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Shakeri, H. R.; Worswick, M. J.; Mayer, R.

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Failure Mechanism and Damage Characterization in Crash-Tested Aluminium Tubes

H. R. Shakeri
Aluminium Technology Centre, National Research Council Canada

M.J. Worswick
Department of Mechanical Engineering, University of Waterloo

R. Mayer
Vehicle Development Research Lab, GM R&D Center.

ABSTRACT

There exist considerable economical-environmental justifications for lighter vehicles. The current focus of research and development in transportation industry is to use lightweight materials such as aluminium alloys for structural components. In this regard, maintaining safety of the passenger and vehicle is the most important, therefore crashworthiness of components made of lightweight materials must be evaluated prior to sizable application of these materials. The focus of the present study is to understand failure and damage mechanisms during the axial crushing of aluminium tubes made of EN AW 5016 alloy. Due mainly to complexity of the crushed tubes, a microstructural examination approach is adopted using optical as well as scanning electron microscopy techniques.

Introduction

In recent years transportation industry has been in ever-demanding situation as contradicting needs imposed to the industry. From one side to comply with the environmental regulations and economical constraints weight reduction has become a major axis of research and development. From another side, the industry must conform to existing crashworthiness regulations [1]. Obviously, the issue of crashworthiness is not confined to road transportation.

Another long-term strategy for the transportation industry is the use of lightweight materials such as aluminium and its alloys in place of structural steel components. Consequently two issues should be addressed prior to substantial application of aluminium alloys in structural components. The first issue is low

formability of aluminium alloys compared to steel. The second issue related to assessing aluminium alloys crashworthiness. and, it is logical to consider tube hydroforming as a manufacturing process for fabricating the complex 3D shapes, including tubes to be used for crash boxes or other structural applications. According to previous studies low cost, lightness, ease of construction and a high-energy absorption density with a constant average collapse load at failure are important characteristics for an energy absorbing components [2]. The first three characteristics are clearly feasible for metallic tubes. However the energy absorption capacity will also depend on the amount of plastic deformation that occurs under axial loading. Therefore in addition to geometrical parameters such as internal/external diameters, thickness and length of the tube, strain hardening characteristics of the tube material both during the manufacturing as well as axial crushing is also very important.

Axial collapse of cylindrical tubes under quasi-static loading is extensively studied both experimentally and numerically and is classified in seven collapse modes as shown in Figure 1 [2]. As the figure suggests, the length to diameter and thickness to diameter ratios determine the resulting collapse mode. Further investigation has shown that axially crushed tubes are most efficient impact energy-absorbing component when deforming into concertina or multi-lobe mode of collapse [3].

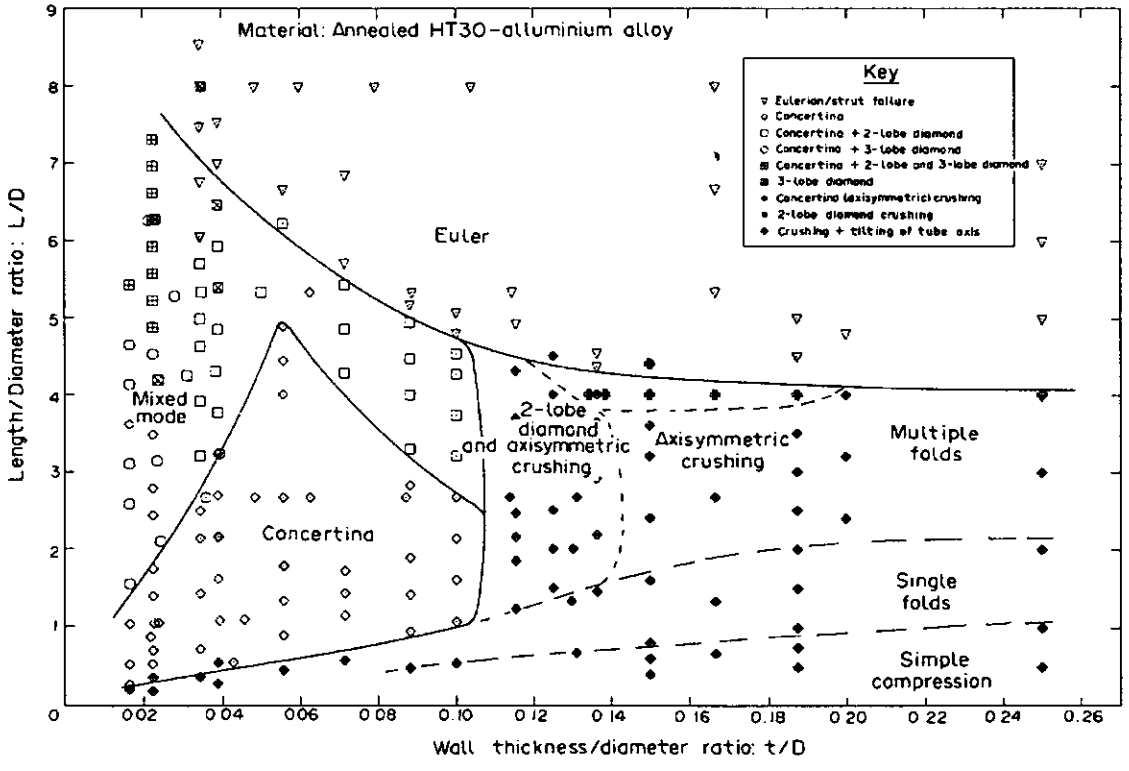


Figure 1 Classification chart of the collapse modes in axially crushed aluminium (HT-30) tubes [2].

In recent years there has been more emphasis on the crashworthiness of the hydroformed aluminium tubes using finite element simulations alongside experimental works. For instance in case of low and high pressure hydroforming processes on aluminium alloy tubes, it was found that the energy absorption during the impact decreases with decreasing corner-fill of the hydroformed tube [4]. In dealing with crashworthiness simulations a comprehensive approach for predicting failure in a component based on macroscopic strains and stresses is also examined. The latter approach requires the use of a number of different failure mechanism representations, such as necking, as well as ductile and shear. However, using such a failure approach one can only predict the crack initiation [5]. Therefore, it is necessary to understand the actual complex deformation and failure mechanisms in a crushing tube in order to have better failure criteria input for finite element simulations. The present investigation takes a microstructural approach to examine damage initiation and failure mechanisms in crushing tubes.

