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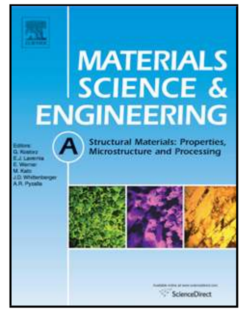

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Effect of Shot Peening on the Fatigue Behaviour of Cast Magnesium A8

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Abstract

Shot peening is known to improve the fatigue performance of structural metallic materials. The improvement in fatigue life is derived primarily from compressive residual stresses that are introduced into the near-surface of the components and which hinder crack initiation and growth. Magnesium alloys are finding increasing use in automotive applications, but their relatively low strength means that they are highly susceptible to fatigue failures. This is particularly the case for cast alloys which may contain high levels of porosity. Shot peening may be of use, but the beneficial effect of the compressive stress may be offset by the surface damage associated with peening of a soft material.

In this study the fatigue life of sand-cast A8 magnesium alloy has been investigated before and after a shot peening treatment to investigate whether shot peening is beneficial for a component with this combination of relatively low strength and relatively poor initial surface finish. Previous studies into the effect of shot peening on magnesium alloys have been limited to wrought alloys and there has been little work on the influence of shot peening on cast magnesium alloys. The residual stress before and after peening was determined by incremental hole drilling which shows that the peening process generated a compressive residual stress in the cast specimens. The fatigue results show that the fatigue life is significantly improved by the shot peening process, and there is also an improvement in the endurance limit. An increase in the surface roughness of the samples was found after peening but this was not found to be detrimental to the fatigue performance.

Keywords

Magnesium, shot peening, fatigue, residual stress

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1 Introduction

Magnesium alloys are increasingly finding applications in the automotive sector. Although magnesium's elastic modulus is low for an engineering alloy, at 40 GPa, its cast alloys can have strengths in excess of 200 MPa, which gives them better strength-to-weight ratios than many aluminium alloys; hence they are attractive materials for reducing weight [1-4]. They are particularly used in motorsport where the relatively high cost of using magnesium alloy is offset by the benefits in performance.

One of the drawbacks of magnesium alloys however is that magnesium has an hexagonal close-packed crystal structure which limits the number of available slip systems [5-7]. Thus, magnesium alloys are relatively brittle, and it is difficult to manufacture components with complex geometries (such as wheels) by forging, and therefore for many applications magnesium components are produced by casting. This has the benefit of being able to produce the necessary complex geometries, but care must be taken to control the level and location of porosity in order to produce components with optimum strength and fatigue properties.

Shot peening is a mechanical surface treatment that is known to improve the fatigue strength of many materials by producing a beneficial near-surface compressive residual stress [8, 9]. The improvement in fatigue life stems from a combination of work hardening of the surface and an increased dislocation density, and the introduction of a near-surface compressive residual stress. Compressive surface residual stresses helps to improve the life of engineering components by retarding fatigue crack initiation and growth [10, 11]. Depending on the peening conditions used and the initial surface state, there may also be an improvement in surface finish.

Previous work on the effect of shot peening on wrought magnesium alloys has shown that peening can be beneficial as long as the peening process parameters are carefully selected [12-14]. The benefits were attributed to process-induced changes in near-surface dislocation densities and the development of residual compressive stresses which reduced the tendency for fatigue crack nucleation and hindered microcrack growth. Zhang *et al.* [15] studied the effect of varying peening parameters on the fatigue life of wrought AZ80. They found that the fatigue strength increased from 100 to 160 MPa for optimum peening conditions.

There has been little work on the effect of peening on cast magnesium alloys, although there have been previous studies on cast irons for example where the peening process was beneficial in closing up surface porosity from the casting process [16].

The aim of the work in this paper was therefore to investigate whether cast magnesium alloy specimens would benefit from being shot peened, or whether the fatigue life was dominated by residual porosity from the casting process.

2 Experimental Details

Sand-cast A8 (L22) magnesium alloy (nominal composition: 7.5Al, 0.3 Zn, 2.2 Mn, balance Mg) was received as cast billet from Dymag Ltd. Constant stress beam specimens (see figure 1) were machined from the billet for flexural fatigue testing [17, 18]. This geometry was chosen as it was amenable to good coverage by the peening process, and during fatigue the stress in the specimen is concentrated on the outer surface of the specimen: therefore it is a particularly good test for assessing the effects of the peening process. Typical tensile properties of A8 are 0.2% proof stress 80 MPa, tensile strength 200 MPa and Young's modulus 44 GPa. Optical microscopy was used to examine the microstructure of the A8 samples and determine the level of porosity, which was found to be approximately 2.2%.

Fatigue testing was performed using an MTS 810 servo-hydraulic testing machine. The set-up is shown in figure 2. A cyclical sinusoidal displacement of 10Hz with an R ratio of –1 was applied to the specimens. Run-out was defined as no failure after 10^7 fatigue cycles.

Shot peening was performed by Metal Improvement Company Ltd, using their recommended peening procedure for improvement of the surface integrity of alloyed magnesium. The peening process used glass beads (0.245 mm diameter) with a peening intensity of 0.127 mmN (which is relatively low) and a coverage of 200%. The surface roughness was measured before and after the peening process with a Talysurf profilometer.

Fracture surfaces of the fatigue specimens were examined by scanning electron microscopy using a Philips XL30 ESEM. Typical imaging conditions used an accelerating voltage of 15kV and spot size 5 in order to maximise resolution and minimize beam spreading. Energy dispersive X-ray analysis was performed using an Oxford ISIS 310.

2.1 Residual stress measurement

The near-surface residual stress profile in samples of the material was determined using incremental hole drilling. The measurements were performed using a Stresscraft Ltd incremental driller, with strain relaxation being monitored by Measurements Group gauges in a standard three-gauge rosette (two gauges at 90˚ with a third at 45˚). The measurements were performed according to the guidance given in the UK NPL Good Practice Guide [19]. A hole of nominal diameter 2 mm was introduced by orbital hole drilling, and the final diameter of the hole was measured accurately (to 0.01 mm) after drilling. The relaxed strains were recorded at 16 depth increments: four increments of 32 μm, four increments of 64 μm, and eight increments of 128 μm, to a total hole depth of just over 1.4 mm. Increasing the increment size with depth counters the reduced sensitivity of the surface gauges as the hole depth increases [19]. Strains from the three gauges were recorded at each drill increment, using a Measurements Group P2 strain gauge amplifier.

The results were interpreted using the integral method developed by Schajer [19, 20], with Stresscraft RS INT software version 5.1.2. The integral method is an extension to standard hole drilling analyses which allow for calculation only of stresses that are invariant with depth. A Young's modulus of 44 GPa and Poisson's ratio of 0.3 were used in calculating the stresses.

An attempt was made to validate the hole drilling results using laboratory X-ray diffraction, but the samples proved to have a crystallographic texture which made it impossible to obtain results using the conventional d vs. $\sin^2\psi$ technique. Individual diffraction peaks were only intermittently present in the diffraction spectrum at different ψ–tilts, and the peening process did not appear to alleviate this. The presence of texture is likely, as this has been observed previously in cast magnesium alloys.

3 Results and Discussion

Figure 3 shows the S-N data for the peened and as-machined samples. It can be seen from this figure that the shot peened specimens show an increase in fatigue life as compared to the as-machined specimens across the whole range of stress amplitudes, as well as an increase in the fatigue limit.

The data does show some scatter, and hence the statistical analysis methods outlined in Standard BS ISO 12107 were applied. The S-N results for a 10% failure probability at a 95% confidence level are shown in figures 4a and 4b for the unpeened and peened samples respectively. Figure 4c shows the comparison between the analyses of the peened and unpeened sample sets.

The average increase in fatigue life for shot peened specimens is often greatest at lower stress amplitudes and diminishes at higher stress amplitudes. At higher stress amplitudes the residual stresses imparted by the peening process are often quickly overcome [21] whilst at lower stress amplitudes the peening can give an order of magnitude improvement in resistance to fatigue life. Figure 5c shows that the improvement in fatigue life is good over the whole spectrum of stress amplitudes tested here. The variation is from a factor of around 2.5 at a stress amplitude of 100 MPa increasing to over 5 at a stress amplitude of 70 MPa. These increases are significant, and show that the peening treatment may be highly attractive in improving the fatigue life of magnesium components. There is also an increase in the endurance limit at 10^7 cycles, from around 50 to 65 MPa, an increase of 30% in the available applied stress amplitude.

The residual stress profiles measured using hole drilling are shown in figures 5 and 6 for as-received, as-peened, and peened-and-fatigued samples. The sample that was fatigued following peening was subjected to a cyclic loading with a applied peak stress of 92 MPa until failure occurred after 112,000 cycles. A near-surface peak residual compressive stress of just over 100 MPa was observed in all the samples that were studied, with the peak stress measured at a depth of around 100 μm, and an overall profile which is typical of that expected from a shot peening process. The results from the fatigued sample appear to show a slight reduction in the peak residual stress, although it is relatively small (20% or less): however, this may be due to the interaction of the applied loading with the residual stress field causing some shakedown of the residual stress. Overall, it appears that the residual stress introduced is sufficiently high not to be changed significantly by the applied loading, as evidenced by the fact that there is an improvement in fatigue life even at the highest stress amplitude that was used.

Scanning-electron-microscope images of the surfaces of the samples before (figure 7a) and after (figure 7b) the peening process. Microscopic cracking and flaking are evident on the surface after peening. The surface profilometry was used to obtain R_a values (R_a is the most commonly used parameter to describe average surface roughness and is defined as total area of the peaks and valleys divided by the evaluation or cut-off length on the profilometer). The R_a value for the as-machined samples was 0.61 μm as compared to 1.25 μm after peening. The R_t (maximum peak to valley height) also increased from 4.86 μm for the as-machined samples to 12.8 μm for the peened samples. These results show that the surface of the peened samples was significantly rougher than the as-machined surfaces.

In order to examine whether the machining and peening processes were influencing the fatigue failures, scanning electron microscopy was used to carefully examine the crack paths. Figure 8a shows a macrograph of the fracture surface of one of the shot peened specimens. In all the samples observed, there was evidence of shrinkage porosity (figure 8b) and crystallographic slip on the fracture surface, mainly near to the fatigue initiation surface (figure 8c). There was no discernible difference in the observable fatigue mechanisms between the peened and unpeened samples, although the peened samples did show a small smooth region on the fracture surface on the edge from which the crack initiated (the upper surface in figure 8c), which may be attributable to the compressive peen stresses causing fretting of the fatigue surfaces during the early stages of crack growth.

Further detail of the mechanics of crack growth in this material can be observed in figure 9. Figures 9a-e show a series of micrographs from the surface of an as-machined sample where fatigue testing was stopped after the onset of cracking, but before complete failure of the specimen. Figure 9a shows a low magnification view of the crack from which several features are evident and shown in greater detail in figures 9b-e. The crack appears to have initiated in a porous region of the specimen (figure 9b) and initially appears intergranular in nature. A secondary crack can be seen in figure 9c branching away from the main crack. It should be noted that neither of the cracks in figures 9b or 9c either initiated at or follow the machining marks that are evident on the specimen surface, but instead appear to be following grain boundaries in the material. The intergranular nature of the cracking is reinforced in figure 9d where two almost-triangular regions can be seen in the fracture path which would be expected from the hexagonal nature of the magnesium's structure. Debris can also be seen on the surface from the mating of fracture surfaces during the fatigue cycling. There is also some evidence of intragranular cracking (see figure 9e) where the slip planes can be seen inside the fracture surface. Thus it appears that the cracking is mainly intergranular but with some intragranular cracking and that the machining effectively plays no role in the failure of the specimens.

