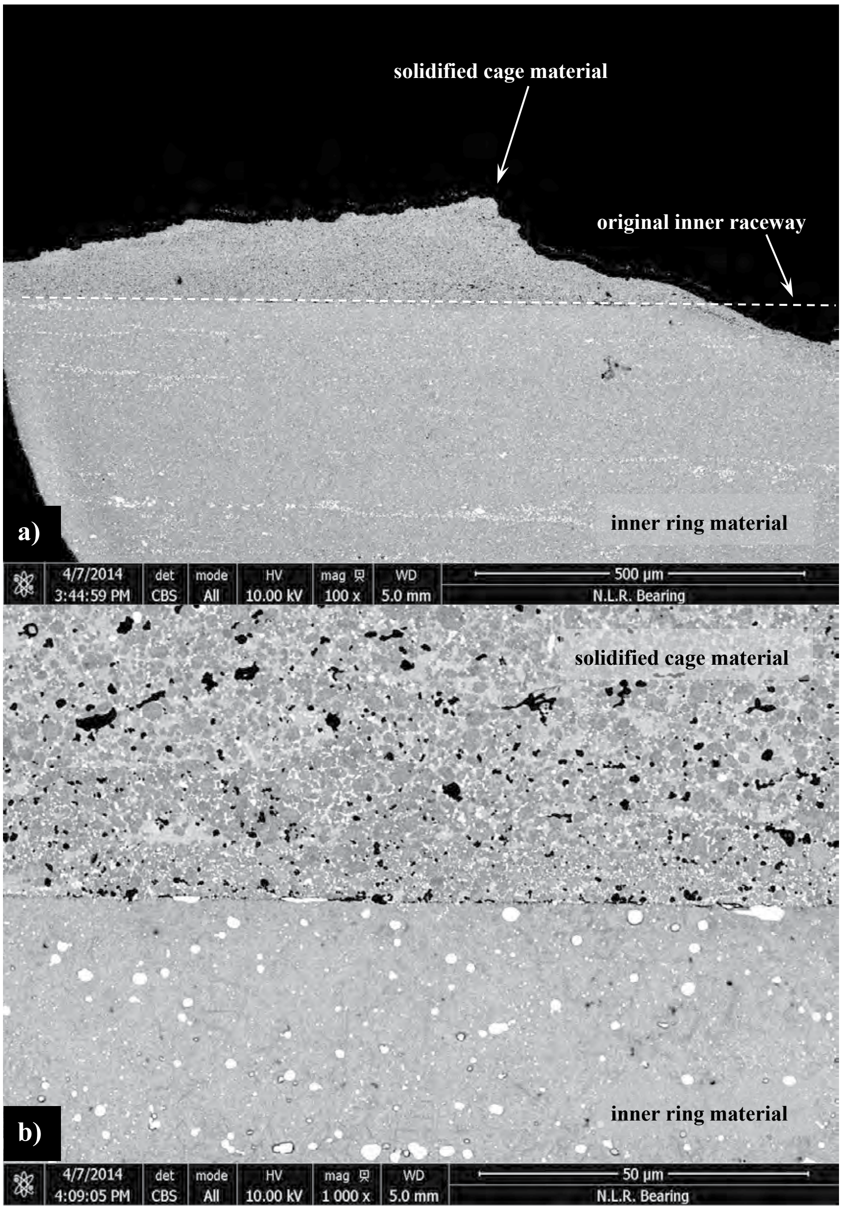


Fig. 5 Scanning electron microscopy image of the cross-section of the bearing inner ring at a) 100x and b) 1000x magnification

