SUPPLEMENT No. 517

Pettersson Kjell - Söderholm P-O - Lange Nils:

Metallographic and fractographic examinations of samples from MV Estonia.

Royal Institute of Technology.

Stockholm 1995.

Metallographic and fractographic examinations of samples from MV Estonia

Kjell Pettersson, P-O Söderholm, and Nils Lange
Department of Materials Science and Engineering, Division of Mechanical Metallurgy, Royal Institute of Technology.

Background

A number of parts recovered from Estonia and its bow visor have been subjected to metallographic and fractographic examinations. The aim of the examinations have been to determine the mode of fracture for the different parts and also to see if there have been any abnormal occurrencies like pre-existing cracks, faulty material etc. The following parts have been examined:

- The remaining parts of three lugs of the bottom lock for the bow visor
- A tension test specimen prepared from one of the lugs.
- Parts of the pivoting joint of the bow visor found on the wreckage and its complement on the visor.
- Parts of the side lock for the bow visor.

Examination of the lugs and tension specimen from the bottom lock

Figure 1 shows one of the lugs. The slightly ondulated lower edge is a result of the cutting under water. The edge to the right and the sloping edge are parts of the original shape of the lug. The lug has failed in the ligaments between the hole and the external edges. Around the hole there is the remains of a fillet weld which has served to keep a housing insert in place. The weld is apparently of low quality and has not had any significant load carrying capacity. The weld has a triangular cross section with a leg size of 4 – 6 mm. The superficial impression of the weld is that in parts of it there is insufficient penetration and lack of fusion. A cross section of the weld is shown in Figure 2. In figure 3 is illustrated the lamellar microstucture of the plate material used for the lugs. It is characterized by elongated slag inclusion with a typical interlamellar distance of 0.06 – 0.09 mm. In some of the specimens examined slag inclusions with a length of over 1 mm have been observed, the largest one being over 6 mm in length..

The fracture surfaces have been examined in an optical stereo microscope and in a scanning electron microscope (SEM). The examination in the optical microscope showed that the surfaces were covered by a layer of rust. Two methods were used for removing the rust. The first method employs a mixture of relatively weak organic acids, which removed most of the rust. Examination of the fracture surfaces in the SEM showed that non-conductive oxides were still present on the fracture surface so a more effective method for removing oxides had to be used. In this method the specimen surface is connected as a cathode in an electrolytic bath of fused lithium nitrate. The current used is 6 A. This treatment is very effective and can be applied until the surface is clean. In order to determine if the metal surface is attacked during the treatment an initially clean fracture surface (from the tension specimen) was first examined in SEM, then treated and again examined in SEM. This experiment showed that some parts of the fracture surface were completely unchanged by the treatment while others showed signs of having been slightly oxidized. We interprete this as a result of the high temperature of the treatment and that the surface is oxidized by the air when it comes out of the electrolyte. However the main character of the fracture surface does not change by the treatment.

All fracture surfaces from the lugs were of a ductile character. There were two features which might suggest an influence of fatigue. One of the fracture surfaces was perpendicular to the plane of the lug while an overload failure normally results in a fracture surface where parts of the surface make an approximately 45° angle with the stress direction. However the detailed SEM examination of the surface showed that it had a completely ductile character.

The other feature was a coarse striation pattern, so coarse that normal ductile dimples can be seen on the striations, figure 4. The striation spacing is aboout 0.05 – 0.01 mm, which is about the same as the spacing between the elongated slag inclusions in the material. It thus seemed reasonable to suspect that these striations were a consequence of the slag inclusions rather than of a fatigue process. In order to confirm this hypothesis the fracture surface from the tension specimen was examined. As can be seen in Figure 5 it is also possible to see striation-like features on the fracture surface from the tension specimen. The most reasonable conclusion thus is that the lugs have failed by a single overload. It should also be added that there were no features on any of the lugs which indicated any pre-existing defects apart from the poor fillet welds for attachment of the housing inserts.

Material from the pivoting joint (hinge)

The piece received was a 5° sector of the pipe insert of the hinge of the bow visor with the attached part of the hinge beam which had fractured. This fracture surface was compared to the four fracture surfaces on the bow visor part of the hinge. The fracture surface from the bow visor which seemed most likely to be the mate of the surface on the pipe section was cut off and the two pieces can be seen in Figure 6. The bearing section is in the top and the hinge beam part below. The conclusion that the two pieces belong together is based on the appearance of the upper edge of the two pieces. The fit between the edges was not perfect but it is conceivable that minor pieces of material at the edges may have disappeared in connection with a relatively fast fracture.

Figure 7 shows the two pieces from another angle. It is now possible to see that the hinge beam piece has become thinned (or necked) somewhat in connection with the failure. From this angle the fit between the surfaces is not particularly good, but that could conceivably be a result of the plastic deformation of the hinge beam part. Figure 8 shows the two pieces from yet another perspective. The most interesting feature from this angle is perhaps the crack in the weld. This is again a sign of the questionable quality of the welds of the bearing inserts. In the gap between the plate and bearing a black stuff identified as an iron oxide is present. The oxide was also magnetic which is a strong indication that it is magnetite. The magnetite is also present in the crack in the weld. Since magnetite forms under conditions of low oxygen partial pressure the most reasonable conclusion is that it has formed under a long period of time when moisture has leaked in through the narrow crack in the weld. This crack is thus a pre-existing weld defect which has been present for a long time. It looks as if the corrosion has reduced the load carrying area of the plate around the hole, see Figure 8. The corrosive attack on the plate around the crevice can also be seen in other samples not included in the present report.

The general impression of the fracture surfaces was that they were more heavily corroded than those on the lock lugs. This led to inital thoughts that this crack might have been present before the shipwreck. However the extensive plastic deformation of the bow visor piece makes this an unlikely possibility since it seems inconceivable that such a crack could have passed unobserved when a significant part of the housing insert weld must in that case also have been failed.

The fracture surface of the plate material welded to the housing insert piece was cleaned with the organic rust remover which in this case removed almost all of the rust. Examination in an optical stereo microscope showed a striation pattern which can also be seen in the SEM picture shown as Figure 9. We again believe that this striation pattern is related to the microstructure of the material which contains elongated inclusions oriented in the same direction as the striation pattern. The material also has a banded perlite-ferrite structure where the perlite and ferrite bands may corrode at different rates and thus give a striated appearance on the cleaned fracture surface. The spacing of the striations, 0.05 mm, matches almost exactly the spacing of the ferrite-perlite bands. Apart form the striations the general character ot the fracture surface was of a ductile dimpled type as can be seen in Figure 10. It also gives the impression that the features of the dimples are not as sharp as on the fracture surfaces on the lock lugs which again suggests that this surface has corroded more than the surfaces of the lugs. However this could have been caused by a difference in corrosion properties between the plates used for the different parts.

Two other fracture surfaces from the hinge were examined later with the aim of determining whether or not any cleavage fracture had ocurred. This examination was decided at a meeting by the committee of investigators of the shipwreck in February 1995. The two fracture surfaces were more heavily corroded than any of the other fracture surfaces we had previously looked at. It was thus more difficult to characterize the type of fracture after removal of the rust. We do however conclude that the mode of fracture is ductile with no indications of any cleavage. We believe that the thick rust layer is a result of the exposure to air during the time to beginning of March 1995. This has apparetly happened despite the fact that the surfaces were sprayed with a protective liquid by one of the investigators fairly early after they came out of the water. It is perhaps conceivable that salt water trapped in an initially formed rust may have contributed to the relatively rapid corrosion.