Experimental Procedure

For the present investigation tubes made of EN AW 5016 aluminium alloy were examined. The original dimensions of the tubes were 76.2 mm diameter, 400 mm length and 2 mm wall thickness. Figure 2 shows the typical stress-strain curve for this type of alloy. The tubes crash-tested at GM's R&D Centre using a drop tower Figure 3 is force-displacement curve for axial crushing a tube with dimension mentioned here. Due mainly to complexity of the tubes after the test it has been concluded that specimens must be sectioned and examined at multiple locations.

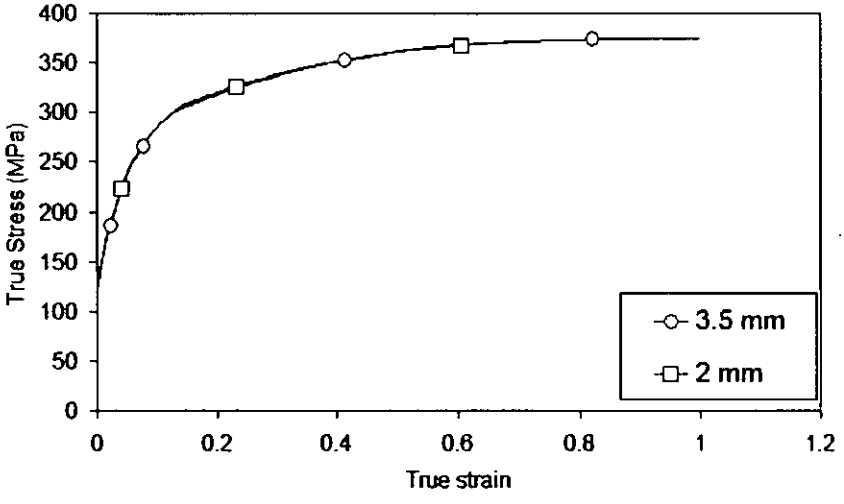


Figure 2 A typical stress-strain curve for the aluminium alloy under consideration.

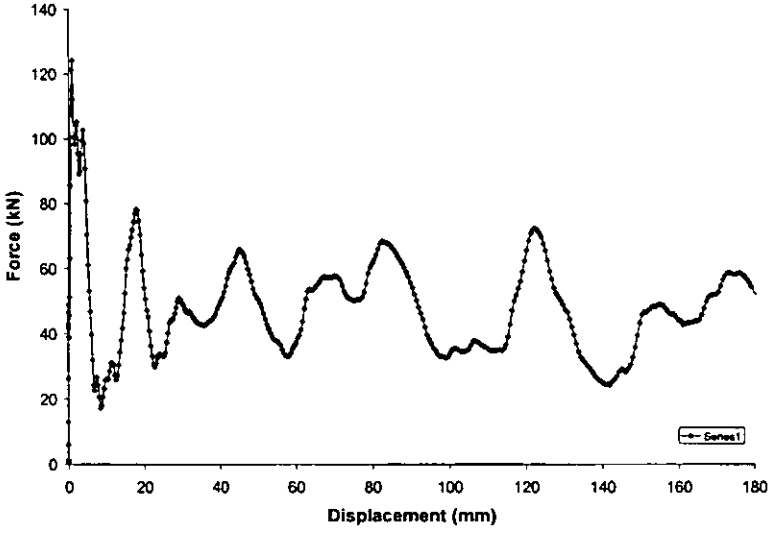
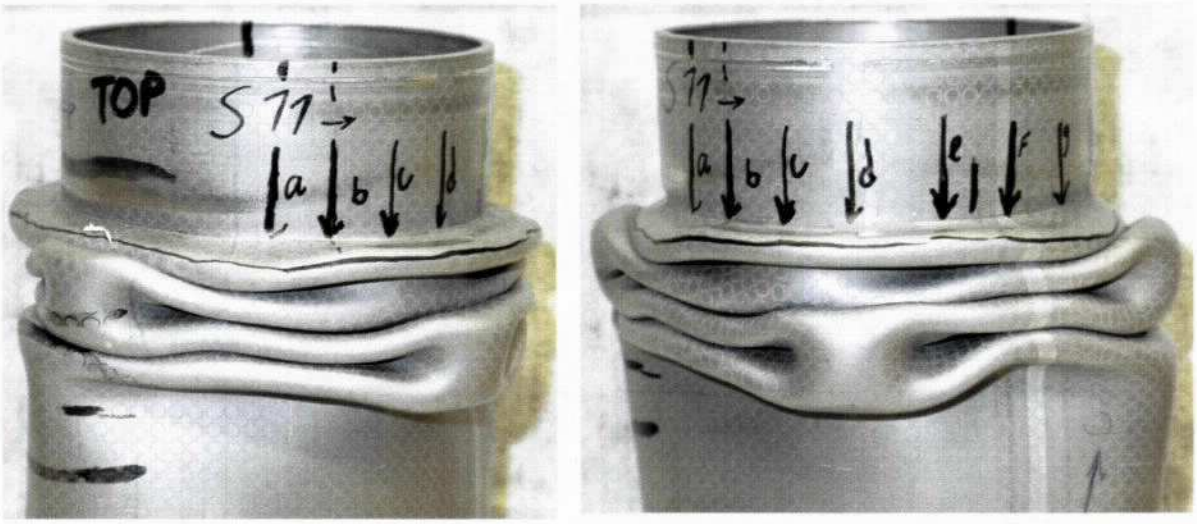


Figure 3 A typical load-displacement curve for a tube that axially crushed.

Specimens sectioned at multiple locations as shown in Figure 4 for one of the specimens. Actual sectioning was done using abrasive cut-of-wheel. Afterwards the sections cold mounted, mechanically grinded and polished before optical microscopy.



(a) (b)

Figure 4 Sections considered on one of the specimens for examination and denoted from "a" to "g".

Figure 5 shows several cross sections of the mounted specimens, as indicated in each image all bends and folds are given a number and examined under the microscope. In addition occasionally the sections include fractured segments that provides good indications on possible chain of events leading to fracture. It seems that whenever several folds align under each other they may act like cutting tool shearing the next neighboring folding segment. In addition during the folding sequence the contact between different folding segments might act like "locking bead" for a neighboring segment limiting the flow of the material in that segment leading to failure. Adding to the complexity of the situation, it is also possible that two ends of the tube do not remain parallel, during the crash test, and add shearing, tearing component or a combination of the two into the equation.