Figure 10 shows an energy dispersive X-ray map of a polished A8 specimen. From this it can be seen that the aluminium and zinc additions in the alloy have segregated to the grain boundaries. This probably forms a brittle grain boundary phase and explains the intergranular nature of the crack propagation that was observed in figures 9a-d. A crack running through this grain boundary phase can be seen in figure 11, which shows a crack on the fracture surface of one of the shot-peened specimens.

Scanning electron microscopy was also used to examine the peened specimens in detail but no interaction was observed between the micro-flakes and micro-cracks from the peening process and the propagation of cracks. Shrinkage porosity in the magnesium samples varied considerably in size but was large (typically 200-500μm in size) compared to hexagonal voids that were sometimes found to occur around inclusions (see e.g. figure 12) as grain growth occurred during solidification.

Conclusions

1 The effect of shot peening on the fatigue behaviour of cast magnesium A8 has been investigated. Shot peening has been found to offer a significant improvement in the fatigue life, with an increase in the fatigue life of up to five times depending on the applied stress amplitude, and a 30% increase in the endurance limit of the material.

2 Hole-drilling residual stress measurements show that the peening introduces a compressive residual stress in excess of 100 MPa within a depth of 100 μm from the surface. The residual stress profile does not evolve significantly with fatigue loading.

3 The peened samples show a significantly higher surface roughness than the as-machined condition. However, crack initiation appears to occur from residual porosity in the samples, rather than from surface features that can be attributed to the peening. It can be surmised therefore that the compressive residual stresses act to retard the initiation and growth of fatigue cracking from the residual porosity and surface damage.

4 Crack growth occurred by a mixture of inter- and intra-granular fatigue. The fatigue crack path was seen to be relatively tortuous, which was attributed to bifurcation and deflection of the crack at the boundaries of the hexagonal grains.

5 Overall it can be concluded that the peening process provided a beneficial improvement in fatigue life, with the residual stress field acting to retard the initiation and growth of cracks. Initiation of fatigue damage was at areas of residual porosity, and the rougher surface introduced by the peening process did not have a negative effect on fatigue life.

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Figure Captions

Figure 1 Constant stress beam geometry used for the specimens. All dimensions are in mm. The holes are 5mm diameter and the plate thickness was 3mm.

Figure 2 Specimen positioning in the MTS servohydraulic testing machine.

Figure 3: Stress amplitude versus number of cycles to failure for the peened and as machined samples (10^7 cycles indicates run-out)

Figure 4a: S-N data for the unpeened sample. The line shows the predicted S-N behaviour for a 10% failure probability, according to BS ISO 12107. The run-out samples were not used in the calculation.

Figure 4b: S-N data for the peened sample. The line shows the predicted S-N behaviour for a 10% failure probability, according to BS ISO 12107. The run-out samples were not used in the calculation.

Figure 4c: Comparison of the 10% failure probability predictions for the unpeened and peened specimen data

Figure 5: Principal stresses determined using hole drilling for the as-peened sample.

Figure 6: Principal stresses determined using hole drilling for the peened-and-fatigued sample.

Figure 7a – as machined surface finish

Figure 7b As peened surface finish. Microscopic cracking (labelled M) and flaking (labelled F) are evident on the surface (arrowed).

Figure 8a: Fracture surface of a shot-peened sample

Figure 8b: Shrinkage porosity on the fracture surface of figure 8a

Figure 8c: Crystallographic slip near the fatigue initiation surface of figure 8a.

Figure 9a Low magnification image of the crack path in as as-machined sample

Figure 9b Crack initiation in a porous region of the sample

Figure 9c Bifurcation of crack showing intergranular nature of cracking

Figure 9d Evidence of crack following grain boundaries around the hexagonal grains.

Figure 9e Evidence of intragranular cracking as the crack follows the material's slip planes. Note also the lack of influence of the machining marks on crack propagation.

Figure 10 Backscattered electron image of the grain boundary phase observed in a polished A8 specimen and corresponding energy dispersive X-ray maps for magnesium, aluminium and zinc. It can be seen that the aluminium and zinc alloying additions have segregated to the grain boundaries.

Figure 11: Crack running through the grain boundary phase on the fracture surface of one of the shot-peened specimens.

Figure 12: Porosity formed around an inclusion during the casting process in one of the samples that was subsequently shot-peened. Note that this is a much smaller structural flaw than the region of shrinkage porosity in figure 12.

