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# A study of the low-cycle fatigue failure of a galvanised steel lighting column

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## ABSTRACT

This paper presents the results of a low-cycle fatigue test on a galvanised steel lighting column. The aim of the test was to simulate the behaviour of the column undergoing large amplitude resonant vibration caused by wind. A metallurgical study of the failure revealed the significant role of the galvanised coating in the failure process. Results from a detailed 3D finite element model are also used to explain the failure mechanism.

The swage joint in the column was confirmed as a failure location by both experiment and finite element analysis. This in itself is not surprising and the position of the fatigue failure is consistent with those observed in the field. Of more importance is the fact that the experiment shows that galvanizing can lead to premature failure of such columns. This is a highly significant conclusion as it implies that improving the weld detail in an effort to improve fatigue life may be ineffective for lighting columns coated in this manner.

Given the detrimental effect of galvanizing on fatigue performance and the fact that the most severe corrosion will be on the outside of columns, then the fatigue life of such structures may benefit if the inner surface was not galvanised in high

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stress regions. An alternative improvement would be the use of a galvanizing coating with higher toughness and less susceptibility to cracking and damage.

Attention is drawn to the need for a better understanding of the fatigue performance of galvanised steel columns resulting from large amplitude wind induced resonant vibration. The approach adopted so far for lighting column resonant vibration, has been to try and avoid it. While this is a laudable objective, clearly this has not always been possible, as designs push the limits permitted by Codes of Practice.

**KEYWORDS**

Low-cycle Fatigue Failure, Experiment, FEA, Lighting Column, Welds, Galvanised Coating.

## 1. Introduction

Fatigue failure of lighting columns, as a result of wind induced vibration, has received particular attention in recent years with the increased number of premature lighting and traffic column failures on exposed sites. This increase is generally a consequence of resonance, at wind speeds well within the column wind-gust design limits [1-3]. This type of failure generally occurs in a matter of hours, due to the rapid accumulation of load cycles and the high amplitudes of vibration facilitated by relatively low damping.

Fig.1 shows the aftermath of such an event during the installation of new 18m lighting columns next to Glasgow Airport in 60mph winds in early January 1993[4]. It may be observed that the columns failed at the fillet weld adjacent to the swage section above the door. The swage joint is the focus for the present investigation. The period of vibration, amplitude of vibration and time to failure for these newly installed columns, observable from video footage, would indicate low-cycle fatigue as the failure mechanism. At this period of time, such failures proved to be a significant problem throughout the UK, with this particular design of column.

Commercial pressure and greater sophistication of design have resulted in lighting columns more closely matched to their design loadings without the additional strength that may have been present in earlier designs [4, 5]. In common with many industrial sectors, design envelopes are being pushed in terms of operating conditions and manufacturing costs. It is not unusual when designs are being stretched in this manner that previously unforeseen failure mechanisms manifest themselves. This has been the case with lighting columns as designs push the maximum 18/20m height limit permitted in some Codes of Practice. Modern designs often have fewer swage joints with fewer changes in section. The column shown in Fig. 1 had the same diameter of tube along its entire length above the swage joint. This results in more mass further from the base and greater sensitivity to wind-induced vibration. In many modern designs, the swage joint above the door is also more abrupt than previous designs, resulting in poorer fatigue detail as a consequence. These changes are no doubt driven by a requirement to minimise manufacturing costs.

Such “mass failure” incidents, where the design of the columns satisfy applicable Codes of Practice at the time, highlight the need for a deeper understanding of the fatigue performance of columns arising from wind induced large amplitude resonant vibration phenomena and this has in turn attracted the attention of researchers. Relevant European Design Codes for lighting columns, along with available literature, currently provide very little guidance and often inadequate detail on design requirements with regard to wind induced resonance and resulting fatigue. This is probably due to the fact that large amplitude wind-induced vibration of lighting columns, resulting in fatigue failure, is assumed not to happen for columns designed to relevant Codes of Practice [6, 7]. While guidance on the fatigue of welded steel structures in general is widely available, very few papers have been published on the fatigue failure of lighting columns. In addition, there is little or no guidance in relevant standards on the prevention of the wind phenomena, which give rise to resonant vibration in lighting columns.

Another problem with the fatigue guidance that does exist for lighting columns is that the fatigue data do not extend down into the low-cycle regime, below $10^4$ cycles. In addition the codes do not provide plasticity correction procedures or procedures for assessment where cyclic plasticity is involved.

A review of lighting column standards and guidance is provided in Ref. [8]. Also contained in this reference, is an overview of wind induced vibration phenomena and the significant parameters involved.

## 2. Experiment

### *2.1 Test Lighting Column Specification*

The 12 metre steel lighting column selected randomly for test, was designed in accordance with BS 5649 [9], now superseded by BS EN 40 [6] and manufactured to BS EN 10210 [10]. Sectional construction was completed by arc welding to BS 5135 [11]. Hot dip galvanising of the column was carried out according to EN ISO 1461 [12].

Tests were carried out to confirm that the column satisfied all tolerance and manufacturing requirements specified in these standards. The welds in particular showed an excessive variation in the thickness of the galvanised coating. A further non-compliance, as will be seen, related to the quality of the welding. It was also noted that the shoulder angle of the swage joint was on the specified limit at 35 degrees. Chemical analysis demonstrated compliance with the standards.

### *2.2 Test Details*

A shortened but otherwise full-scale lighting column was fatigue tested in cantilever bending. The test arrangement used for the low-cycle fatigue test is shown in Fig. 2. The column was mounted horizontally in a test frame (with the door facing downwards) and the load was applied via a servo-hydraulic test machine. The shortening of the column was necessary due to the particular capacity of the test machine, in terms of load, cross head travel and cyclic rate.

The shortened lighting column was instrumented with strain gauges (on both the tension and compression sides of the column) as shown in Fig. 3.

During testing, load, number of cycles, column end deflection, rig deflection and strain gauge readings were logged. The cyclic test was carried out under displacement control and the displacement amplitude of 58mm was selected to ensure that stresses in the vicinity of the weld were above initial yield.  Due to the constraints inherent in the servo-hydraulic machine, a saw-tooth cycle was applied varying from zero to 58mm. This meant that only one side of the column was subjected to maximum tensile stress and this was the door side of the column. The resulting stress cycle (neglecting the effects of yielding and weld residual stresses) exhibited a mean stress level equal to half the applied stress range.

The resonant vibration of a lighting column is inherently a load controlled process and the degree of damping as well as the natural frequency of vibration will change as the fatigue crack grows and as the column approaches failure.  The test loading represents a fixed amplitude resonant vibration and is a reasonable approach to determining the number of cycles required to grow a visible fatigue crack.

Column material properties were obtained from tests on 6 column specimens taken from the removed length of column. Prior to fatigue testing, dye penetrant testing showed no surface cracks in the welds of the column.

### *2.3 Test Results*

Testing was carried on until 16500 cycles. At this point a crack had developed at the swage joint weld toe, on the tension side of the column. The test lasted approximately 10 hours. The through-thickness crack was found to be approximately 102mm long in the hoop direction along the weld toe, as illustrated in Figs. 4 and 5.

It should also be noted that a crack had developed at the base weld of the column. This area was not the subject of the present investigation however and is clearly not relevant to the buried installations in [4].

Figure 4 shows the strain-time variation for the 10000 and 16500 cycles, for the longitudinal gauges closest to the swage joint on both the compression (a) and tensile (b) surfaces. Fig. 5(b) illustrates the strain drop-off on the gauge on the tensile side as the crack developed around the circumference of the tube. There is clearly no such drop-off on the compression side.

Shown in Fig. 5 is the location of the assumed crack initiation site on the outer surface of the column.  Due to the nature of the low cycle fatigue test, the usual beach marks, characteristic of high cycle fatigue, were not apparent in this case. This made identification of the initiation site difficult. It may also be noted that the cyclic strain range precluded ratcheting, which is another failure mechanism associated with cyclic plastic straining.

Also shown on the figure is the position of the maximum tensile stress, for reference purposes – on the outer surface at “bottom dead centre” in the test set-up.

### *2.4 Metallurgical Study*

To allow analysis of the fatigue failure, various micrographs were produced as shown in Figs. 5- 9. Section S2 was chosen as a position of through-thickness cracking, whereas sections S1 and S3 are sections where the crack has not yet propagated through the wall thickness.

First of all it may be observed in Fig. 6, that the quality of the weld is very poor. At section S1 there is lack of penetration, poor root formation, wall thinning and irregular weld profile. This un-fused weld metal is referred to as a “cold lap” and is a common problem in high deposition rate welds. They can inhibit the successful application of weld toe improvement techniques and have the practical disadvantage that the growing fatigue crack is under the weld and is therefore not visible and hence is less easy to detect. The root formation is variable across all three sections, as is the thickness of galvanised coating. Cracks are evident at the weld toe in all three sections.

