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Failure of backstay rod connectors on a luxury yacht

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Contents

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Abstract

A backstay rod connector from a luxury yacht fractured while the vessel was docked, bringing down the backstay assembly. A second connector contained a large crack. Both were made from 17-4 PH stainless steel. One half of the fractured connector was recovered, and was found to have failed by pitting and crevice corrosion, followed by stress corrosion cracking. The second connector most probably had cracked in the same way. Adverse conditions inherent to service use of the connectors could have facilitated stress corrosion. Nevertheless, use of a stress corrosion susceptible material is unacceptable. This means that any connectors made from 17-4 PH steel aged below 1100 F (866 K) should be replaced. Candidate replacement materials are stainless steels 316, Nitronic 50, a duplex steel like SAF 2205, and also 17-4 PH in the H1100 and H1150 conditions.

Keywords: stress corrosion, yacht, stainless steel

1 Introduction

On 6 July 2002 a backstay rod connector from a luxury yacht fractured while the vessel was docked. Half of the connector was recovered from the quay. The fracture caused the backstay assembly to come down on the deck. Subsequent examination revealed a large crack in a second connector. Figure 1 shows the connector locations schematically, and gives an impression of the yacht's size. The
backstay collapse could have had serious consequences: the assembly consisted of three steel connectors weighing between 3 and 5 kg, and five steel rods 1 inch (25.4 mm) in diameter and several metres long.

Figure 2 shows the fractured and cracked connectors after superficial cleaning. The fracture surfaces of the broken connector were initially black, then greenish-brown with so-called "beach markings", and finally light grey, which represented overload fracture. The cracked connector showed external surface corrosion pits, which were also present on the fractured connector. All these features will be discussed.

During the last two years up to the incident, the yacht's log showed it was mainly docked. Between November 2000 and July 2002 there were only two short strips in mid-April 2002 (on engine, no sails, normal weather) and on 29 and 30 June 2002 (light weather). From 30 June to 6 July 2002 the yacht was docked.

This paper describes the investigation involving the fractured and cracked connectors, and suggests remedial measures. A new backstay assembly was installed on the yacht in July 2002.

2 Failure Investigation Scope

Table 1 gives the failure investigation main and subsidiary topics. Most of these are straightforward, but two points should be noted. First, the rod ends that had been seated in the connectors were obviously non-uniform, hence the profile and dimension measurements. Second, the investigation's sponsor did not allow connector 2 to be opened up to examine the fracture characteristics. This restriction was based on the similarity of the cracking locations in both connectors, see figure 2, and cost *versus* potential benefit of the examination.

3 Macroscopic Examination

3.1 Connectors

Figure 3 shows the fracture surfaces and internal surface condition of connector 1. Significant features are:

- Fracture surface "beach markings", including some delineating light grey bands between greenish-brown areas, see figure 3b. The beach markings radiate from black initial regions that are just beyond the smaller cylindrical bore.
- The internal shoulder between the cylindrical bores shows relatively severe corrosion and rust-staining.
- Figure 3a shows a local indent of the internal shoulder. The indent was later determined to be post-fracture secondary damage.

3.2 Rod Ends

Figure 4 shows views of the rod ends that had been seated in the connectors. The rod ends were asymmetrical and non-uniform in surface finish, but they were free of corrosion: the staining in figure 4 originated from connector corrosion. Profile and dimension measurements at the NLR showed the out-of-roundness to be mostly within 0.5 mm, though the maximum values were nearly 1.2 mm. These eccentricities were within the manufacturing limits. In other words, the rod ends were not required to be precision-made.

4 Material Determinations

Information from the shipyard and backstay manufacturer indicated that the connectors could be either 316 or 17-4 PH stainless steel, and that the rod ends were Nitronic 50 stainless steel. The NLR determined the connectors were magnetic, which eliminates 316; and the rod ends were non-magnetic, like Nitronic 50.[1]

Table 2 compares the chemical analyses of connectors 1 and 2 and the rod ends with the AMS specification for wrought 17-4 PH and a nominal composition for Nitronic 50, respectively. The more precise ICP-OES method was used for connector 1, it being deemed sufficient to use SEM-EDX for the other components. From the results it is reasonable to conclude that the connectors were 17-4 PH steel and the rod ends were similar to Nitronic 50 (higher nickel and molybdenum).

The average Rockwell “C” hardnesses of connectors 1 and 2 were respectively 39.4 and 38.0, corresponding to ageing below or at 1025 F (825 K).[2] The Rockwell “C” hardnesses of the rod ends ranged from 36 to 40. This range is consistent with cold-worked Nitronic 50,[1] or a similar alloy.