Figure 1

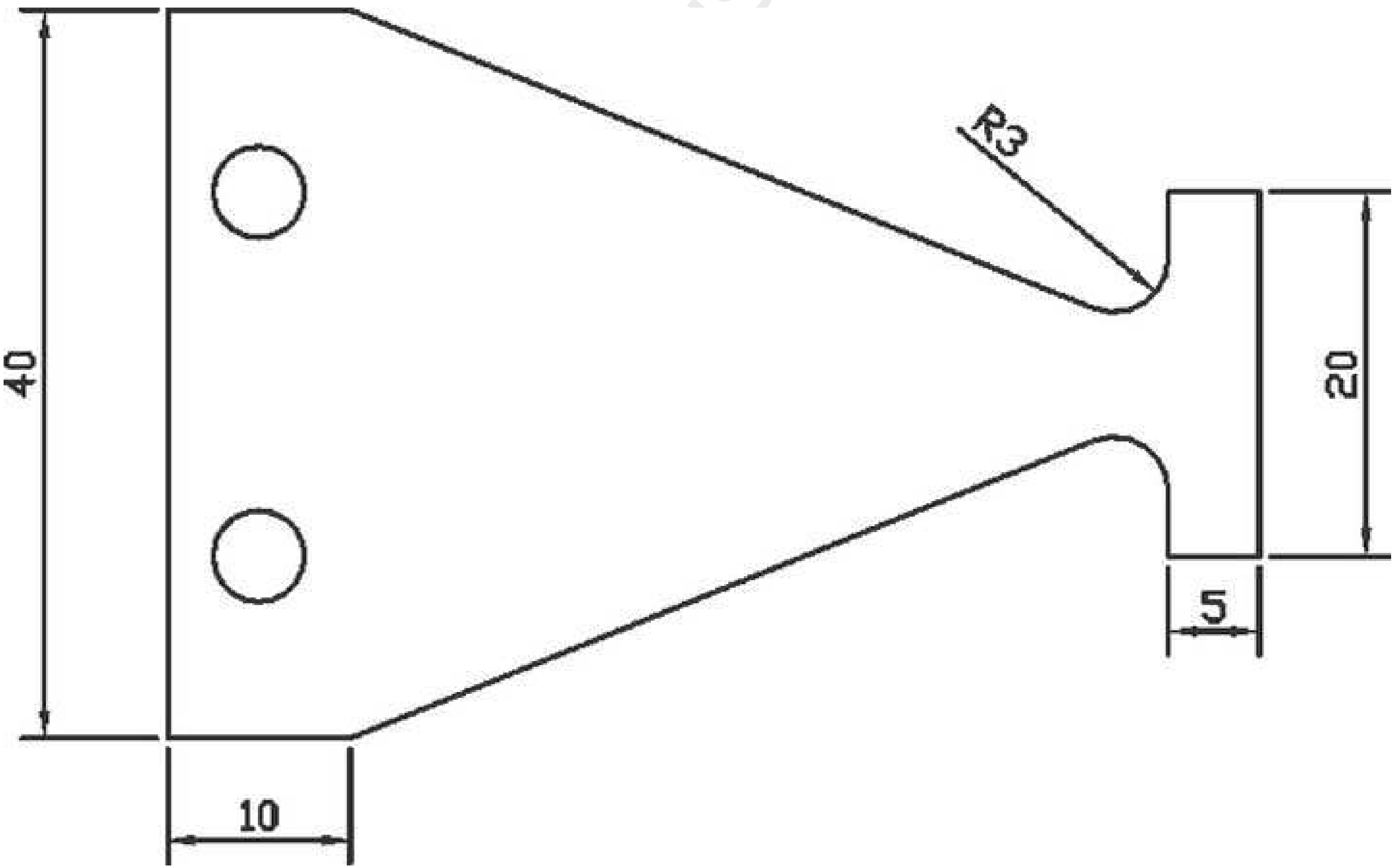


Figure 2

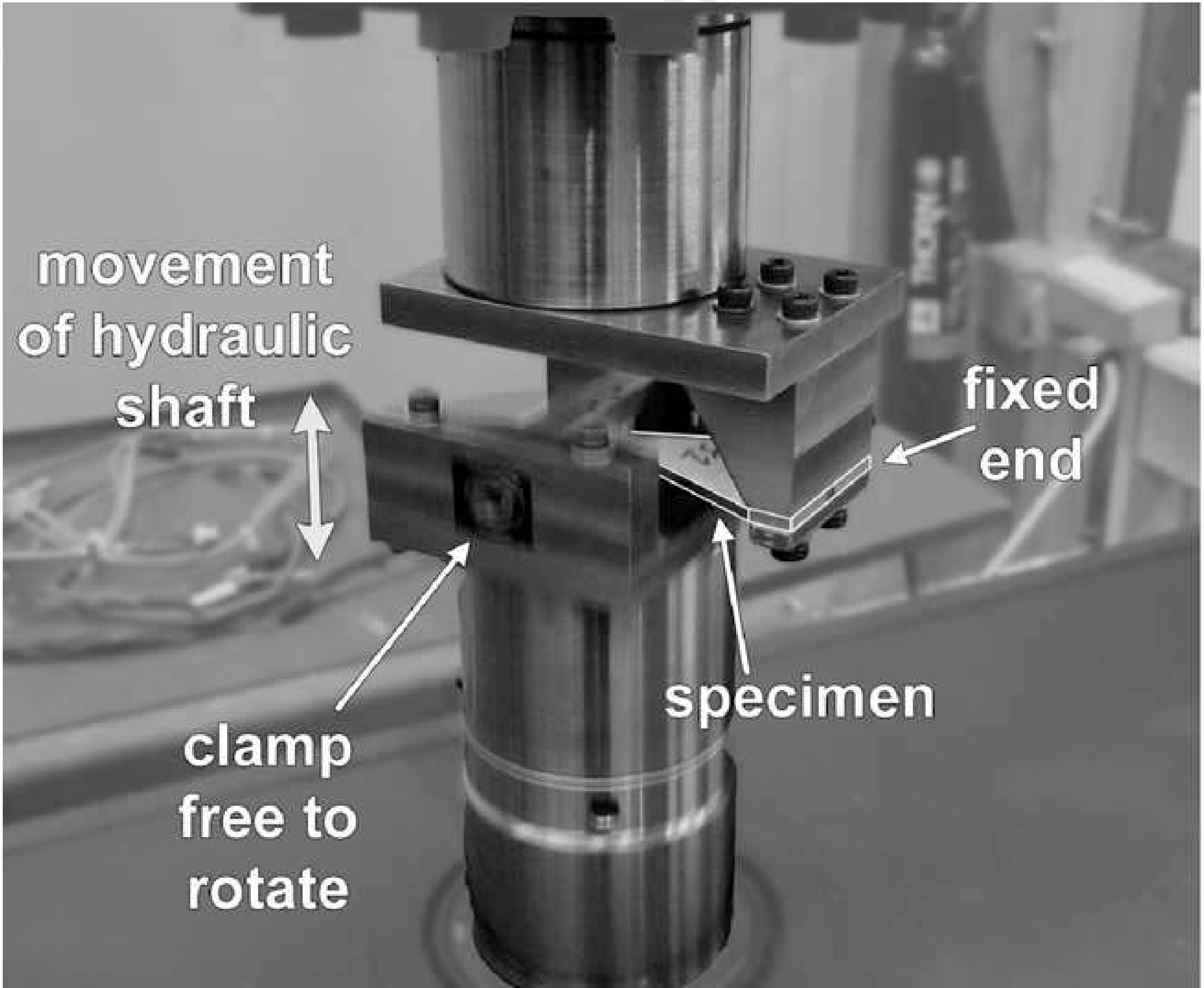
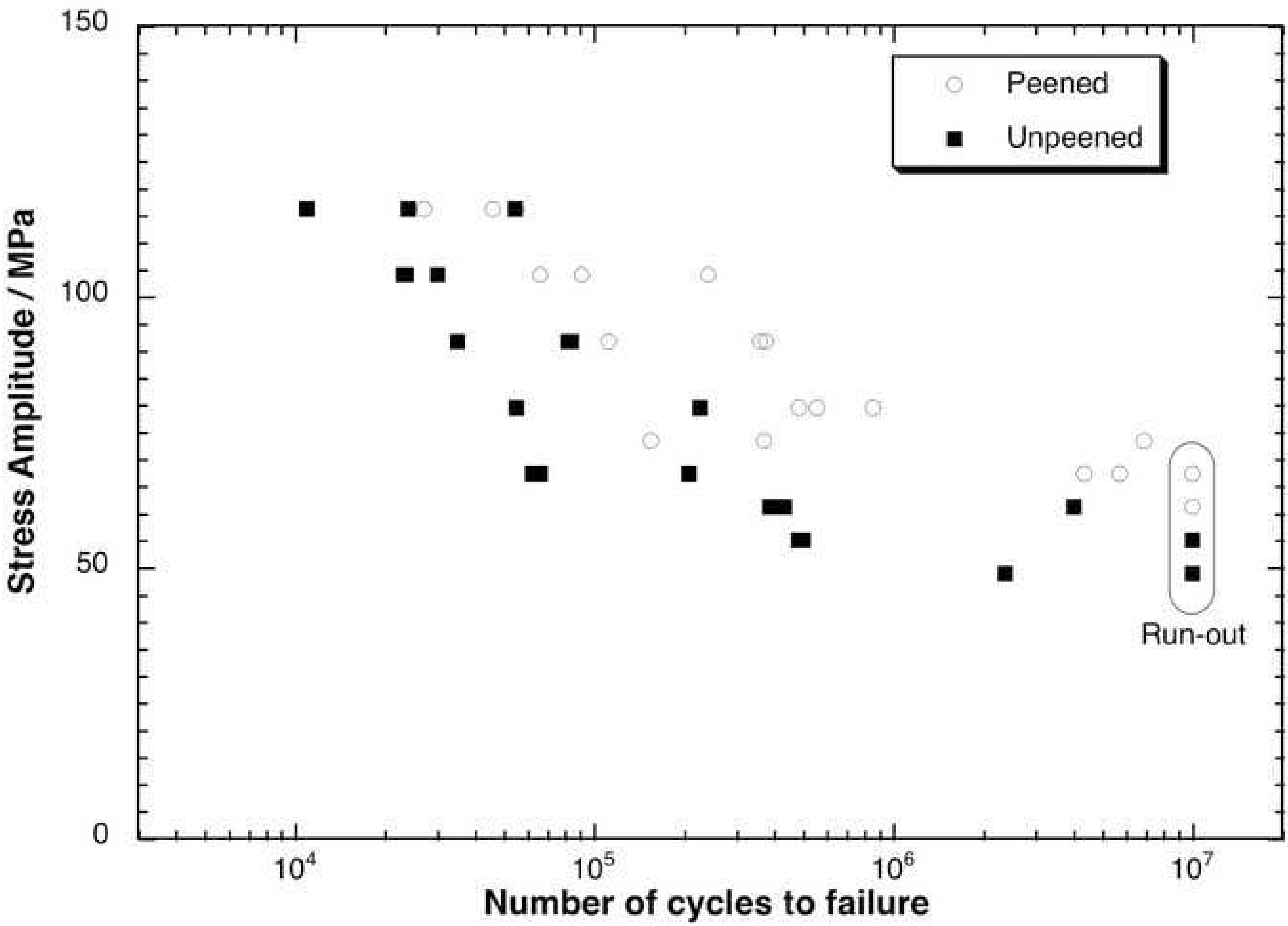
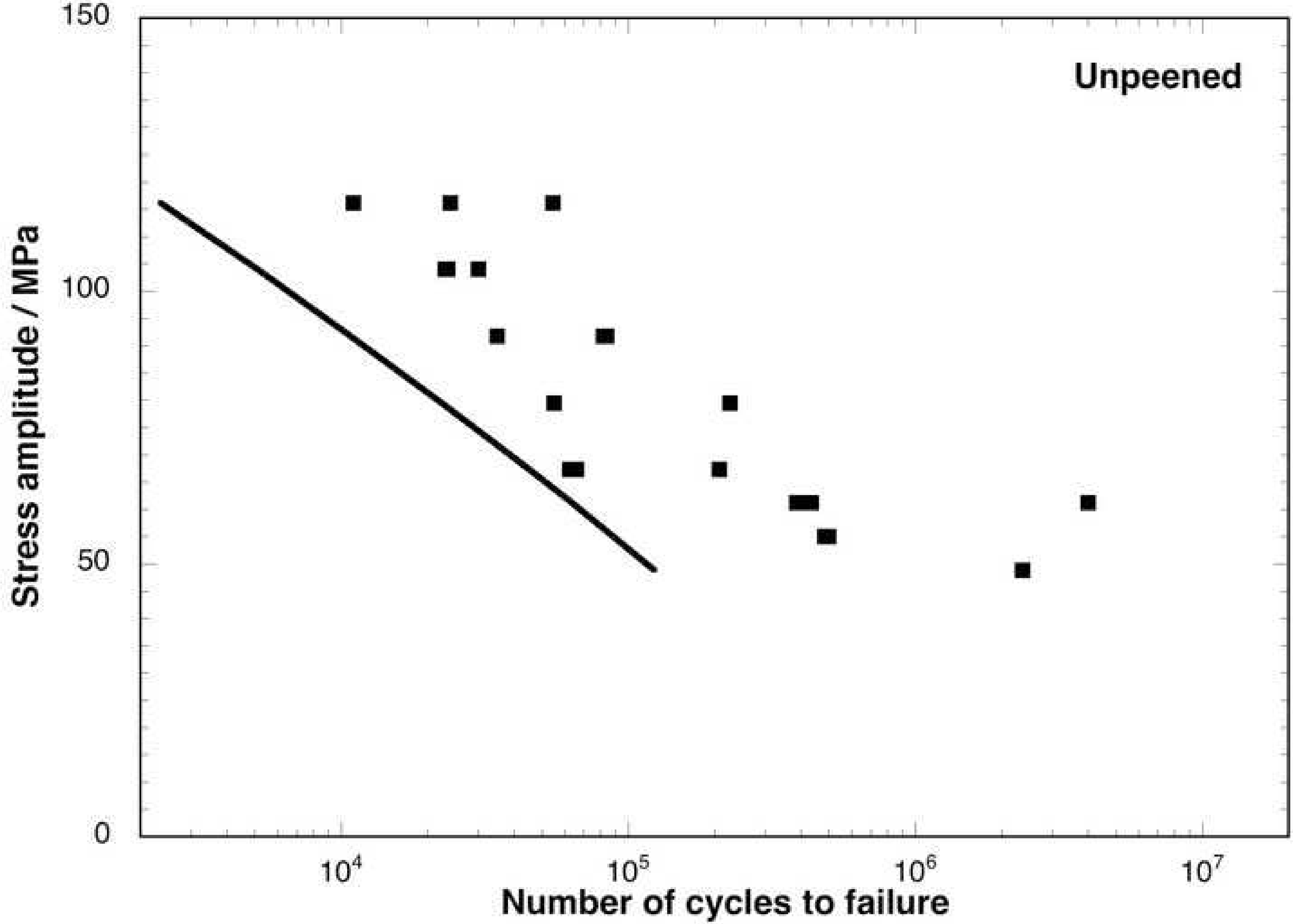

movement
of hydraulic
shaft
fixed
end
specimen
clamp
free to
rotate

Figure 3



Peened
Unpeened
Run-out
Stress Amplitude / MPa
Number of cycles to failure
150
100
50
0
10^4
10^5
10^6
10^7

Figure 4a



150
100
50
0
Unpeened
Stress amplitude / MPa
10^4
10^5
10^6
10^7
Number of cycles to failure