The detailed micrographs for section S1 in Fig. 7 show that the toe crack, instead of propagating through the thickness, as would be expected, has joined with the “cold lap”. The fact that these “cracks” are probably due to lack of fusion is apparent in Fig. 6, as the cold lap at the root of S1 is still sealed with galvanizing.

Interestingly however, Figs. 7(a) and (c) show fatigue cracks developing from the inside surface of the tube. This is somewhat unexpected, in that the inner surface is not welded and lacks the stress concentrating toe. In addition, the nominal bending stress is not as high on the inner surface as it is on the outer. All the more surprising therefore that there is a section of the galvanised coating missing on the inner surface. It is postulated that the coating has suffered damage and eventual de-bonding from the steel substrate due the perhaps unexpected local axial compressive stresses and strains in this vicinity as seen in Figs.12 and 13. This in turn may have acted as a severe stress concentration, leading to the development and propagation of the crack shown. The galvanised coating in this general area shows evidence of significant damage and cracking. Fig. 7(d) shows a crack just starting to run from the galvanizing into the steel. It would therefore appear that the coating de-bonding scenario is not always necessary either. These are significant observations and indicate that weld improvement may not in fact increase the fatigue life of galvanised steel lighting columns. There may also be residual stresses in this region that could affect damage initiation and development.

The micrographs for section S2 in Fig. 8 show the through-crack. The precise sequence of crack growth is unknown. However, from the cracks apparent in section S1, it is possible that a similar scenario developed, with the crack from the inner surface galvanizing propagating until it met with the crack along the line of poor fusion. Fig. 8(d) shows evidence of trans-granular cracking in the steel, which is typical of fatigue.

Fig. 9 shows the normal expected fatigue crack development, initiating and running from the weld toe, through the thickness of the shell in a direction perpendicular to the maximum principal stress. Fig. 9(d) shows a fatigue crack running from the galvanizing on the outer surface into the steel. Fatigue cracking of the galvanised coating is clearly not limited to the inner surface of the tube.

The galvanising is seen to vary greatly in thickness. Thicker galvanising results in a slower cooling time, allowing more inter-metallic phase to form. Thick areas of inter-metallic phase can cause a loss of strength in the steel, owing to its embrittlement. Additionally, as shown in the micrographs, long needles are present in the zinc. These needles can act as stress raisers and may have arisen from a long emersion time or excessive temperature during the galvanising process. These factors reduce the ductility of the coating and increase the ease with which the zinc can crack and chip.

The detrimental effect of galvanizing on the fatigue performance of steel components is not new, although other studies have related to high cycle fatigue. Vogt, Boussac and Foct [13] showed that, under cyclic loading, cracks in the galvanised coating rapidly develop, propagating into the ferritic steel substrate, accelerating the fatigue damage of the material. They noted that resultant thermal pre-existing crack networks of the galvanising process were not related to the fatigue process, clearly demonstrating that the damaging of the steel substrates arises as a consequence of cracking in the coating. This is not thought to be the case in the present study however. Additionally, they observed that galvanising influences crack distribution resulting from fatigue, together with reducing the fatigue strength, particularly when the coating is thick. Under cyclic stresses, Bergengren and Melander [14] showed that the high cycle fatigue strength of high strength steel was reduced when the alloy was galvanised.

A chemical analysis of the galvanised coating on the test column was carried out for specimens at the shoulder and in the main tubing using a Glow Discharge Optical Emission Spectrometer. Results from a typical analysis are shown in Fig.10 and all maximum percentages are within the allowable as specified in EN 10210 [10]. It may also be observed for this specimen, that the coating thickness is approximately 70microns thick.

There are various ways of zinc coating components, including hot-dip galvanising, electro-plating, mechanical coating, zinc spraying and zinc dust painting. Each process results in different characteristics in relation to adhesion, continuity, uniformity, thickness, formability and mechanical properties. It is likely that in the case of a lighting column, the requirement for a fatigue-resistant coating was not part of the original specification. However, it is possible that an improvement in the mechanical properties of the coating may be made by altering the chemical composition and if necessary, coating method.

## 3. Finite Element Analysis

The linear elastic, small displacement, finite element model of the lighting column examined in the present investigation is shown in Fig. 11. A half model was used as a result of symmetry. The finite element model consisted of 16011 tetrahedral solids, as implemented in the Pro-Mechanica Applied Structure system [15] from Parametric Technology Inc. The Applied Structure system uses adaptive-p element technology. In the analysis reported, the maximum polynomial edge order was 5 with an RMS stress error estimate of 1.3%. Given the high order nature of these elements, the mesh in the vicinity of the swage joint, as shown in Figure 11, must be regarded as extremely fine, having effectively 6 solids through the thickness, each with a 5th order polynomial shape function.

The base of the column was assumed fully fixed. This is in contrast to the experimental set-up, where slight flexibility in the rig leads to much larger tip deflections due to the rigid body rotation. To ensure a valid comparison, the finite element model was not subjected to an end deflection, but instead was subjected to an end load. The load used (4655N), was the experimental load required to cause the initial 58mm experimental deflection.

Fig. 11 shows 3 areas of high stress – the base weld, the lower corner of the door opening and the swage joint. As has been previously indicated, it is the swage joint which is the focus of attention in this study.

Selected finite element results were compared with strain gauge results and hand calculations and the comparisons were generally favourable. The highest error (14%) occured in the comparison with a strain gauge 2mm from the toe of the weld. Given the steep strain gradient in this area shown in Fig. 12 and the very small length of these gauges, this is perhaps a reflection of the difficulties in precise location and alignment. The irregular nature of the weld will also influence the experimental results.

The localized nature of the stress concentration at the swage joint is illustrated in Fig. 12. The stress distribution on the toe side tends to infinity with mesh refinement, due to the singularity. The extremely localised effect due to the weld (within a quarter of the tube thickness of the weld toe) is superimposed on the gross geometric stress concentration due to the swage.

The stress distribution on the inner surface is continuous however. This distribution is terminated opposite the toe, in Fig. 12, for comparative purposes. The very steep gradient on the inner surface is also apparent and the axial bending stress becomes compressive within a distance of one wall thickness of the weld toe position. The inner surface compressive strains, shown in Fig. 13, are likely to be the source of damage to the relatively low-ductility galvanised coating in this region. This in turn will result in fatigue cracks developing from the inner surface as observed in the experiment.

## 4. Conclusions

Attention is drawn to the need for a better understanding of the fatigue performance of columns resulting from large amplitude wind induced resonant vibration. For future cost effective design and safety, further work in this area is necessary.

The swage joint was confirmed as a failure location by both experiment and finite element analysis. This in itself is not surprising and the position of the fatigue failure at the swage joint is consistent with failures observed elsewhere [4]. Of more importance is the fact that the experiment showed that galvanizing can lead to premature failure of such columns. This is a highly significant conclusion in that any improvement of the weld detail may not in fact increase the fatigue life of lighting columns coated in this manner.

It should be noted that the randomly selected specimen column did not in fact meet the requirements of the codes of practice to which it was designed, as the weld at the swage joint was of sub-standard quality and the galvanising was found to be too thick in some areas.

Given the detrimental effect of galvanizing on fatigue performance and the fact that the most severe corrosion is likely to be on the outside of columns, it is therefore possible that columns may benefit if the inner surface was not galvanised in the region of stress concentrations. An alternative improvement would be the use of a galvanizing coating with higher toughness and less susceptibility to cracking and damage.

While one test does not provide a very satisfactory basis for drawing conclusions, it is argued that the general thrust of the observations and conclusions presented in this paper are worthy of further investigation and consideration.