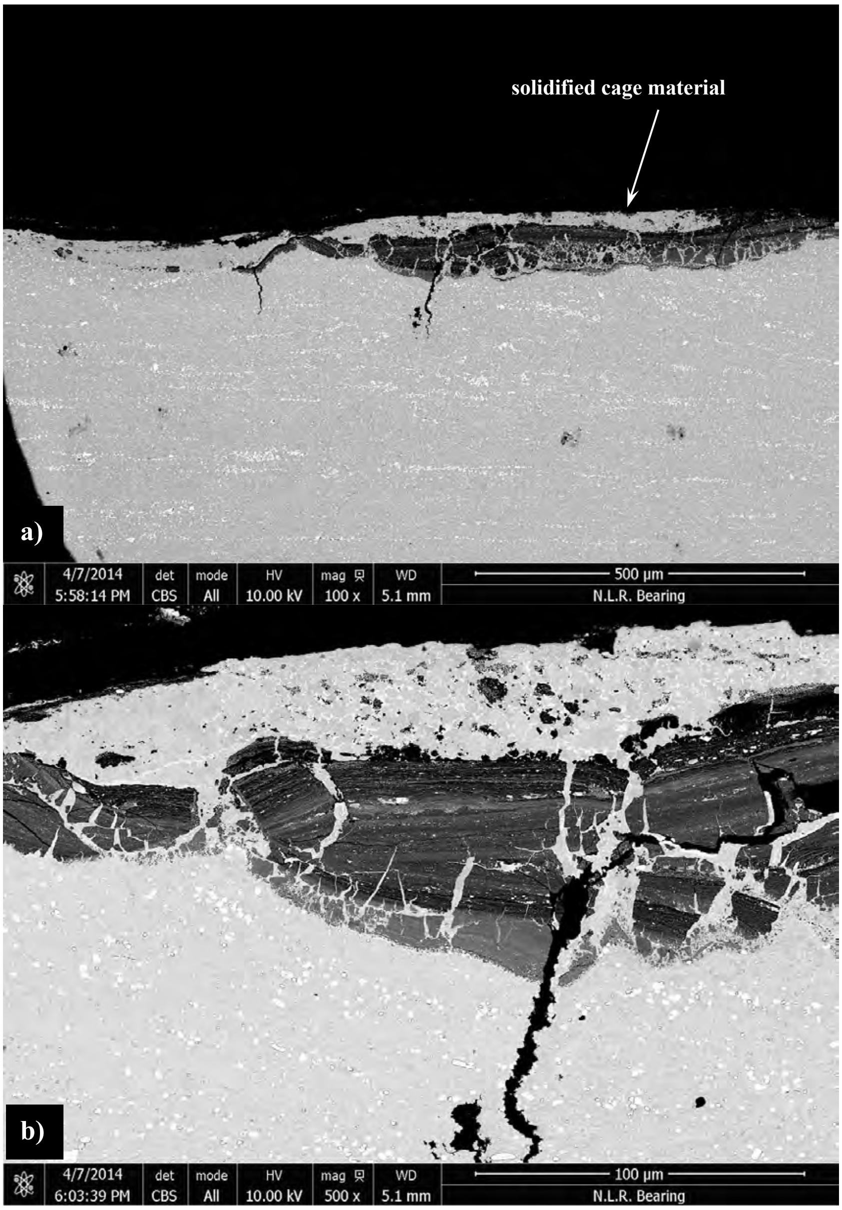


Fig. 6 SEM image of crack 1 at a) 100x and b) 500x magnification

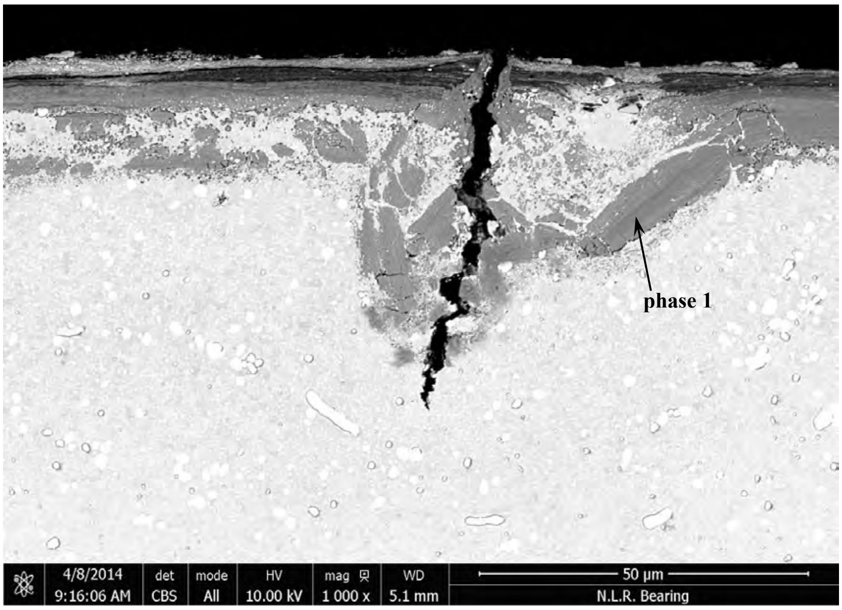


Fig. 7 SEM image of crack 2 at a) 100x and b) 500x magnification

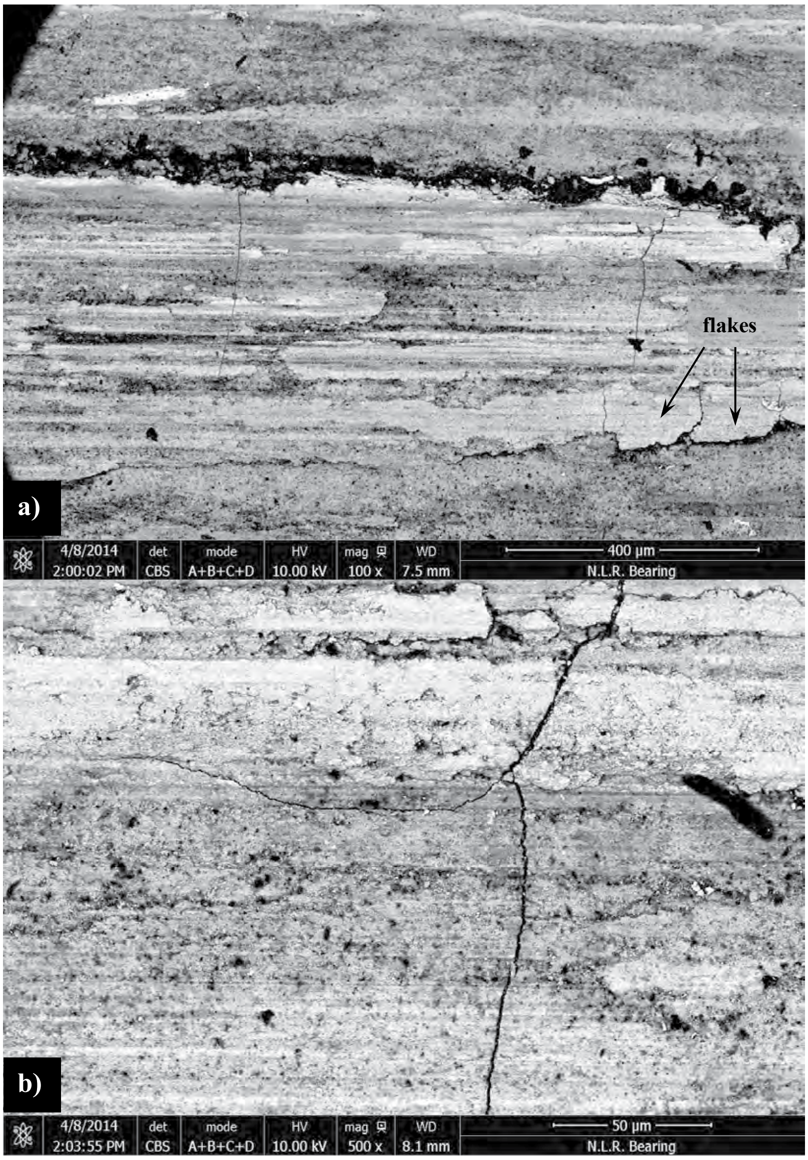


Fig. 8 SEM image of the black inner raceway surface at a) 100x and b) 500x magnification

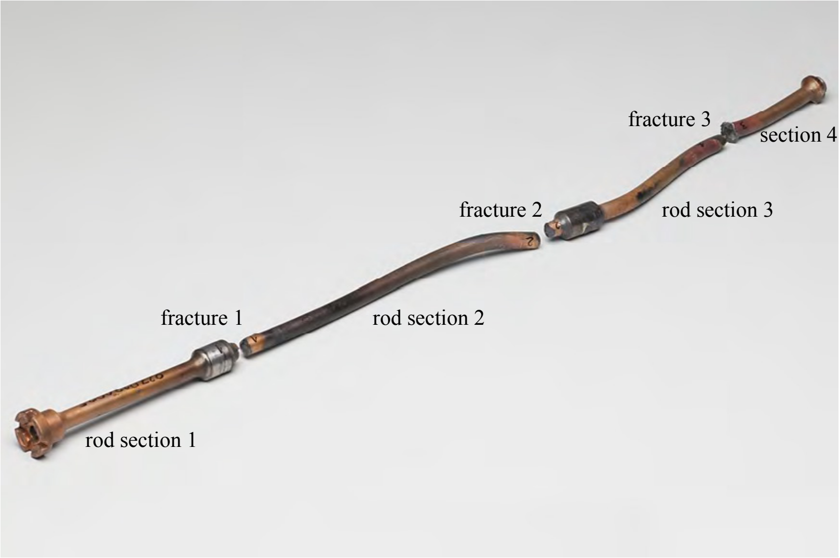
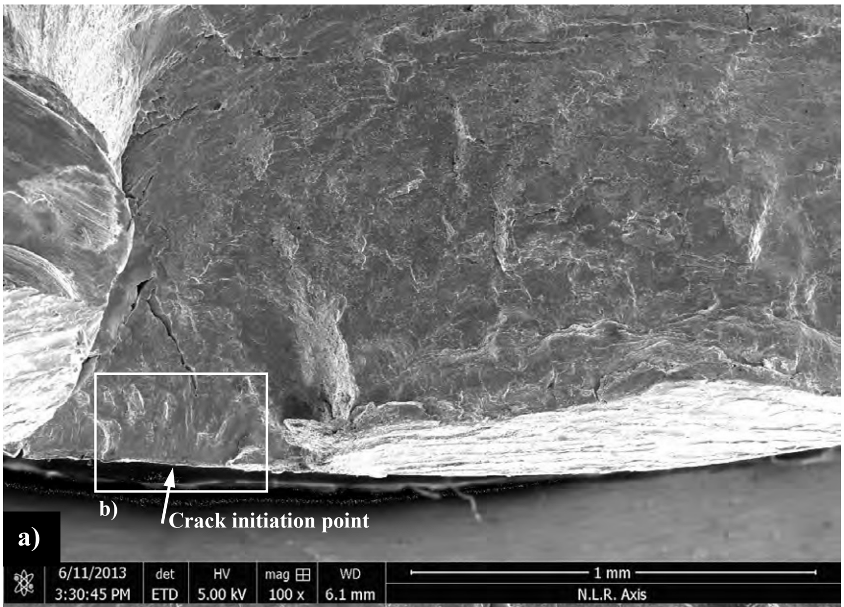
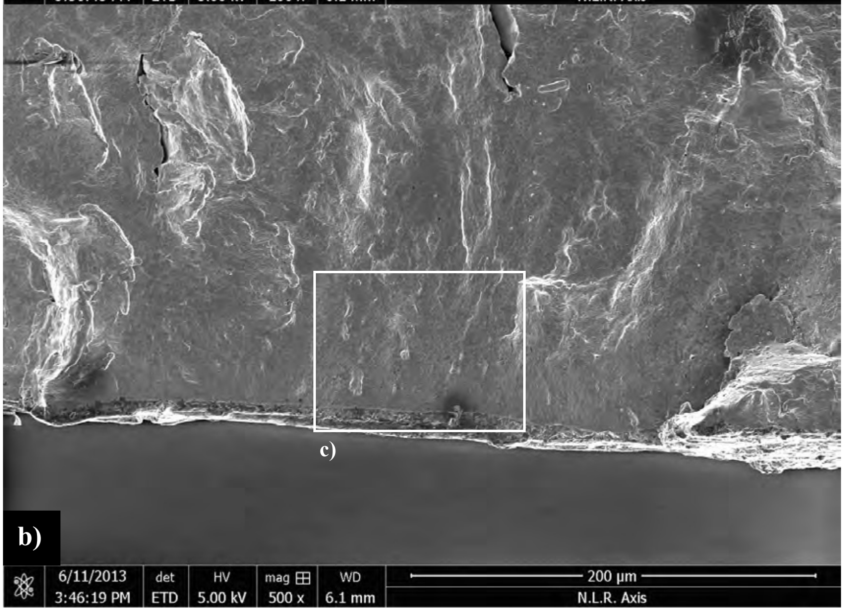