Figure 4b

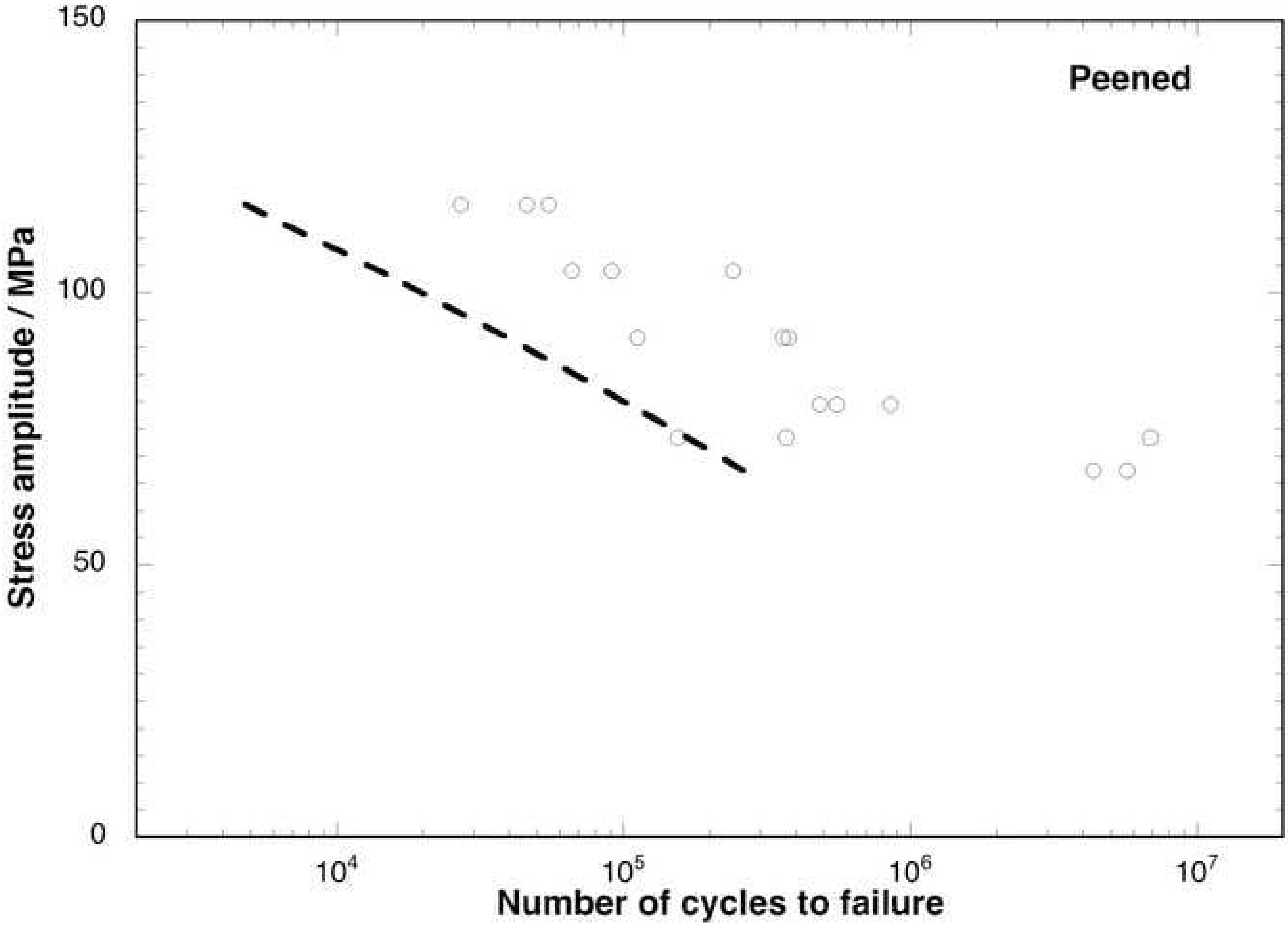
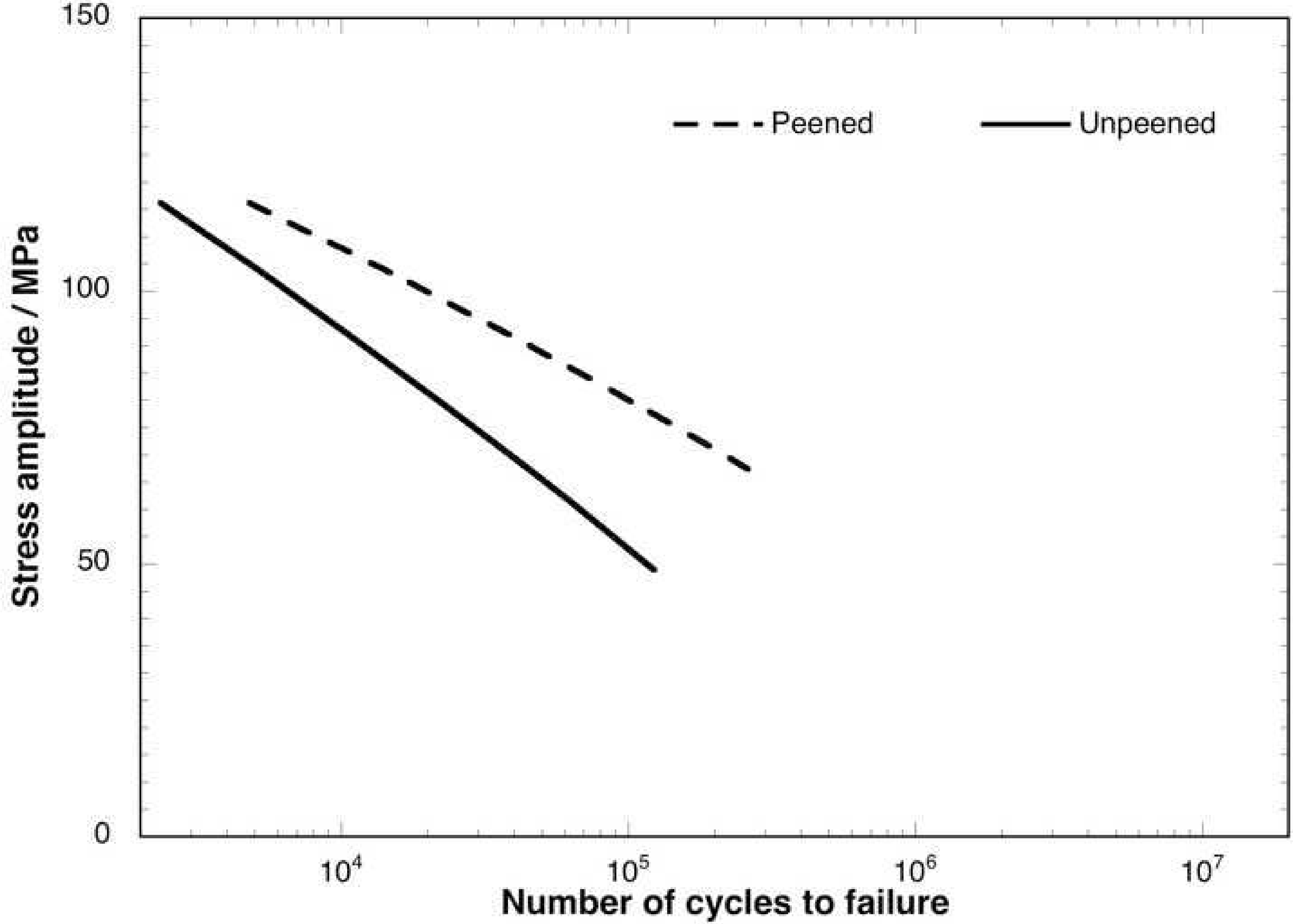
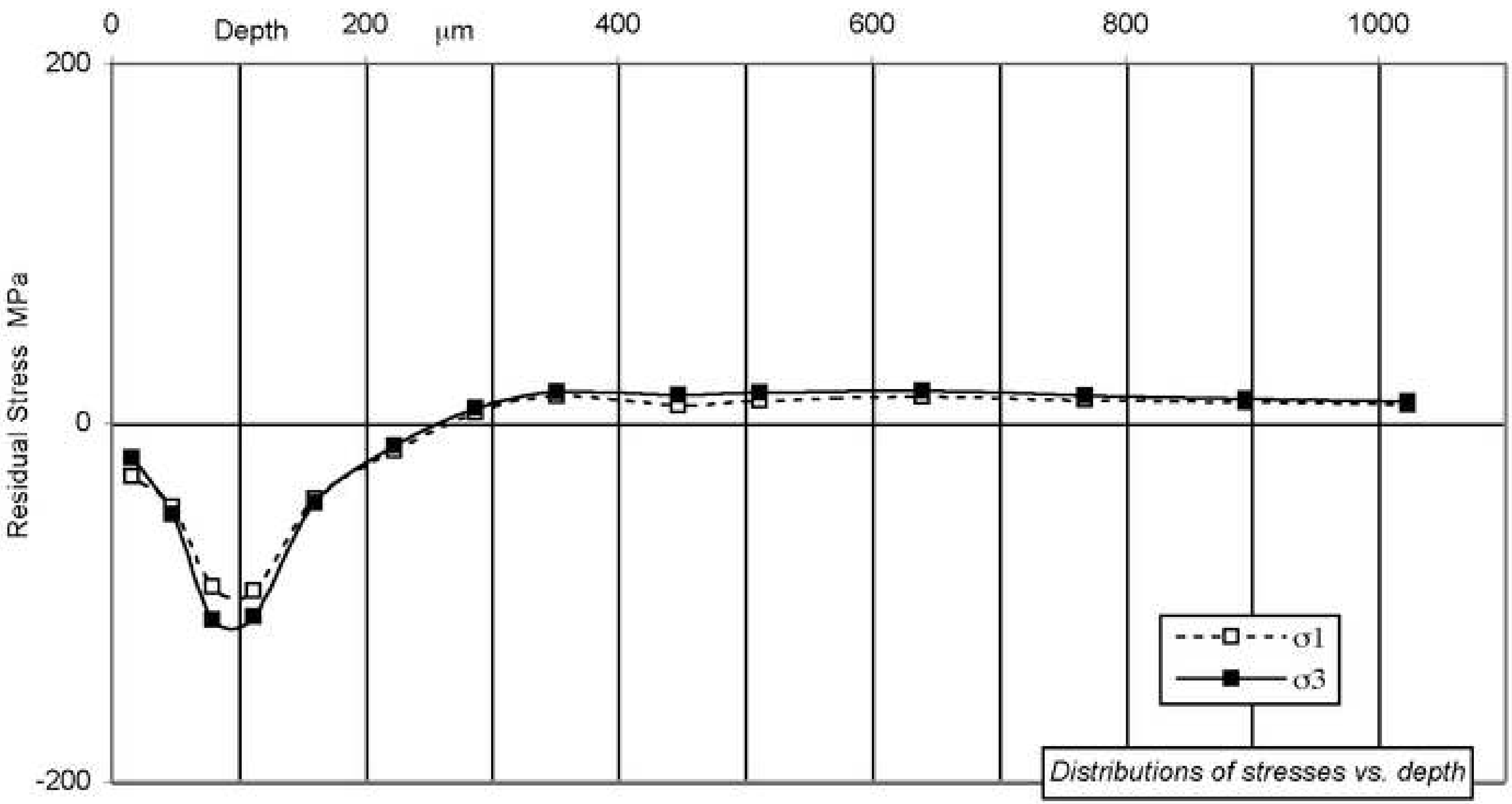

Peened
Stress amplitude / MPa
150
100
50
0
10^4
10^5
10^6
10^7
Number of cycles to failure

Figure 4c



150
100
50
0
Stress amplitude / MPa
Peened
Unpeened
10^4
10^5
10^6
10^7
Number of cycles to failure