The side lock

The material from the attachment of the side lock to the ship was a piece of 8 mm thick plate from which a semi-elliptic flap of material had been teared. The flap was still attached to the plate along a length a 30 mm where the material had bent nearly 180°. This demonstrates the high ductility of the 8 mm plate material. The actual fracture surface was as expected of a typically ductile character. The microstructure was completely normal for the type of steel used.

The lugs of the side locks were attached to the 8 mm thick plate. On the other side of the plate was a 20 mm thick support plate. According to the information given to us the support plate was not attached directly under the lug plate but rather a few cm to the side. Sections were made through the 8 mm plate and the two support plates in order to see if these had ever been repaired. One of the sections, from a piece marked SL1, can be seen in Figure 11. It is obvious from the Figure that there has been some deformation of the weld but there is no indication of any repair work having been done to the weld. Apart from a few minor defects the weld looks perfectly sound. There is also some indication of corrosive attack in the crevice between the two weld beads but not so much that there has been any significant threat to the integrity of the weld. It can be that the thickness of the 8 mm plate in this section is only about 4–5 mm. We interprete this as a result of a delamination failure of the plate when the lug was pulled away, a failure mode not unlikely for a plate with an abundance of elongated slag inclusions in the plane of the plate. The triangular gap between the 20 mm plate and 8 mm plate may have been caused by a slight bending of the 20 mm plate relative to the 8 mm plate.

The other cross section, from a piece marked SL2, is shown in Figure 12. Here we note that the etchant has attacked the weld material differently, a difference which suggests that two different electrode materials have been used. The weld is however perfectly sound and there is no indication of any repair work, at least not any work which has impaired the integrity of the weld. The odd feature in Figure 12 is the small apparently loose piece of material just under the support plate. On inspection of the whole piece of 8 mm plate with attached support plate it became clear that the apparently loose piece of material is part of a tongue of material from the 8 mm plate just under the support plate which appears to have been hammered away from the rest of the plate by one or several severe blows to the plate. Such a conclusion is supported by several markings on the 8 mm plate. From the appearance of these markings it seems reasonable to conclude that the markings come from the lug plate which first have been pulled loose from the 8 mm plate and then as a result of movement of the bow visor has struck and slid against the 8 mm plate several times.

In order to confirm the hammering against the 8 mm plate a new metallographic section was prepared a few cm below the section of Figure 12. This cross section clearly showed that where there were markings on the surface it is also possible to see severe cold work on the surface. This tends to confirm a hammering action as the cause of the surface markings. It is alternatively possible that a similar structure could be caused by chiselling. However the visual appearance of the surface gives more the impression of hammering with some lateral sliding than chiselling. The metallographic cross section is shown in Figure 13.

A piece of the fractured weld between the lug plate and the 8 m plate was inspected in SEM. Despite the flat appearance of the fracture surface the micro character of the fracture was that of a dimple fracture with no signs of cleavage.

Discussion

All observations on the fracture surfaces are consistent with failures caused by overloading of the structures. The question mark is that we do not have any experience with the effect of salt water corrosion on the present type of fracture surfaces. Therefore we can not say with absolute certainty that the striations observed are actually a result of the banded structure of the material with subsequent corrosion. It may thus be interesting to do some control experiment where fracture surfaces of the present materials are exposed to salt water, the rust removed, and the appearance of the fracture surfaces before and after corrosion with rust removal, is compared. Such an experiment might also throw some light on the question about the age of the fracture surface on the hinge.

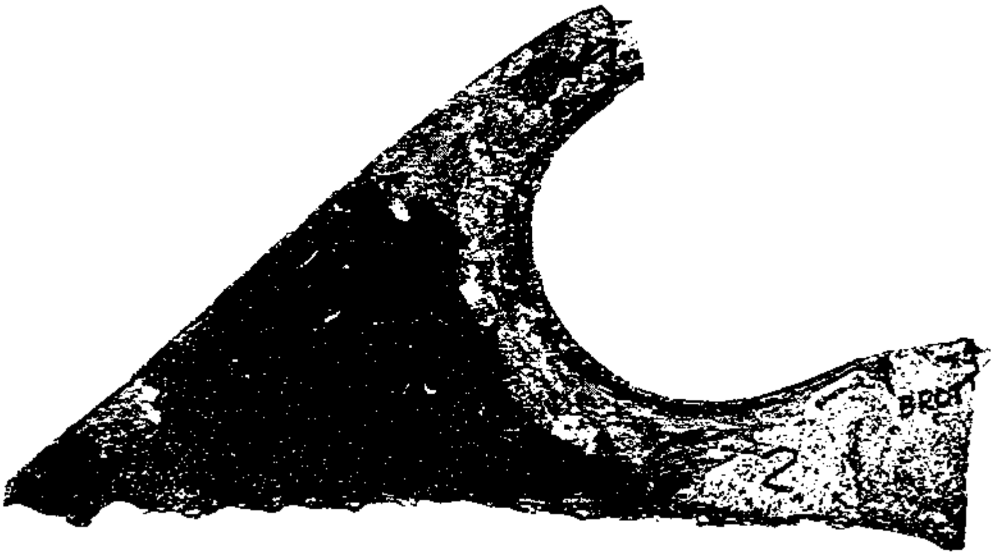

Figure 1. One of the lugs

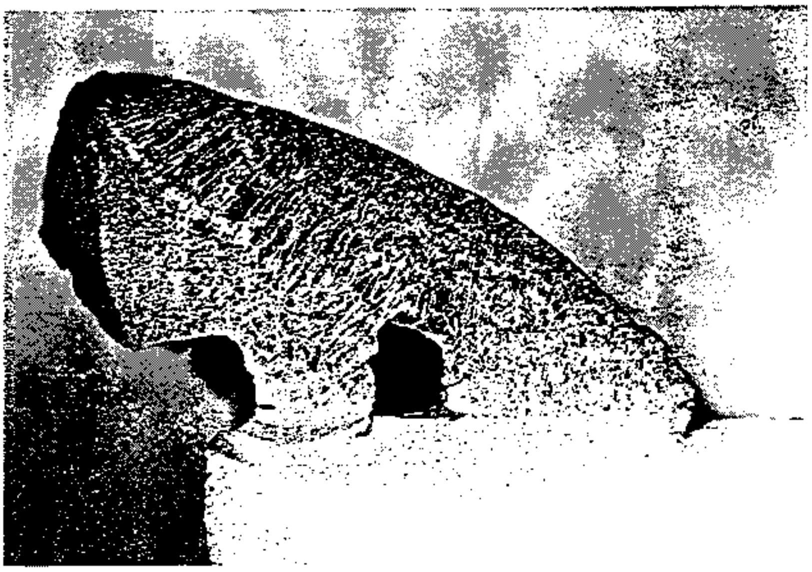

Figure 2. Cross section of fillet weld Note the large pore, the undercut and poor penetration. 10x.