Figure 5 gives an example of the microstructure of connector 1, in the same macroscopic orientation as the fracture surfaces, i.e. parallel to the longitudinal axis of the connector. The microstructure is as expected for 17-4 PH steel heat-treated after working. The overall direction of working (longitudinal) is shown by elongated manganese sulphide (MnS) inclusions.

5 Fracture Mechanisms in Connector 1

5.1 Fractography

The fracture surfaces shown in figure 3 were extensively mapped by SEM at magnifications up to 2000X. There were three basic types of fracture topography:

(1) Severe local corrosion in the black initial regions.

(2) Faceted and angular cracking, appearing mainly transgranular, in the greenish-brown areas, for example figure 6.

(3) Microvoid coalescence in the light grey areas, including the light grey bands between the greenish-brown areas on fracture surface #2, see figure 3. An example from one of these bands is shown in figure 7.

5.2 Metallography

Fracture surface #2 was sectioned from the black initial region to point “B”, see figure 3. A representative metallograph is given in figure 8. This shows secondary, branched cracks below the fracture surface. The cracks ran both transgranularly, including along martensite laths, and intergranularly.

5.3 Interpretation

The severe local corrosion started by pitting and crevice corrosion, owing to the narrow space between the internal shoulder of the connector and the rod end that had been seated in it. At a depth of 2-2.5 mm the local corrosion changed to transgranular + intergranular stress corrosion cracking. The stress corrosion cracks became large: for fracture surface #1 the overall extent of stress corrosion reached at least the first internal screw thread, figure 3a; for fracture surface #2 the overall extent of stress corrosion was less, compare figures 3a and 3b. It seems most likely that the stress corrosion cracking that resulted in fracture surface #1 began earlier than the stress corrosion cracking causing fracture surface #2.

At this point it is opportune to mention the backstay loading and refer to the yacht’s service history (log) leading up to fracture of the connector. The backstay was continuously pre-loaded at 75 kN, which was increased to 107 kN during sailing trips. The service history implies that the backstay had experienced mainly pre-loading during the last two years before fracture of the connector, with no more than four main load changes. (75 kN to 107 kN) during short trips in April and June 2002. Also, there would have been few or no opportunities for significant weather-induced load changes during sailing. In other words, the yacht’s service history of sustained loading, with very few load changes for two years until fracture of the connector, is consistent with stress corrosion being the main fracture mechanism.

Secondary, but significant, aspects of the fracture process are the light grey bands of microvoid coalescence between the greenish-brown areas of stress corrosion cracking, most clearly seen in figure 3b. The bands of microvoid coalescence are the result of “tensile crack jumping”,[3] which is a transient instability that is often caused by a peak load. One might think that since the tensile crack jumping was intermittent, then the peak load would have to be transient, otherwise the connector would have fractured. However, this is not necessarily so. For example, a peak load representing an increase in backstay load from 75 kN to 107 kN could be responsible for a tensile crack jump, even though the peak load would be sustained for several hours during even a short sailing trip.

The reason for this possibility lies in the variation in stress through the wall thickness of the connector. At the internal and external surfaces there is a state of plane stress; in the middle of the wall thickness the stress state approaches plane strain. In plane strain the fracture toughness, and hence resistance to tensile crack jumping, is lower than in plane stress. Consequently, as figure 3b shows (more clearly for the band labelled “A”), tensile crack jumping has its greatest extent in the middle of the wall thickness, while it is negligible at the internal and external surfaces. In other words, completely unstable fracture is prevented, at least for the time being, by the local variation in stress state along the crack front. Final instability occurs when the crack has become sufficiently large that a steady load or peak load results in the overall fracture toughness being exceeded.

6 Stress Analysis

The finite element code MSC. Marc was used for stress analysis of an intact connector having the same overall dimensions as the fractured connector 1, and subjected to a local internal surface pressure as though loaded by a seated rod end.

Figure 9a shows the shape and dimensions for the finite element mesh, which was a two-dimensional axisymmetric model using 8 node quadrilateral elements. The model was fixed in the longitudinal and radial directions, as indicated by the arrowheads at 1 and 2 in figure 9b. This figure also gives the surface pressure, 470 MPa, applied to three element faces, and the analysis results. The surface pressure was derived by assuming that the seated rod end was loaded to 107 kN and made contact with the connector over an annular area of width 2.7 mm. The material properties required for the stress analysis were the Young’s modulus (E) and Poisson’s ratio (ν) of 17-4 PH steel: the values selected were E = 197 GPa and ν = 0.272.[4]

In figure 9b the connector deflection with respect to the undistorted mesh is greatly exaggerated for clarity (note that this deflection has nothing to do with the local indent of the internal shoulder, shown in figure 3a, which was due to post-fracture secondary damage). Figure 9b shows a peak tensile stress of 228 MPa (red colour) close to the assumed contact area. Comparing figure 9b with figures 3a and 3b shows that the predicted position of the peak tensile stress agrees with the location of the black initial regions. Thus this stress analysis, which is straightforward, indicates that the tensile stresses required for stress corrosion cracking are a direct consequence of the load transfer between the seated rod end and connector.