Figure 5



0
Depth
200
μm
400
600
800
1000
200
0
-200
Residual Stress MPa
σ1
σ3
Distributions of stresses vs. depth

Figure 6

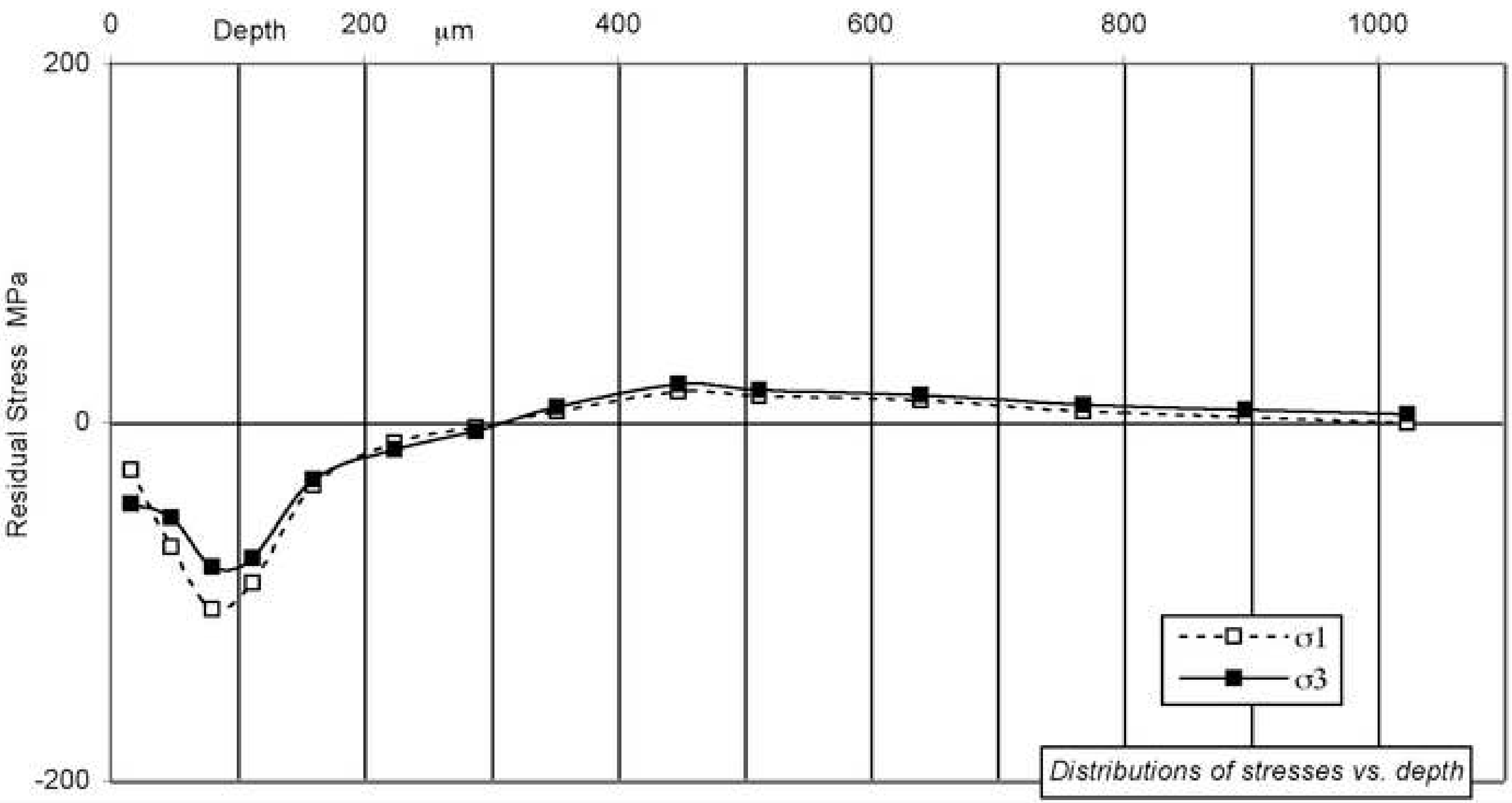

0
Depth
200
μm
400
600
800
1000
200
0
-200
Residual Stress MPa
σ1
σ3
Distributions of stresses vs. depth