Fig. 9 Overview of the failed connector rod parts

Fig. 10 Fracture surface {1,2} from two angles a) and b). The white rectangles indicate the locations of subsequent figures


b)
Crack initiation point
a)
6/11/2013
3:30:45 PM
det
ETD
HV
5.00 kV
mag
100 x
WD
6.1 mm
1 mm
N.L.R. Axis


c)
b)
6/11/2013
3:46:19 PM
det
ETD
HV
5.00 kV
mag
500 x
WD
6.1 mm
200 μm
N.L.R. Axis

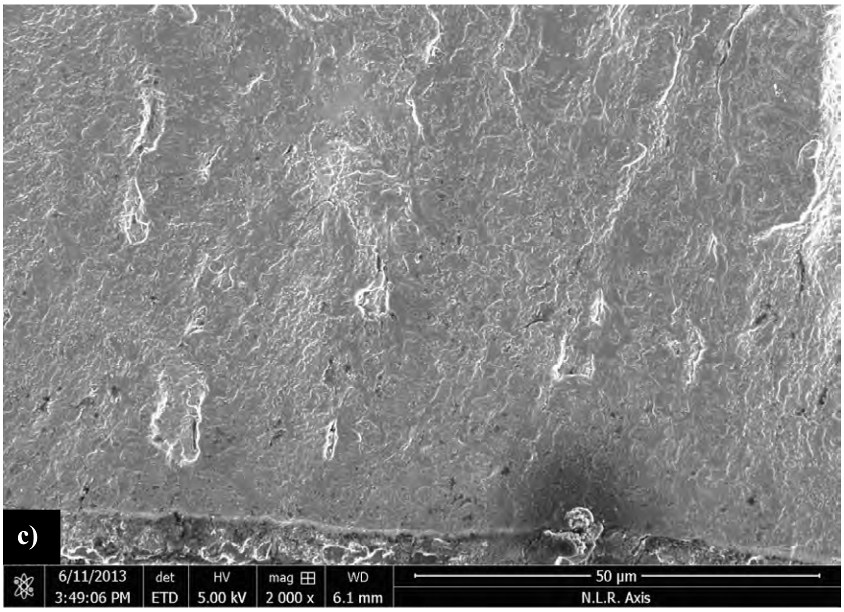
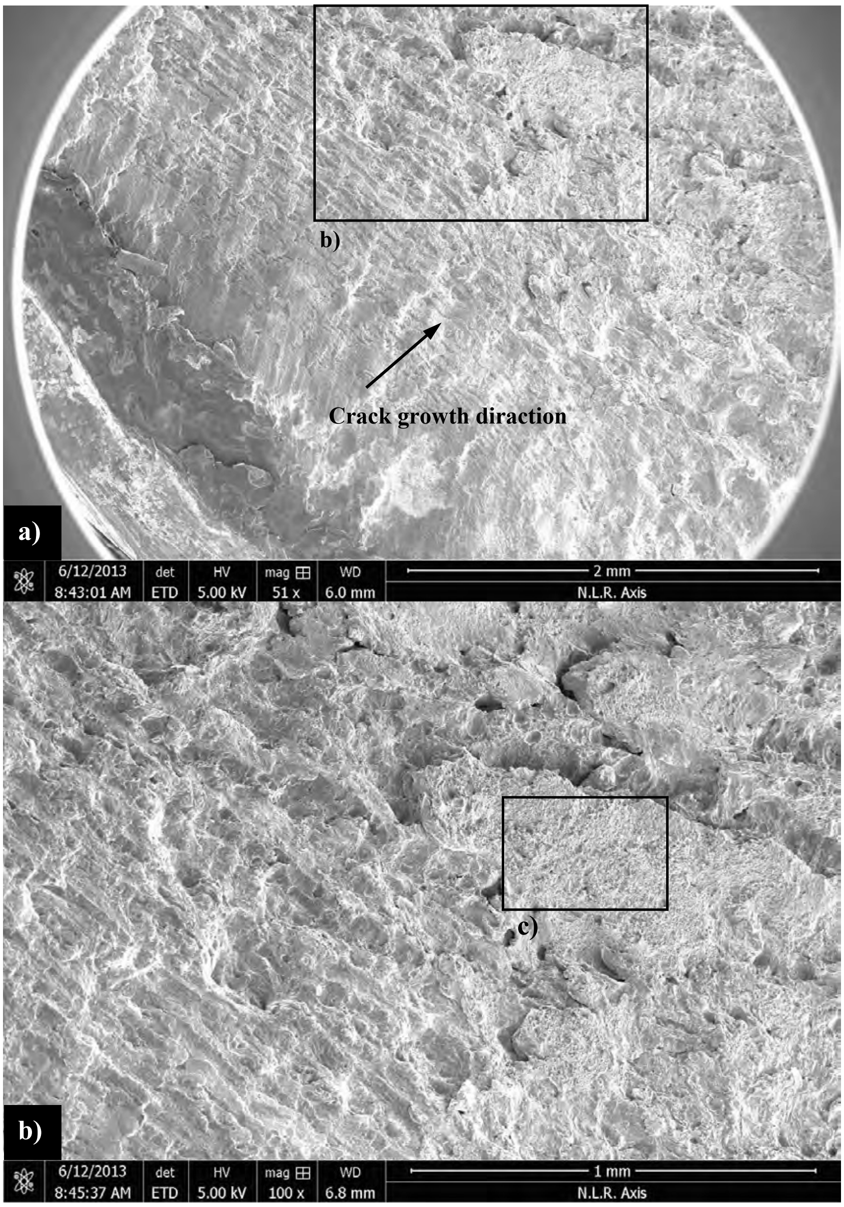