7 Material Selection for Backstay Rod Connectors

Many stainless steels, including 17-4 PH[5] and 316 [2,6] are susceptible to pitting and crevice corrosion in quiet (or stagnant) seawater. On the other hand, Nitronic 50 is unaffected.[1] More to the point, for the problem encountered in the present investigation, is stress corrosion susceptibility. Austenitic stainless steels, which include 316 and Nitronic 50, are highly resistant[6] or not susceptible[7] to stress corrosion cracking in chloride-containing environments. However, 17-4 PH steel is susceptible in marine environments, depending on the ageing temperature.[8] Ageing at 1025 F (825 K) or above makes 17-4 PH much more resistant to stress corrosion: for maximum resistance 17-4 PH should be aged at the highest temperature commensurate with meeting the strength requirements, but *not less* than 1025 F (825 K).[8]

From the present investigation, notably the Rockwell hardness measurements, it is likely that both the fractured and cracked connectors were aged at temperatures no higher than 1025 F (825 K). This means they could be susceptible to stress corrosion under adverse conditions. Several adverse conditions, inherent to backstay rod connector use, can be thought of:

- Quiet or stagnant seawater in the connectors, promoting pitting and crevice corrosion processes that often serve as initiation sites for stress corrosion cracking.
- Alternate wetting and drying that could lead to local increases in salt concentration, which increase the stress corrosion susceptibility of precipitation-hardening stainless steels.[9]
- Low pH within crevices,[10] reducing the stress corrosion resistance.[9]
- Non-uniform contact between the rod ends and connectors, owing to asymmetry of the rod ends (see figure 4) and non-uniformity of their surface finish. Such non-uniform contact would cause local peak tensile stresses higher than those arising from uniform contact.

Be that as it may, the single most important requirement for the connectors (and rod ends) is that they should not be susceptible to stress corrosion in service. A change of material, i.e. discontinuing the use of 17-4 PH steel, or using it in the H1100 or H1150 conditions, is indicated. An obvious candidate is 316. According to the literature,[6,7] this steel should not be susceptible to stress corrosion in marine environments. However, it is susceptible to crevice corrosion in stagnant seawater. Even better choices, for overall resistance to corrosion and stress corrosion are Nitronic 50[1] and a duplex (austenite + ferrite) stainless steel like SAF 2205.[11]

8 Conclusions and Recommendations

(1) The fractured and cracked backstay rod connectors were made from wrought 17-4 PH steel aged at temperatures no higher than 1025 F (825 K).

(2) Cracking of the fractured connector was due to stress corrosion, which began from pitting and crevice corrosion. Most of the subcritical cracking before final failure was stress corrosion cracking. Some intermittent tensile crack jumping occurred, but this was secondary.

(3) The cracked connector most probably had undergone the same process of pitting and crevice corrosion, followed by stress corrosion.

(4) The rod ends seated in the fractured and cracked connectors were made from a cold-worked alloy similar to Nitronic 50, but with higher nickel and molybdenum contents. These were corrosion-free.

In view of the foregoing conclusions it is clear that use of a stress corrosion susceptible material for the connectors (or any other locally highly loaded components) is unacceptable. Any such components known (or found) to be made from 17-4 PH steel aged below 1100 F (866 K) should be replaced by components made from materials immune to stress corrosion in marine environments. Candidate replacement materials are 316, Nitronic 50, a duplex steel like SAF 2250, and also 17-4 PH in the H1100 and H1150 conditions.

9 Acknowledgement

The stress analysis was done by T. Tinga, NLR.

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Table 1 Scope of Failure Investigation

Macroscopic examination	
• Fracture surfaces connector 1 • External surfaces connectors 1 and 2 and rod ends • Profile and dimension measurements rod ends	
Material determinations	
• Magnetic/non-magnetic • Rockwell hardness • Chemical composition	} connectors 1 and 2 and rod ends
• Microstructure connector 1	
Fracture mechanisms: connector 1 only	
• Macro-to-microfractography • Metallographic section of a fracture surface	
Stress analysis for intact connector + seated rod end	
• Assumed uniform internal surface circumferential load • 2-D Finite Element Method (FEM)	

Table 2 Chemical analyses of connector 1 (ICP-OES) and connector 2 and rod ends (SEM-EDX)

Element (wt.%)		C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Nb
AMS spec. 17-4 PH steel	min	-	-	-	-	-	15.00	-	3.00	3.00	5xC
	max	0.07	1.00	1.00	0.040	0.030	17.50	0.05	5.00	5.00	0.45
Broken backstay rod connector 1		0.05	0.32	0.59	0.021	0.027	15.5	0.45	4.15	3.25	0.26
Cracked backstay rod connector 2		-	0.60	0.68	-	-	16.2	0.38	4.14	2.91	0.31