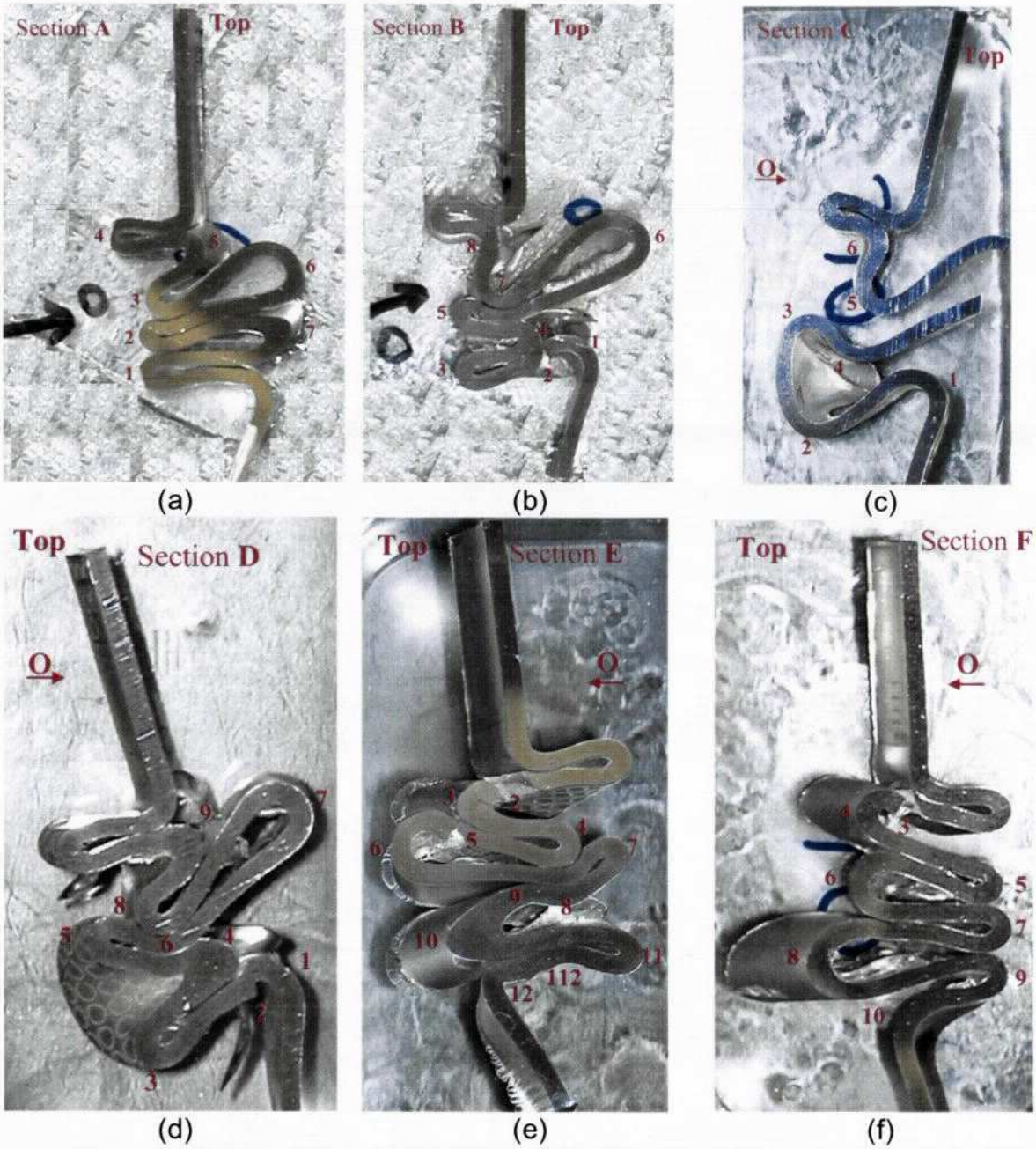


Figure 5 Some of the mounted sections of one of the specimens. The letter "O" indicates the outside of the tube and also the topside of the tubes is also marked.

Results and Discussion

Optical Microscope Examination

Since each specimen contains multiple folds to obtain a realistic understanding of the material flow, damage and final failure it is necessary to examine a large

number of folded segments. In general the bending radius for each fold is important, in addition the interaction of each folding segment with the neighbouring segments also plays an important role as it may impose additional constraint or increase the friction. Therefore, in this section it has been tried to separate simple folding cases from those with constraint from the adjacent segments.

Figure 6 shows some of the segments without any apparent interaction with the adjacent segments. As it could be seen in the figure, the outer part of the fold segments (deformed in tension) hardly shows any significant sign of damage, while the inner segments that are in compression consistently exhibit tremendous amount of materials flow toward the centre of the bend and as a result at the inner edges numerous cracks are observable that produces fish-tail or tooth-like sub-segments as can be seen in Figure 6 c, e and f. It should be noted that in cases such as the one shown in Figure 6, the direction of crack growth and materials flow are against each other. In another word, as the cracks moves toward the centre of the thickness it enters the material that is both less compressed and less strain-hardened.

Interaction with the neighbouring segments imposes additional constraint to the folding segments. In this case unlike the simple bending condition illustrated in Figure 6, evidences of damage often are observable in inner as well as outer part of a folded segment. Figures 7 a, c and e are three different segments that clearly show the effect of contact and interaction between the neighbouring segments. Figures 7 c and e clearly shows change of the thickness as a result of impact from the adjacent segment. Figure 7a illustrates a case of damage at outer area of a bend, details of such damage is shown in Figure 7 b. Figures 7 d and f are higher magnification of the regions of interest in Figures 7 c and e, respectively and show asymmetry of the bend as a result of the impact as well as formation of the larger cracks at the inner area of the bend that are slanted to the opposite direction of the impact.