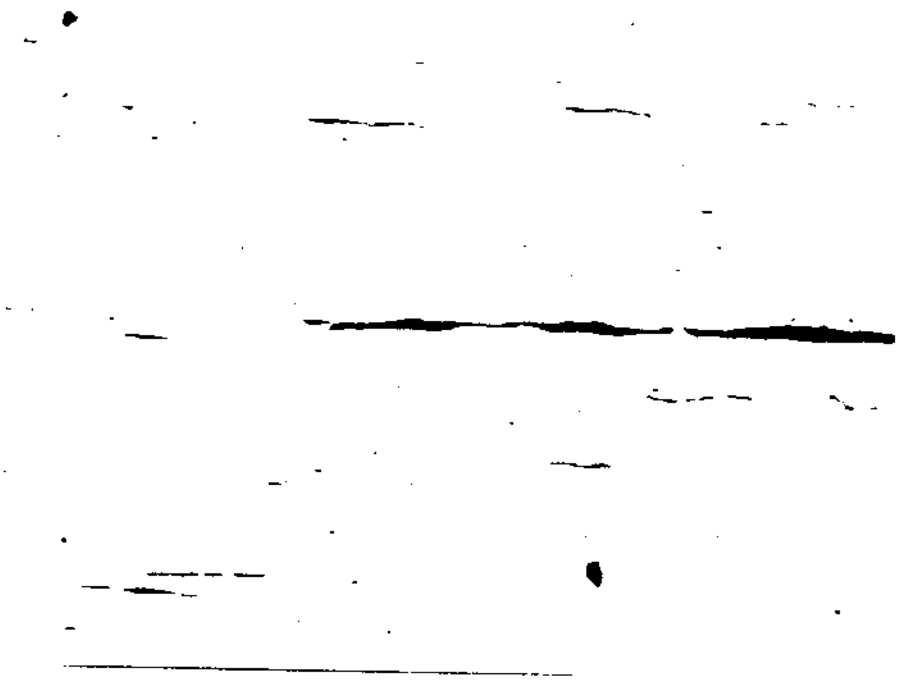

Figure 3. Metallographic cross section of the base metal. Note the elongated slag inclusions. Unetched. 66x.

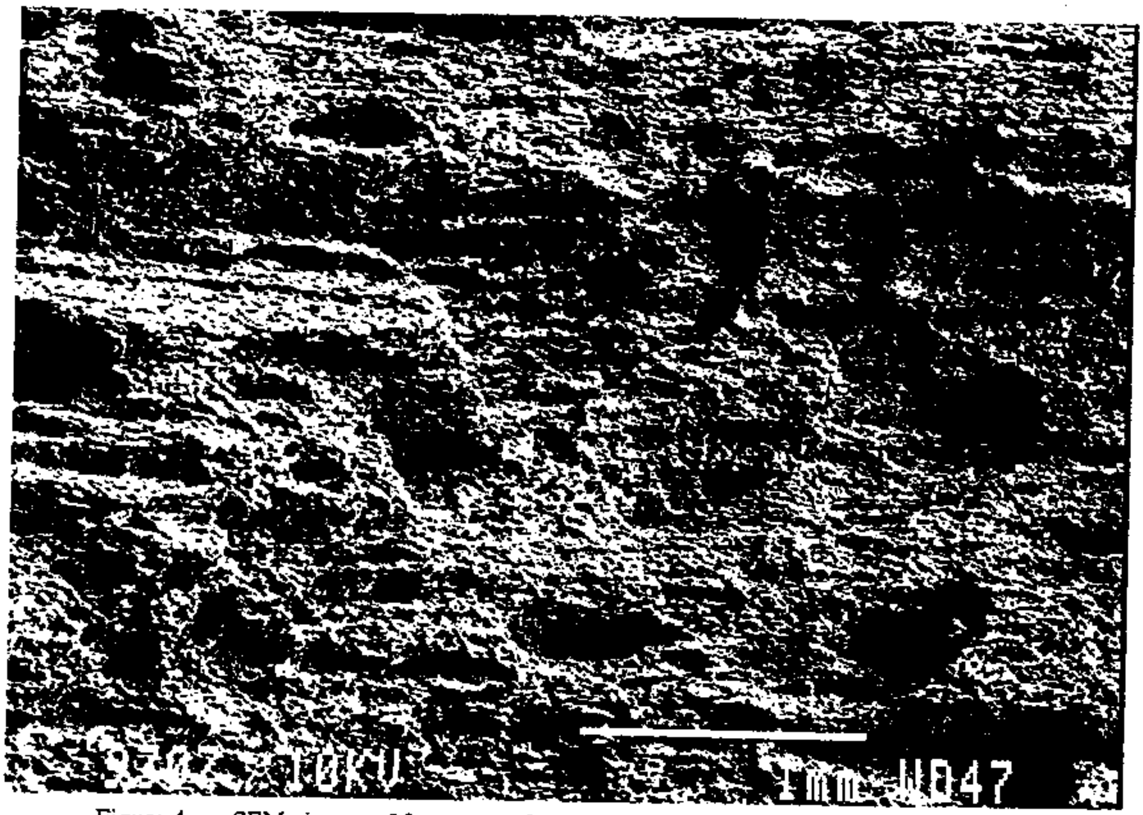

Figure 4. SEM picture of fracture surface of lug. The "striations" are oriented parallell with the slag inclusions. 38x.

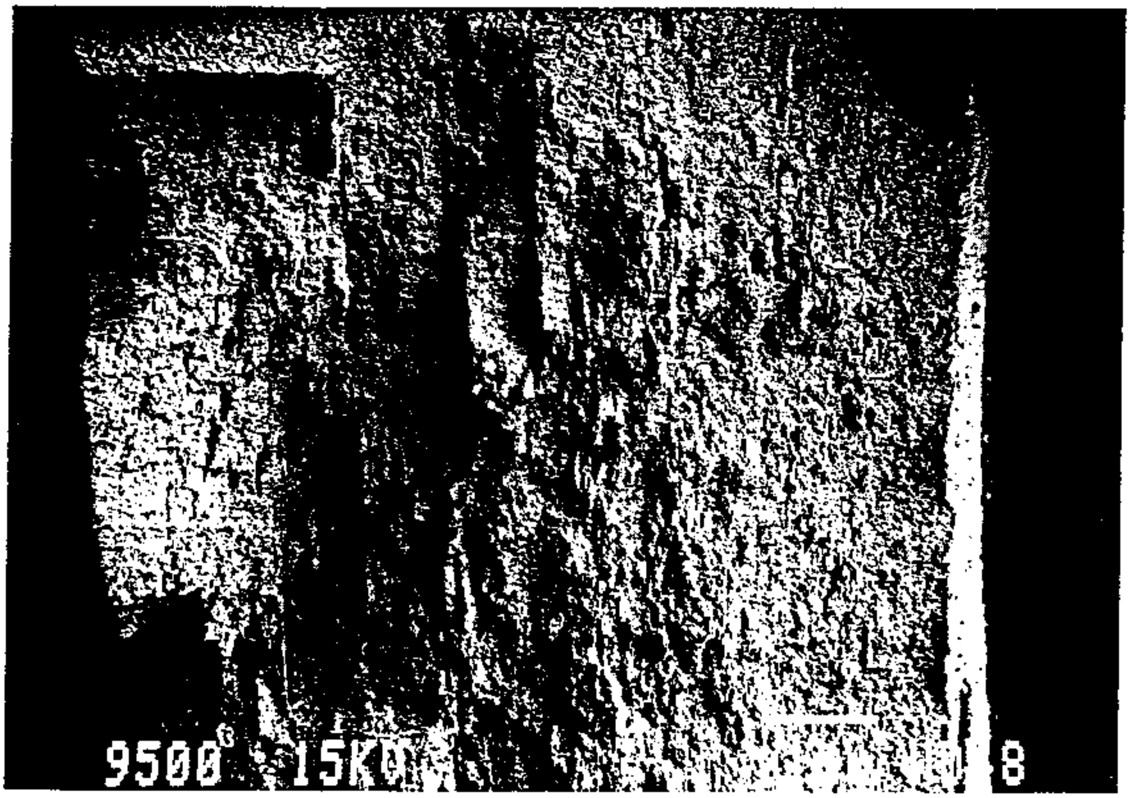

Figure 5. Fracture surface of tension specimen. 13x.

