MPT Solutions [irl]

Plant Reliability Specialists

Title: Rotor Blade Failure

Clients Name:

Civil Aviation Authority of New Zealand
PO Box 31 441
Lower Hutt

Attention: Richard White

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Prepared By: C W Thomas

Checked and Approved By: D M Firth

New Zealand Office
Gracefield Road : PO Box 31-310
Lower Hutt : New Zealand
T +64 4 931 3027
F +64 4 931 3431
E info@mptsolutions.co.nz

Australian Office
Unit 6 : 26 Brandl Street
PO Box 4551 : Eight Mile Plains
Queensland 4113 : Australia
T +61 7 3341 2900
F +61 7 3341 2944
E info@mptsolutions.co.nz

www.mptsolutions.co.nz

Executive Summary

Part of a rotor blade from a Robinson R22 helicopter has been examined to determine the reason for failure. The blade failed due to fatigue cracking that initiated at the edge of a bolt hole in the blade root fitting. It was concluded that the primary reason for failure was that the helicopter had been operated in such a way that the loading on the blade was frequently higher than that expected by the manufacturer when the specified retirement life of these components was defined. No evidence that corrosion contributed to the failure was observed.

Two findings may have had an influence on the fatigue life of the blade.

1. The glue joint between the spar and the root fitting failed at the interface between the glue and the spar. In a good glue bond, it would be expected that the failure would have occurred within the glue. This glue joint may therefore have been defective.

2. The tool used to cut the thread in the bolt hole left a spiral groove in the parallel section of the bolt hole. This would normally be considered poor engineering practice since such grooves represent sites of stress concentration that could encourage the initiation of fatigue.

Both of these factors have been addressed by the manufacturer. The glue joint is understood to have been a modification prior to which all the loads were satisfactorily taken by the bolts. The modification was intended to reduce fretting and no such problem was observed in this blade. The spiral groove in the bolt hole is a known part of the design and the retirement life is based on fatigue data obtained from blades with this groove in place in the bolt hole.

Contents

1. Introduction

It was reported that a Robinson R22 had suffered a major crash after a main rotor blade had separated from the helicopter shortly after take-off. Parts of the rotor blade which included the fracture area were received by MPT Solutions with the objective of examining the components to determine if possible, the reason for failure.

2. Samples

The samples as received are illustrated in Figure 1. The bulk of the blade had been cut away for convenience of handling before receipt by MPT Solutions. Both the blade and hub parts had an identification sticker. The information on these stickers is reproduced in Table 1.

Table 1. Part Identification numbers.

	Blade	Hub
Part No.	A016-2	A158-1
Serial No.	A1-13443A	11947
Rev.	A1	Z

3. Visual Examination

The blade had failed approximately 20mm outboard from the end of the hub section. The fracture was approximately at right angles to the blade leading edge. At the trailing edge however, it had run along the blade away from the hub for a short distance before again running normal to the blade axis to the trailing edge (Figure 1).

Various features of the fracture and the blade construction are illustrated in Figure 2. The fracture had run through the blade root fitting. This fitting appeared to be a solid aluminium component. A bolt hole was present at the position of the facture. This bolt hole ran from the leading edge of the blade into the blade root fitting which had been drilled and threaded. The bolt attached the stainless steel spar to the root fitting (Figure 2). Behind the root fitting, the blade had a honeycomb filling between the skins. At the location of the fracture, there were 2 skins on either side of the blade. On one side of the blade (the black convex face), the skins had failed flush with the fracture surface through the root fitting. On the other side (the white concave face) of the blade, the skins had not fractured. Rather the glue joint between the skin and the root fitting had failed and the circular shape of the skins where they originally butted up against the hub were revealed (Figure 3).

The failed glue joint between the skin and root fitting on the white concave side of the blade is shown in Figure 4. The upper illustration in Figure 4 shows part of the hub after it had been cut from the main part of the hub. The lower illustration shows the underside of the skin still attached to the blade root fitting. These two photographs therefore show the two faces of the original glued joint between the skin and the root fitting. Glue was present over most of the skin to fitting surfaces on both sides indicating that the glue joint had mostly been sound prior to the failure ie the glue was well attached to both surfaces. There was some minor disbonding where the failure had occurred at the glue to metal surface as illustrated in Figure 4.

The part of the blade as received contained part of the spar through which the bolt passed. The end of the spar that projected beyond the fracture position in the main root fitting had no apparent trace of glue on the surface (Figure 5, upper picture). The opposite face to which the spar had originally been attached however, was completely covered in glue (Figure 5, lower picture). This particular joint therefore failed at the glue to metal interface rather than within the glue itself. It is possible that a poor glue joint existed at this location.

The fracture surface of the main root fitting is shown in Figure 6. The fracture was typical of a fatigue, almost a text-book example in fact, showing the characteristic “beach marks” spreading from the fracture origins as the crack propagated. These beach marks are produced by the crack arresting and re-starting. The number and distribution of these marks suggest that the crack propagated over a reasonably long period of time probably involving a number of take-off and landing cycles. There were two distinct fracture origins and these were on either side of the bolt hole approximately 1 to 2 mm from the leading edge of the root fitting (arrowed positions in Figure 6). The fracture propagated by fatigue through almost the entire depth of the root fitting before final failure occurred. Initially, the crack propagated outwards from the bolt hole towards the skin of the blade implying that the principal driving load was bending of the blade in the vertical plane (relative to the helicopter). The cracking then propagated to the rear of the root fitting. The pattern of beach/arrest marks indicate that the crack first initiated on the “black” side of the blade and may have propagated for some time prior to the crack forming on the other side.

The skin failed by failure of the glue joint on the white concave side of the blade as described above. The failure of the skin on the black convex side of the blade is illustrated in Figure 7. The fracture in the black-side skins was fatigue originating at the indicated position in Figure 7. Also shown in Figure 7 is the position to which the crack had propagated by fatigue prior to final overload failure of the remaining section. The glued joint between the skin and between the inner skin and the root fitting appeared to be intact and in good condition along this joint.

The location of the fracture origins (Arrowed in Figure 6) were examined in some detail on both sides of the fracture and before and after removal of the bolt. The threads on the bolt had been of slightly greater diameter than the hole into which it screwed. Before the threads commenced there was a parallel section of the hole. Within this parallel section, the original threading tool had cut a shallow helical groove. On one side, the fracture origin appeared to coincide with this groove but on the other side it did not (Figure 8).

Other than the spiral groove , in the area of the origins, the bolt hole looked clean with no apparent corrosion or other damage (Figure 9). There was one area that was black in colouration and may have been caused by corrosion (Figure 8). However, this small patch was not associated with either fracture origin.

On one side of the fracture, there was a second crack (Figure 10). This was believed to have been caused by a second fatigue crack that originated just blow the main crack. The second crack then propagated until it merged with the main crack. Adjacent to this was a damaged/abraded area (Figure 10). This was probably caused by the bolt as it moved past the edge of the hole at the time of the failure.

Examination of the threads cut into the root fitting revealed that a number of these had also begun to crack. An example is illustrated in Figure 11. These small cracks were at right angles to the main crack that caused the failure and were caused by loads along the axis of the bolt hole acting to separate the root fitting and the spar. The source of these loads is not known but they may have been caused due to reduction in stiffness of the root fitting as the main fatigue cracks propagated. i.e. the root fitting would have flexed to a greater extent as the main crack propagated. This in turn would have generated higher loads tending to separate the spar and the root fitting.

4. Detailed Fractography, SEM Examination

The samples were examined in a scanning electron microscope. In the main root fitting, typical fatigue striations were observed (Figure 12). Attempts were made to identify defects or pits for example that may have encouraged initiation of fatigue. However, no such features were observed (Figure 13).

The fracture in the skin was similarly examined. The fracture origin had a number of steps or "castellations" typical of fatigue and fatigue striations were observed (Figure 14). Again, no defects or other features that may have initiated fatigue were noted.