## Acknowledgements

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Figure1

**Figure2**

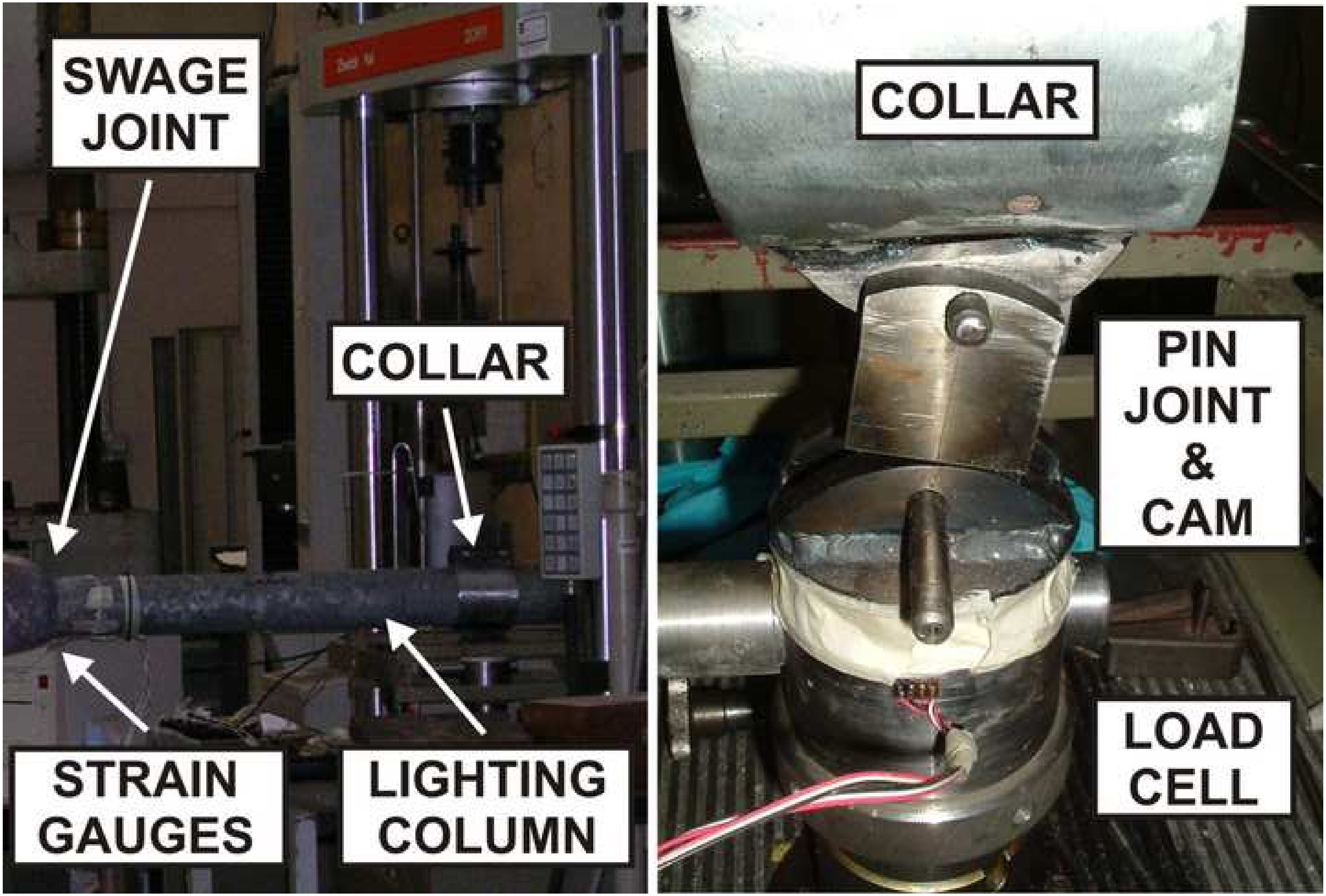
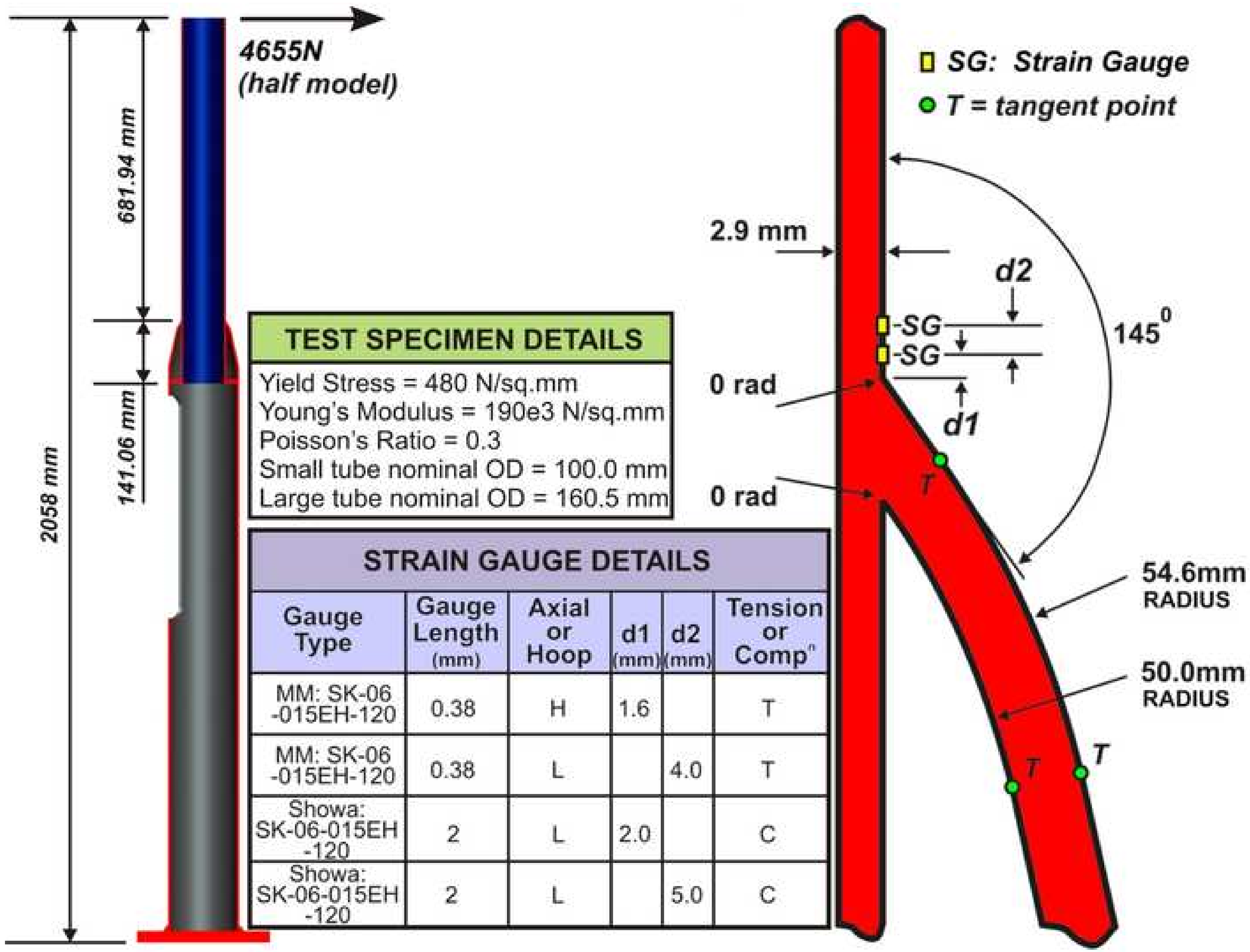