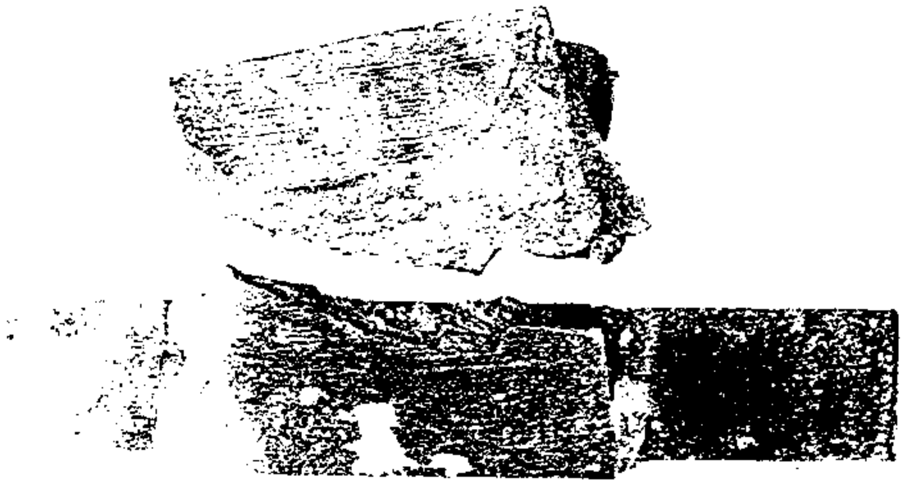

Figure 6. Mating fracture surfaces at the hinge. (ca 1x)

Figure 7. The two pieces from the hinge seen from the side. (ca 2x)

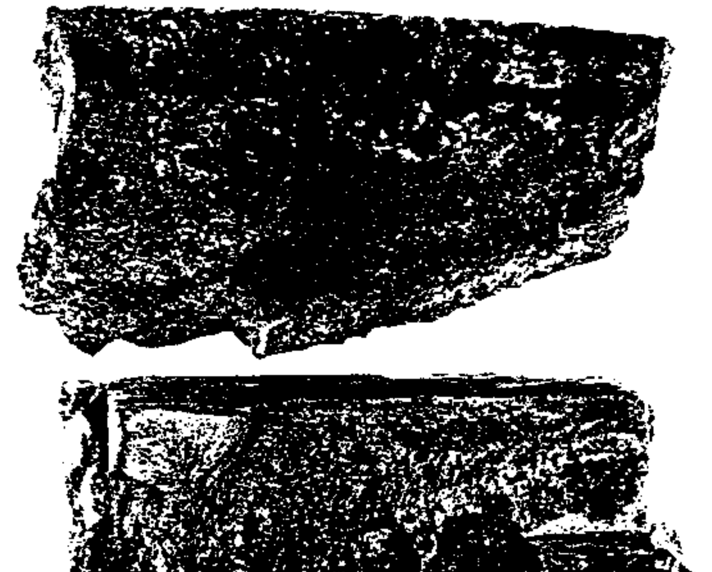

Figure 8. The two pieces of the hinge seen from a third angle. Note the crack in the weld. (ca 2x)

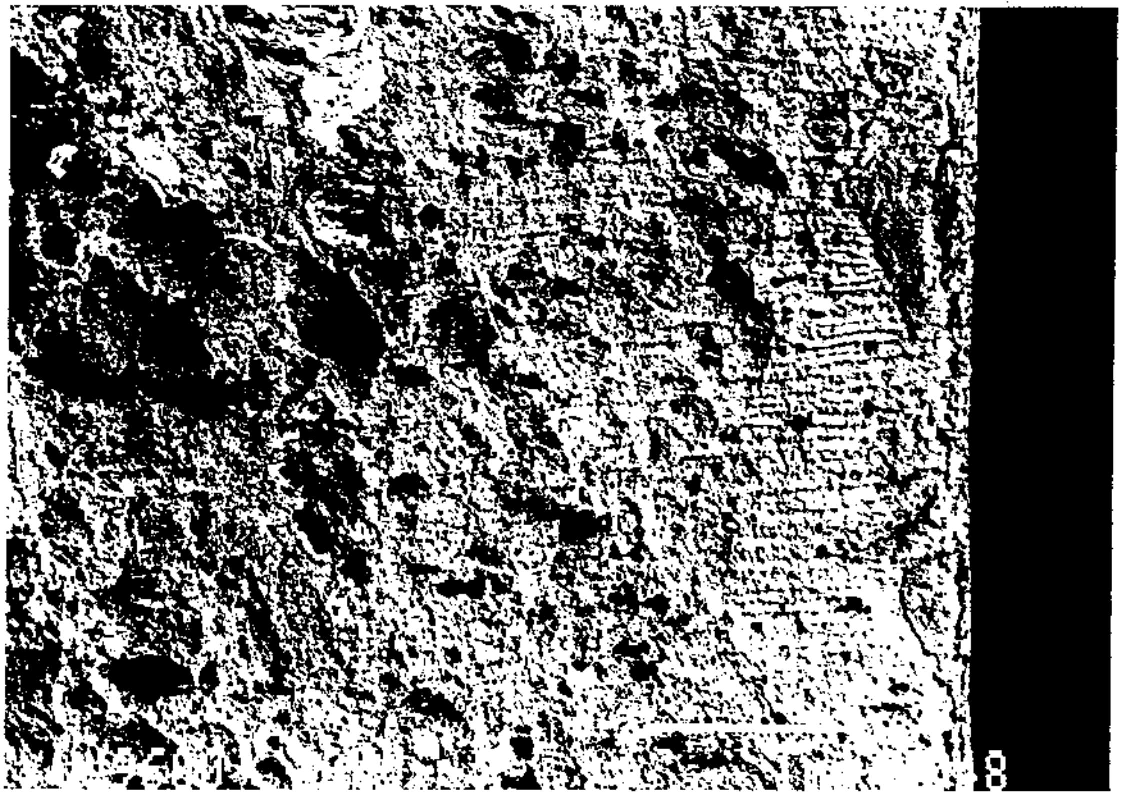

Figure 9. Fracture surface of hinge. SEM 29x.