Element (wt.%)	C	Mn	Cr	Mo	Ni	Nb	V	N
Nitronic 50[1]	0.04	5.0	21.2	2.2	12.5	0.20	0.20	0.30
rod end 1	-	4.3	23.7	5.4	17.6	-	0.08	-
rod end 2	-	4.6	23.8	5.8	17.1	-	0.14	-

D571-02N

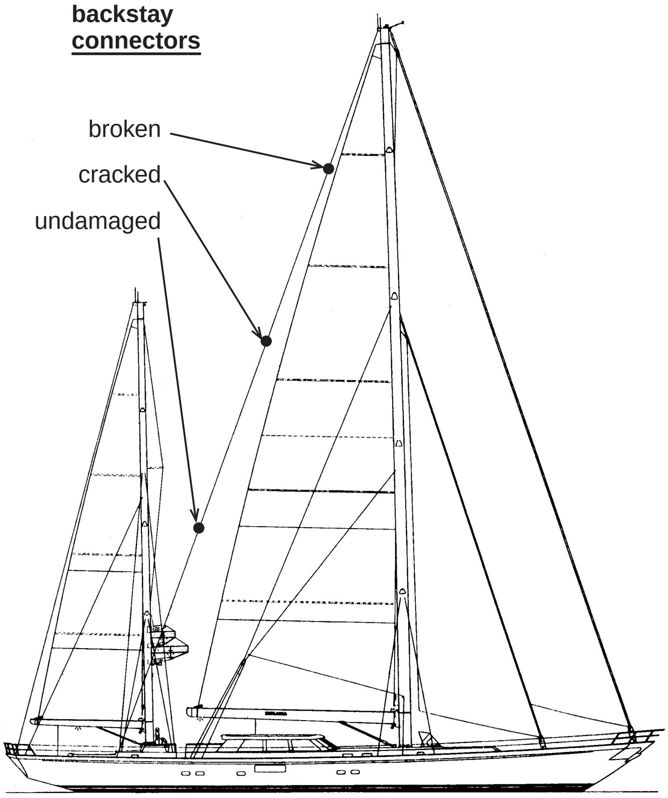

Fig. 1 Schematic of the backstay failure: mainmast is 49 m above waterline

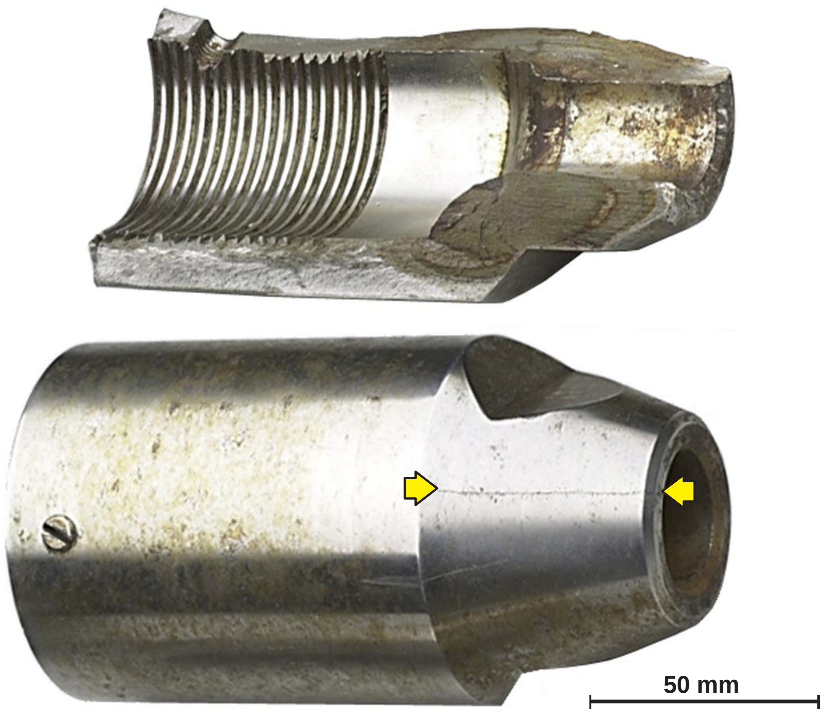

Fig. 2 Superficially cleaned failed connectors, with male end fitting and backstay rods removed from the cracked connector: arrows indicate the large crack