SWAGE JOINT
COLLAR
STRAIN GAUGES
LIGHTING COLUMN
COLLAR
PIN JOINT & CAM
LOAD CELL

Figure3



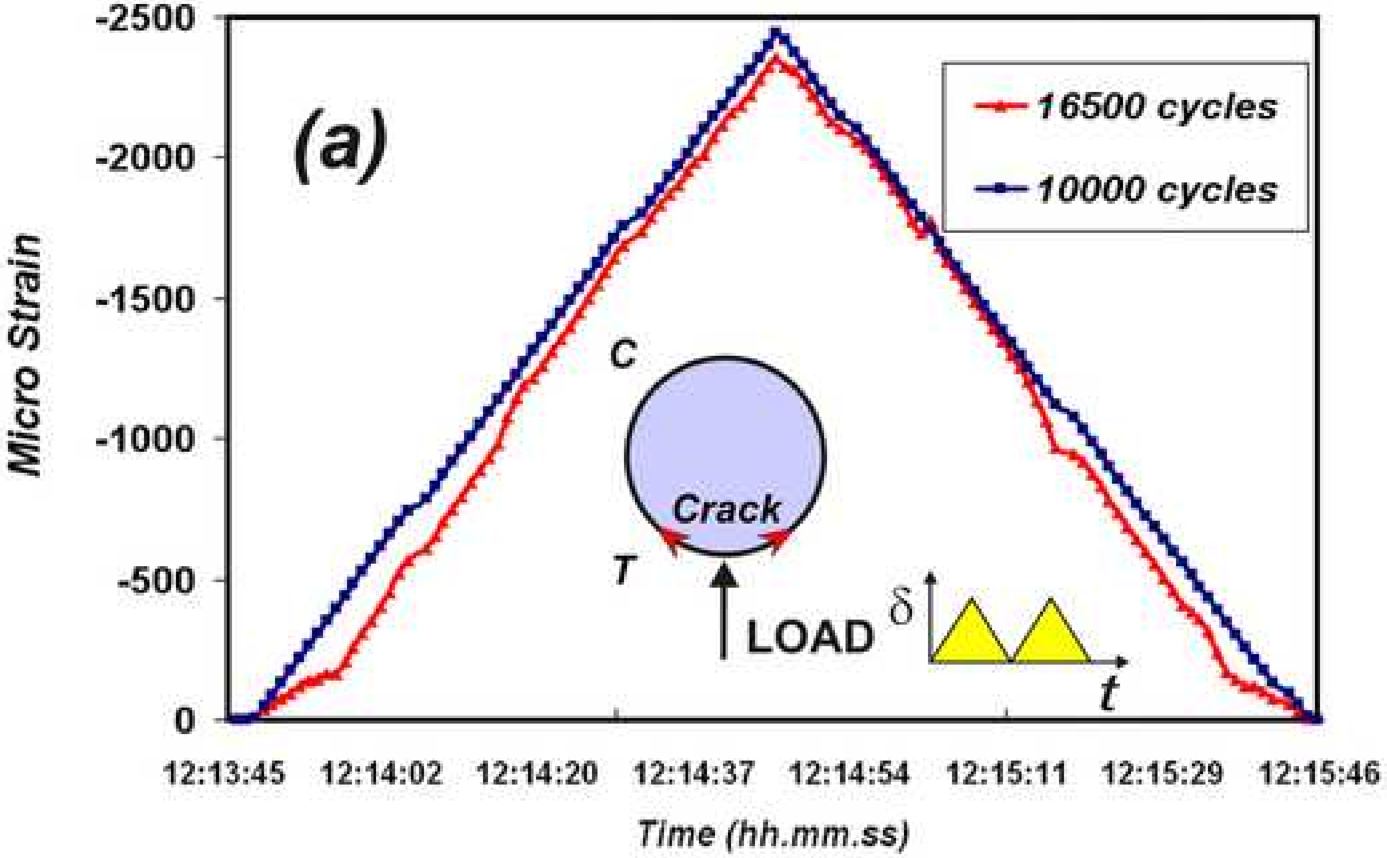
**TEST SPECIMEN DETAILS**

Yield Stress = 480 N/sq.mm
Young's Modulus = 190e3 N/sq.mm
Poisson's Ratio = 0.3
Small tube nominal OD = 100.0 mm
Large tube nominal OD = 160.5 mm

**STRAIN GAUGE DETAILS**

| Gauge Type | Gauge Length (mm) | Axial or Hoop | d1 (mm) | d2 (mm) | Tension or Comp" |
|---|---|---|---|---|---|
| MM: SK-06 -015EH-120 | 0.38 | H | 1.6 | | T |
| MM: SK-06 -015EH-120 | 0.38 | L | | 4.0 | T |
| Showa: SK-06-015EH -120 | 2 | L | 2.0 | | C |
| Showa: SK-06-015EH -120 | 2 | L | | 5.0 | C |

Figure4


(a)
Micro Strain
-2500
-2000
-1500
-1000
-500
0
16500 cycles
10000 cycles
C
Crack
T
LOAD
δ
t
12:13:45
12:14:02
12:14:20
12:14:37
12:14:54
12:15:11
12:15:29
12:15:46
Time (hh.mm.ss)

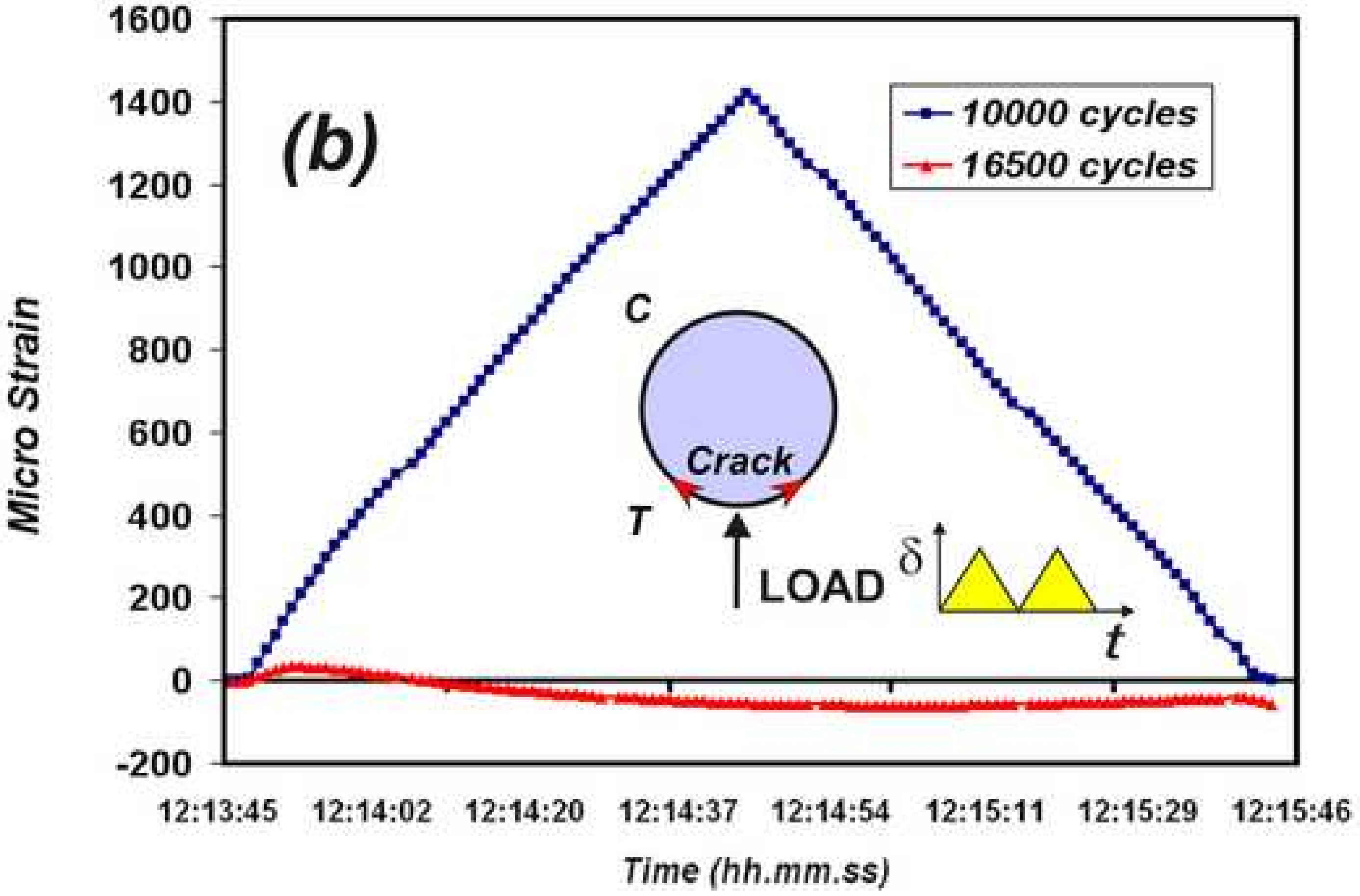

(b)
Micro Strain
1600
1400
1200
1000
800
600
400
200
0
-200
10000 cycles
16500 cycles
C
Crack
T
LOAD
δ
t
12:13:45
12:14:02
12:14:20
12:14:37
12:14:54
12:15:11
12:15:29
12:15:46
Time (hh.mm.ss)