Another frequently observed features in these sections have been blunt cracks as shown in Figure 8. The reason for the occurrence of these cracks is not clear yet. There are a few possible explanations for the blunt cracks. One possibility might be the spring back of the tube after the test. It is also possible that due to a secondary deformation cracks became blunt. It is also possible that blunt cracks might be artifacts produced during the clamping or cutting stages of specimen preparations.

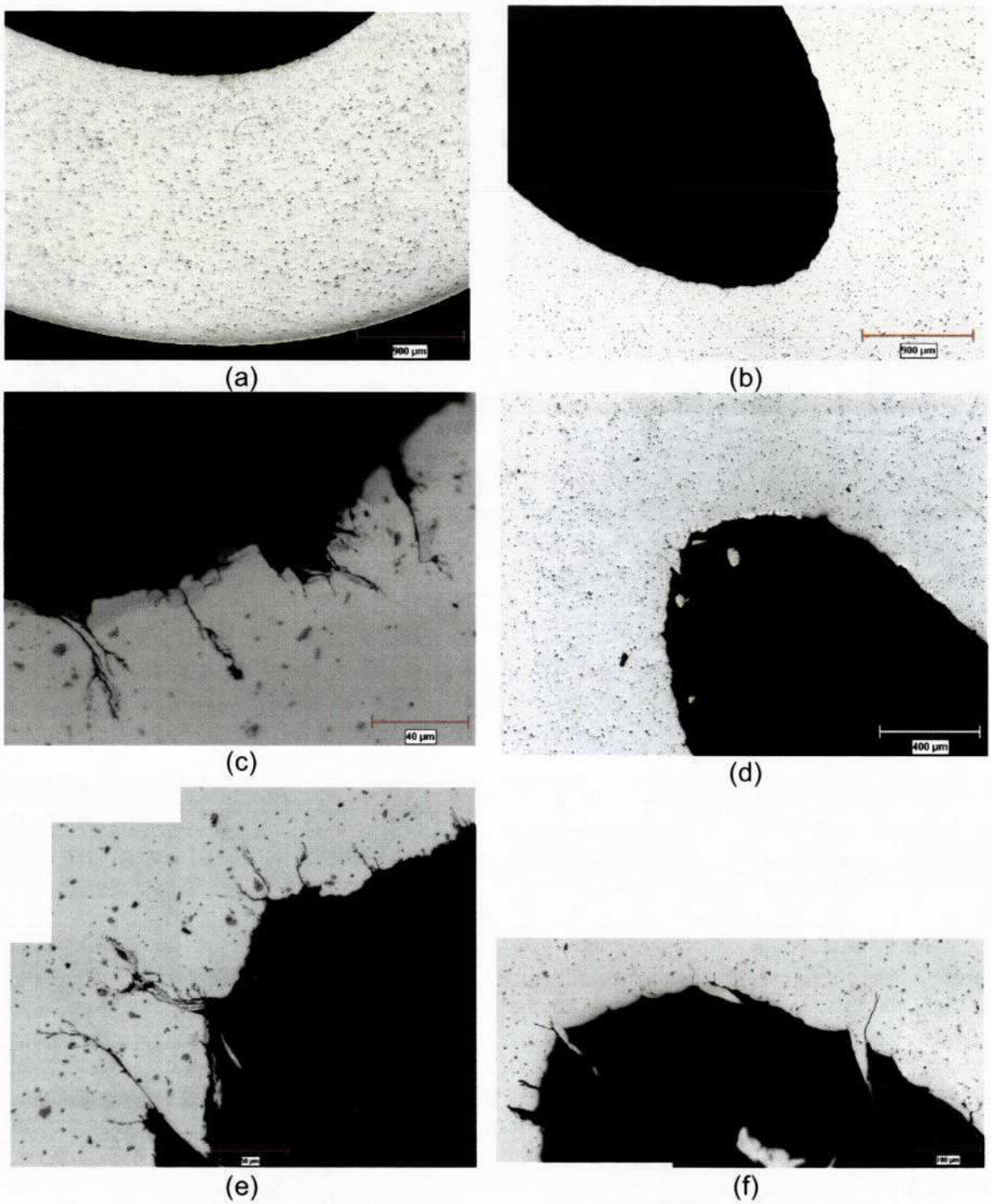


Figure 6 Some of the folding segments without apparent interaction with the neighbouring segments, (a) Section "B" #6, (b) Section "A" #7 at a lower mag., (c) Section "A" #7 at a higher mag., (d) Section "A" #1 at a lower mag., (e) Section "A" #1 at a higher mag., and (f) Section "F" #9.