Attempts were made to strip deposits etc from the fractures and the bolt hole using either adhesive tape and/or cellulose acetate tape (replica tape), softened in acetone. The samples were subsequently analysed using an Energy Dispersive Analysis system (EDA) attached to a scanning electron microscope. Analyses were largely inconclusive. The spectrum shown in Figure 15 was of deposits on a replica stripped from the main fracture surface. The aluminium and silicon etc together with the high oxygen peak are believed to be representative of the soil that contaminated the blade at the time of the crash. A replica stripped from the bolt hole contained a small amount of deposit which yielded the spectrum shown in Figure 16. This had a small peak indicating the presence of chloride which may indicate some contamination. Other areas were found to have peaks indicative of high carbon content and it is believed that these analyses were of the organic glue material. Such a spectrum is shown in Figure 17. The same Si, Al and Ca peaks indicate soil. The cadmium (Cd), is probably from the coating on the bolt. The iron (Fe) and chromium (Cr) may be from the bulk of the bolt. The high carbon (C) peak however, is suggestive of organic material and this may well be the glue.

The root fitting base material was analysed by Spectrachem Analytical using an x-ray fluorescence technique (XRF). The relevant aspects of their report are reproduced in Table 2 along with the standard specification for aluminium alloy 7075.

Table 2. Elemental analysis (wt%)

	%Mg	%Cu	%Zn	%Cr	%Si	%Ti	%Mn	%Fe
Sample	2.27	1.55	5.52	0.197	0.123	0.029	0.025	0.094
Specif	2.1-2.9	1.2-2.0	5.1-6.1	0.18-0.28	0.4max	0.2max	0.3max	0.3max

The analysis is consistent with the root fitting having been manufactured from aluminium alloy 7075.

5. Metallography

A sample of material from close to the fracture in the root fitting was polished and etched using metallographic techniques suitable for aluminium alloys. The microstructure is shown in Figure 18. The material had a strongly textured structure consistent with the manufacturing process eg extrusion used to manufacture the root fitting ie the grains were heavily elongated parallel to the fitting axis. The various microstructural features have not been positively alloyed but the microstructure was considered to be consistent with grade 7075 series wrought aluminium alloy.

The hardness of the material was measured using a Vickers Hardness Machine and a 10kg load. The hardness obtained was 157HV (approximately 135 H Brinell and 84 Rockwell-B) . This is considered to be relatively hard for an aluminium alloy implying high strength. This hardness is considered to be consistent with Alloy 7075 in the T73 heat treated condition.

6. Discussion

The blade failed due to fatigue that initiated at either side of the bolt hole in the leading edge of the main root fitting. Other than the grooves cut into the bolt hole by the bolt threads or the cutting tool, no defects that may have initiated fatigue were noted. No corrosion damage was noted at the location of the fatigue crack origins in the fitting. Small amounts of chloride were detected in deposits stripped off the samples and this may indicate the presence of a corrosive environment. However, the levels of chloride detected were low and no visible evidence of corrosion was present at the fatigue fracture origins. It is concluded that corrosion damage did not play a significant role in the failure.

The parallel bore of the bolt hole had been scored by the original thread cutting tool. The groove that this caused may be considered to be a defect. However, on one side of the bolt hole at least, the fatigue fracture origin did not appear to coincide with the position of the groove. Furthermore, very close by are the actual threads which constitute deep grooves regardless of the fact that they are intended to be present. The fact that initiation occurred near the front of fitting/bolt hole and not at the actual threads implies that the bending load which caused the failure reduced in magnitude rapidly from the front to the rear of the fitting.

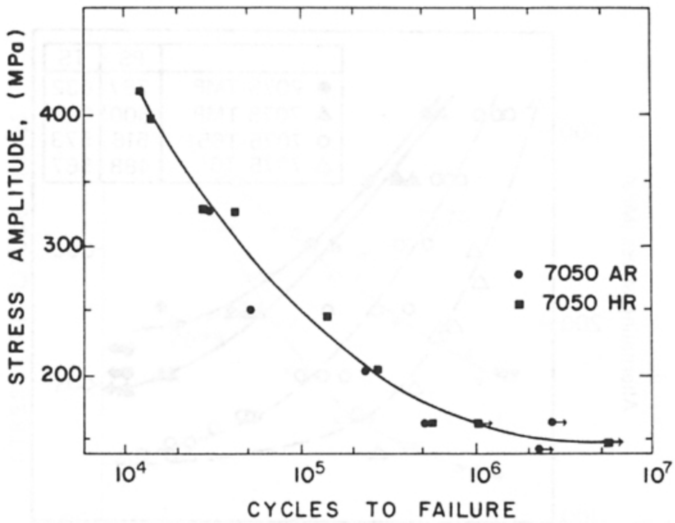
Despite this, the formation of a spiral groove in the parallel shank of the bolt hole is not good practice in the design of a component known to be life limited due to fatigue. The presence of grooves and notches are known stress concentrators and their presence can have a profound effect on fatigue performance. These grooves may well have had an effect on reducing fatigue performance. It has been noted that on one side, the fatigue crack did not coincide with one of these grooves. On the other side, however, the crack DID appear to coincide with one of these groove; this was the side on which the crack first initiated. It is understood that the formation of these grooves is standard practice on these blades. Furthermore, the fatigue testing undertaken by Robinson was on blades that contained these grooves. It is considered that regardless of this, the grooves should not be present since these such features are known stress raisers and therefore potentially reduce fatigue life.

The front of the spar through which the bolt passed attaching it to the root fitting had separated from the fitting during the failure (Figure 5). The separation occurred along the glue joint between the glue and the root fitting. It is possible that this glue joint was poor or ineffective. It is not known how this glue joint would influence the failure. In principle at least, the joint would provide reinforcement against those stresses that acted to initiate and propagate the fatigue cracks in the root fitting. However, the total area of this glue joint is not great compared to the cross sectional area of the root fitting and it would be surprising if a sound joint at this position would sufficiently strengthen the assembly to prevent failure. The manufacturer has stated that the adhesive bonding helps transfer load between the spar and the root fitting. They further state however, that the bolts can handle the entire load.

The skin had separated from the root fitting on the white concave side of the blade as opposed to the crack propagating through the skin as occurred on the other side. This was consistent with the root fitting and opposite skin failing first and the final failure occurring by “pealing” of the skin from the root fitting on the white side of the blade. This separation occurred by failure within the glue for the majority of the contact area. The glue bond was therefore probably satisfactory. Visual inspection of other areas did not indicate that the glue joint was defective.

The above discussion leads to the conclusion that the root fitting and blade failed because it was subject to loading in excess of its fatigue strength. It is understood that the manufacturer has performed fatigue tests on similar blades and when they fail, they do so in the very location that this blade has failed. It is also understood that these blades are subject to retirement ie they have a limited fatigue design life. Furthermore, the results of these fatigue tests conducted by the manufacturer have led to the setting of safe working loads which can be exceeded by the operators of the helicopter.

Normally, component fatigue lives over a series of tests or applications under the same conditions, will have a normal distribution. The manufacturer will set the design lives so that the chance of failure at the set retirement time will be extremely low. However, if the applied loading is higher than specified then this can have a significant effect on fatigue life. Furthermore, the reduction in fatigue life is NOT proportional to any increase in stress or operating load. Relatively small increases in load can cause large reductions in fatigue life. The graph below is reproduced from “Atlas of Fatigue Curves edited by Howard Boyer and Published by the American Society for Metals”. It was used in the Atlas to illustrate the difference ,or lack of difference, between two batches of aluminium alloy 7050, these being “AR” and “HR”. It does also however, illustrate the way in which fatigue life measured in terms of “Cycles to Failure” varies with load recorded in this case as “Stress Amplitude MPa” for this alloy. The material from which the blade root fitting was manufactured was 7075-T73 rather than alloy 7050 used to generate the data in the diagram. However, the way in which cycles to failure varies with stress will be very similar for both materials.