Fig. 11 SEM images of a crack initiation point on fracture surface {1,2} at a) 100x, b) 500x and c) 2000x magnification


b)
Crack growth diraction
a)
6/12/2013 8:43:01 AM
det ETD
HV 5.00 kV
mag 51 x
WD 6.0 mm
2 mm
N.L.R. Axis
c)
b)
6/12/2013 8:45:37 AM
det ETD
HV 5.00 kV
mag 100 x
WD 6.8 mm
1 mm
N.L.R. Axis

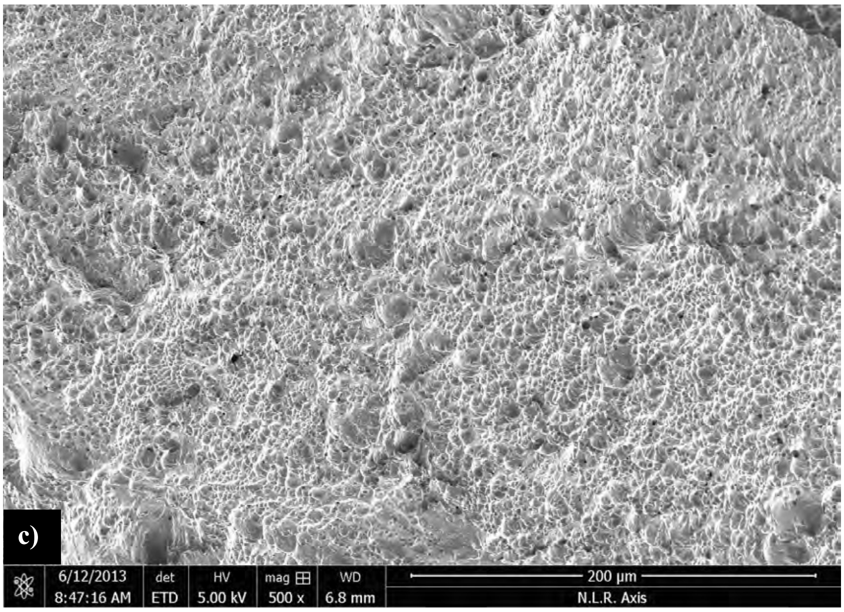


Fig. 12 SEM images of beach marks and dimples on fracture surface {1,2} at a) 51x, b) 100x and c) 500x magnification

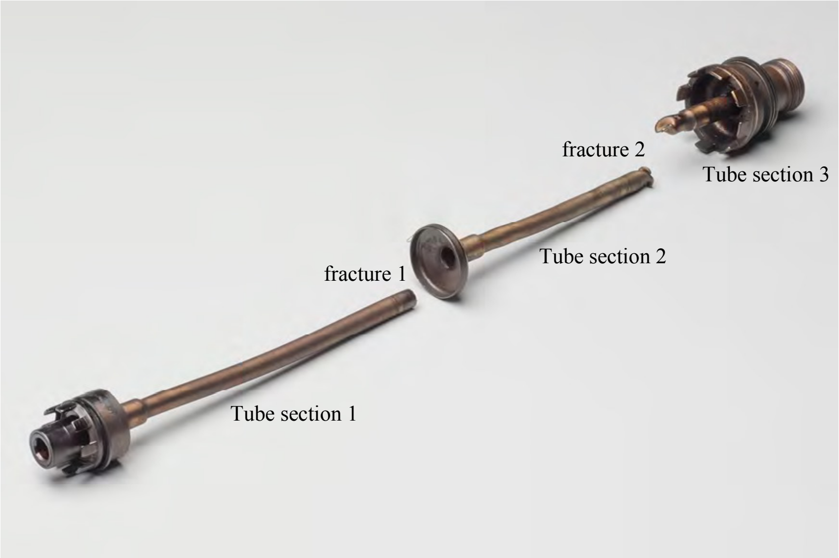


Fig. 13   Overview of the failed oil tube

Fig. 14   Higher magnification photographs of the fracture locations a) 1 and b) 2

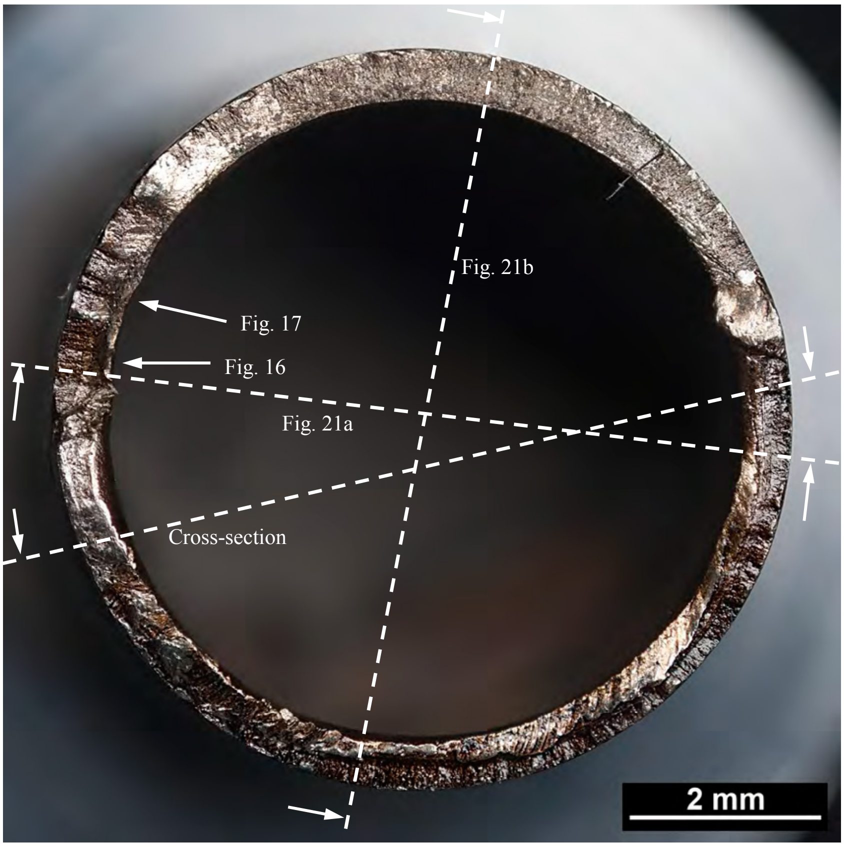
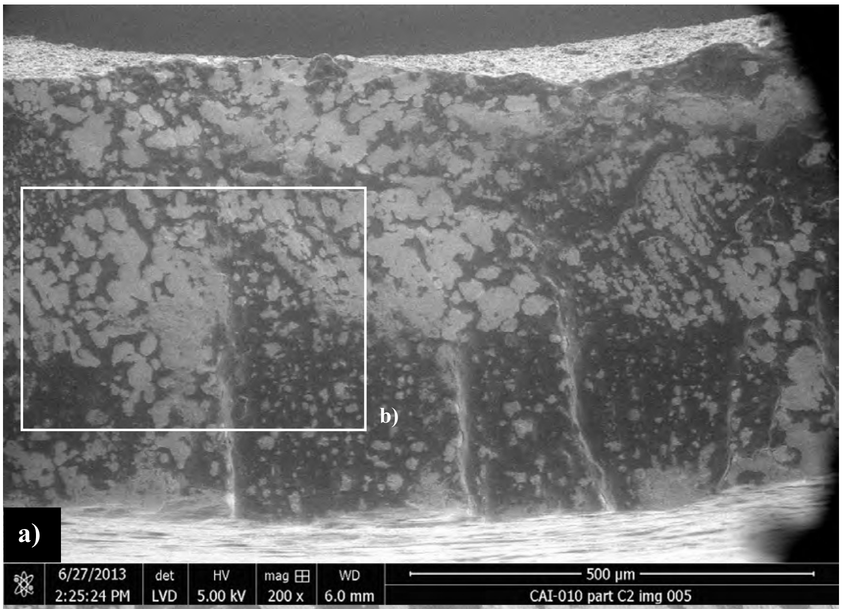
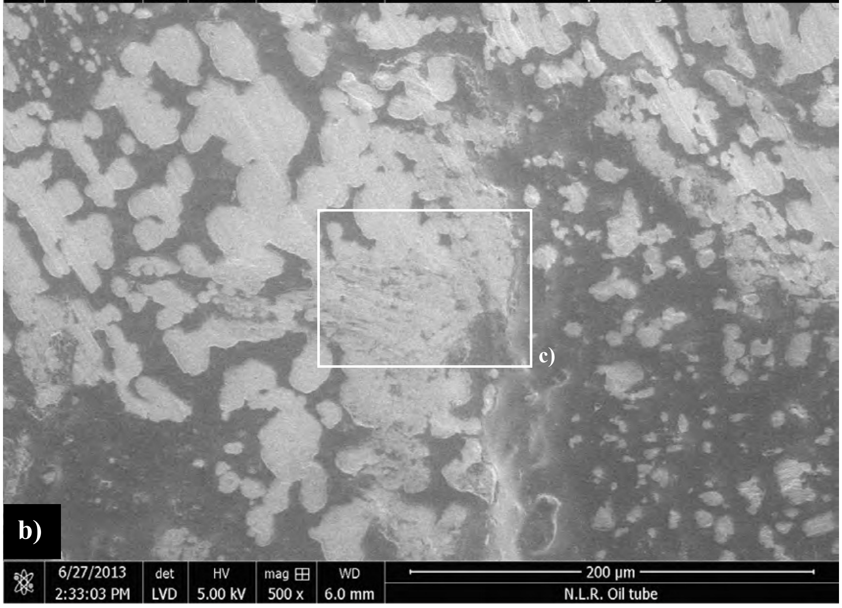