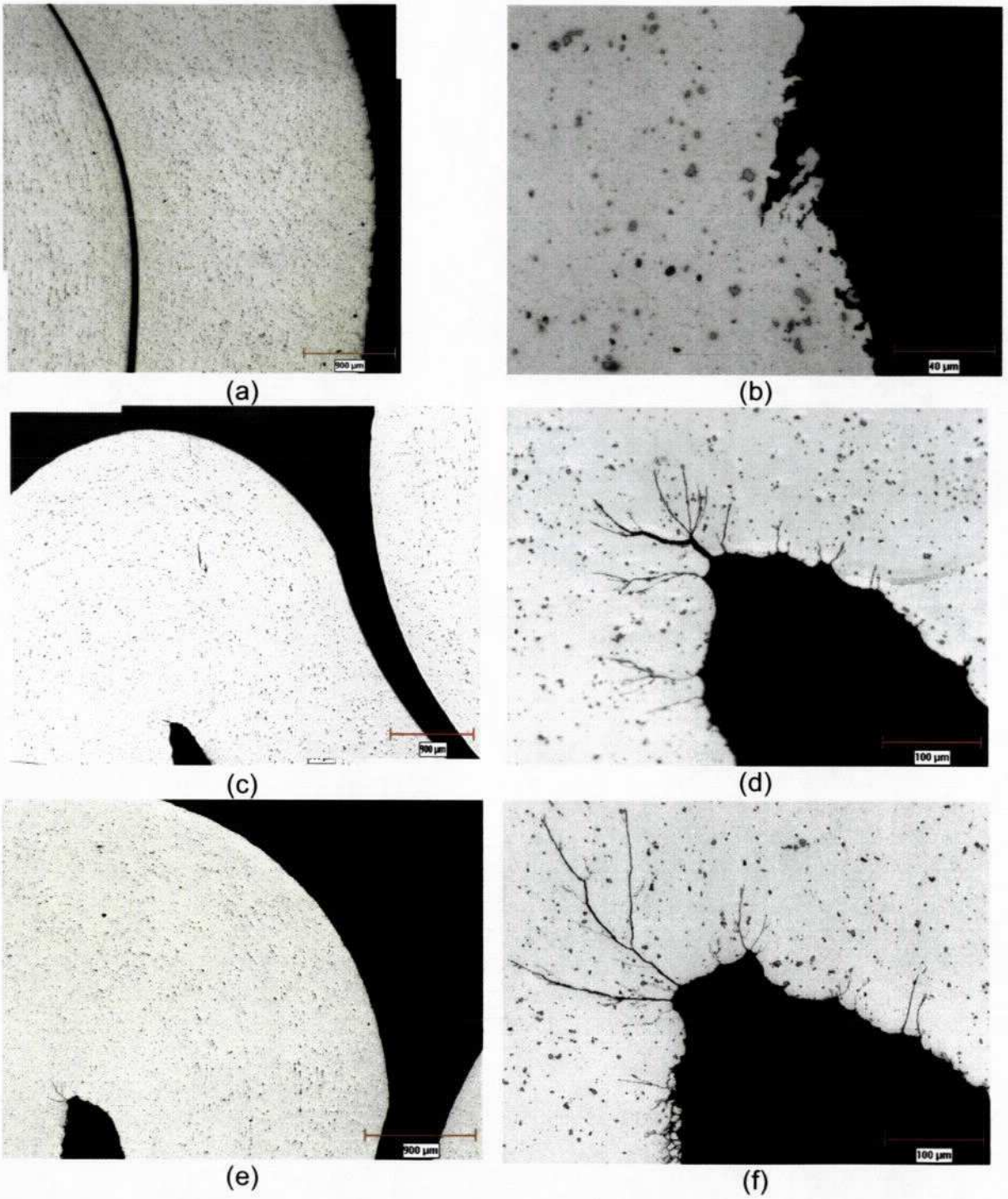
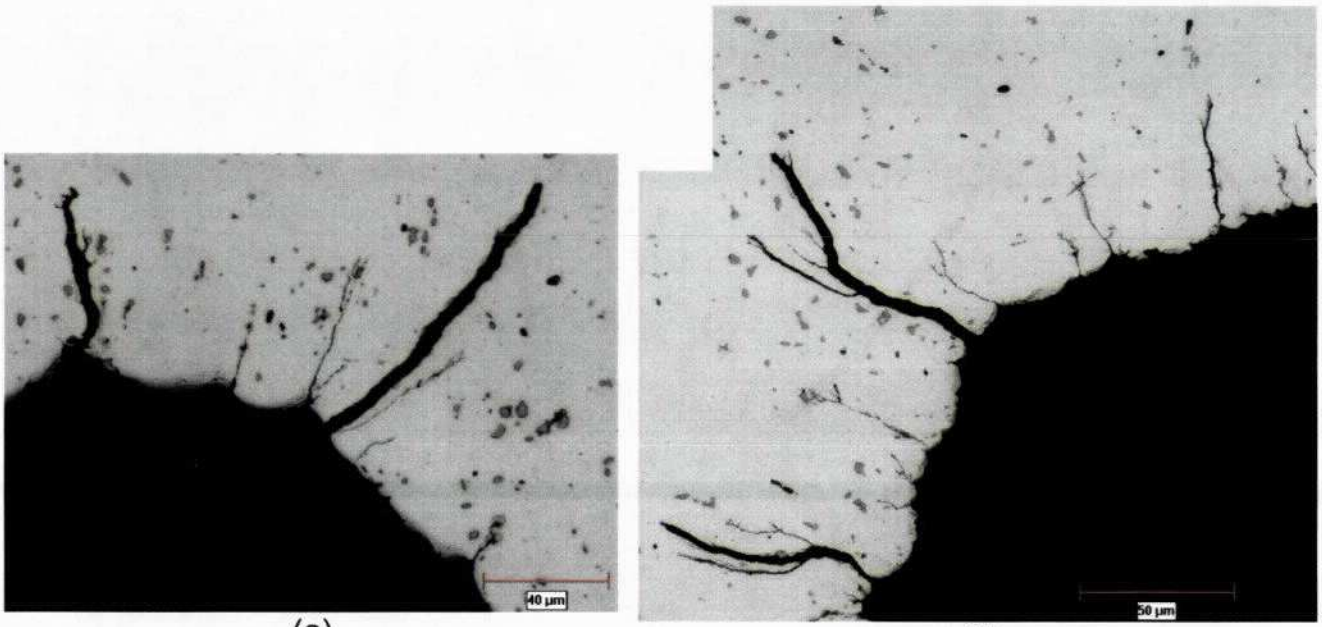


Figure 7 (a) Section E, #8 at low mag., (b) Section E, #8 at higher mag., (c) Section A, #2 at low mag., (d) Section A, #2 at a higher mag., (e) Section B, #5 at low mag., and (f) Section B, #5 at higher mag.



(a) (b)

Figure 8 Occurrence of blunt cracks in specimens for example (a) Section E, #1, and (b) Section B, #9.

Failure Mechanisms

A. Metallographic Observations

Based on the up to date examination of the specimens and characterization study it is still too soon to determine the active failure mechanisms conclusively. One of the difficulties associated with identifying failure mechanism is unknown sequence of events, for instance in the section shown in Figure 9, it is not clear if the segment failed before or after folding of the adjacent area. The situation became further complicated due to lateral movement of the tube during the test.