Figure5

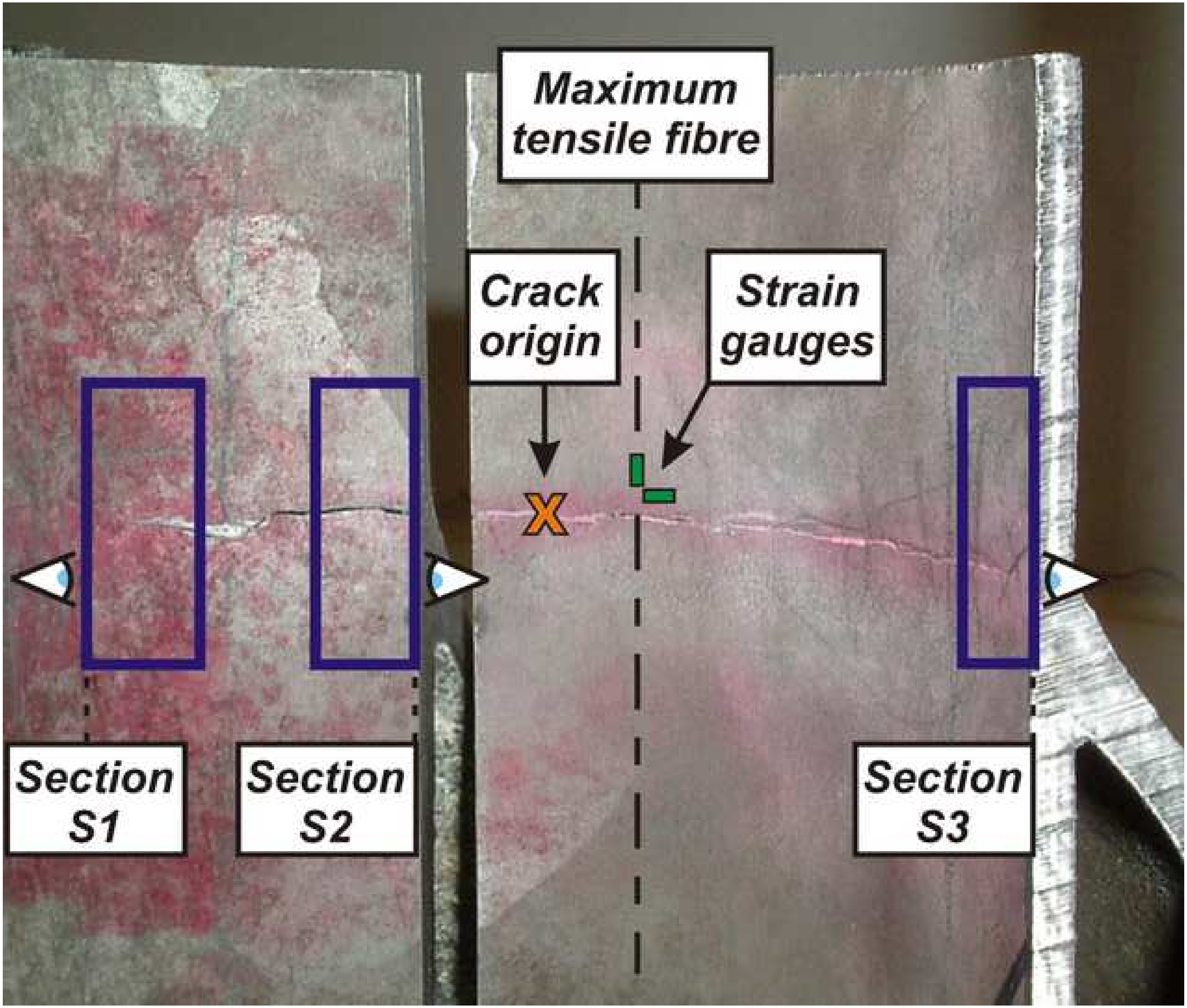

Maximum tensile fibre
Crack origin
Strain gauges
X
Section S1
Section S2
Section S3