Fig. 15 Fractograph of fracture surface {1,1}

Fig. 16 SEM images showing microscopic steps and deposits on fracture surface {1,1} of the oil tube at a) 110x and b) 200x magnification (see Fig. 14 for location)


b)
a)
6/27/2013
2:25:24 PM
det
LVD
HV
5.00 kV
mag
200 x
WD
6.0 mm
500 µm
CAI-010 part C2 img 005


c)
b)
6/27/2013
2:33:03 PM
det
LVD
HV
5.00 kV
mag
500 x
WD
6.0 mm
200 µm
N.L.R. Oil tube

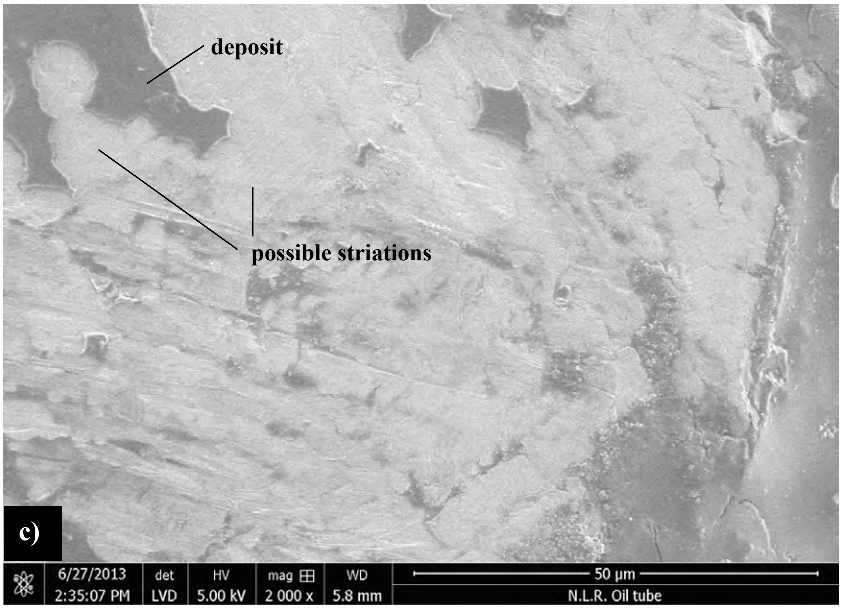


Fig. 17 SEM images of the oil tube fracture surface {1,1} at a) 200x, b) 500x and c) 2000x magnification (see Fig. 14 for location)

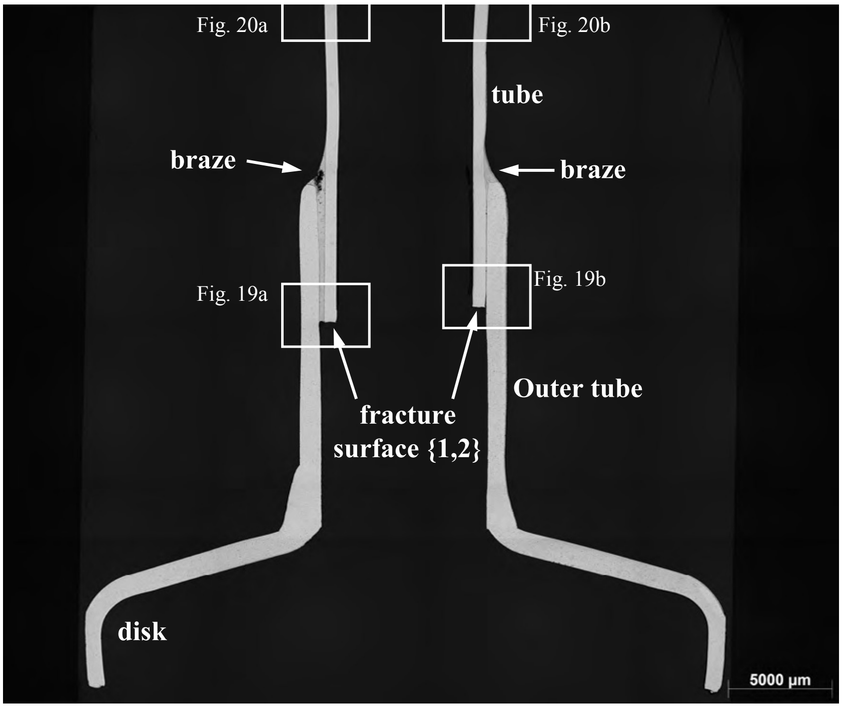


Fig. 18 Optical microscopy image of the cross-section of tube section 2 with fracture surface {1,2}