Generally, manufacturers will design their components to be as resistant to fatigue as possible. The blades are however, life limited which implies that fatigue may occur. The data in the graph indicates that below approximately 150MPa stress amplitude, long fatigue lives in excess of 10^7 cycles are obtained. However, a modest increase in cyclic stress amplitude rapidly results in a marked decrease in cycles to failure. For example, a modest increase in stress amplitude from 150 to 160MPa, will reduce the cycles to failure from approximately 10^7 cycles to 10^6 cycles ie a factor of 10. (Note, this graph is used to illustrate the relationship between fatigue life and applied load; it is not used to indicate the actual cyclic loads in the rotor blade under consideration.)

Fatigue failures occur because the material experiences repeated cyclic loading of sufficiently high stress. The stress may be higher than expected or alternatively, the stress to cause fatigue may be lowered for some reason. The stress may be higher than expected thereby leading to premature fatigue failure due to localised stress concentration that has not been taken into account in the design and this may include rough machining, cracking caused during manufacturing, poor design and stress corrosion cracks amongst others. Factors which may lead to an apparent depression of the tolerable stress limit include the presence of a corrosive environment or fretting for example. In the present investigation, no such factor which could have influenced the fatigue performance of the blade was identified. It is concluded therefore, that the short fatigue life of the blade was caused by application of cyclic stresses higher than those applied when the fatigue life was set by the manufacturers.

In summary, it is believed that this helicopter blade failed because it was operated in a manner that resulted in the applied cyclic loading to exceed manufacturer’s recommended operating envelop for a significant period of time.

7. Conclusions

1. The blade failed due to fatigue crack initiation and propagation at a bolt hole in the blade root fitting.
2. The bolt hole had a spiral groove in the parallel unthreaded area where the fatigue crack initiated. This is considered non-ideal since such grooves are potential stress raisers and the first cracking did initiate at one of these grooves. This groove is understood to be present in all such blades and the blade retirement time is set based on fatigue tests undertaken with this groove in place.
3. Other than the spiral groove, no other defects that may have led to the initiation of fatigue were observed.
4. Traces of chloride were detected in the bolt hole and fracture surface area. However, no pitting or other corrosion damage at the crack origins was observed. Corrosion was not considered to have contributed significantly to the failure.
5. Visual examination of the various components suggested that the glue joints were sound EXCEPT for the joint between the leading edge spar and the root fitting (Figure 5). The manufacturer has stated that this joint is not necessary for satisfactory performance of the blade.
6. The failure probably occurred because the helicopter was operated in such a way that the loads on the root fitting regularly exceeded those anticipated by the manufacturer when the design life of the blades was defined.
7. Conclusion 6 assumes that the glue joint between the root fitting and the leading edge spar was unimportant in preventing or reducing the likelihood of fatigue and the spiral groove in the bolt hole is taken into account when defining the blade life. These assumptions are supported by statements made by the manufacturer.

Figure 1. Samples of rotor blade as received.

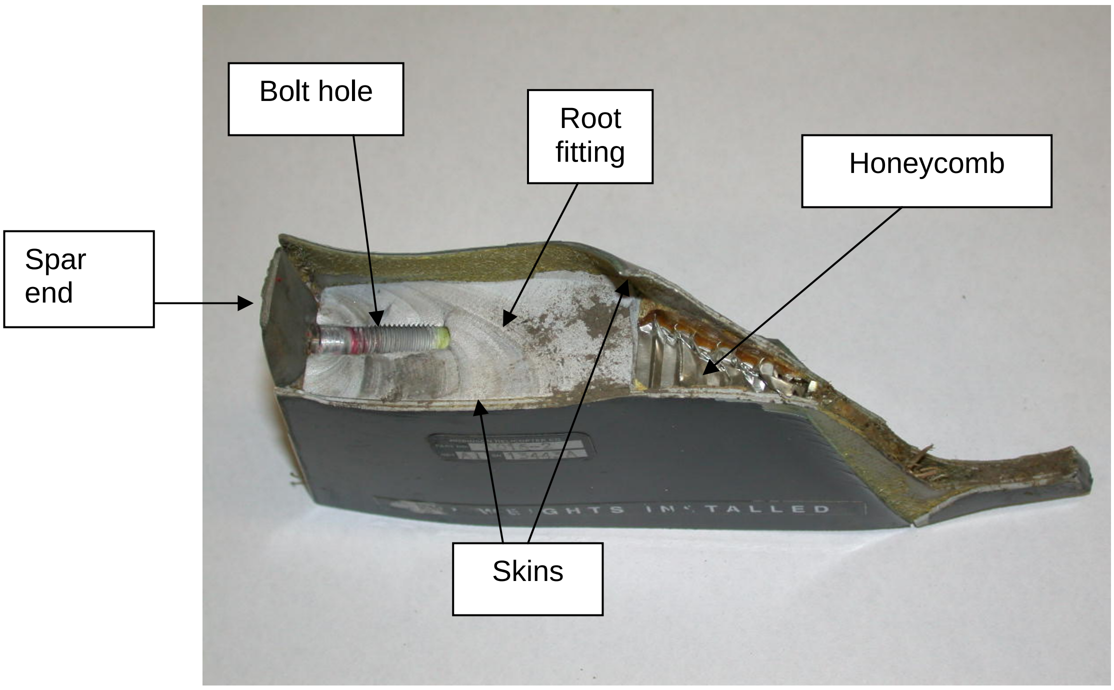


Figure 2. The fracture through the root fitting, the location of the bolt hole, the skins on either side of the root fitting and the honeycomb construction behind the root fitting.

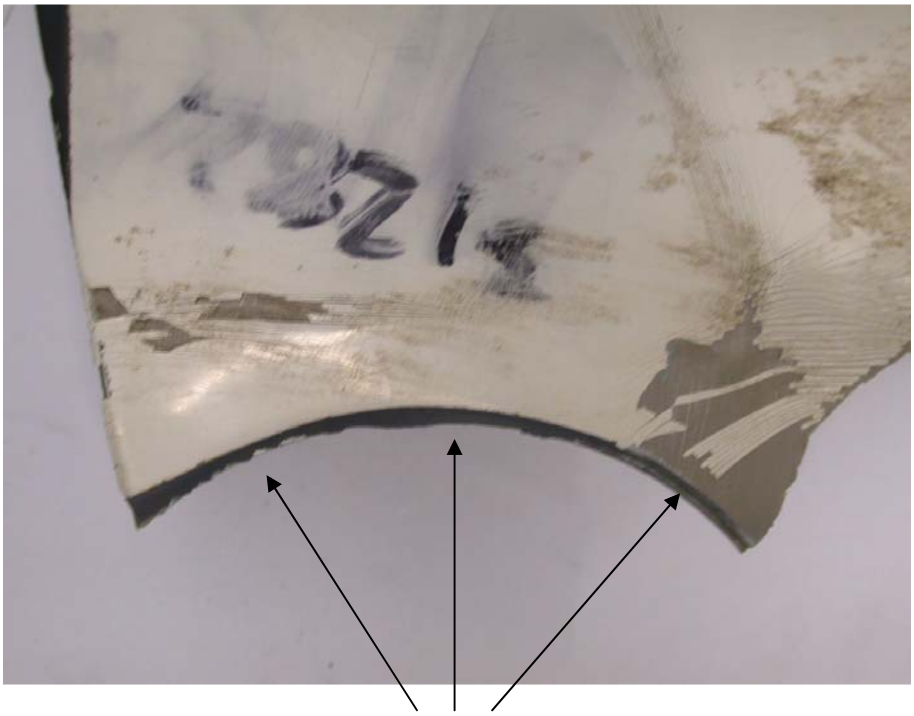


Figure 3. The “circular” end of the skins on the white concave side of the blade.