Figure 7a

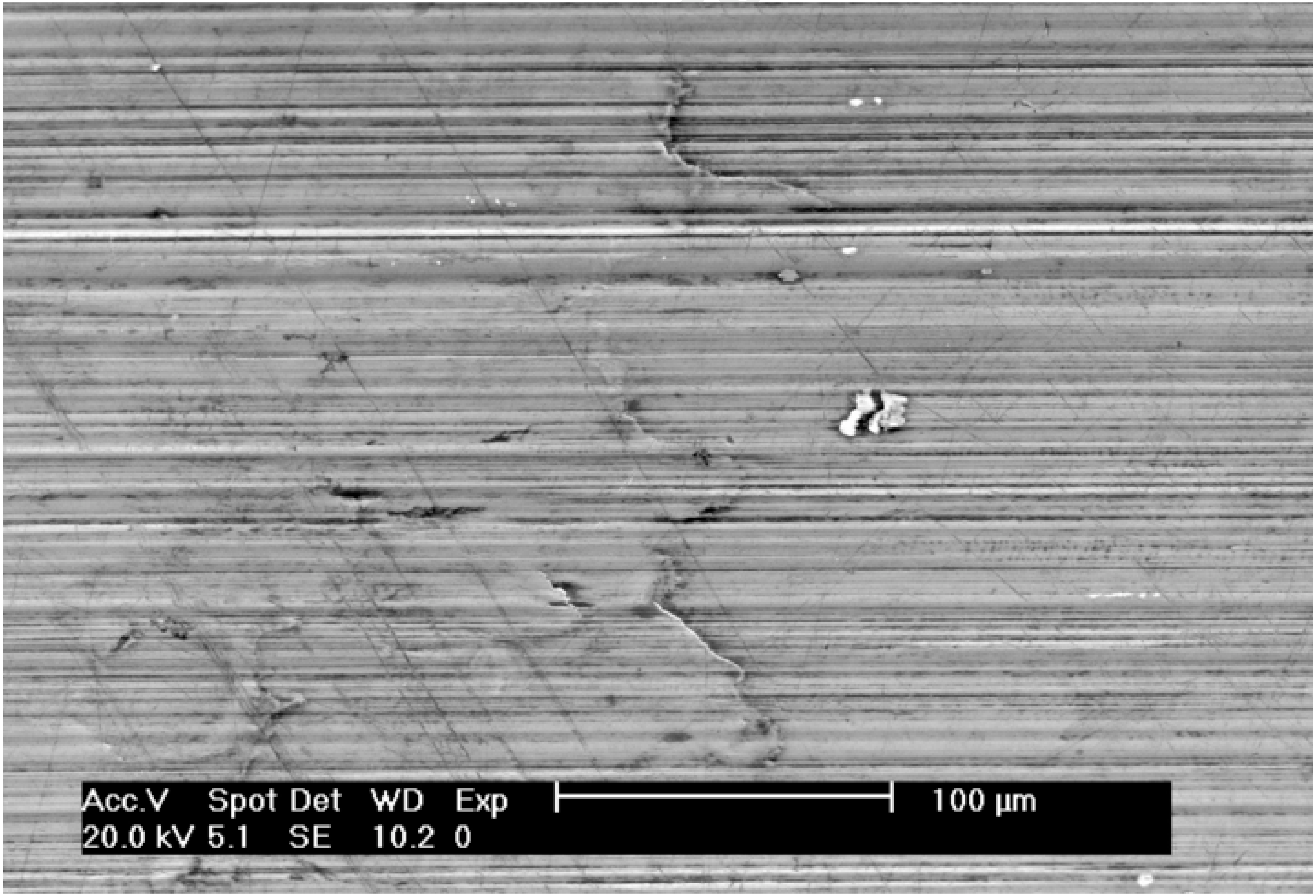


Figure 7b

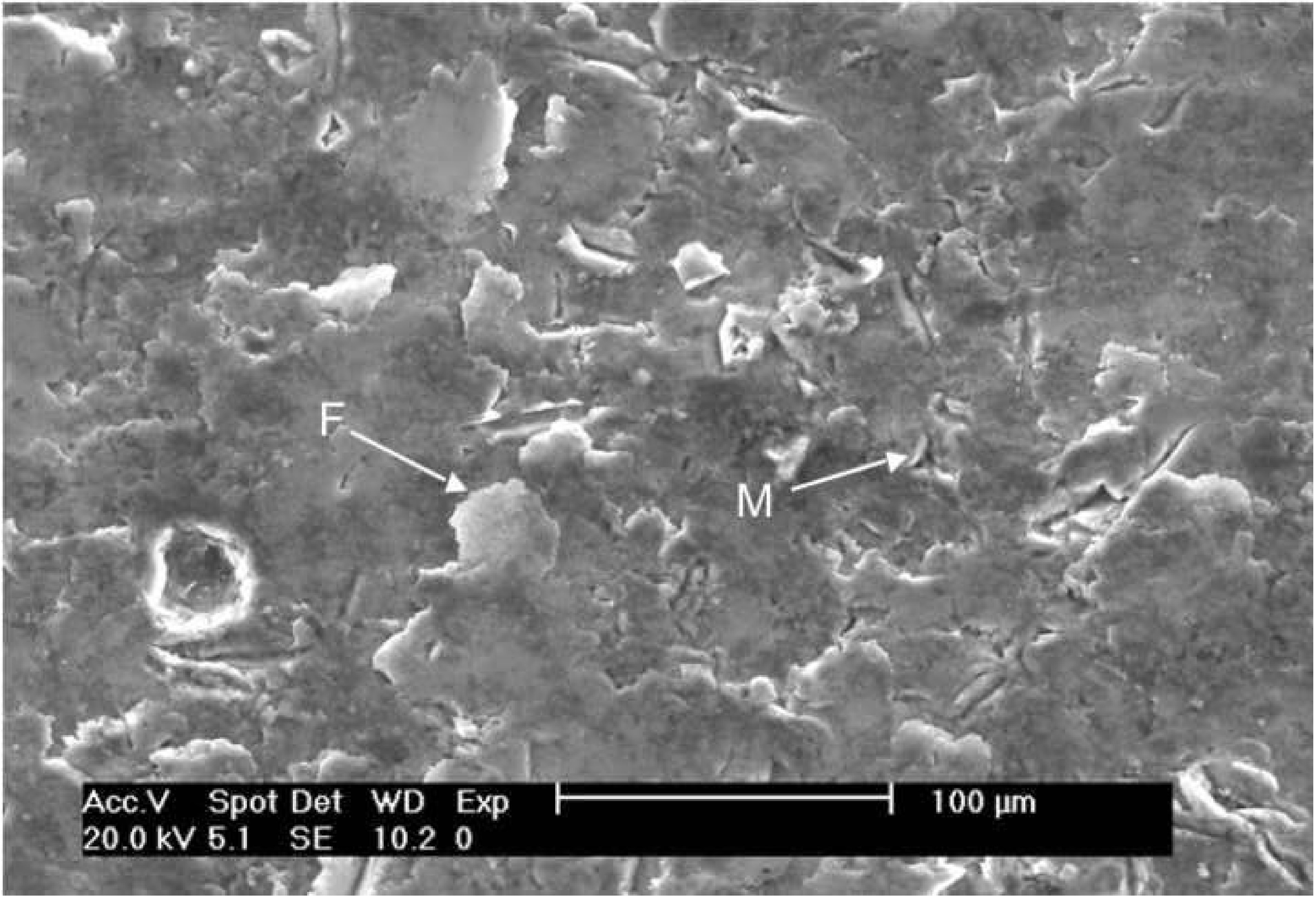


Figure 8a

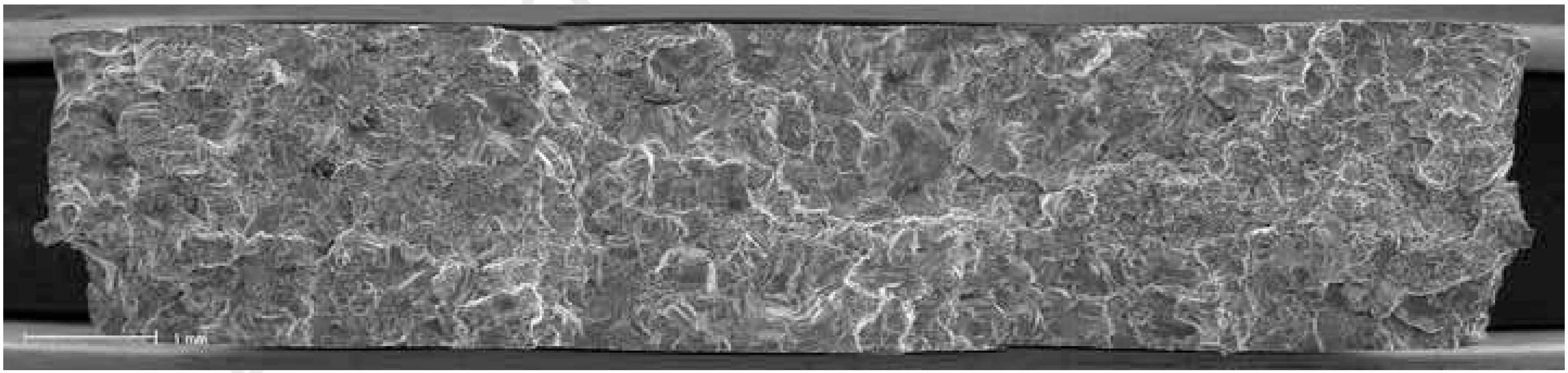


Figure 8b

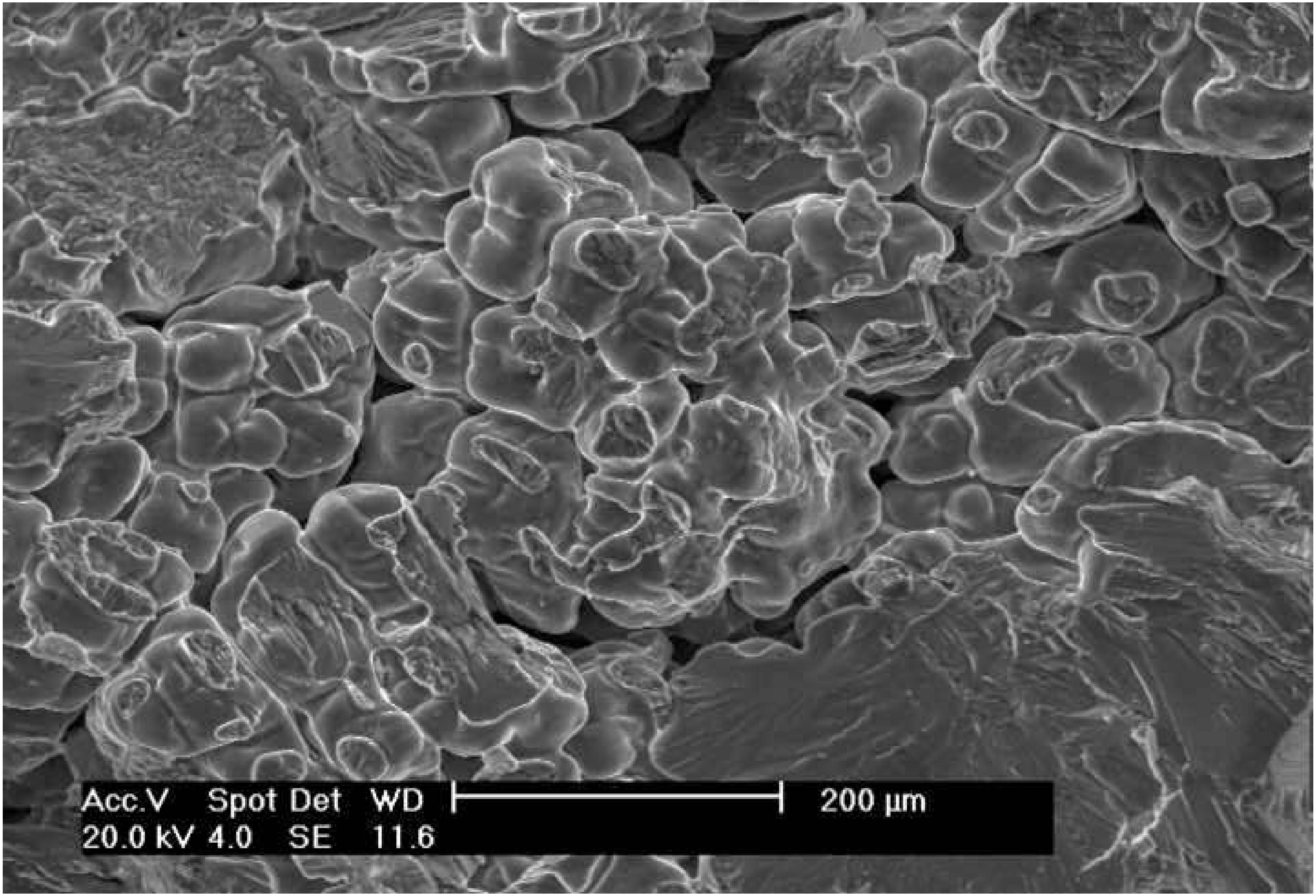


Figure 8c