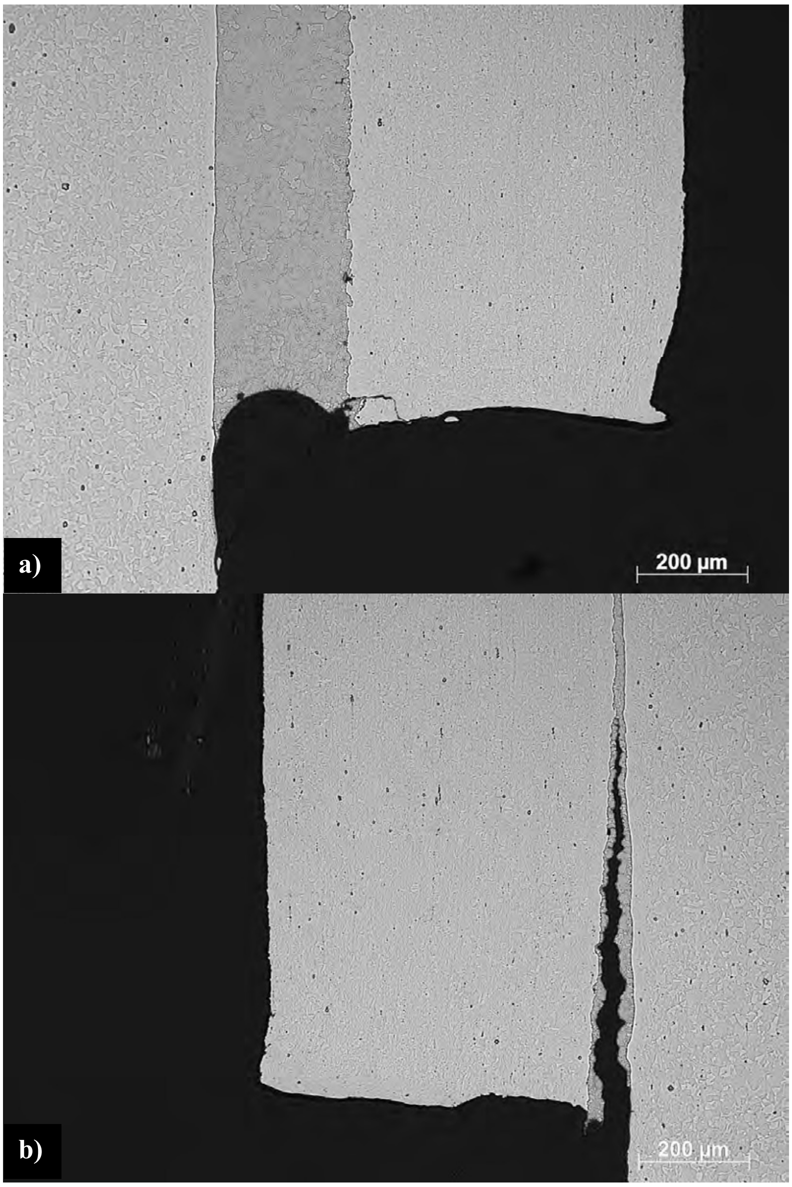


Fig. 19 Higher magnification OM images of fracture surface {1,2} on the a) left and b) right side of the cross-section of tube section 2 (see Fig. 18)

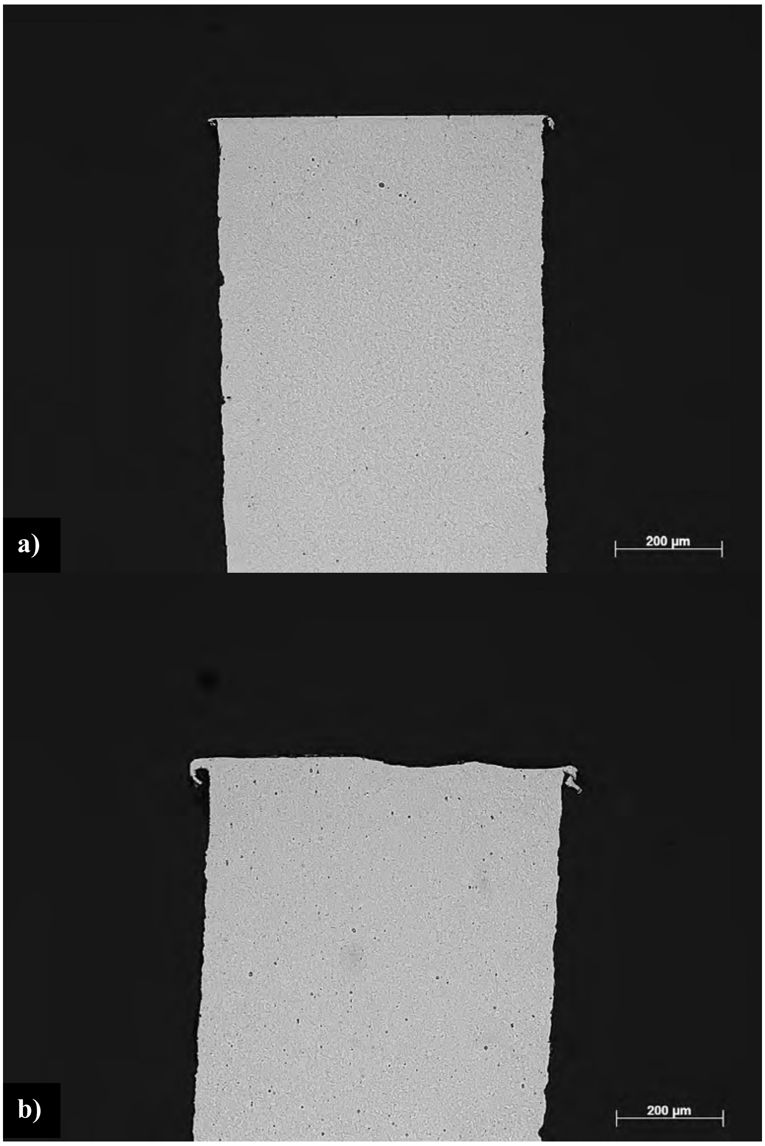


Fig. 20 Higher magnification OM images of the cross-section of the tube on the a) left and b) right side of the cross-section of tube section 2 (see Fig. 18)