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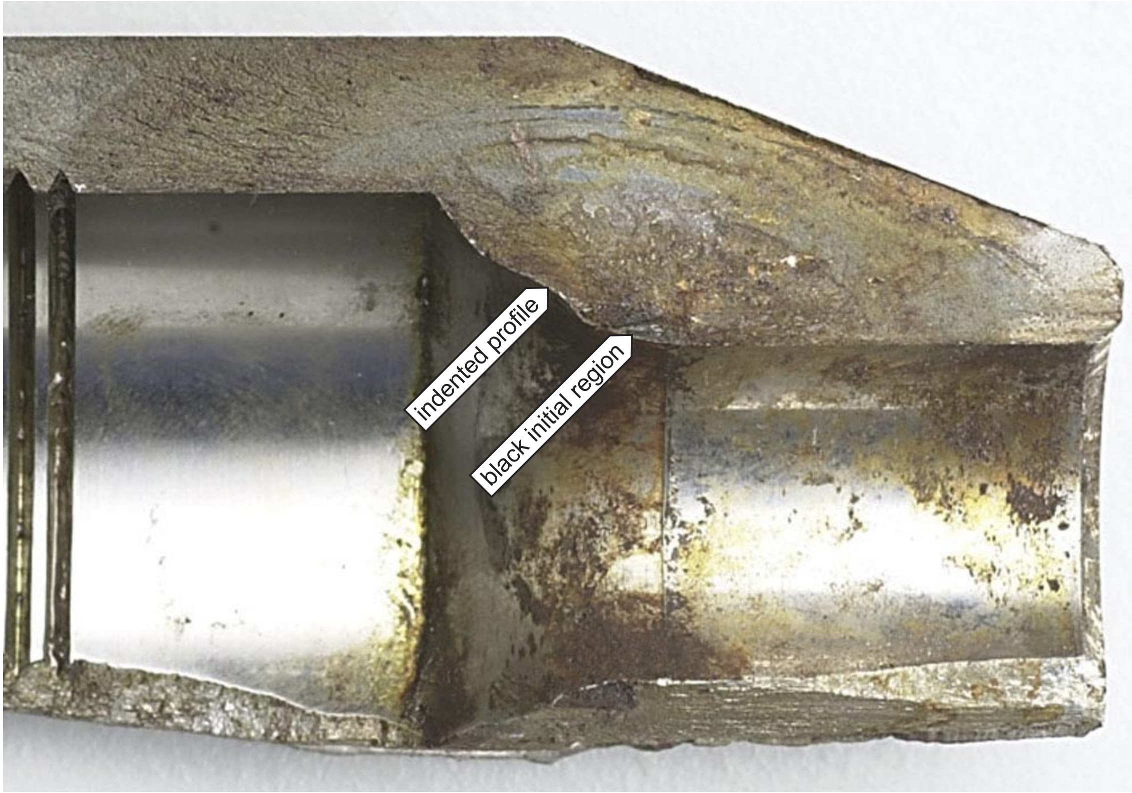
a | **fracture surface #1**