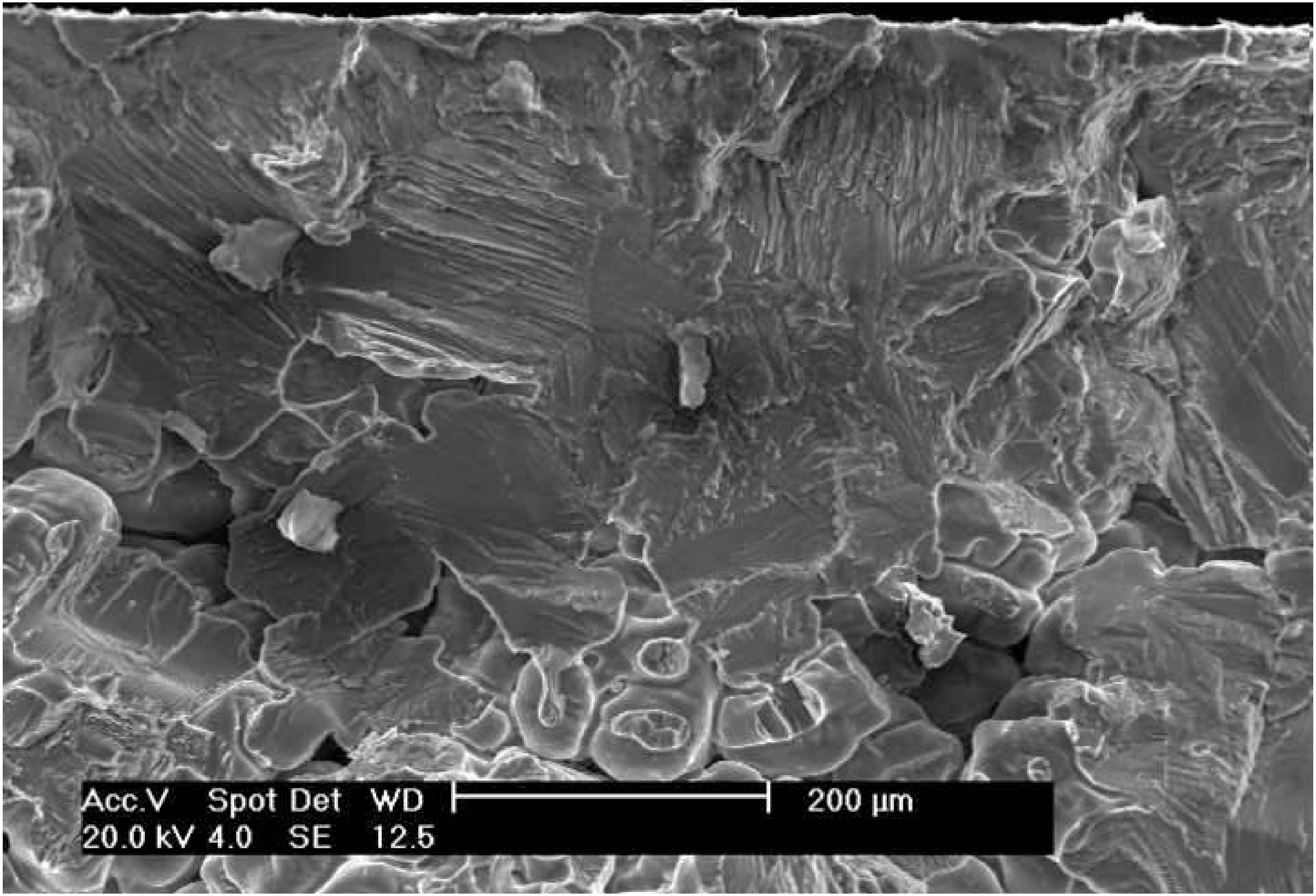


Figure 9a

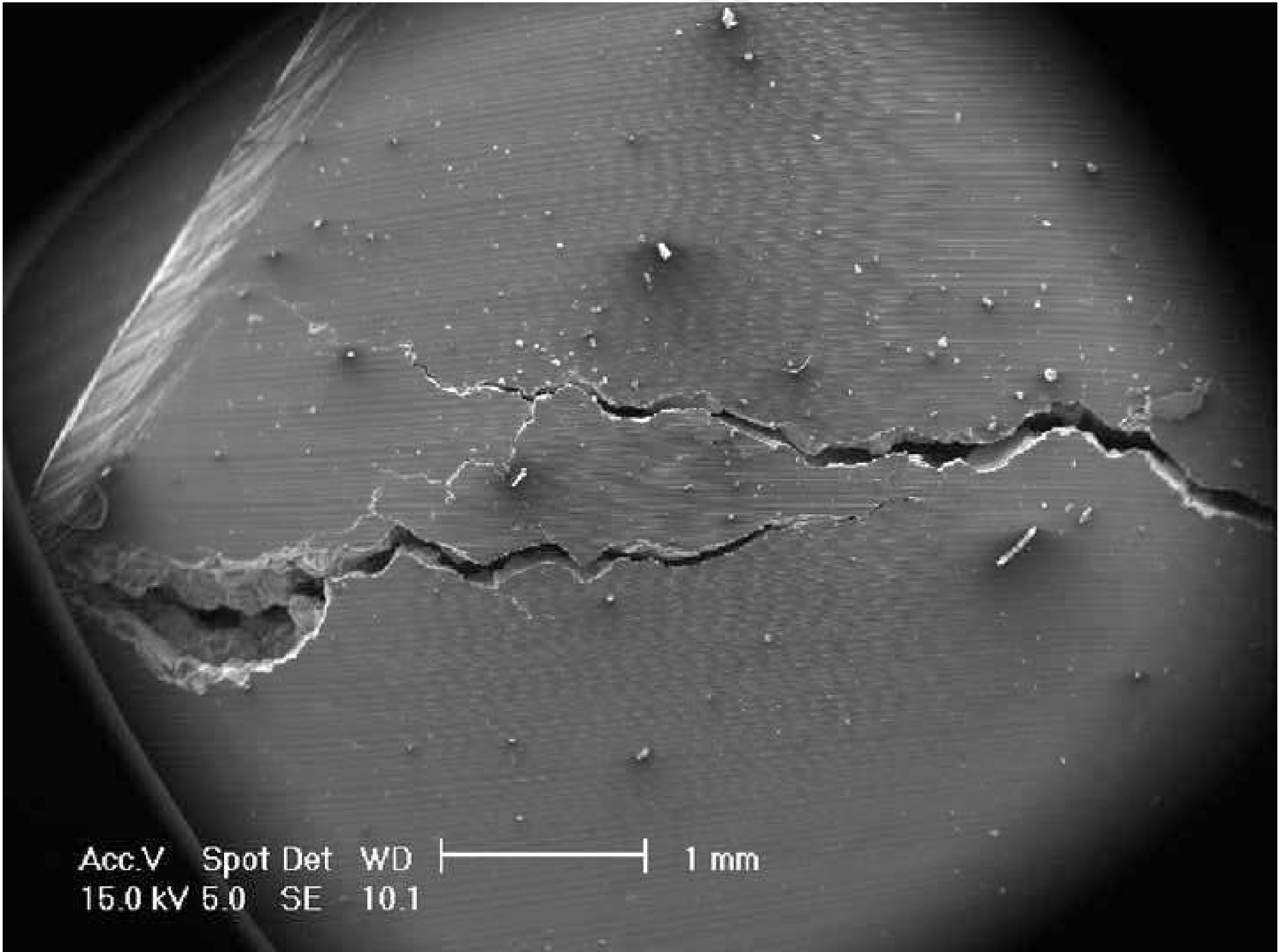


Figure 9b

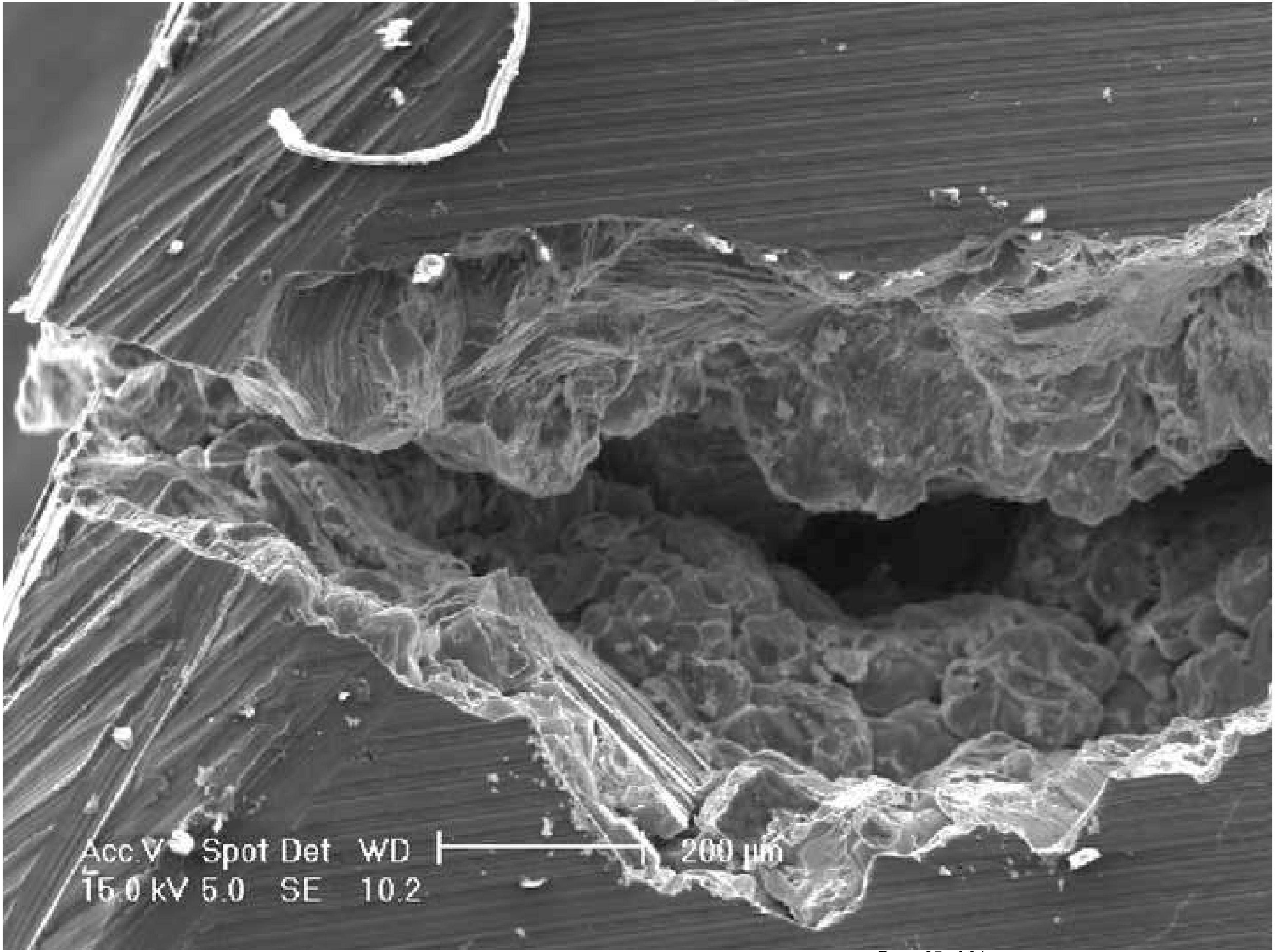


Figure 9c

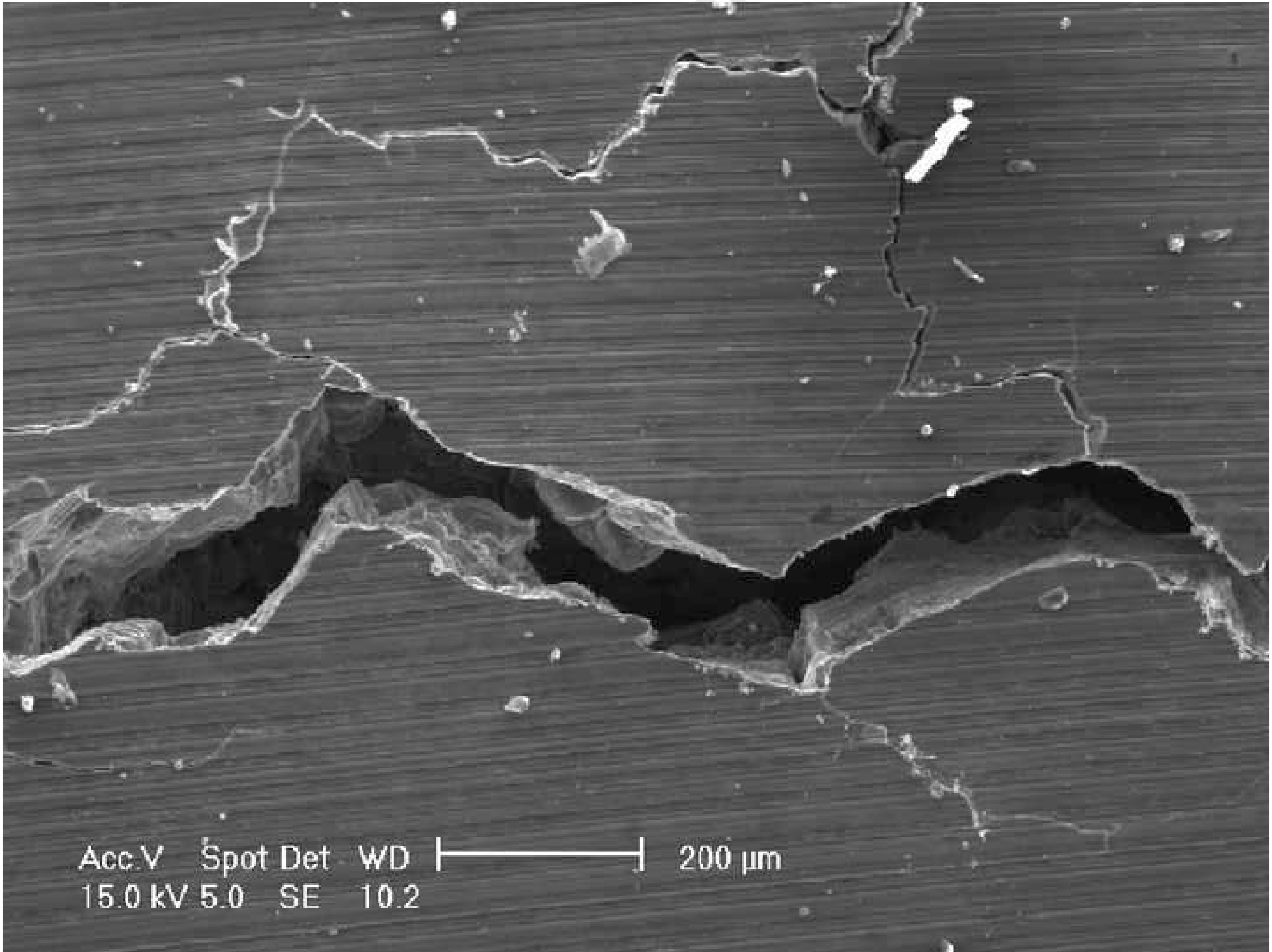


Figure 9d

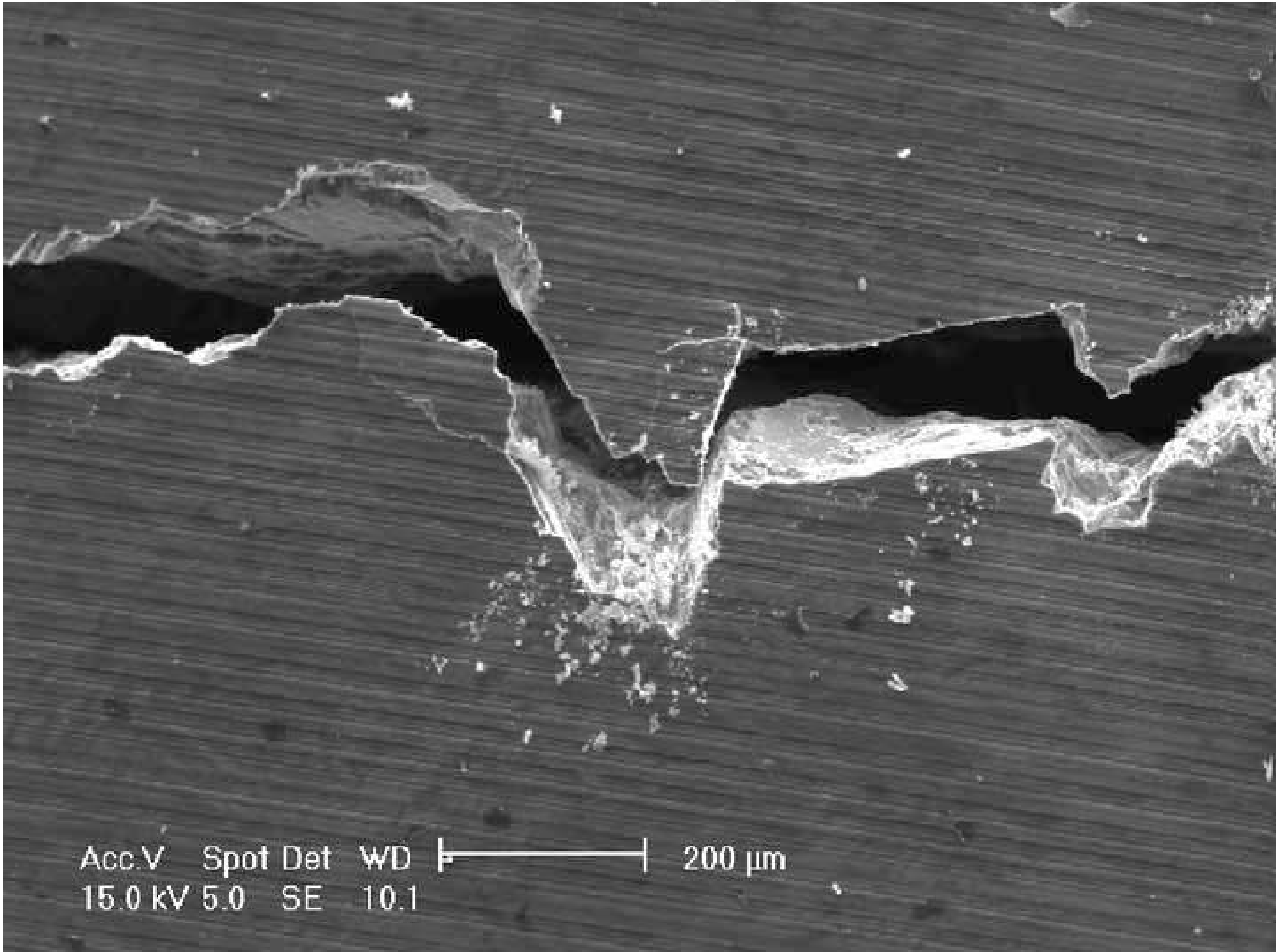


Figure 9e