Metallographic examination of the sections cut from the tube is helpful in determining the micro-mechanisms of damage, however such information must be viewed along with the loading mode in the specimen in general and in each fractured segment in particular and in the present case as explained the situation is complex rather than simple. Figures 10 a and b are composite images of the two sides of the fractured segment shown in Figure 9, along with several inserts that shows some of the details, the general view of the failed section exhibit the general characteristics of a specimen failed under shear, however it is also possible that the specimen failed under tearing mode since in a two dimensional view it is difficult to distinguish one from the other. It is also possible to have mixed mode situation. As the inserts suggests, there is significant amount of

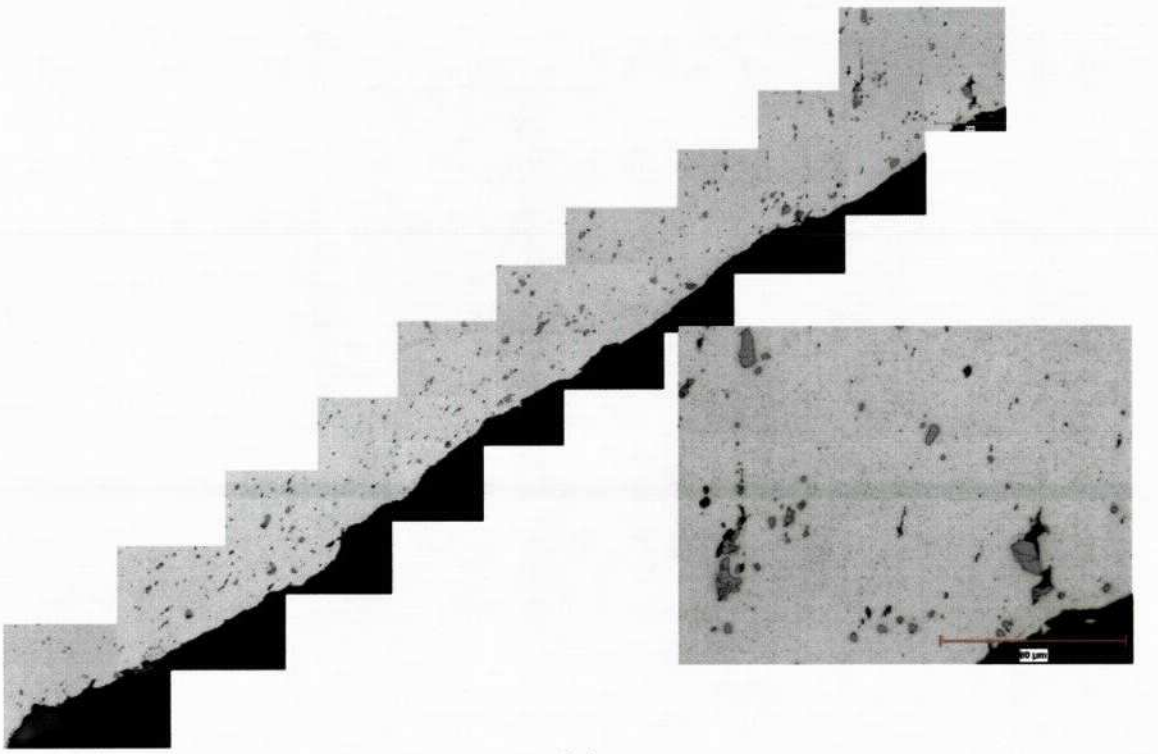
particle-induced damage prior to failure. Therefore, it is clear that we have particle-induced damage assisted shear (or tear) as possible failure mechanism.

Figure 9 Section E, #2 that shows a failed region near a folded segment.

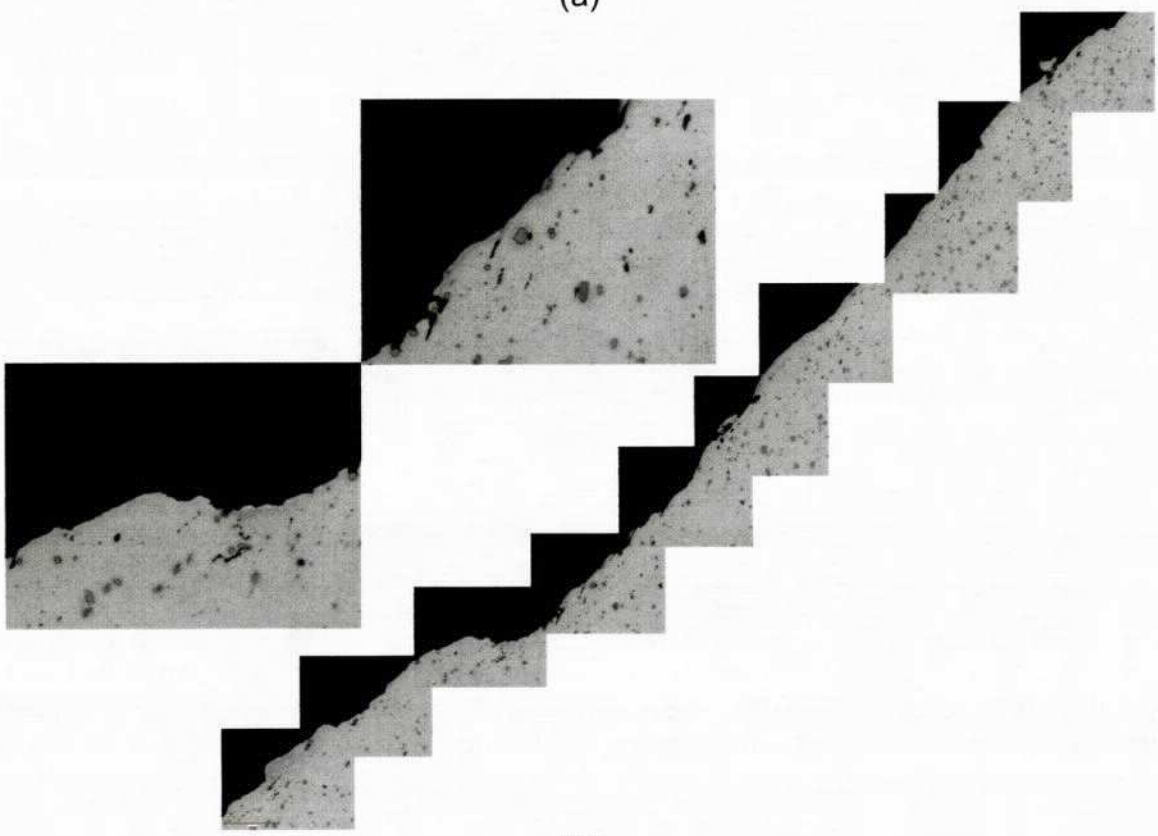
Figure 11 shows another fractured segment with different characteristics from the case shown in Figure 10. In the latter case the fractured edges are rougher, therefore comparatively the fracture is more ductile than the case shown in Figure 10. As the inserts in Figure 11 show significant amount of particle induced damage in form of voids occurred prior to the final stages of fracture. Like the previous case it is difficult to be certain about the failure mode, mainly due to the 2D nature of the observations, however considering the overall loading condition of the tube and the observed characteristics the segment could be failed under tearing mode. It is also worth mentioning that in both cases shown in Figures 10 and 11 the role of neighbouring segment should also be considered.