b | **fracture surface #2**

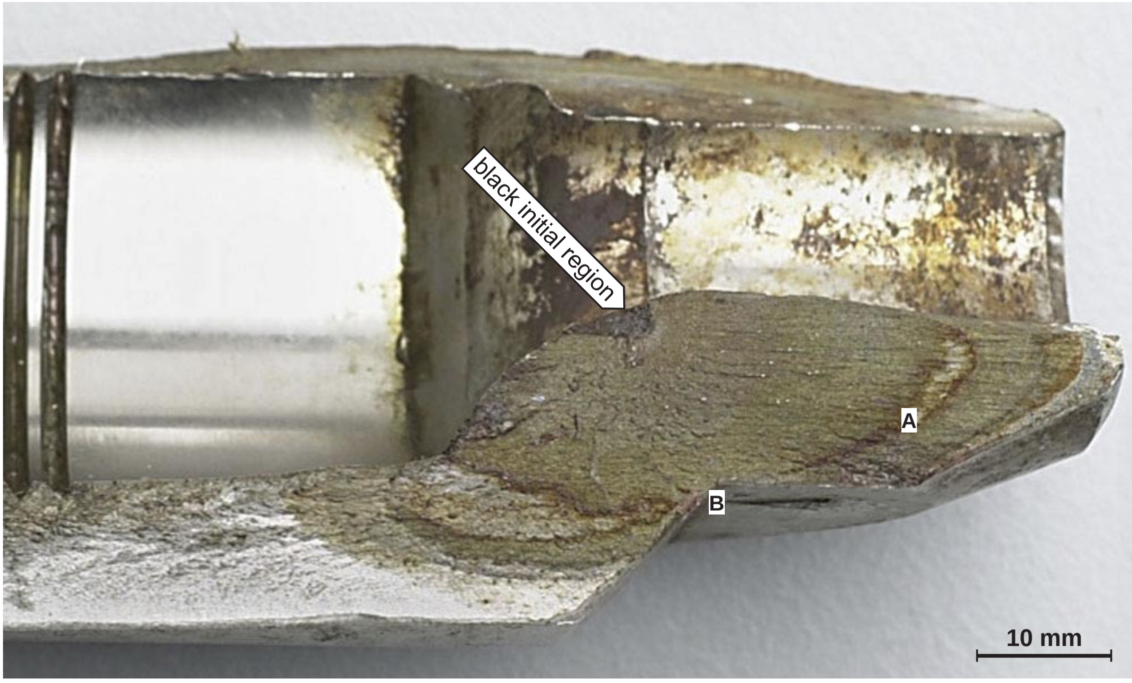


Fig. 3 Macrofractographs for connector 1

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a | **connector 1 rod end**

b | **connector 2 rod end**

Fig. 4 Two similar views of the rod ends that were seated in the connectors

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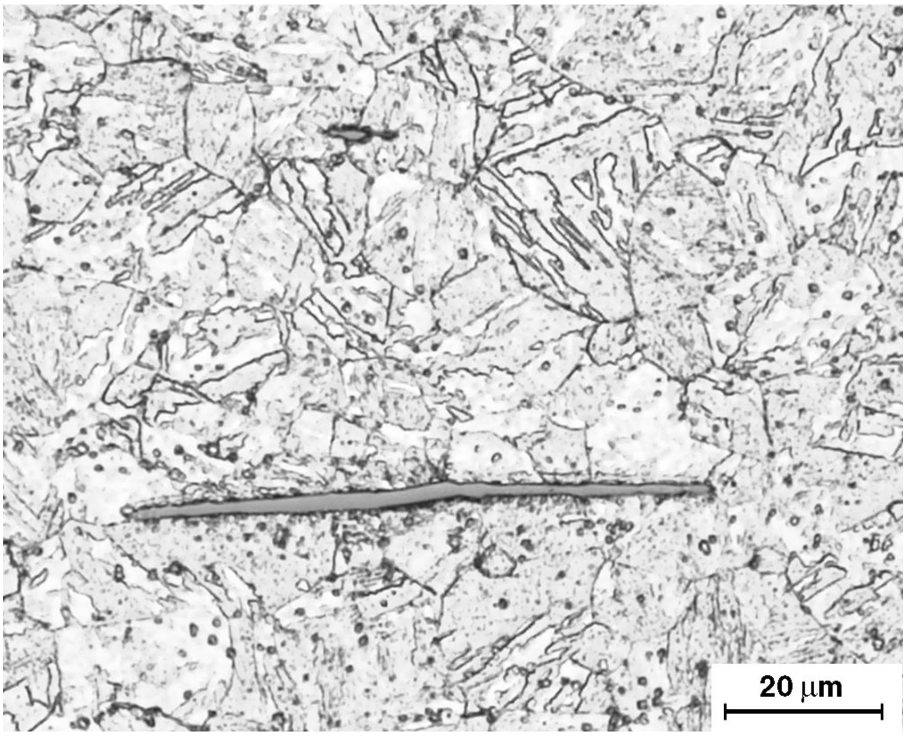

Fig. 5 *Example microstructure of connector 1: Fry's etch reagent. Note the elongated MnS inclusions*