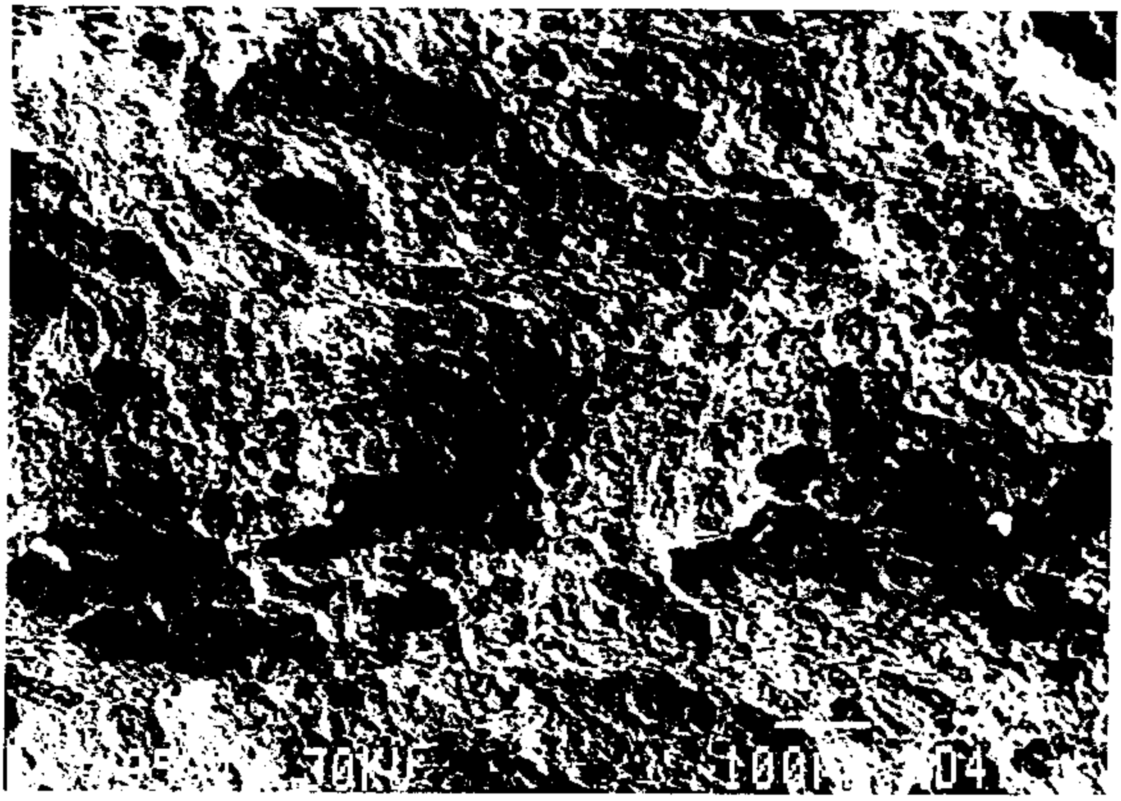

Figure 10. Fracture surface of hinge. SEM 130x.

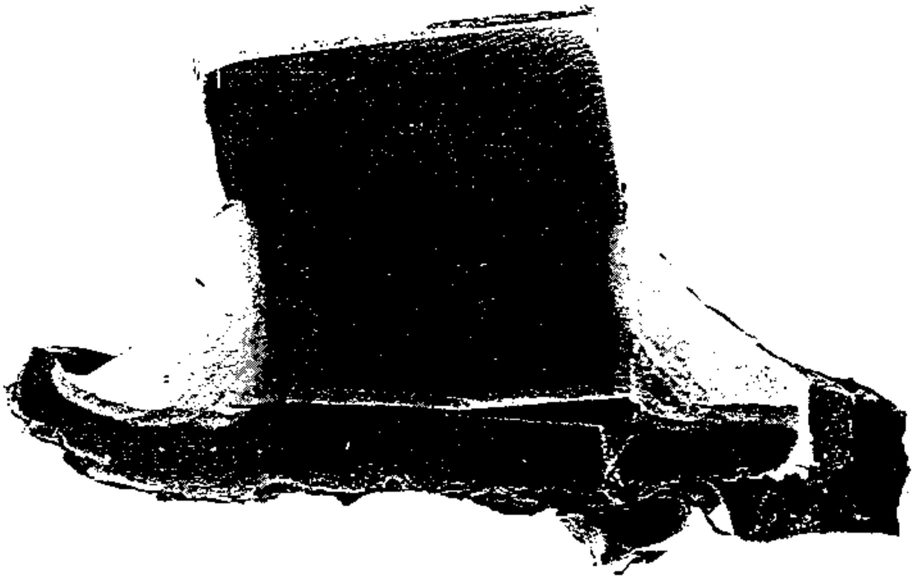

Figure 11 Cross section of side lock specimen marked SL1 (ca 2.5x)

Figure 12 Cross section of side lock specimen marked SL2 (ca 2.5x)

SUPPLEMENT No. 518

Pettersson Kjell - Söderholm P-O: Notes from metallographic and fractographic examinations of samples from MV Estonia.

Royal Institute of Technology.

Stockholm 1996.

Notes from metallographic and fractographic examinations of samples from MV Estonia

Kjell Pettersson and P-O Söderholm
Department of Materials Science and Engineering, Division of Mechanical Metallurgy, Royal Institute of Technology.

Background

In a previous report dated 1995-04-12 [1] we discussed the results of examinations of the following parts from MV Estonia:

- The remaining parts of three lugs of the bottom lock for the bow visor
- A tension test specimen prepared from one of the lugs.
- Parts of the hinge of the bow visor found on the wreckage and its complement on the visor.
- Parts of the side lock for the bow visor.

The main conclusion in that report was that there were no indications of any pre-existing cracks which might have played a role in the failure of the bow visor. It was noted however that the welds joining the housings to the bottom lock lug plates were of very poor quality which meant that the main load carrying area of the bottom lock were the remaining ligaments of the lug plates. It was also noted that there were defects in the welds between the bushing and hinge plates of the hinge. The corrosive attack in the gap between bushing and hinge plate showed that these defects had been present for a long time before the shipwreck.

Since then we have been assigned by the Swedish Board of Accident Investigation to do a few additional examinations of the pieces previously stored at KTH and also on some new pieces of material both from Estonia and the sister ship Mare Balticum. The present report which documents our observations and interpretations of these observations has been written on the request of the Swedish Board of Accident Investigation. We would like to stress that we did not at any time have any assignment to make a full investigation of the extent and causes of any cracking prior to the shipwreck. Such an investigation would have required a considerably larger effort than spent on the present examinations. In particular, as suggested in our previous report, such an investigation would have required an investigation into the effects of salt water corrosion on the appearance of fracture surfaces and the time dependence of such effects.

Observations on hinges.

We noted in our previous report that there were defects in the welds between the hinge plates and the bushing. This had resulted in the formation of a corrosion layer in the gap between plate and bushing. This corrosion layer was identified as magnetite and must have been formed before the failure. Figure 1 shows an overview of the two visor hinges after removal from the visor. There is a difference in the fracture character between the ligaments A1–A4 and those marked A5–A8. The latter ligaments have failed in pure tension as evidenced by a plastic contraction over the the whole ligament in connection with the failure. The orientation of the fracture surfaces is such that large portions of them make an angle of approximately 45°with the tensile direction. The examination of A7 showed a typical ductile failure [1]. (Note that these comments refer to A5 and A7 since A6 and A8 have been severely damaged due to impact on or from other objects). The ligaments A1–A4 have another character. The fracture surfaces are more perpendicular to the direction of the ligaments. These are contracted on the inside and expanded on the outside, suggesting a failure by bending. Evidence of this bending can still be seen on ligament A3, Figure 1, which has bent at a secondary crack. A fractographic examination of A4 was conducted with the object of finding evidence of cleavage fracture [1]. However that examination only revealed ductile dimpled fracture. Some features on the surface which in low magnification in an optical stereo microscope looked like striations were identified to be a result of the banded microstructure of the material.