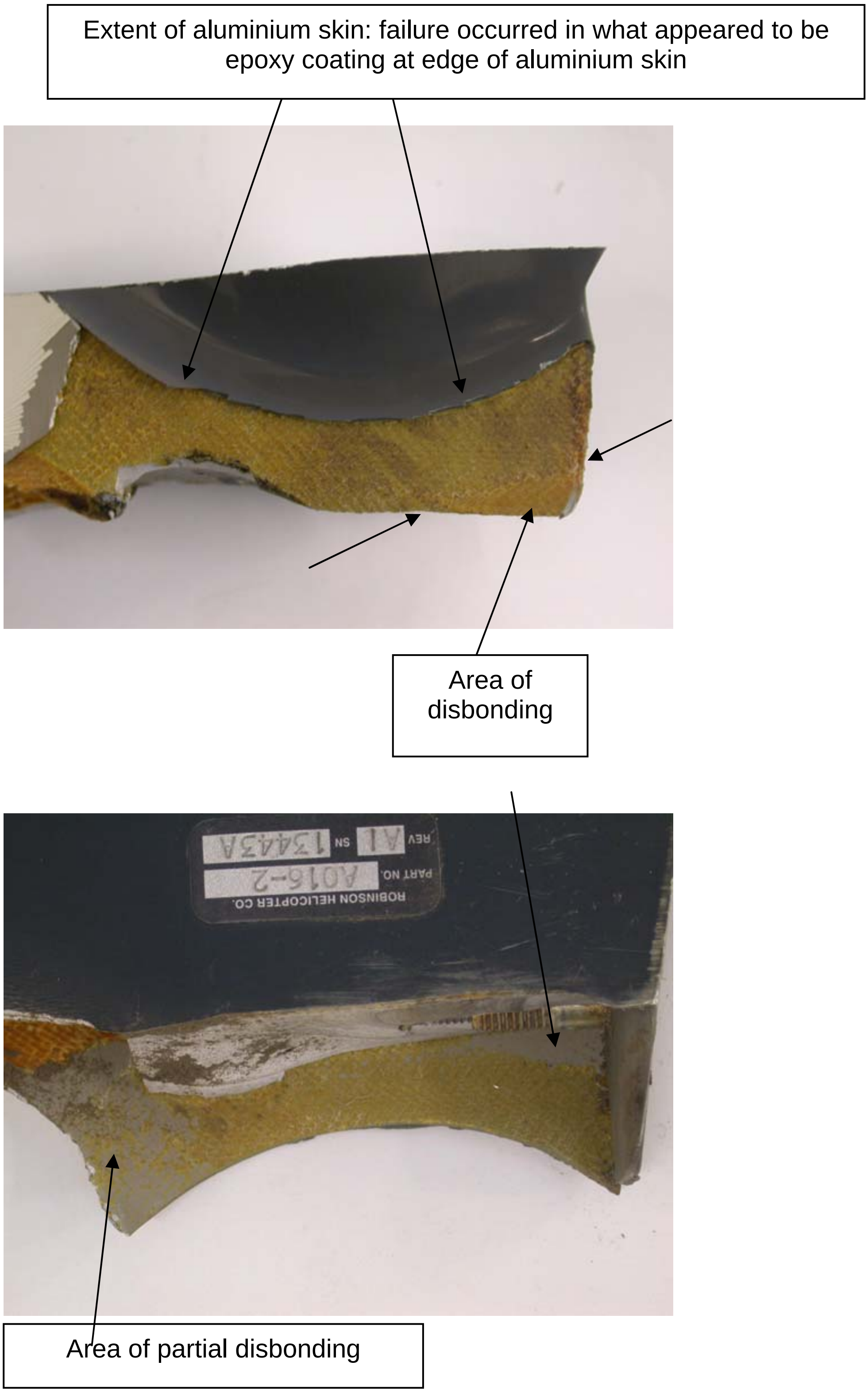
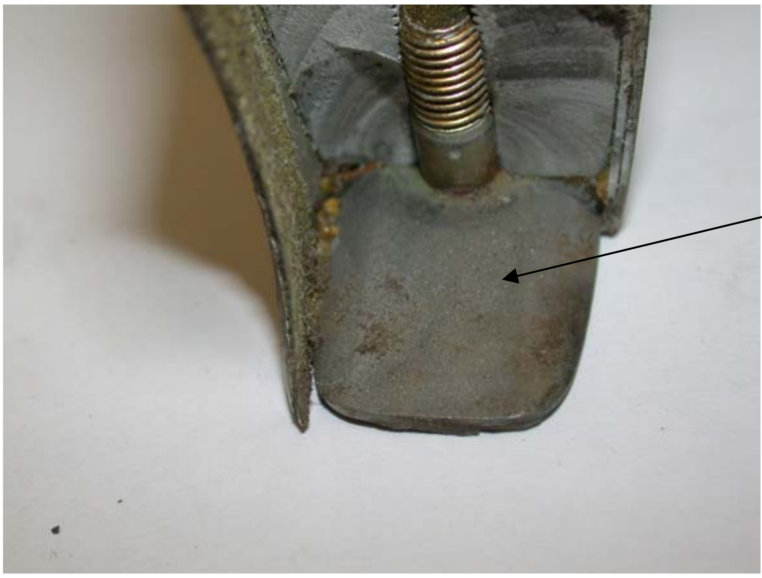


Figure 4. The glue joint failure of the skin on the white, concave side of the blade.



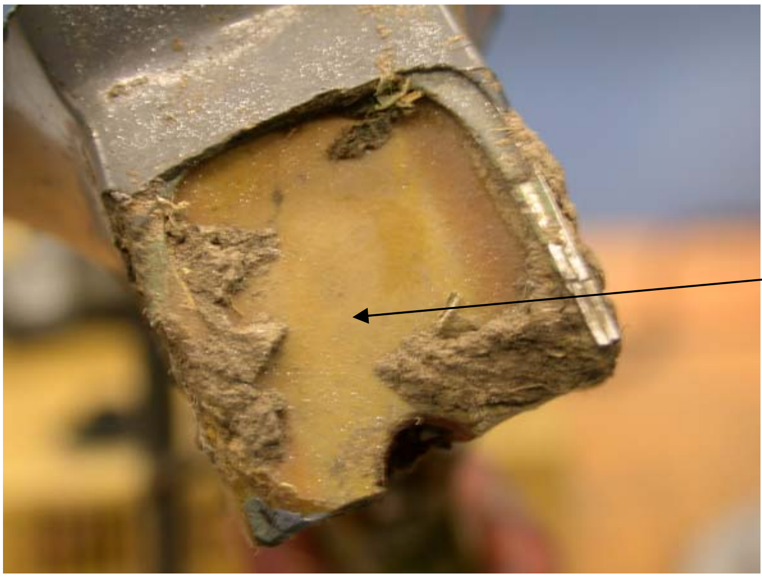


Figure 5. The joint faces between the leading edge spar (top picture) and the main part of the root fitting. (lower picture)

Figure 6. The fracture through the root fitting. The arrows indicate the location of the fracture origins on both sides of the bolt hole very close to the leading edge.