B. Stereomicroscope Observations

It is difficult to perform this type of examination, since the failed regions are usually between the folds. Figure 12 shows a partially failed region of one of the specimens from two different angles viewed under stereomicroscope. This figure clearly shows the material flow as a result of bending as well as the effect of the impact from the neighbouring segment. From this observation one may also get the impression that the failure is under a combination of sliding and tearing mode rather than a single mode.



(a)



(b)

Figure 10 (a) & (b) composite images of the opposing edges of the fracture segment shown in Figure 6, inserts show particle-induced damage occurred prior to failure.

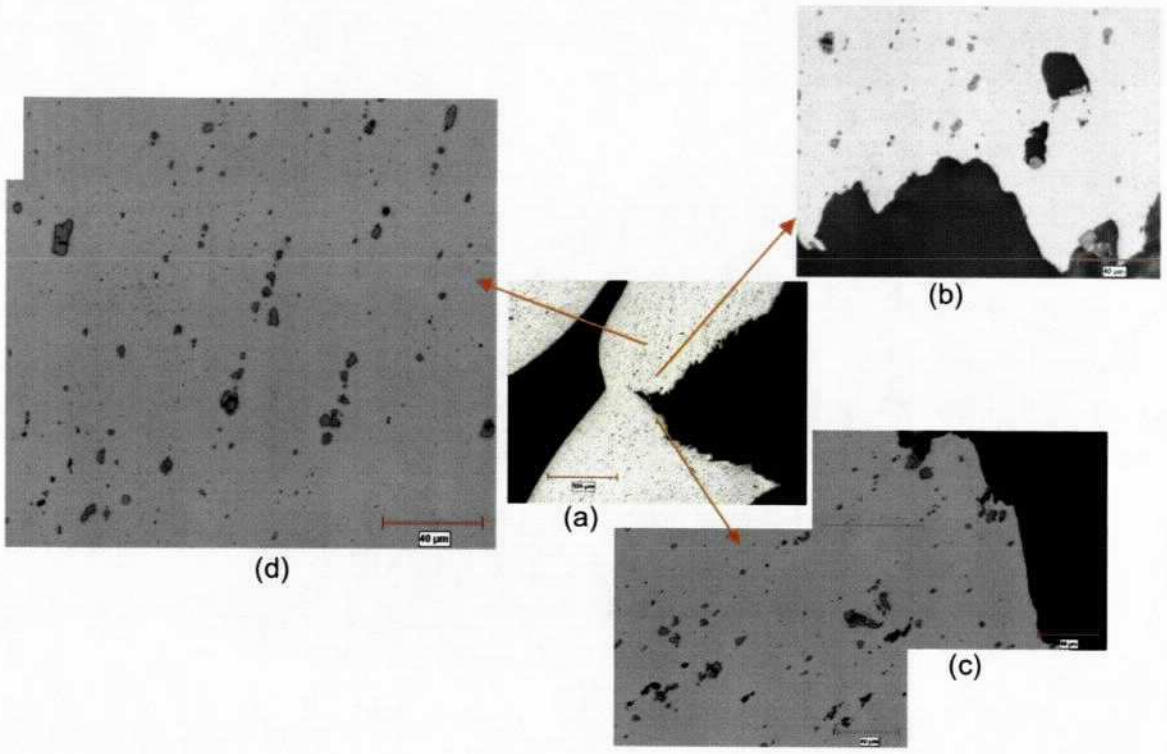
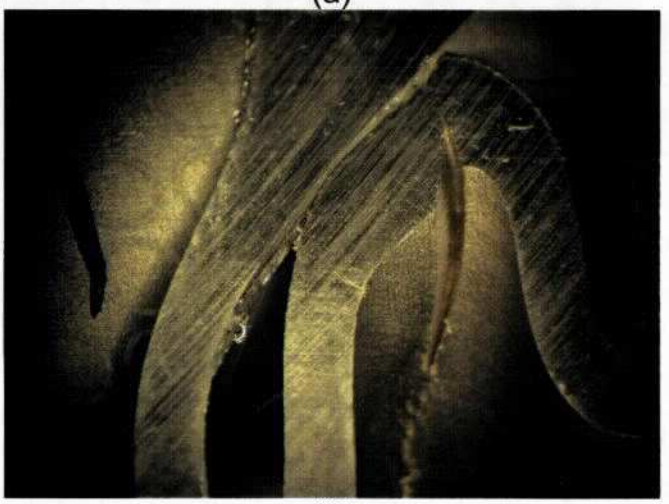


Figure 11 Failed region in Section E, #5, (a) the overall view of the failed segment, (b), (c), and (d) show different location of (a) at higher mag. that indicates particle induced damage prior to ductile failure probably in tearing mode.

C. Scanning Electron Microscopy

Figure 13 is a specimen examined using SEM. Eye examination of the specimen prior to microscopy suggests that the segment failed under tearing mode or a combination of shearing and tearing failure mechanism. The fracture surface is relatively very smooth and the dimples are shallow. In addition there are many microcracks observable near the second phase particles or in the alloy itself. The latter observation is better shown in Figure 14 at relatively higher magnification. In general considering the fracture surface and the observed microcracks it could be concluded that the final failure has been done without absorbing that much of energy, however the material seems to have been exhausted its energy absorbing capacity as evidenced by formation of a large number of cracks and microcracks.

(a)



(b)

Figure 12 (a) and (b) stereomicroscope images of the failed segment in one specimen that shows material flow at the bend region as well as the effect of impact from the neighbouring segment.