It can be noted that the inside surface of the holes in the visor plates for the bushings has been formed by flame cutting with fairly deep cut markings. This flame cutting can also be noted by the presence of a heat affected zone layer in metallographic cross sections of the hinge lugs. The secondary cracks on ligament A3 have initiated in the cut markings. This is also true of the primary fracture of A3. There are a few indications in connection with the cracking of A3 and A4 which suggest that they may have formed by a process of corrosion assisted fatigue. This evidence is crack branching and the presence of corrosion products in the cracks. We have examined one of the primary fracture surfaces, A4, without seeing any evidence of fatigue. This was done on a surface which had been cleaned of rust by an electrochemical process described in the previous report [1]. We have no reason to believe that the cleaning process leads to any false structure on the surface or that it would remove any striations if they had been present on the surface. It is interesting to compare the observations on A4 with the examinations of fracture surfaces of two bend test specimens prepared of material from the hinge plate. In one of the tests the notched specimen was bent to complete failure. Macroscopically the fracture surface is nearly perpendicular to the specimen surface with shear lips only at the edges. This demonstrates that fracture surfaces with a similar macroscopic appearance to those of the ligaments A1–A4 can be produced by bending. In the SEM the general appearance is similar to that observed on A4. On the other bend specimen the crack was grown by fatigue. Figure 2 shows an example of the fracture surface at a location where the crack growth has been about 0.6 µm per cycle. It does not seem very likely that any of those striations would be visible after a corrosive attack and the general appearance of this surface is totally different from that of A4.

Another indication of a fatigue process can be seen on one side of one of the pieces from the ligament A4 used for examination of the fracture surface. On that side there is a surface where the fillet weld has separated from the plate. If that surface is viewed in an optical stereo microscope with oblique illumination striation like features can be seen. We do not however conclude that these features necessarily are a result of a fatigue process. We feel that they can equally well be the result of the banded microstructure of the material. The bands are parallel with the plate surface. The fracture surface between the plate and fillet weld makes a slight angle with the plate surface so it cuts through several bands of the microstructure which then show up as striations.

As noted above there is some inconclusive evidence of pre-existing fatigue cracking. However the noticeable expansion of the cross section on one side and reduction on the other of ligaments A1–A4 clearly suggests a bending type of failure. It is difficult to envisage that this could have occurred prior to the clearly tensile failure of the ligaments A5–A8. It is clear that the fillet welds must have contained cracks for a significant period of time as evidenced by the thick magnetite layer. However we would not like to speculate on the cause of these weld defects.

In summary we feel that the available information does not support a conclusion that pre-existing fatigue cracks have played a significant role in the failure of the hinges.

The stempost

We have made a visual examination of a crack surface on the stempost. This crack is one of many cracks in the stempost and goes right through the cross section of the piece. Macroscopically we see so called chevron markings, a feature typical of a fast cleavage failure. The orientation and location of the markings are such that they indicate that the fast fracture has started at a weld defect on one of the sides of the stempost. This type of crack is typically formed at a fast impact at low temperature. In the present case it may have formed if the bow visor fell down on the bulb as indicated in the preliminary accident investigation report [2]. Whether or not that is a probable scenario is dependent on the brittle to ductile transition temperature of the material in the stempost. It should be noted that if we regard the stempost as a large impact specimen it can be expected to have a noticeably higher transition temperature than the standard Charpy-V specimen normally used for measuring the transition temperature since specimen size can have a significant effect on impact properties [3].

The bottom lock lugs.

A closer examination of the bottom lock lugs has shown the presence of cracks at several locations along the weld between lug and housing. Figure 3 shows a metallographic cross section of one of these cracks. As can be seen in the picture the crack is about 1 mm deep. None of the other cross sections of similar cracks examined contained a deeper crack. The cause of the cracking has not been determined. The crack faces are corroded and it will be impossible to see for instance any fatigue striations since these will have corroded away. As evidenced by the opening of the crack, 20–60 μm, seen on Figure 4 the corrosion on the faces have removed at least 10 μm of metal. The crack branching might be taken as evidence of a corrosion assisted crack growth. On the other hand the branches are parallel to the band structure of the material so they may be the result of a localized corrosive attack on elongated slag inclusions. Such inclusions can be seen in higher magnification than that used in Figure 4. It should be noted that the elongated features in Figure 4 are colonies of pearlite which actually have dissolved and reprecipitated as rounded colonies in the heat affected zone where the crack is located.

A comparison between the hinge materials on Estonia and Mare Balticum.

The bow visor hinges on Estonia and the sister ship Mare Balticum are of similar design. They consist of a cylindrical bushing welded to the hinge plate. Inside the bushing is a bronze cylinder functioning as a bearing. A piece of a hinge on Mare Balticum was cut out in order to provide a comparison with the Estonia hinges. Figure 5 shows a metallographic cross section of the weld between hinge plate and bushing of Mare Balticum. To the left in the figure it is possible to see the heat affected zone after flame cutting of the hole in the hinge plate. Several cavities and a crack can be seen in the weld. In connection with the crack there was a grey-black deposit which we believe is magnetite because it looks like magnetite and is magnetic. This indicates that somewhere along the weld there must be a penetrating defect.

The crack is shown in higher magnification in Figure 6. The wide part marked with an arrow is not actually part of the crack but a cavity formed during welding which just happened to be located in the cross section. The main part of the crack is the branch extending to the right in the figure. It is interesting to note however that a very fine crack has initiated in the bottom of the cavity as shown in Figure 7. This indicates that the hinge is subjected to fatigue loadings which can initiate and grow cracks.

The compositions of the materials in the hinges from Estonia and Mare Balticum were also determined. The compositions of the bronze bearings were deterimined by wet chemical analysis after that it had been determined by EDS analysis in SEM that the only significant elements were Cu, Sn, and Pb. The following results were obtained:

	Estonia	Mare Balticum
Cu	85±2	88±1.5
Sn	11±0.5	9.5±0.4
Pb	0.56	0.46

The fact that the amounts do not sum up to 100% is just a reflection of the imperfections of the analysis.

The compositions of the bushings were determined by X-ray fluorescence for most of the elements. For carbon IR measurement on gases released in connection with combustion of the material in oxygen was used. For sulphur both methods were used. The following results were obtained:

	Estonia	Mare Balticum
C	0.22	0.35

Si	0.29	0.41
Mn	0.61	0.62
P	0.008	0.025
S	0.031(0.029)	0.047(0.05) (=combustion method)
Cr	0.02	0.23
Cu	0.025	0.27

Results were also obtained for Al, Ni, V, Mo, W, and Ti but these were all below 0.1% for both samples. The carbon content of the sample from Mare Balticum was considered surprisingly high. Therefore an additional sample was analysed as a check on the previous analysis. None of the values for that sample deviated from the values in the table by more than 0.03% and for C the value was identical.

Discussion

The additional observations reported here do not change the main conclusions of the previous report. The load carrying area at the bottom lock lugs was limited to the ligaments in the lug plates. The weld was of poor quality and as noted in the present report it contained pre-existing cracks. For the hinge there is clear evidence of pre-existing defects in the weld between plate and bushing. It is possible that these defects have grown by a process of corrosion assisted fatigue. The importance of these defected welds is the same as for the bottom lock lugs: the load carrying area is reduced to the ligaments around the hole in the hinge plate. It should however in this context not be forgotten that tensile samples of the weld between bushing and plate were prepared and tested by the department of Solid Mechanics at KTH. Those tests showed that intact welds had an adequate strength. The problem is that we do not know the extent of the weld defects and therefore we can not be certain to what extent the weld has contributed to the load carrying capacity of the hinges.