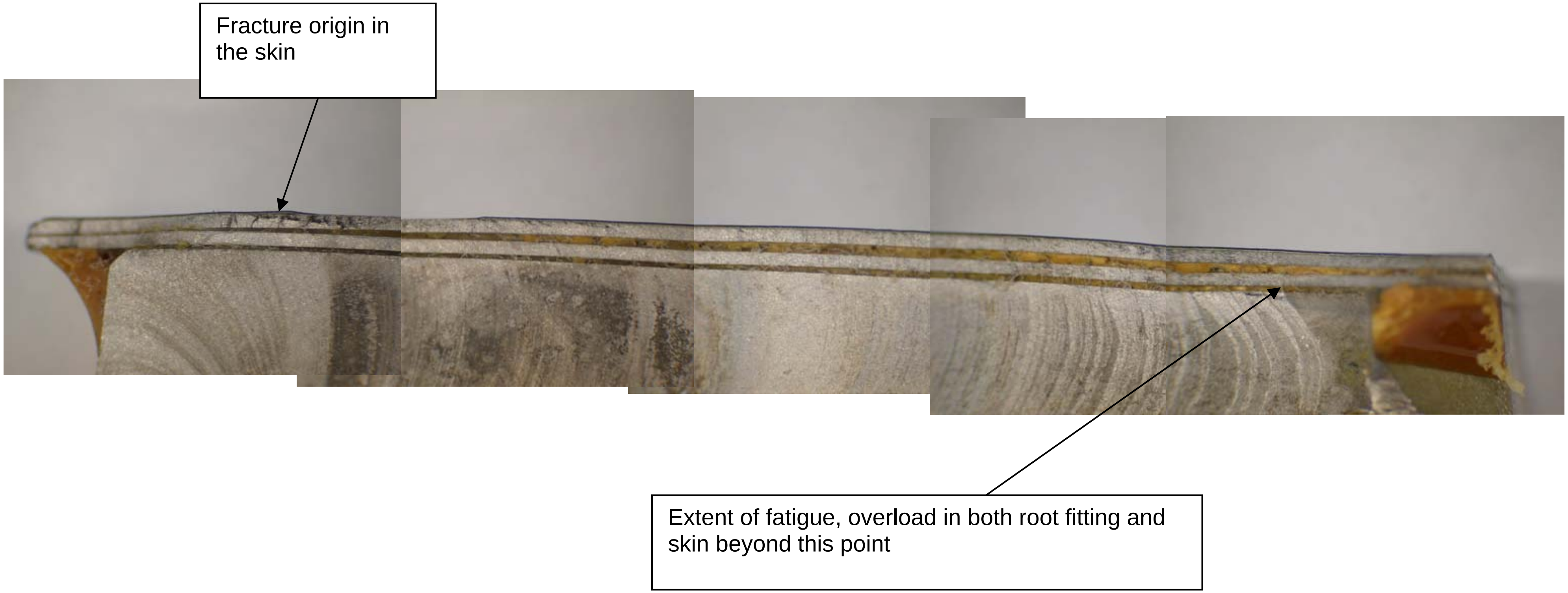


Figure 7. The failure of the skins on the black convex side of the blade.

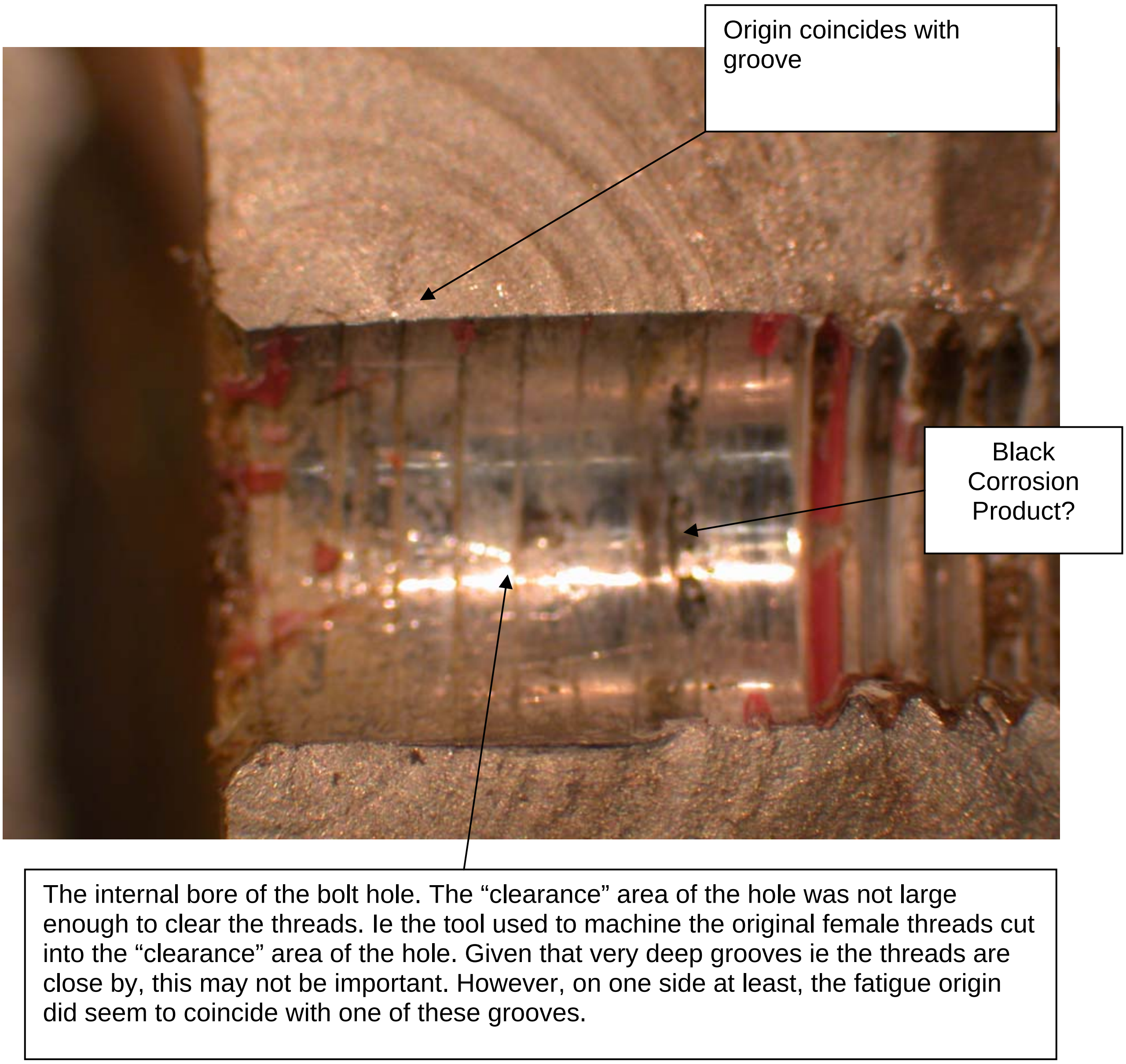


Figure 8. Bolt hole and fracture origins.

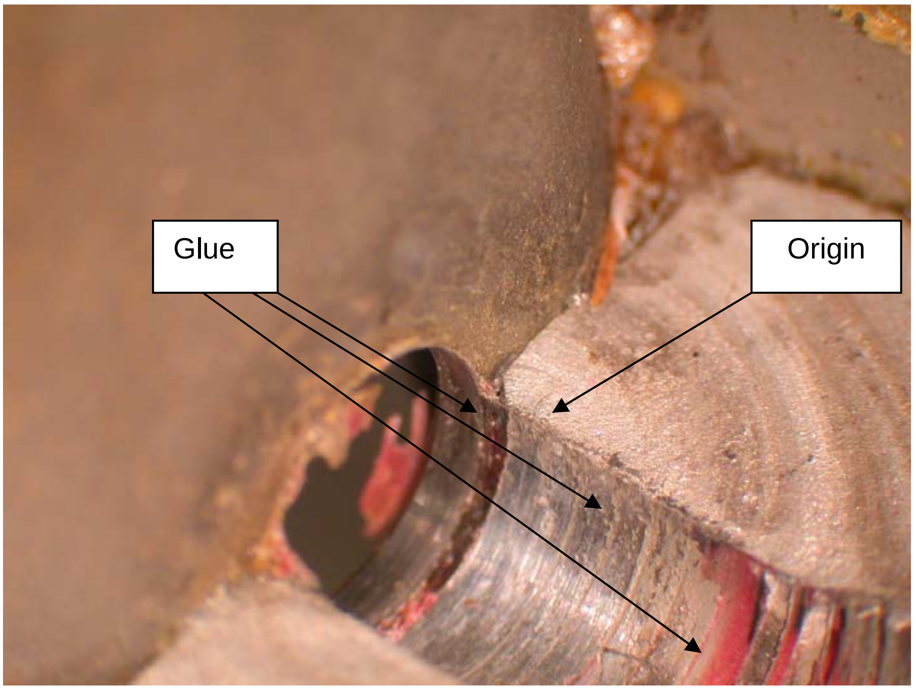


Figure 9. Bolt hole bore at position of fracture origin in root fitting.