Figure6

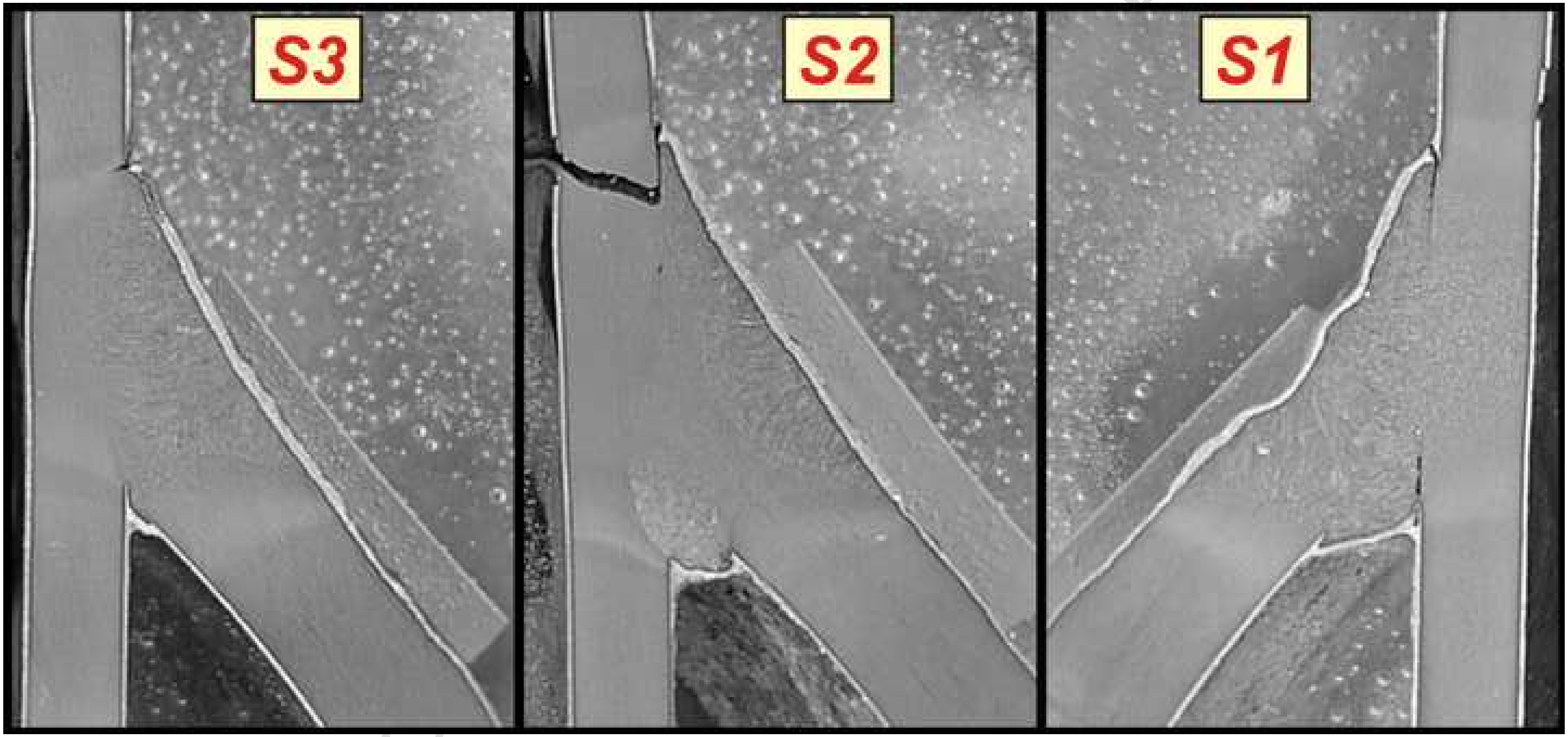


Figure7

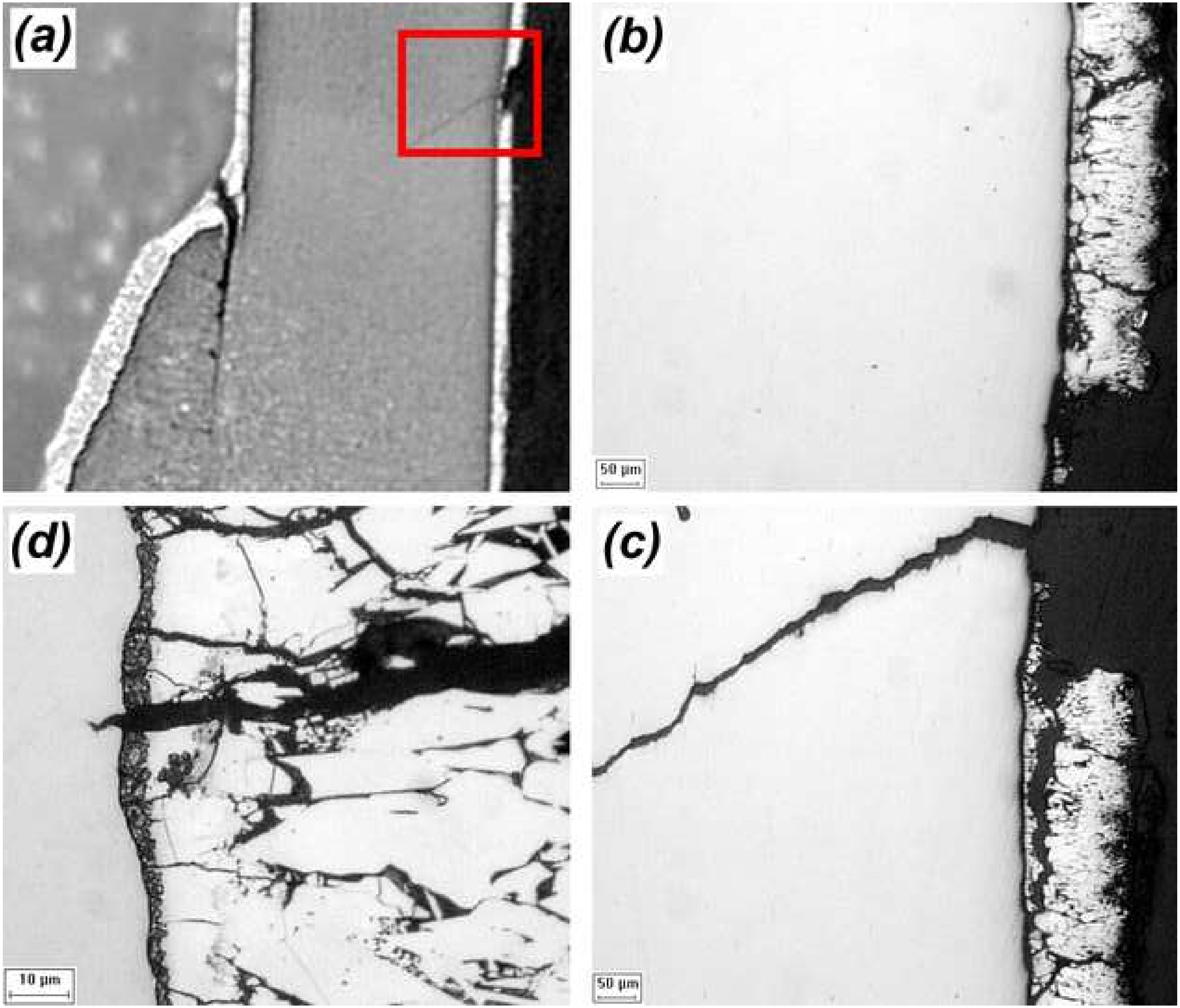


Figure8

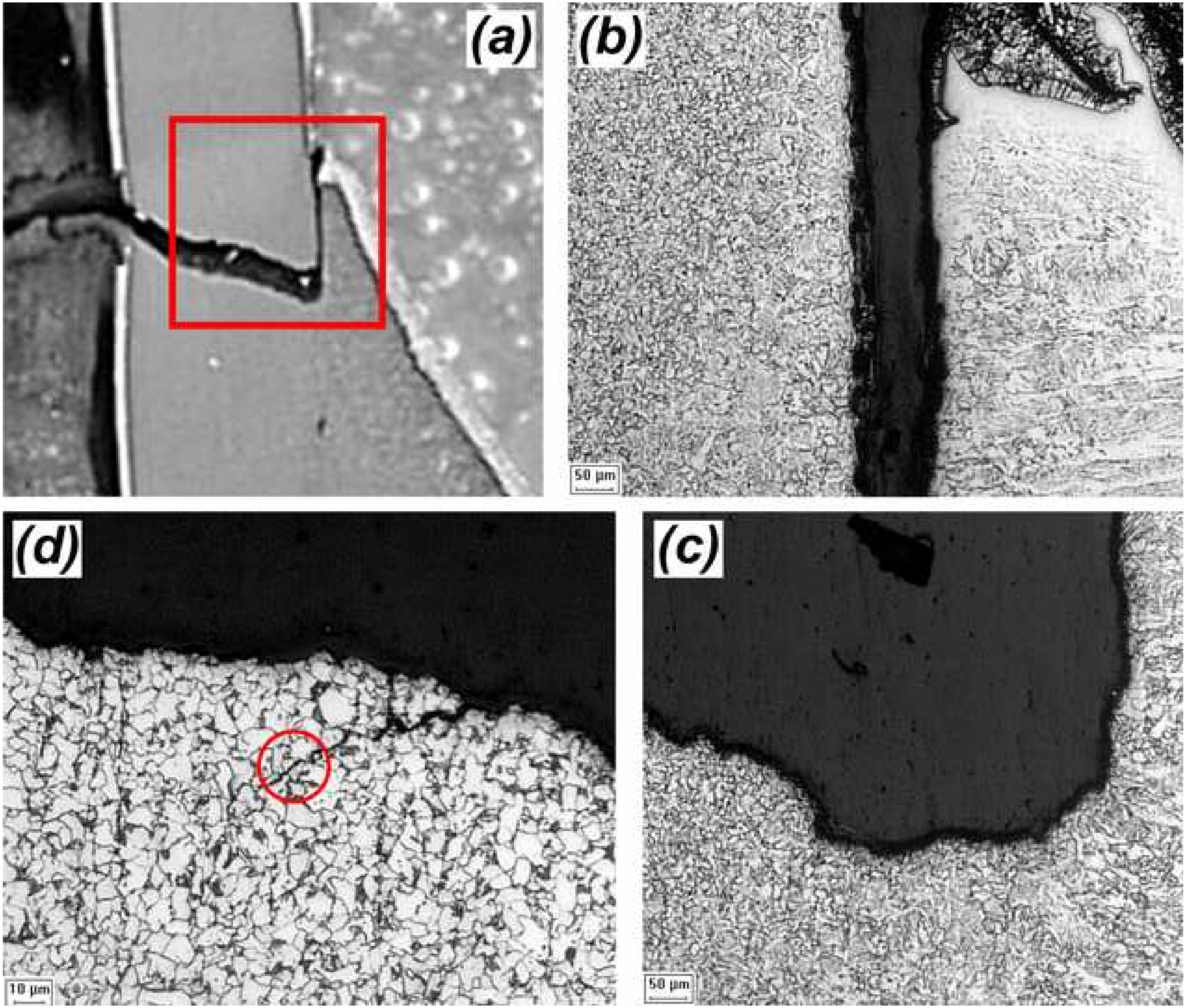


**Figure9**

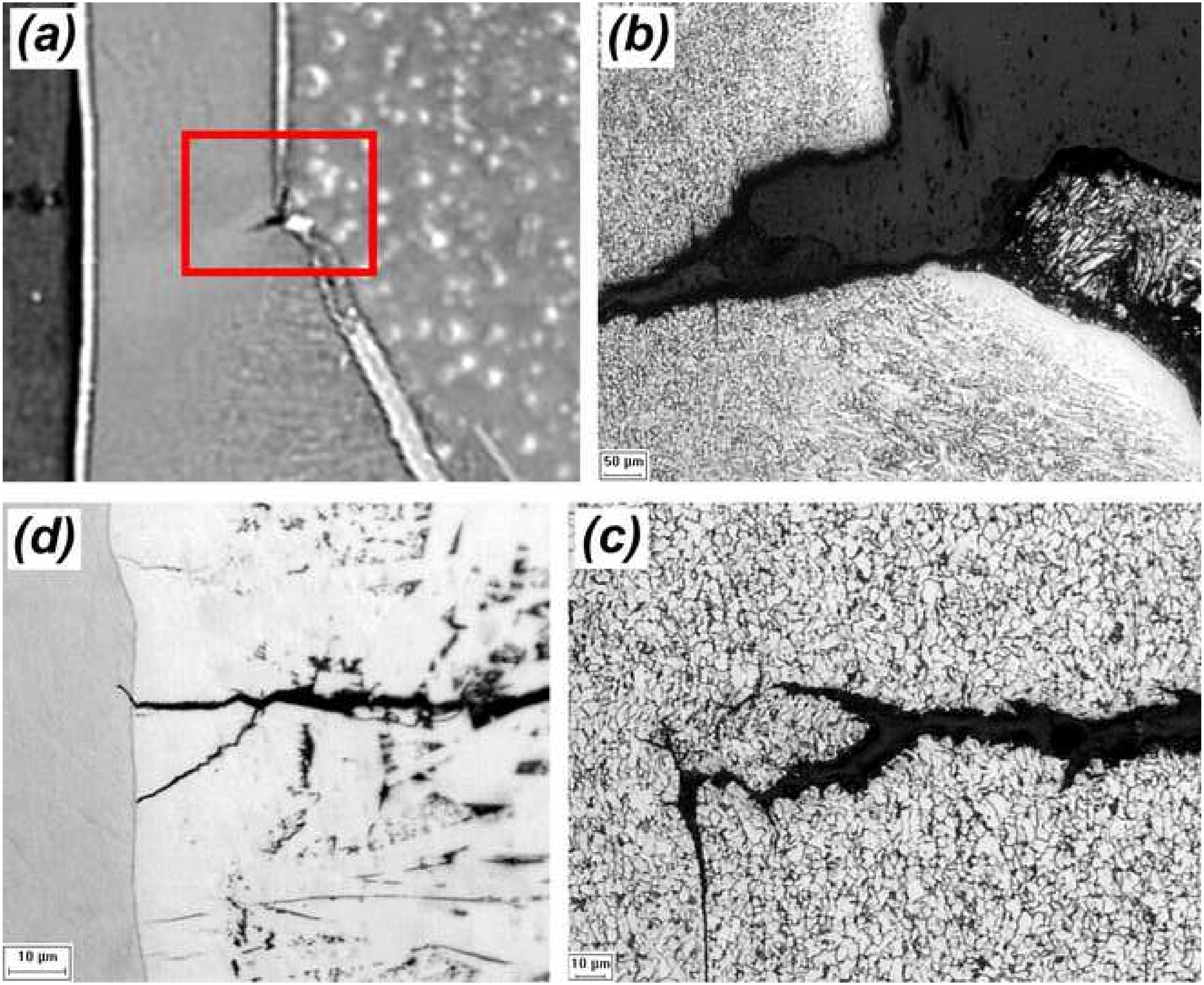


Figure10

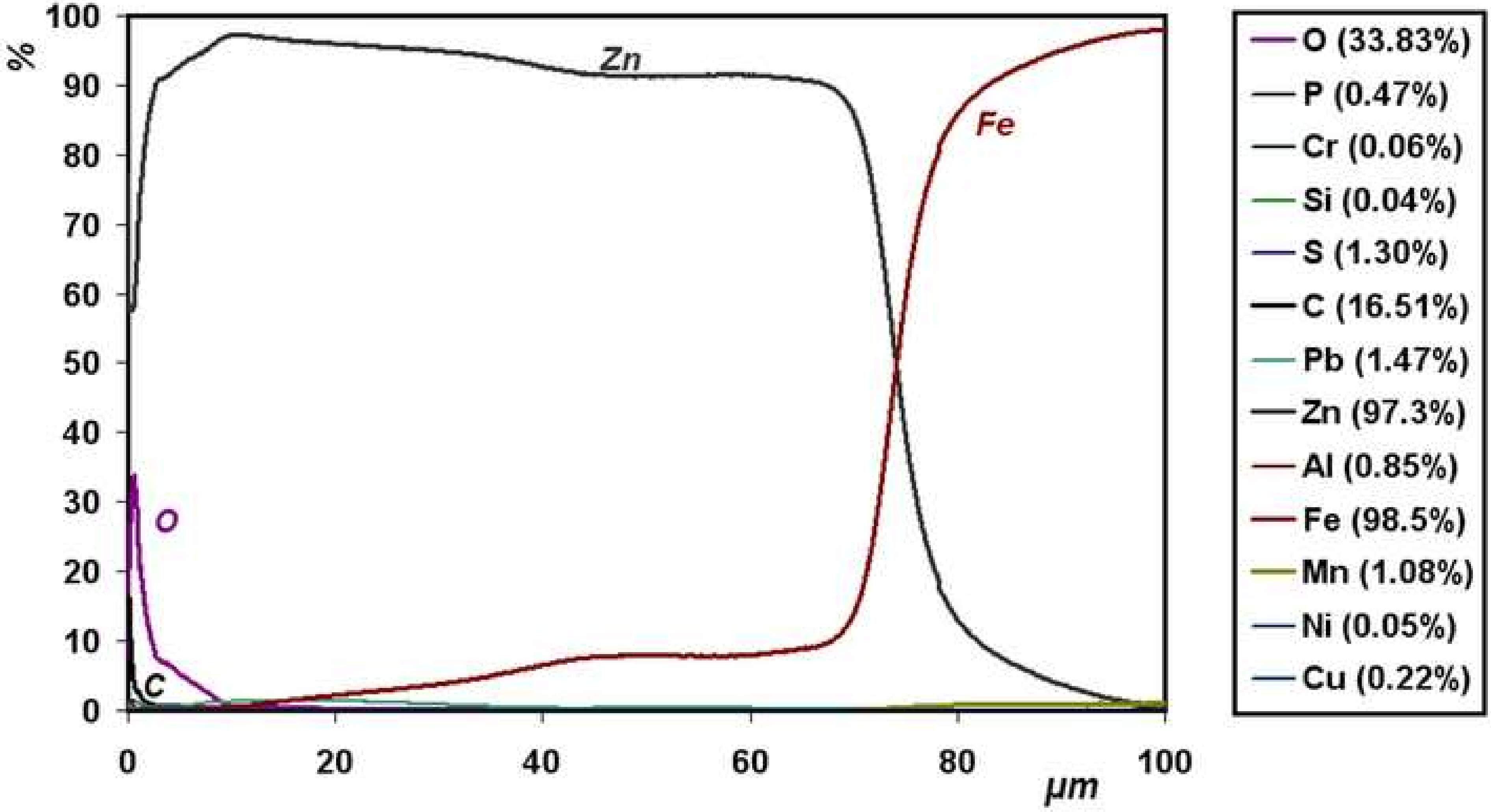

%
100
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
µm
Zn
Fe
O
C
O (33.83%)
P (0.47%)