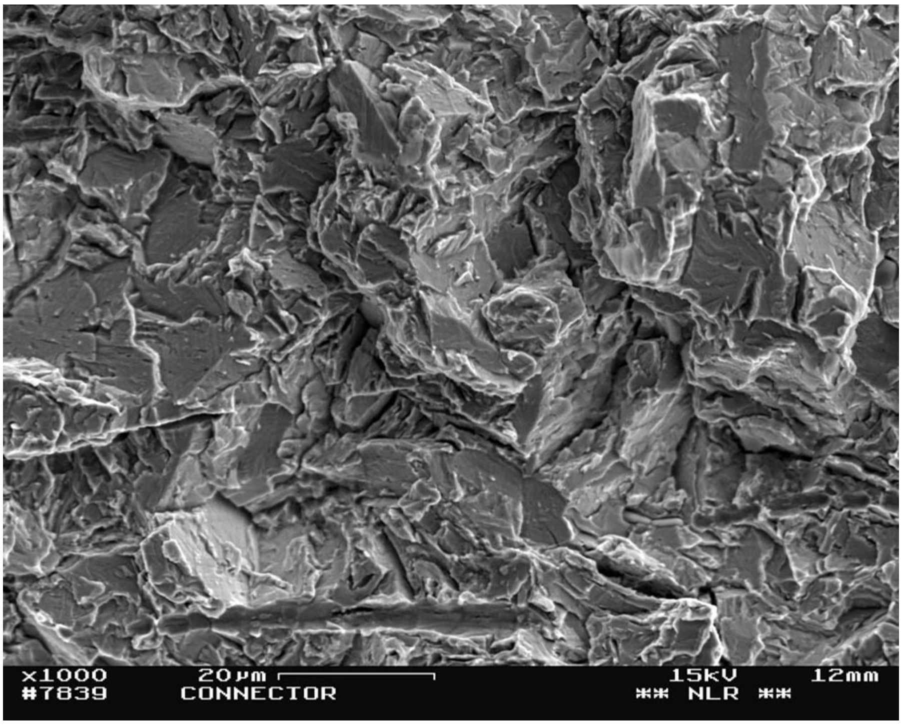

Fig. 6 *Example of faceted and angular cracking in the greenish-brown areas of the fracture surfaces of connector 1. The elongated feature near the bottom of the fractograph represents separation between the steel matrix and an MnS inclusion*

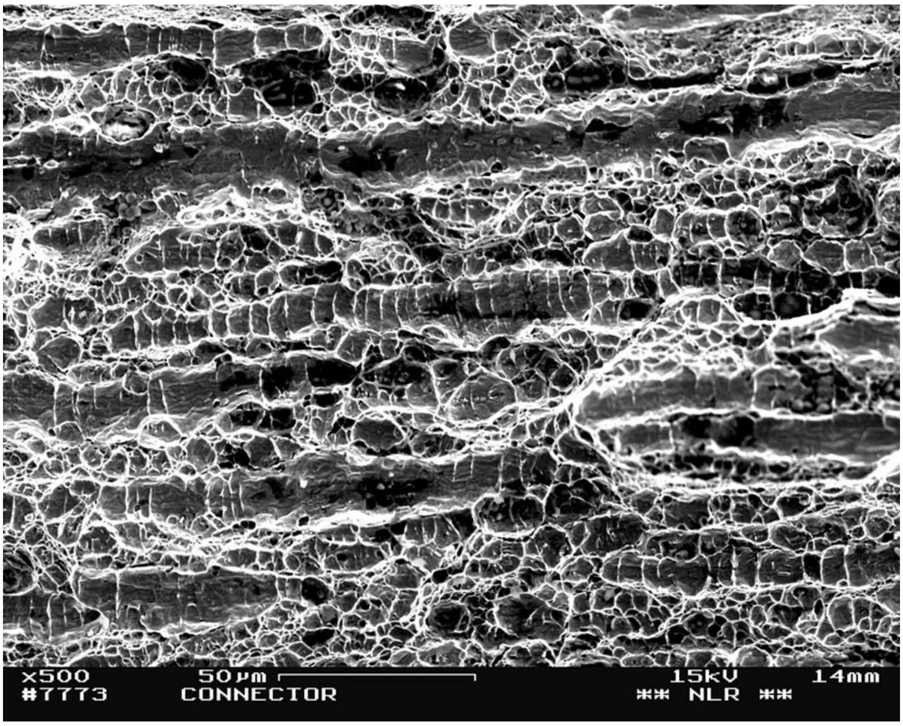

Fig. 7 Example of microvoid coalescence. This is in the light grey area labelled "A" in figure 3b. The elongated features represent separations between the steel matrix and MnS inclusions

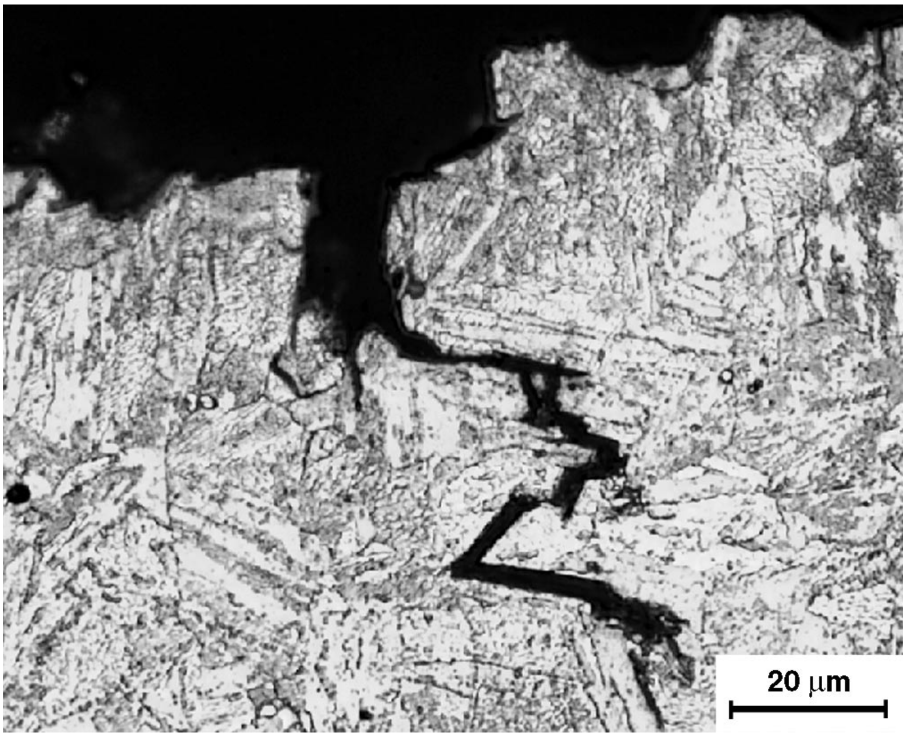

Fig. 8 Example metallograph of secondary cracking below fracture surface #2 and along the line from the black initial region to point "B", see figure 3b