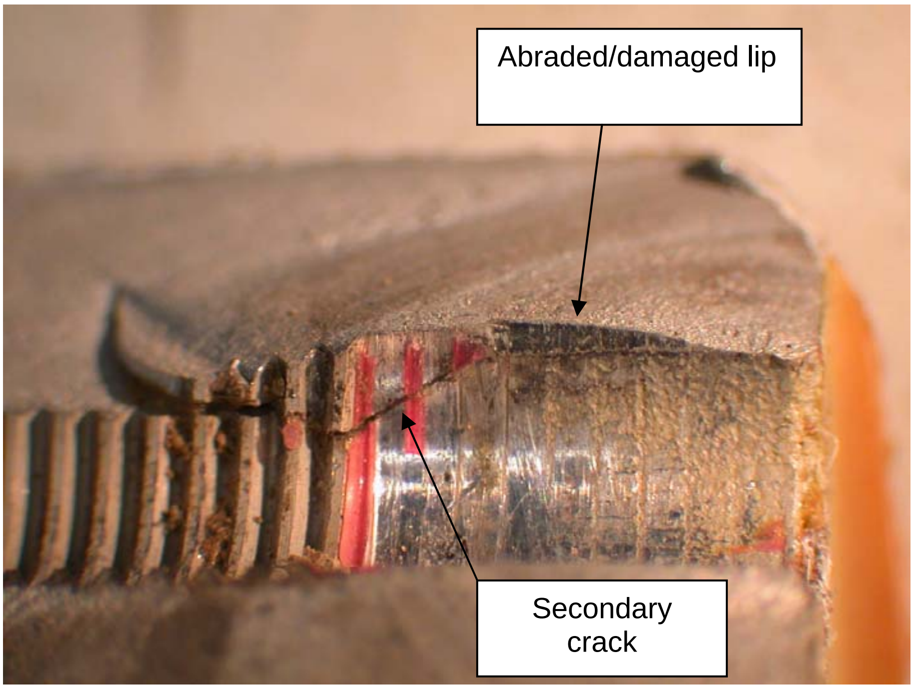


Figure 10. Second crack at origin.

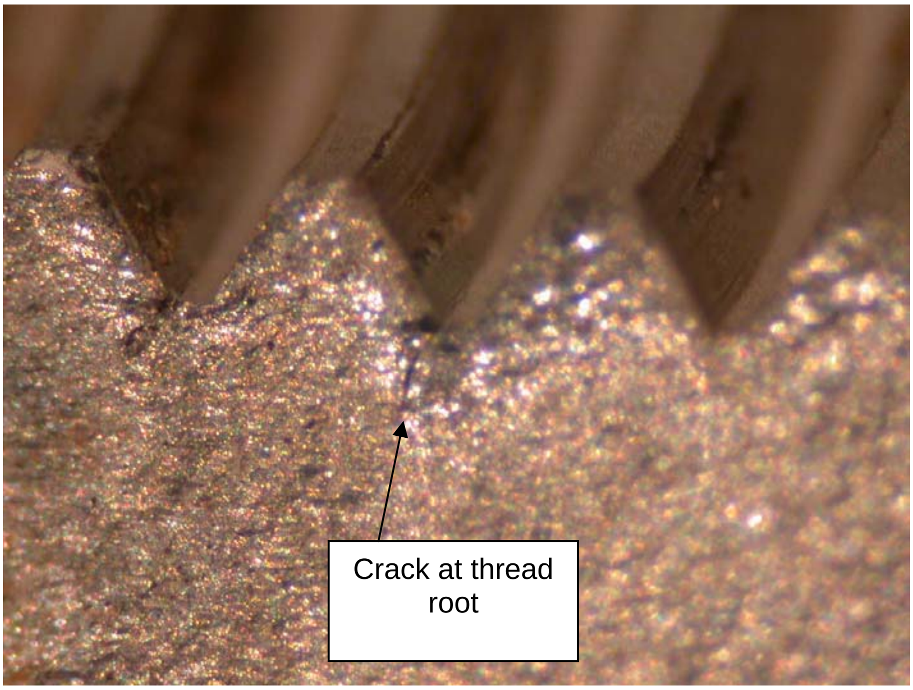


Figure 11. Cracking at root of thread.

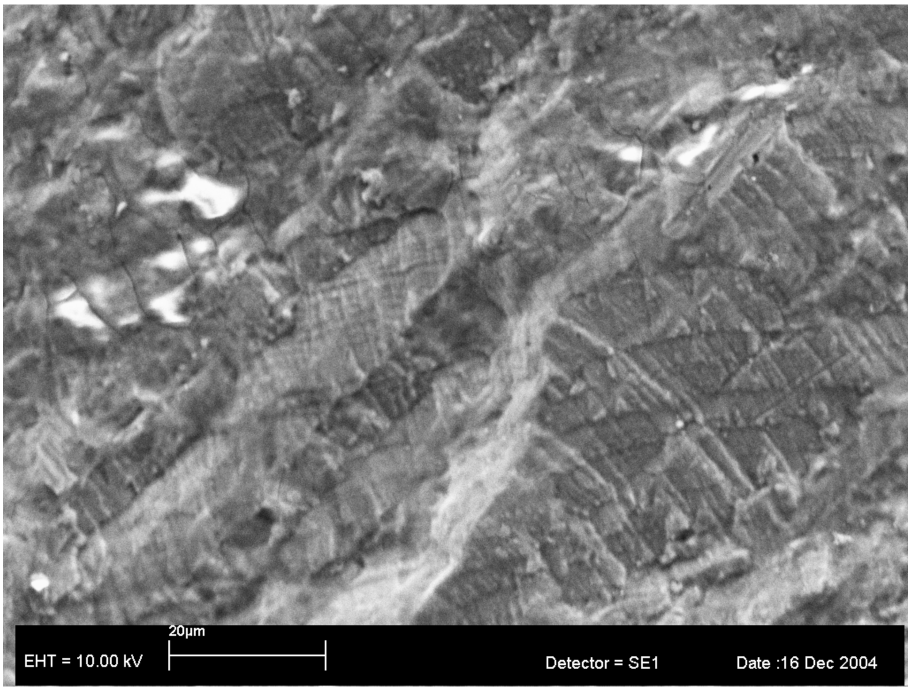


Figure 12. Fatigue striations on fracture surface of root fitting, Scanning Electron Microscope image.