Cr (0.06%)
Si (0.04%)
S (1.30%)
C (16.51%)
Pb (1.47%)
Zn (97.3%)
Al (0.85%)
Fe (98.5%)
Mn (1.08%)
Ni (0.05%)
Cu (0.22%)

Figure11

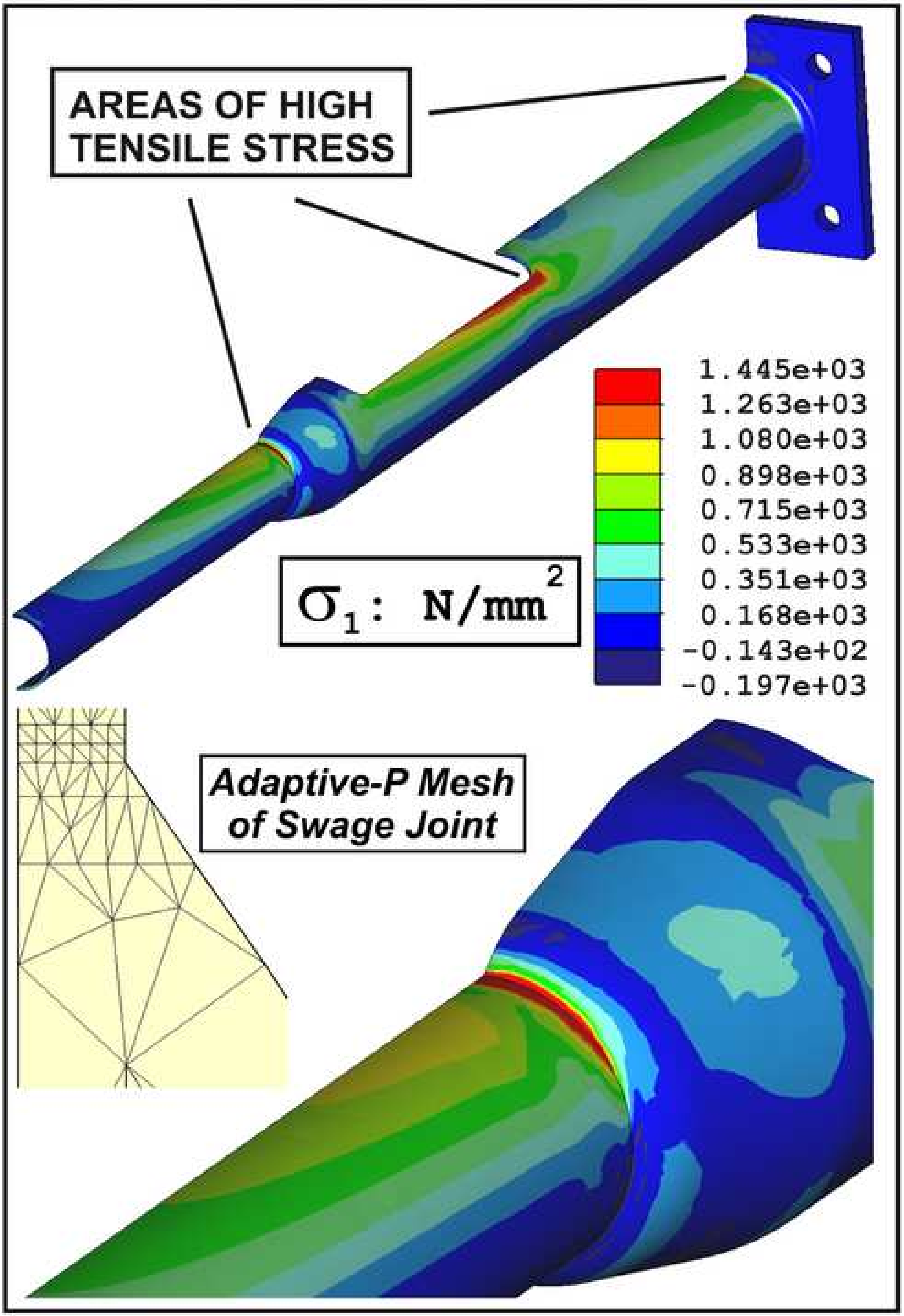

AREAS OF HIGH
TENSILE STRESS
1.445e+03
1.263e+03
1.080e+03
0.898e+03
0.715e+03
0.533e+03
0.351e+03
0.168e+03
-0.143e+02
-0.197e+03
$\sigma_1$: N/mm$^2$
Adaptive-P Mesh
of Swage Joint