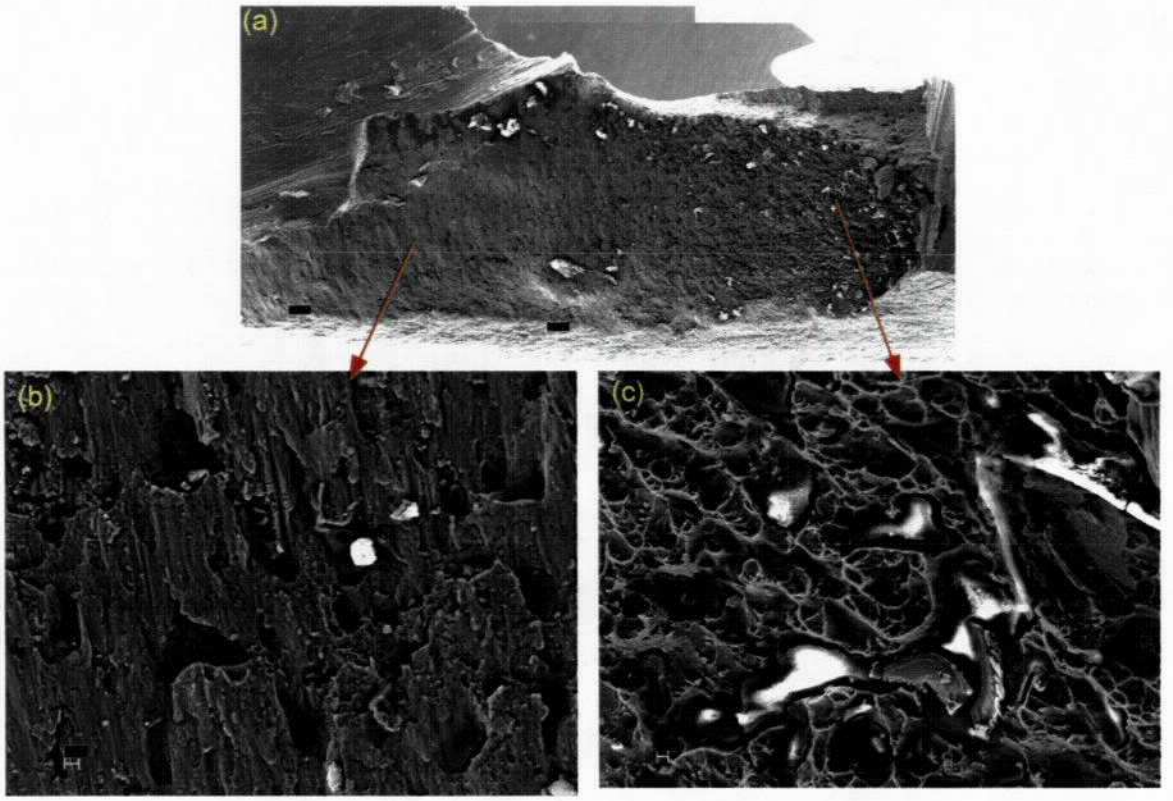


Figure 13 Fracture surface of a segment in specimen S11 examined using SEM, (a) general view of the fractured area, (b) and (c) are higher magnification of two regions shown by the arrows.

Conclusions

The main objective of the present on-going study is to understand acting damage and failure mechanisms in tubes during the crash situation under axial loading. Results are valuable both industrially as well as scientifically not only as an stand alone investigation but also in terms of providing realistic view of failure mechanisms to be used in conjunction with simulation studies based on finite elements methods (FEM).
The up-to-date examination of the specimens have shown that:

The local folding pattern of the tube is very influential in both deformation as well as failure mechanisms.

Depending on the interaction between the neighbouring segments, a given segment might be deformed in a pure sliding mode, tearing mode or a combination of the two.

In cases that there was no impacts from the neighbouring segments, the side of a folded segment in tension did not show any evidences of

significant damage. In contrast the side of the folded segments in compression always exhibited significant amount of damage both with and without impact from the neighbouring segments.

Regardless of the acting failure mechanisms, significant amount of particle-induced damage has been observed in fractured segments.

Future works include more similar works on crashed tubes of different thickness with more emphasises on SEM as well as stereomicroscope studies.

Acknowledgments

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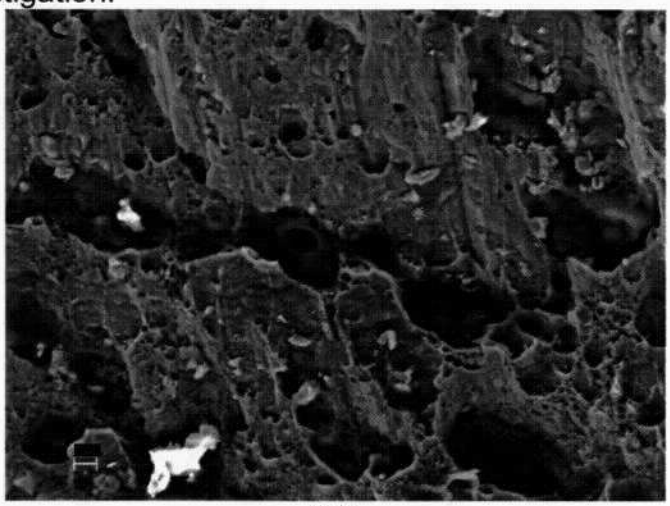
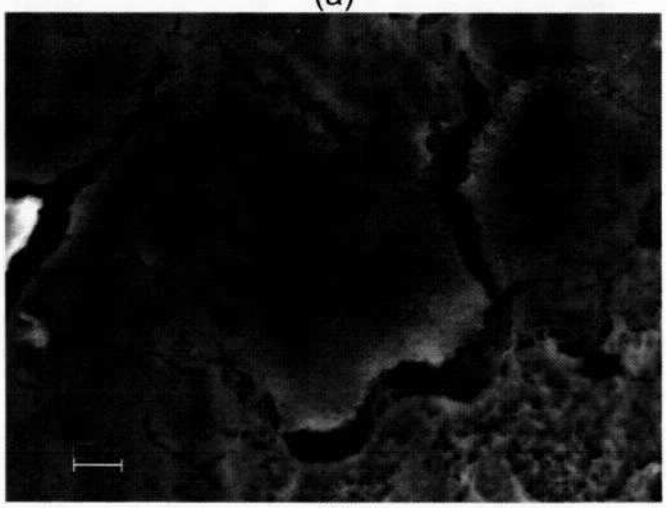


(a)



(b)

Figure 14 (a) and (b) formation of cracks and microcracks observed in fracture surface of one of the specimens.

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