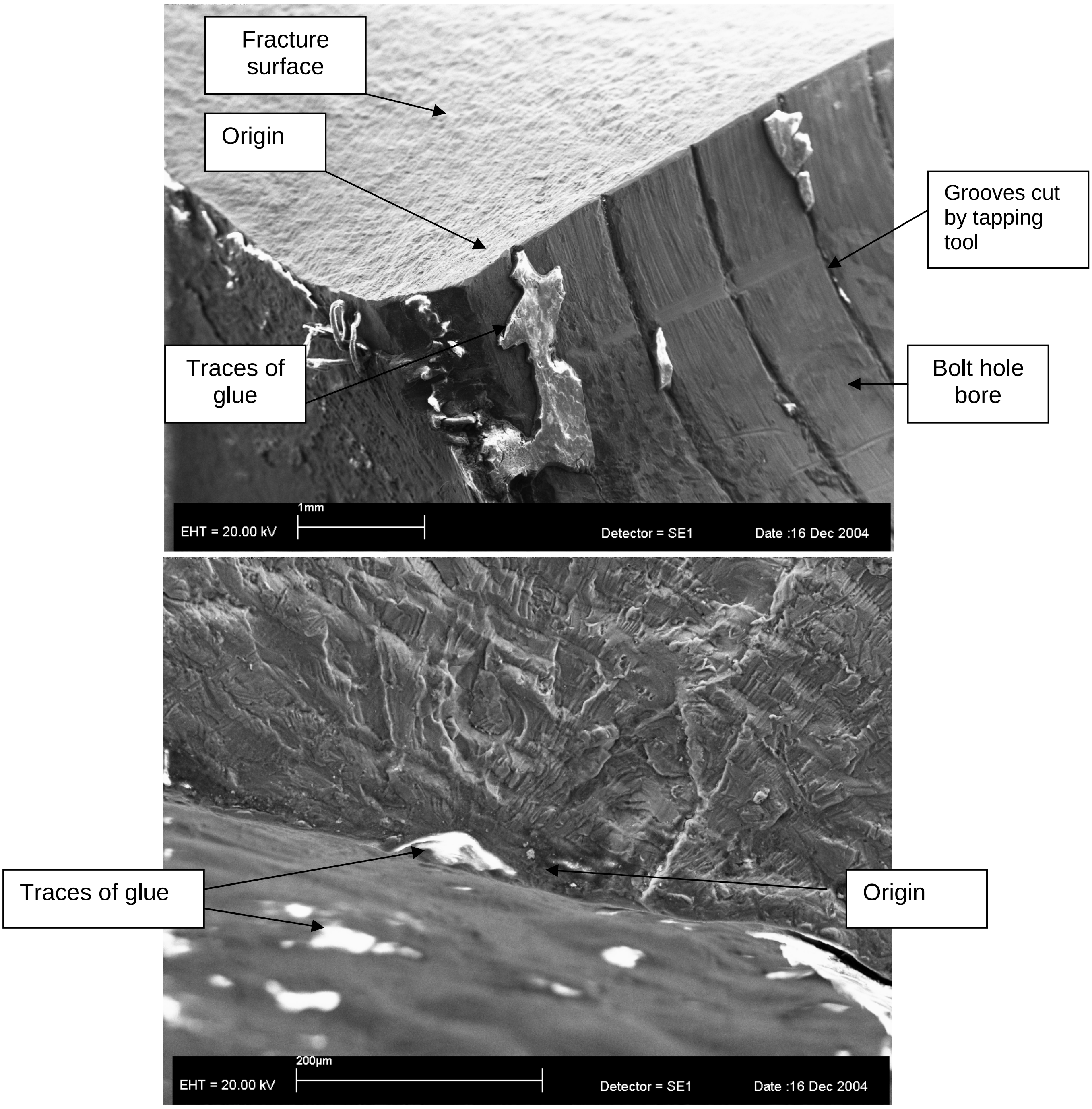
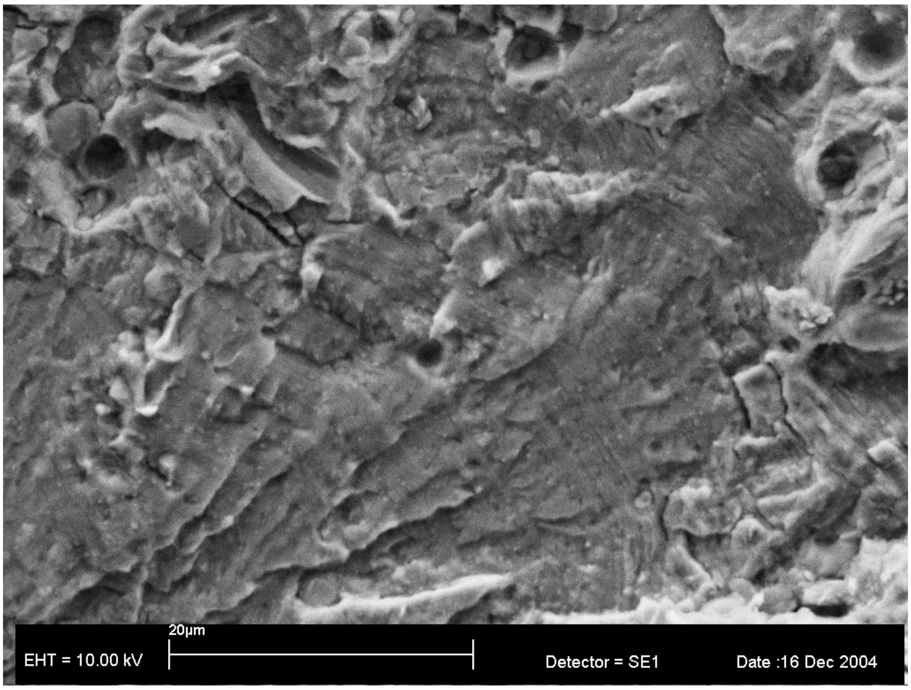


Figure 13. Junction of fracture surface and bolt hole bore at fracture origin.



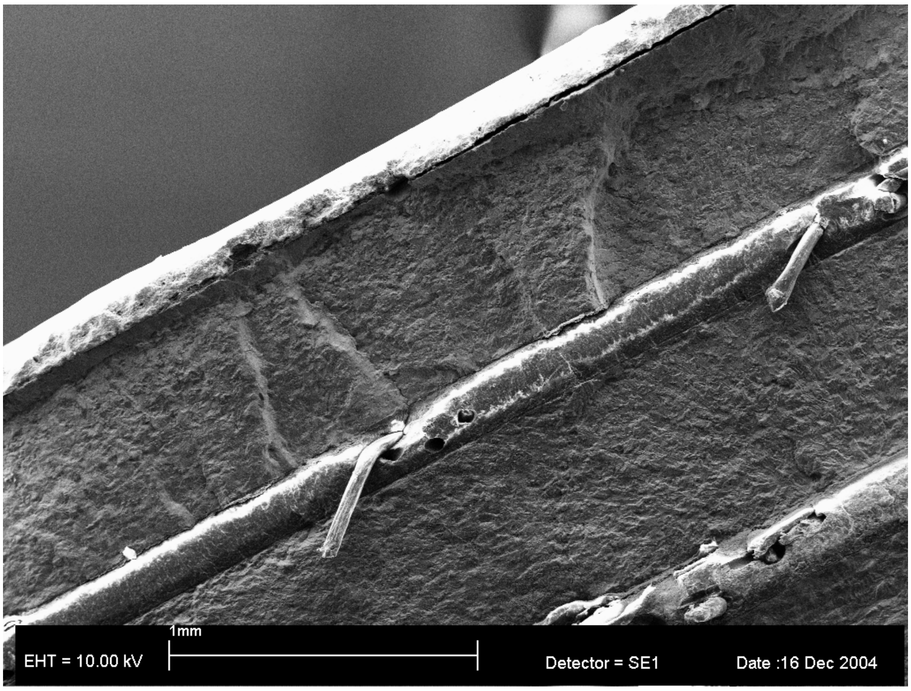


Figure 14. Fatigue striations (top) and castellations (bottom) at the origin indicative of fatigue crack initiation and propagation.

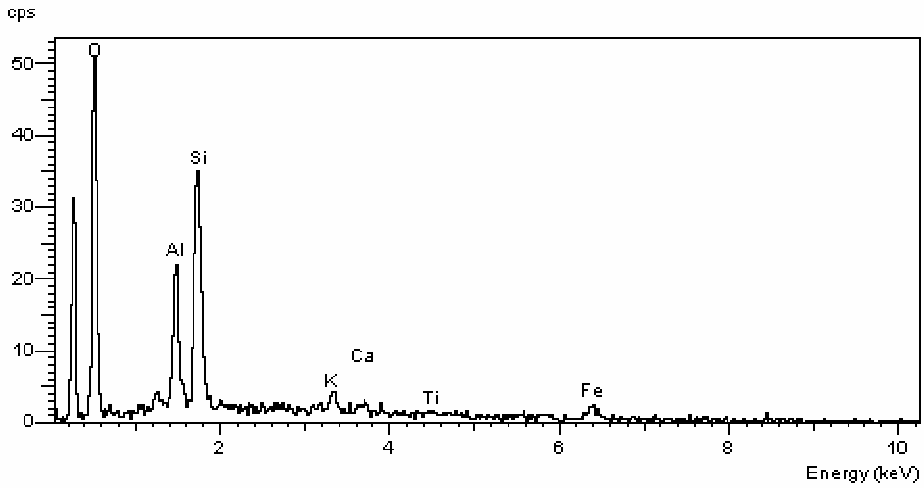


Figure 15. EDA spectrum of small amount of deposit stripped from fracture surface; believed to be indicative of soil contamination picked up at the time of the crash.