**Figure12**

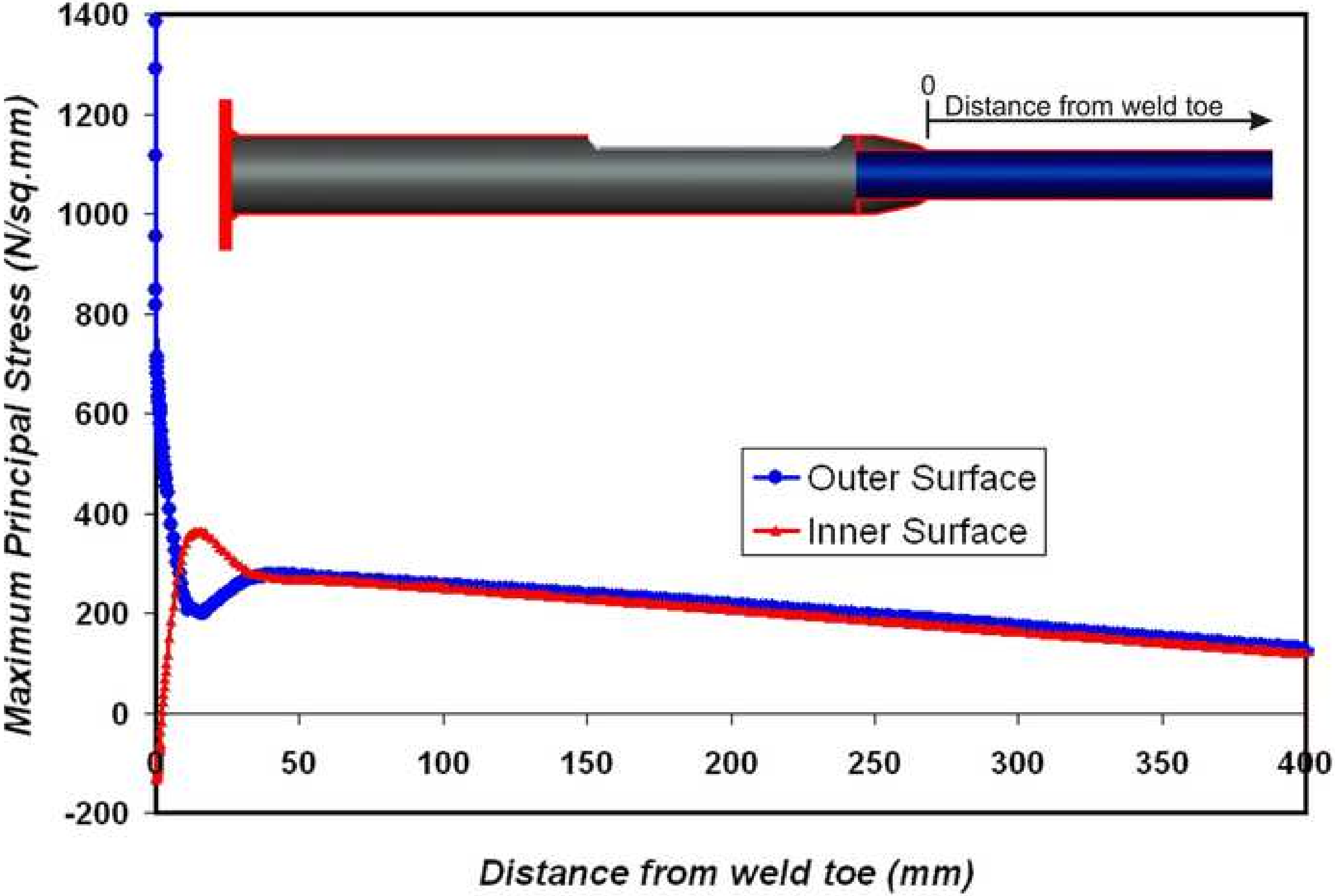
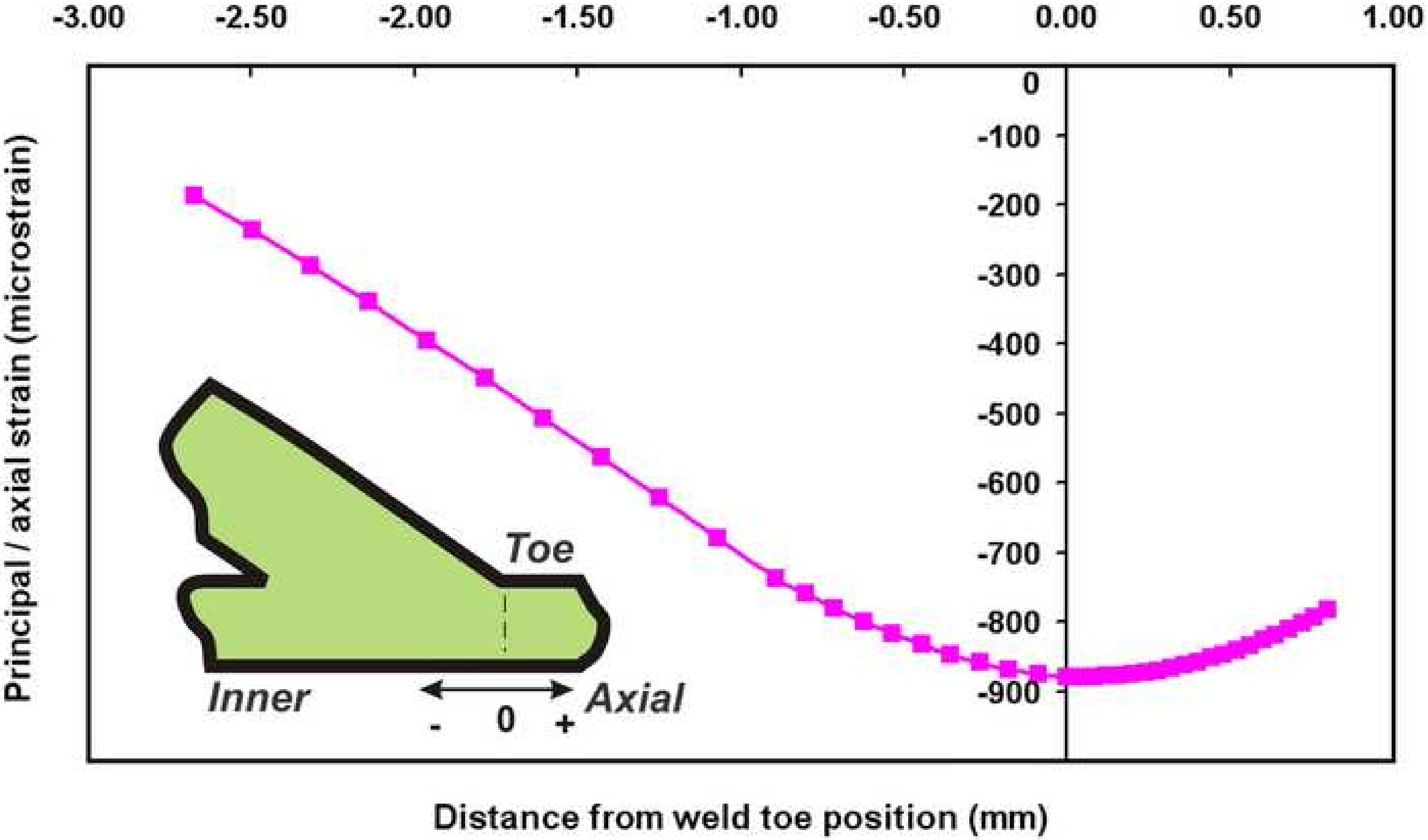

Maximum Principal Stress (N/sq.mm)
1400
1200
1000
800
600
400
200
0
-200
0
50
100
150
200
250
300
350
400
Distance from weld toe (mm)
0
Distance from weld toe
Outer Surface
Inner Surface

Figure13


-3.00
-2.50
-2.00
-1.50
-1.00
-0.50
0.00
0.50
1.00
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
Principal / axial strain (microstrain)
Toe
Inner
Axial
-
0
+
Distance from weld toe position (mm)