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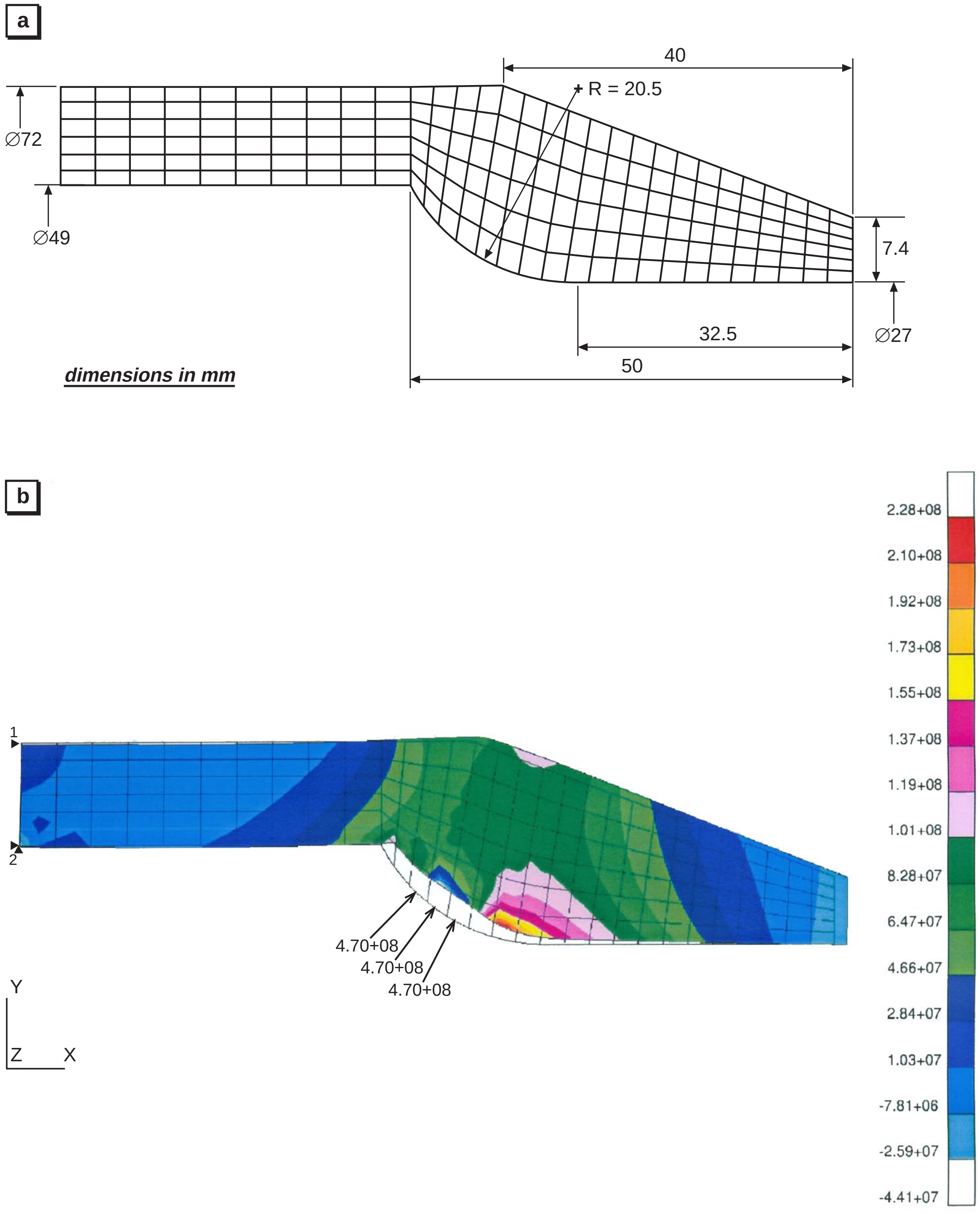

Fig. 9 (a) Finite element mesh representing part of an intact connector with the same overall dimensions as the fractured connector 1; (b) Uniform circumferential stress distribution for the connector sustaining a surface pressure of 470 MPa, as though loaded by a seated rod end with a loading of 107 kN