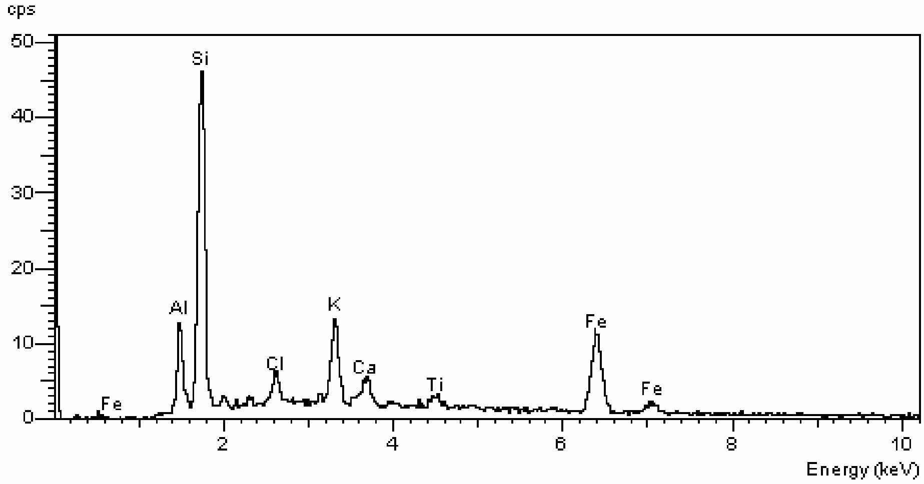


Figure 16. EDA spectrum of small amount of deposit stripped from the bolt hole. Believed to be mainly soil but possible a small amount of chloride.

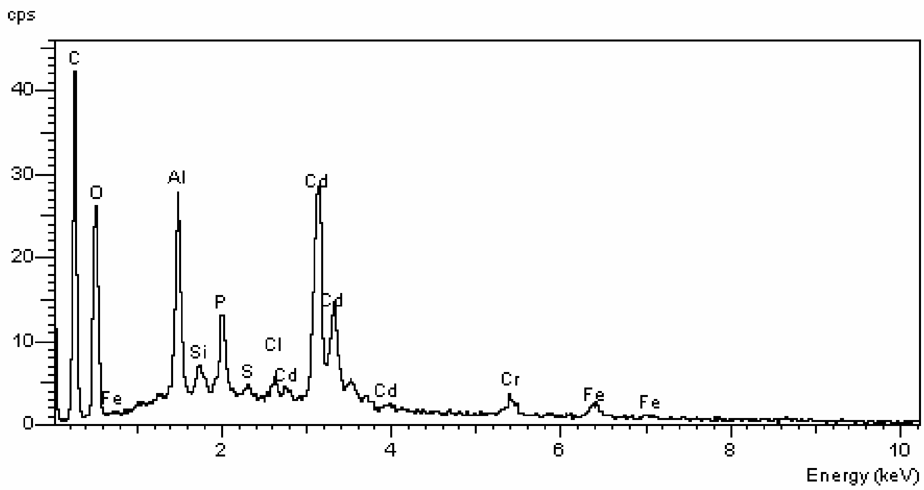


Figure 17. Spectrum from deposit from bolt hole. Al, Si etc indicative of soil. Cd, Fe and Cr possibly from the bolt and the high carbon (C) peak may be from the organic glue.

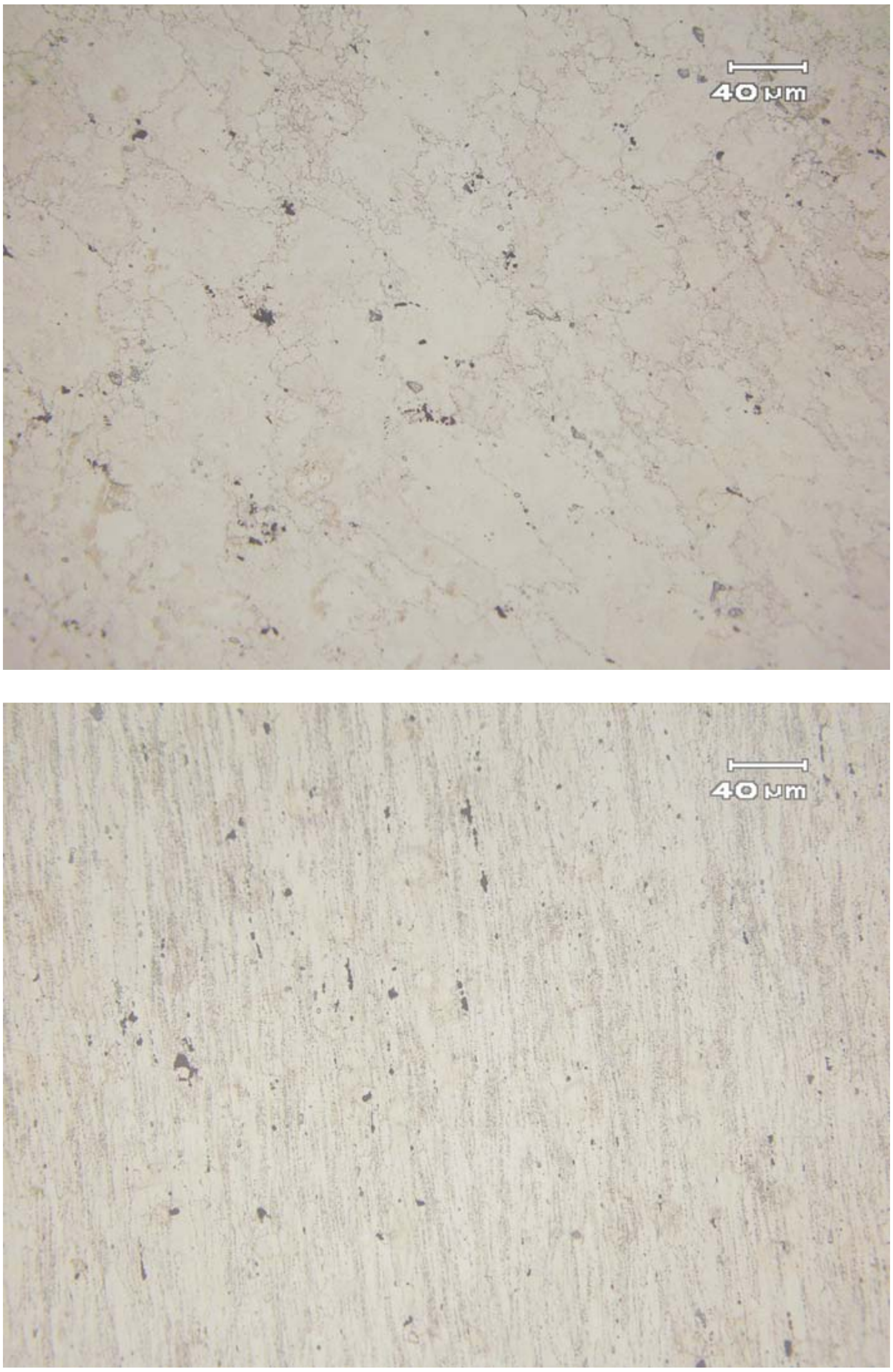


Figure 18. Microstructure of root fitting material; top transverse section; bottom longitudinal section.