Other evidence of fatigue is the secondary cracks seen on the inside of the hole in the hinge plates. These cracks have initiated in the grooves formed by the flame cutting of the holes. To us it is conceivable that these cracks might equally well have formed in connection with the final failure of the hinge. The material in the zone heat affected by flame cutting is brittle so it is quite possible that cracks may form in connection with a temporary overload.

References

1. Pettersson, K., Söderholm, P-O., and Lange, N.
   Metallographic and fractographic examinations of samples from MV Estonia.
   Materials Science and Engineering, KTH, 1995-04-12

2. The Joint Accident Investigation Commission
   Part-Report on the Estonia disaster of 28 September 1994.
   April 1995

3. Alexander, D. J. and Klueh, R. L.
   Specimen size effects in Charpy impact testing.
   Charpy Impact Test: Factors and Variables, ASTM STP 1072, John M. Holt, Editor, American Society for Testing and Materials, Philadelphia, 1990, pp. 179–191.

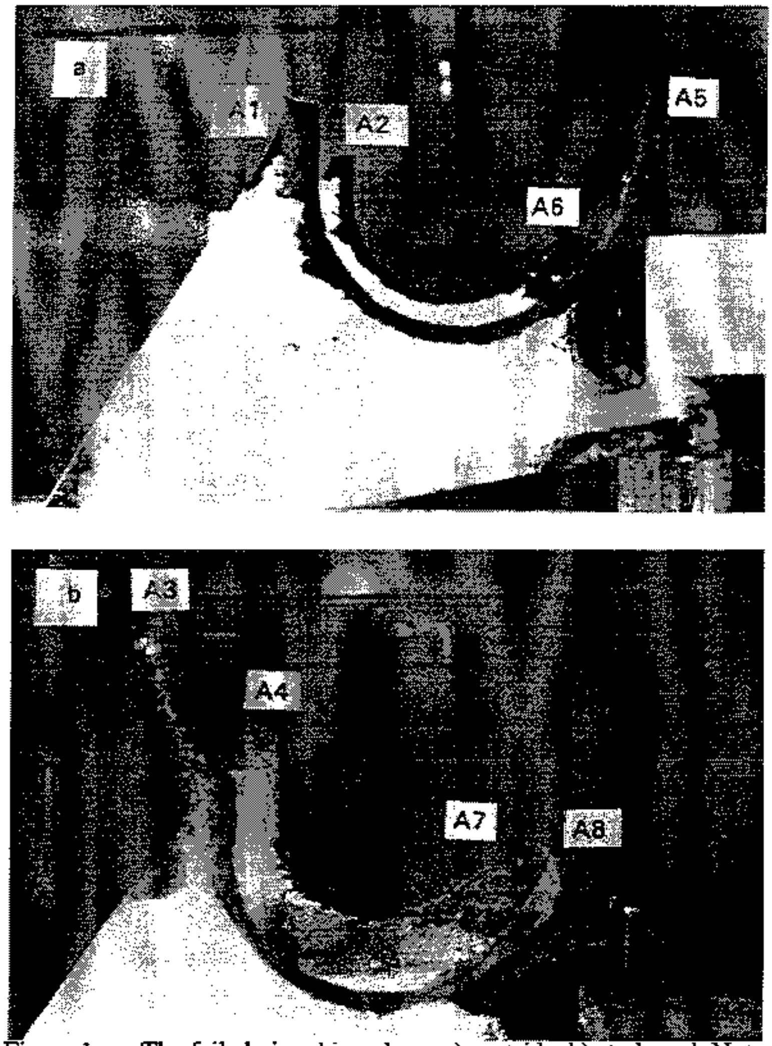

Figure 1. The failed visor hinge lugs. a) portside, b) starboard. Note that A7 is on the near side of the lug and A8 on the far side.

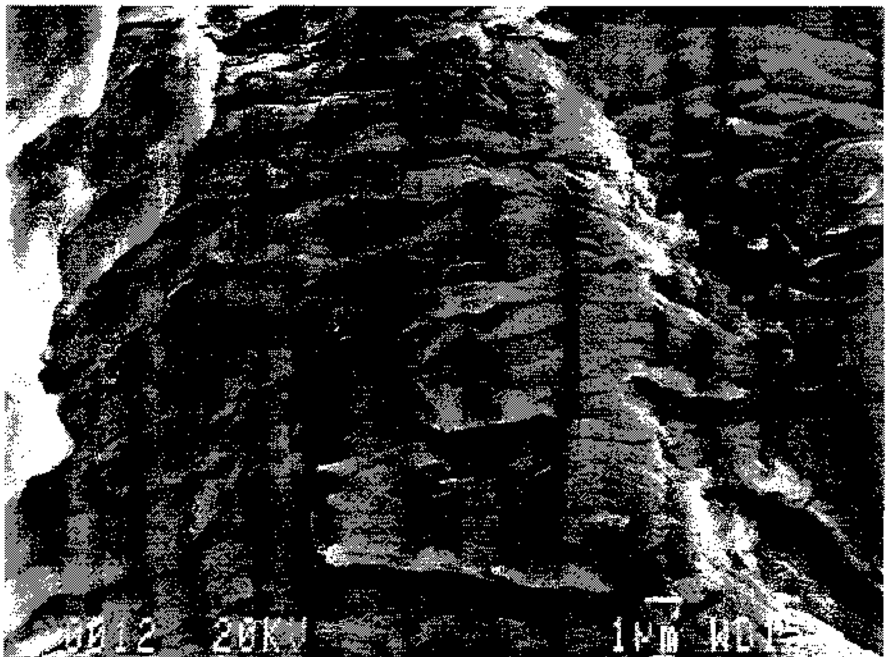

Figure 2. Fatigue fracture surface on laboratory specimen from visor hinge plate. 5000x.

Figure 3. Metallographic cross section of crack in bottom lock weld. 8x.