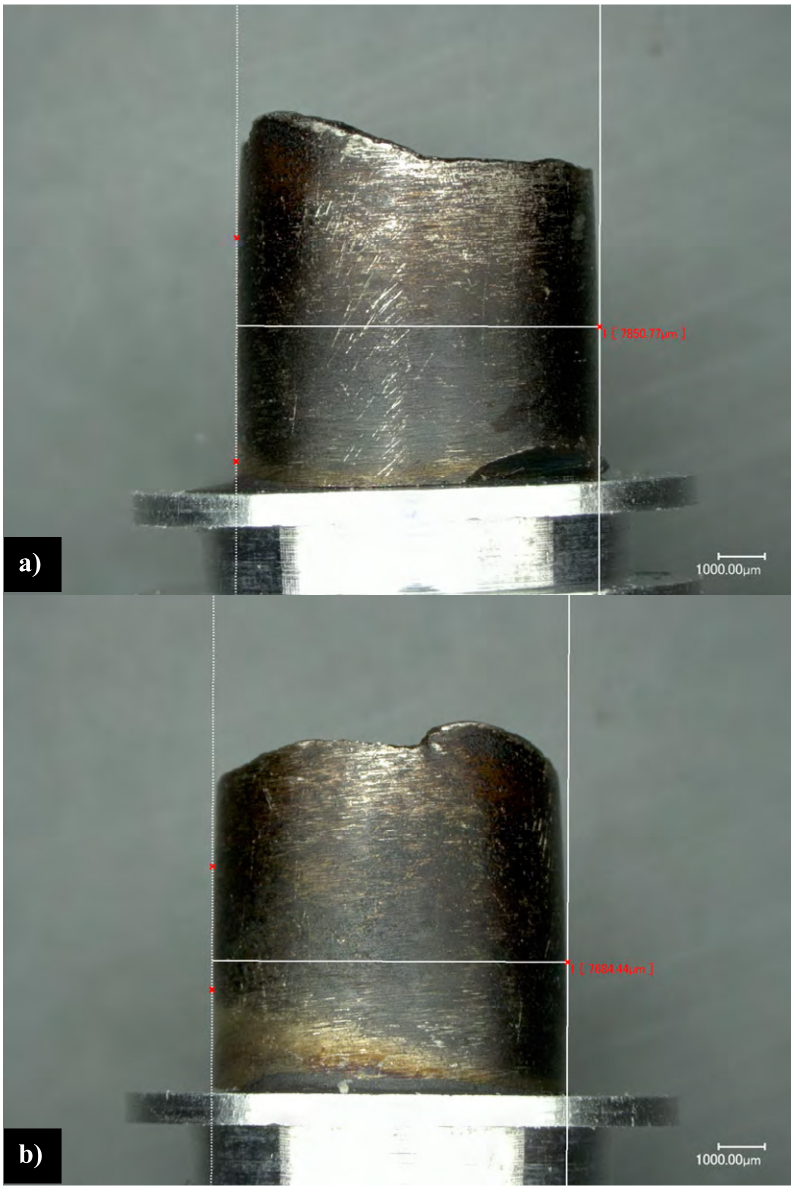


Fig. 21 Side view of the oil tube fracture surface {1,1} showing tube necking from the directions indicated in Fig. 15

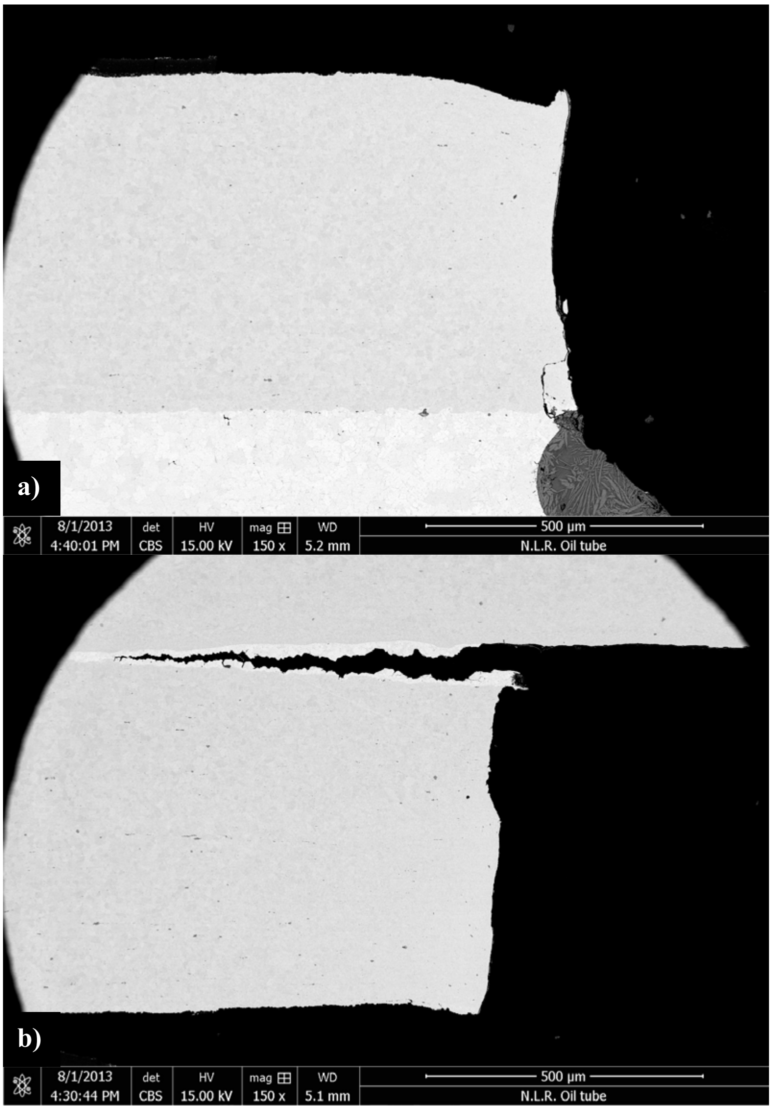
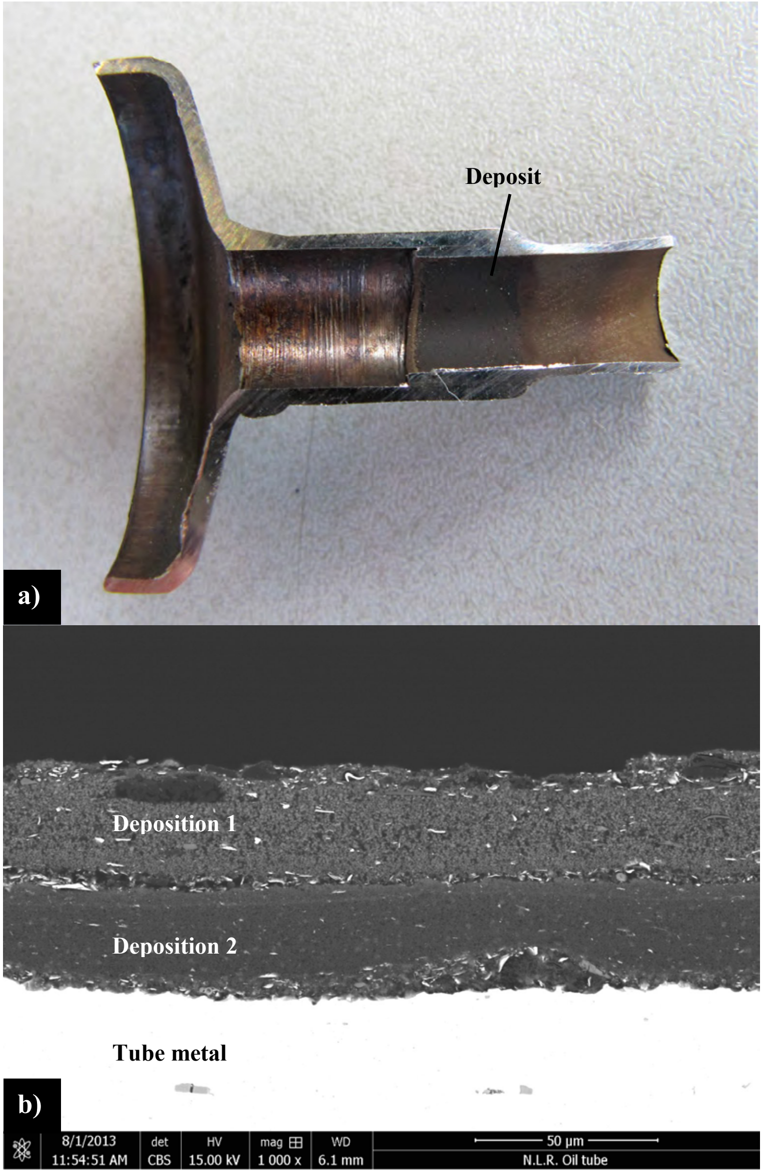