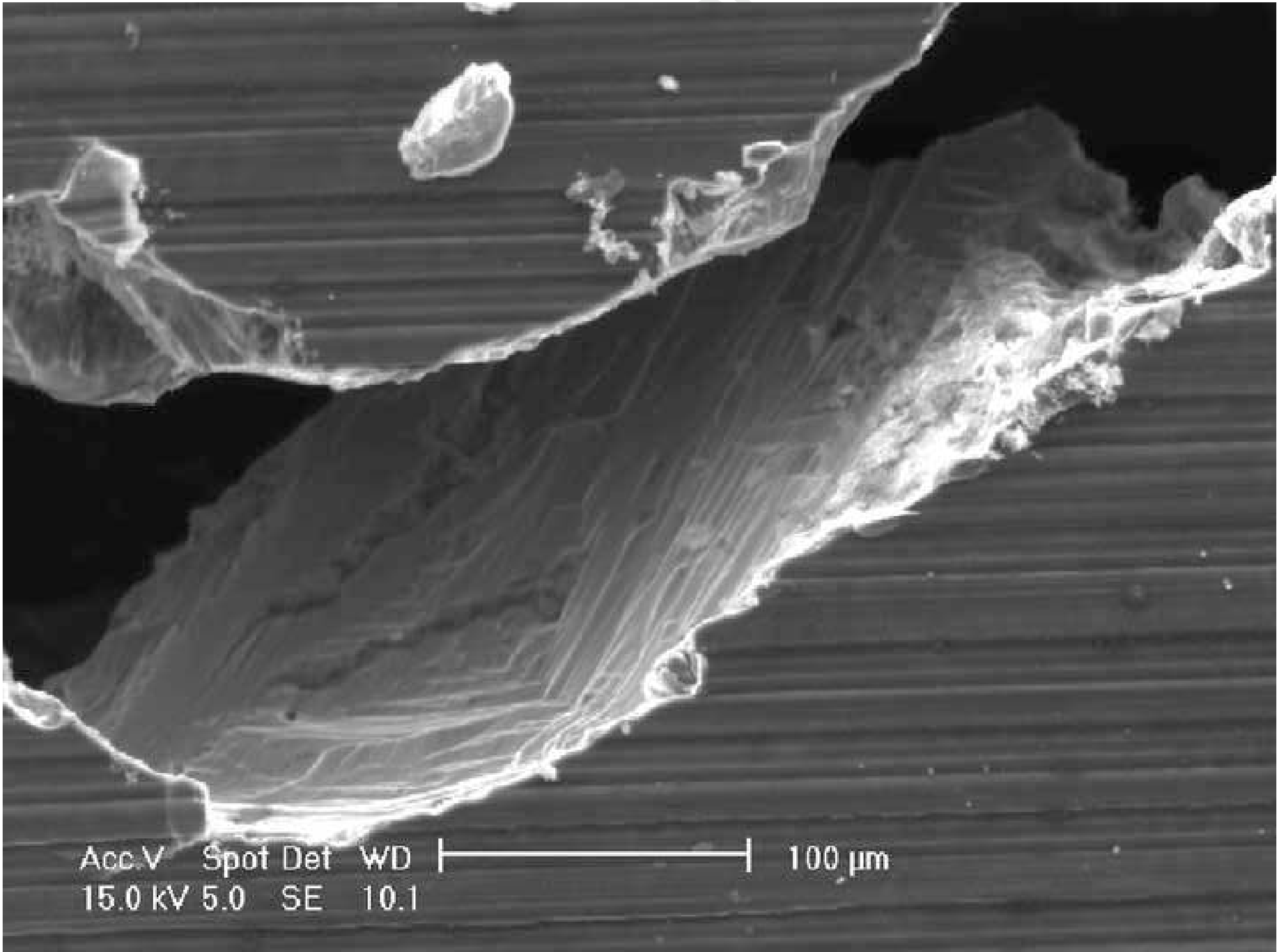


Figure 10

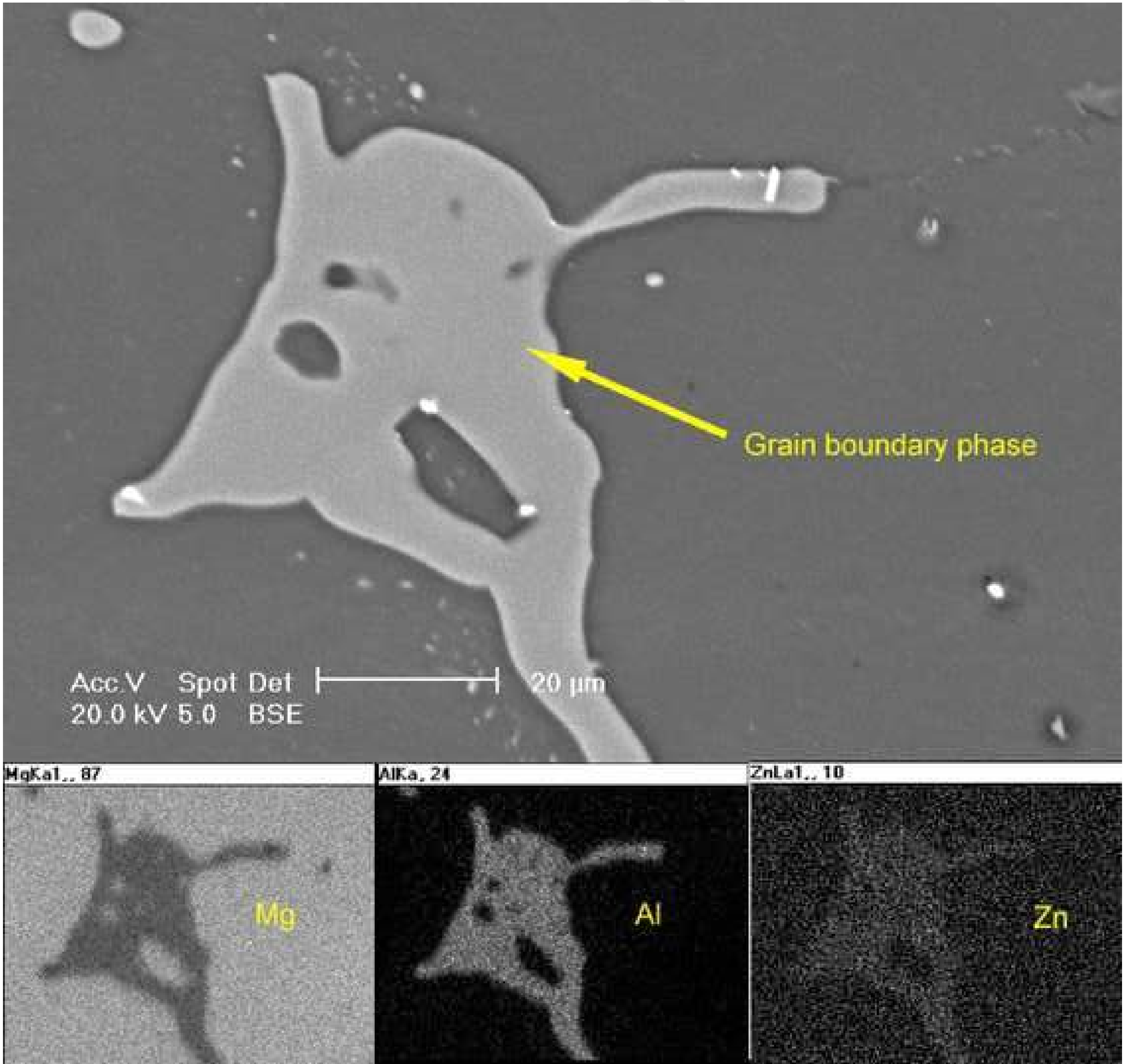

Grain boundary phase
Acc.V Spot Det
20.0 kV 5.0 BSE
20 µm
MgKa1,, 87
Mg
AlKa, 24
Al
ZnLa1,, 10
Zn

Figure 11

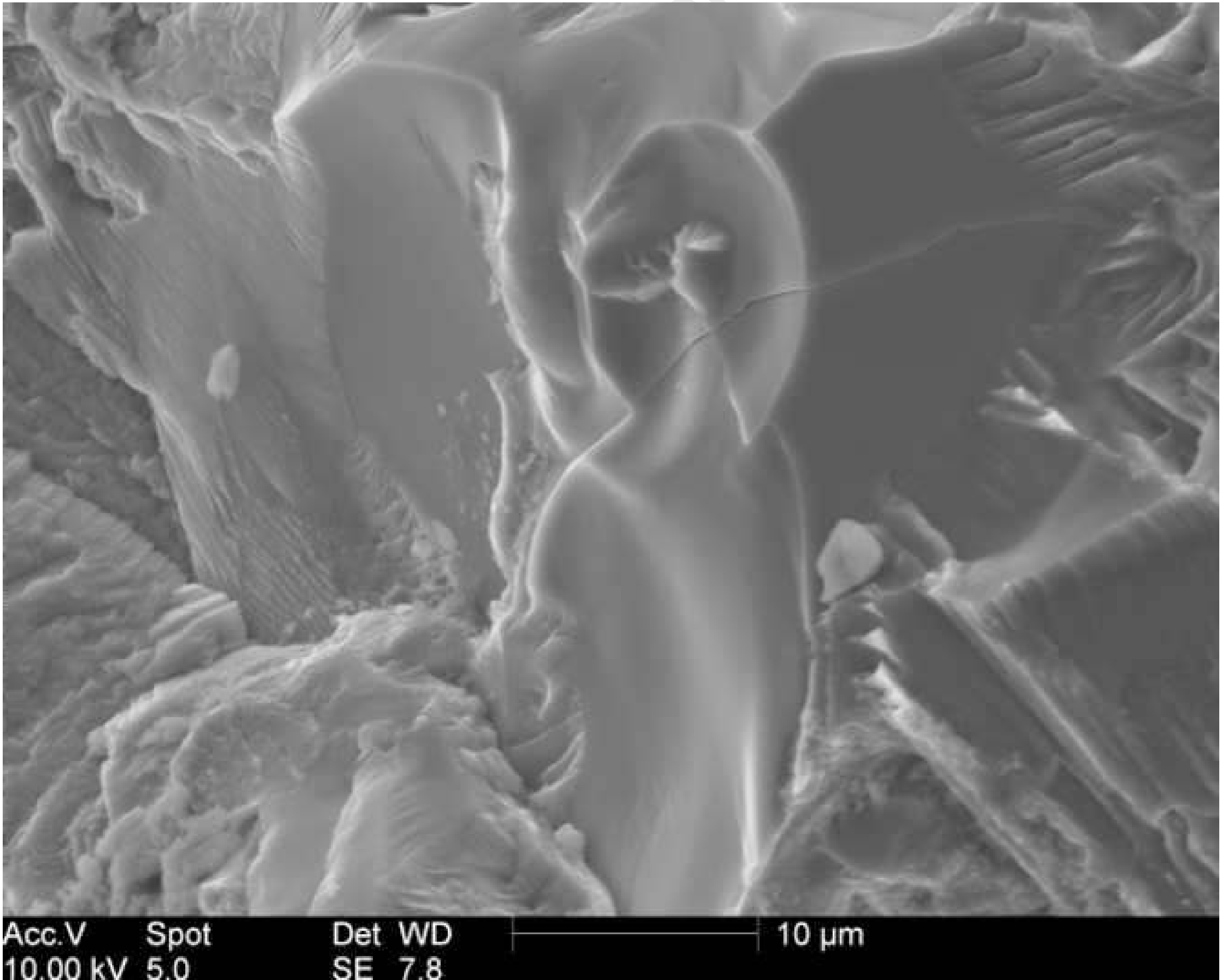


Figure 12