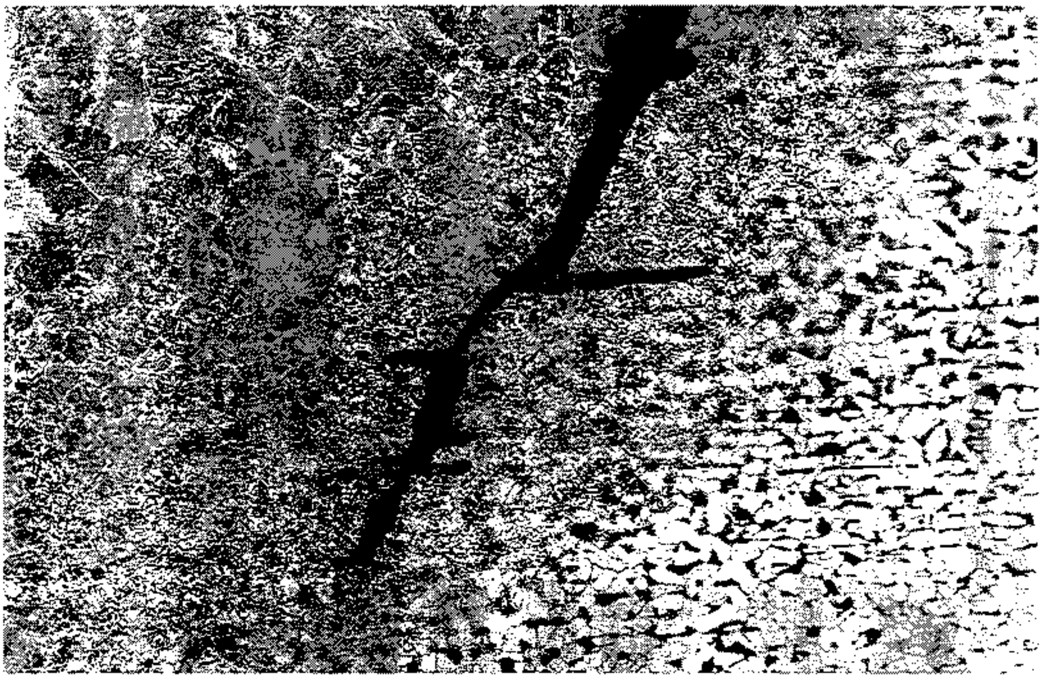

Figure 4. Metallographics cross section of crack in bottom lock weld. 100x.

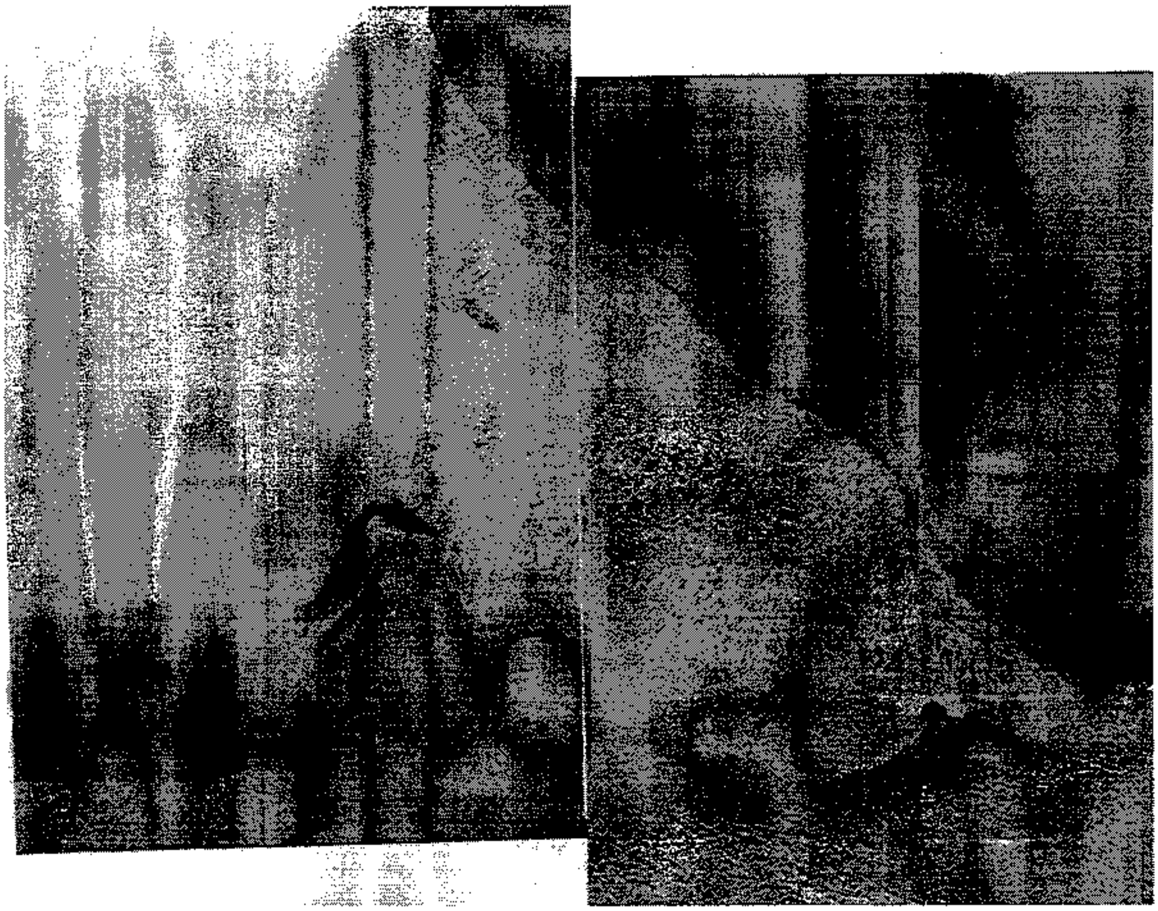

Figure 5. Cross section of weld between hinge plate and bushing on Mare Balticum. 7x.

Figure 6. Cross section of weld in higher magnification. The wide part of the crack is actually a pre-existing cavity formed during welding. 50x

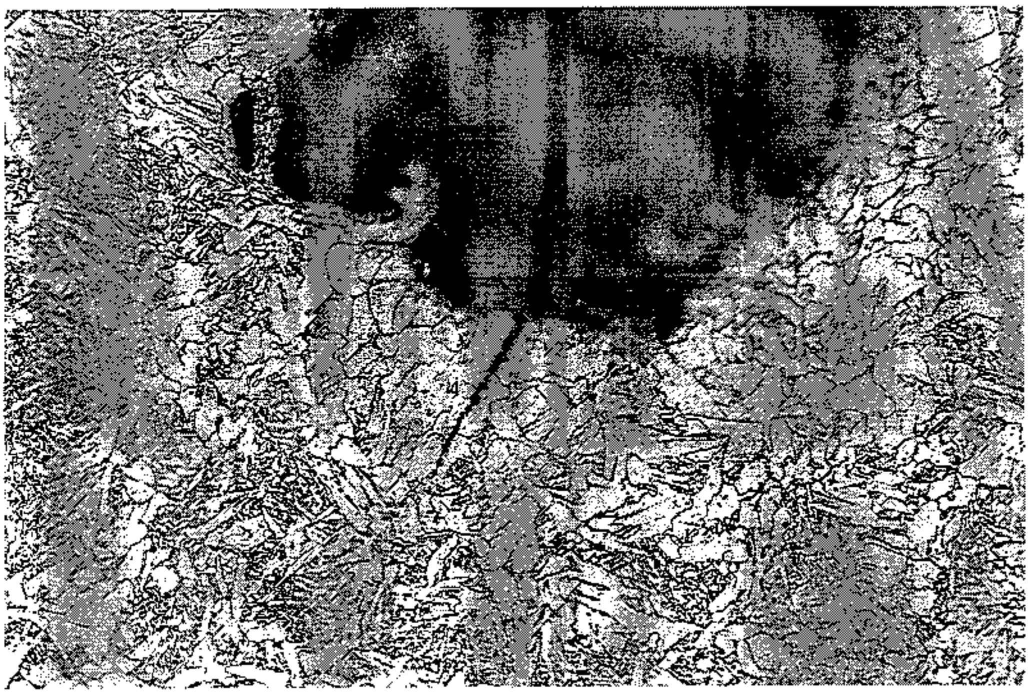

Figure 7. A sharp crack initiated in bottom of cavity, presumably by fatigue. 500x.