Fig. 22 SEM images of fracture surface {1,2} on the a) left and b) right side of the cross-section of tube section 2 (see Fig. 18)


Deposit
a)
Deposition 1
Deposition 2
Tube metal
b)
8/1/2013 11:54:51 AM
det CBS
HV 15.00 kV
mag 1 000 x
WD 6.1 mm
50 µm
N.L.R. Oil tube

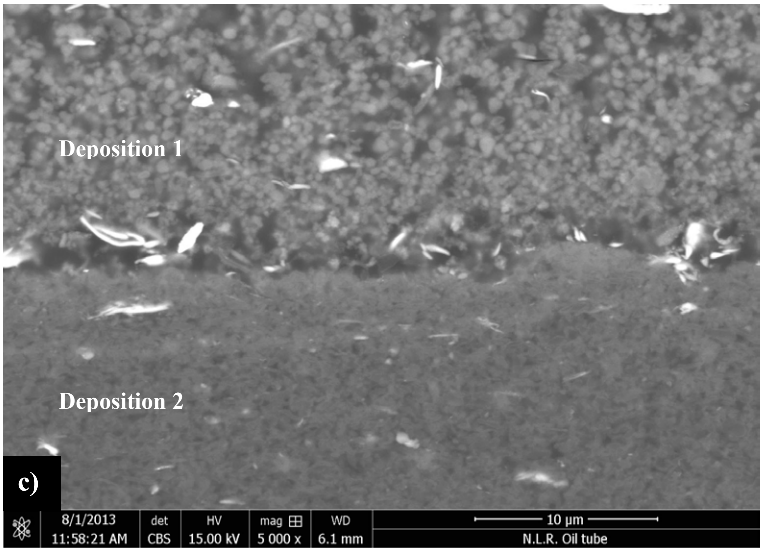


Fig. 23 a) Photograph of the remaining half of the disk and tube after sectioning. SEM images of the cross-section of the deposition on the inside of the oil tube at b) 1000x and c) 5000x magnification

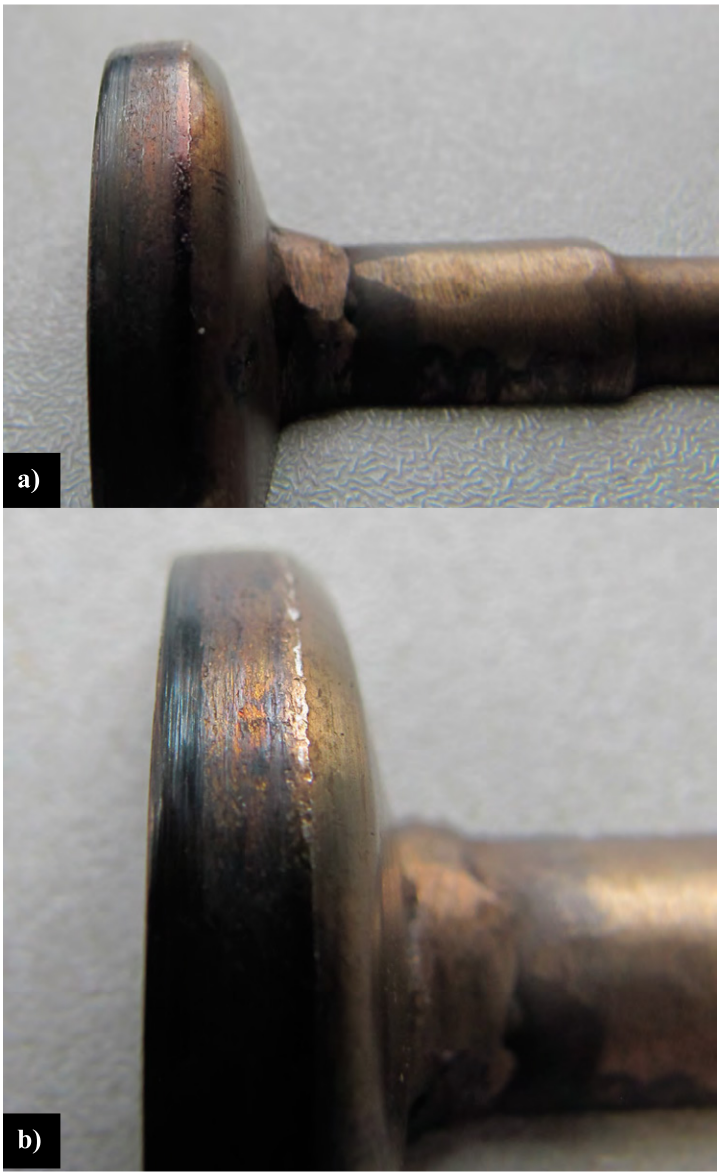
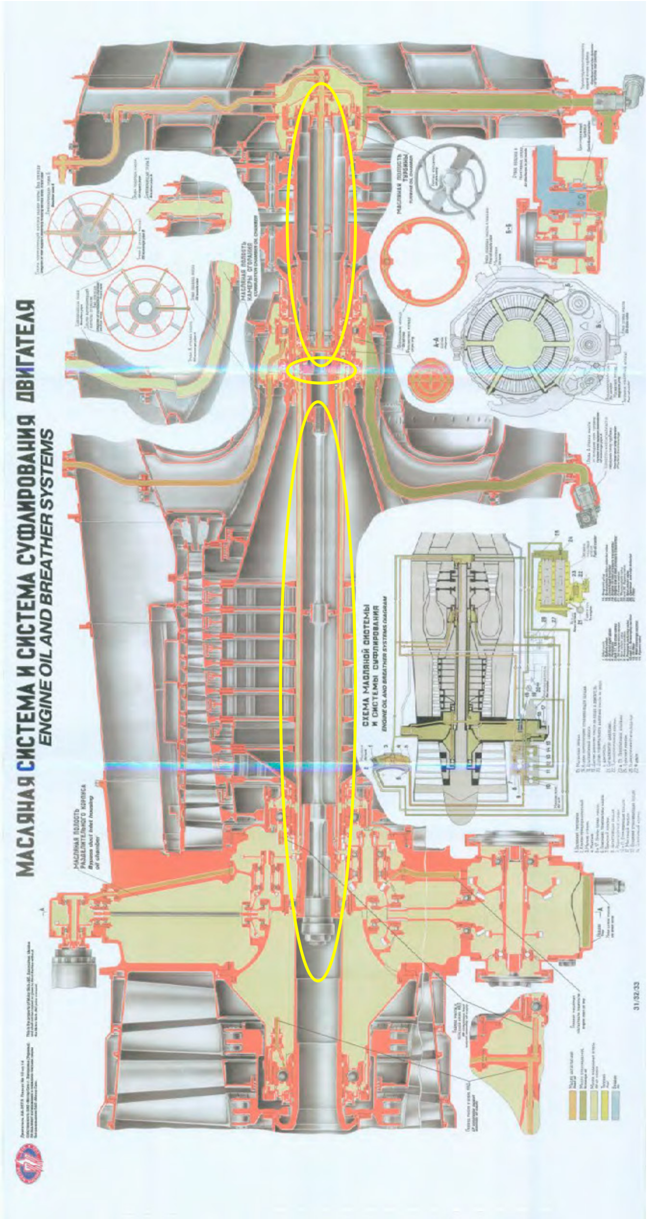


Fig. 24 Photograph of the outer edge of the disk around the oil tube with slightly different angles a) and b)

Appendix A Cutaway engine illustration



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