Chapter 8
Exploring the Influence of Localized Mechanical Details on ShearBand Evolution in Collapsing Thick-Wall Cylinders

Zev Lovinger, Kobi Cohen, and Shmuel Osovski

Abstract Thick-wall cylinder (TWC) experiments have been widely used to investigate shear band initiation and evolution in various materials. Under a collapsing load, shear bands emanate at the cylinder's inner boundary. As the boundary is free of stress concentrations, the shear bands evolve in a spontaneous manner, addressing the intrinsic susceptibility of the material to shear. The degree of susceptibility is often characterized by the radial strain at which shear bands first appear. In previous work, premature local initiations of shear bands were observed, indicating possible localized mechanical flaws that are caused during machining or assembly processes. Such a result could also be relevant when addressing engineering parts, including practical mechanical joint details for manufacturing or assembly considerations, that introduce localization sites. In this study, we introduce controlled mechanical features into Ti-6Al-4V cylindrical specimens and subject them to TWC experiments. Post-mortem micro-CT analysis reveals early shear initiation at the mechanical detail site, significantly affecting the final specimen's deformation. Complementary numerical simulations, incorporating a shear-sensitive material model, successfully replicate key aspects of the experimental results. The simulations highlight the profound impact of early localized shear bands on the overall deformation kinetics.

Keywords Thick-walled cylinders · Shear Bands · High strain-rate · Dynamic failure · Shear localization

Introduction

The Thick-wall cylinder (TWC) technique is used to explore the spontaneous evolution of shear bands [1–3]. In this technique, the TWC specimen is sandwiched between two cylindrical copper shells, which are driven inwards by an external force, either by explosives [4] or by magnetic forces [5], while the outer and inner copper shells control the extent of collapse of the sample. The main diagnostic of this technique is post-mortem analysis: the recovered sample is analyzed to reveal the shear bands in the specimen. This could be done by cutting and polishing a cross-section of the post-tested specimen [1], or, as shown more recently, by using high-resolution micro-CT of the entire specimen [6]. The external pressure induces an inward collapse of the cylinder, and shear bands that evolve from the inner surface of the collapsing cylinder do not form on a clear boundary or by stress concentration. Free of transverse boundary constraints, the initiation of the shear bands occurs spontaneously. The spontaneous evolution, differing from forced shear localization [7], allows addressing the intrinsic susceptibility of the material to shear.

The shear bands' distribution is characterized by their lengths and the spacing between them, and they are mostly related to material characteristics [8, 9] and to the dynamics of evolution, introducing a shielding effect due to rarefaction waves emanating from the developed shear surfaces, affecting the adjacent shear bands [1]. In previous work [3, 4], some specimens have shown significant local deviations from the typical shear-band distribution observed for the material. Fig. 1 shows two cross-sections of post-tested TWCs obtained from two SS304L specimens under similar loading conditions. Figure 1(a)

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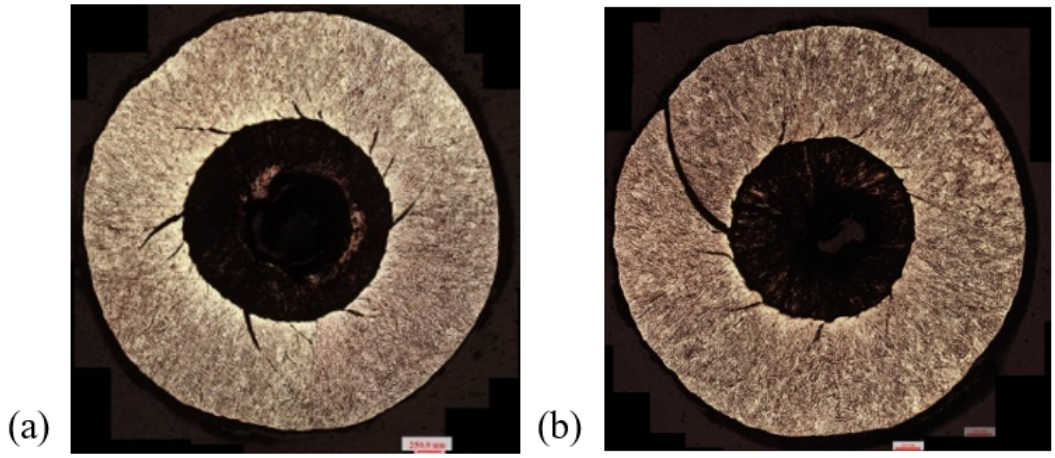

Fig. 1 Cross sections of two SS304L specimens: (a) a standard SB distribution result, (b) a shear-band distribution, and a single developed through-the-thickness shear band, as a result of early initiation.

shows a standard shear band pattern, with several developed shear bands and smaller shear bands in between. Figure 1(b) shows, aside from the similar shear-band distribution in most of the perimeter, a single well-developed shear-band across the entire thickness [3]. This anomaly is also seen in other works, such as that of Xue et al. [1]. Previous analysis in [3] has explained this phenomenon as premature local initiations of shear bands, possibly due to localized mechanical flaws that are caused during machining or assembly processes. This explanation was demonstrated through numerical simulations by locally changing the initial damage parameter in a single 'weak' cell, on the specimen's inner boundary [3]. As this shear surface initiates at an early stage, it manages to develop to a large distance and to reach the full thickness. Furthermore, the shielding effect becomes more significant on a wider section, yet, aside from its vicinity, the shear band distribution seems similar to the 'standard' distribution, as seen in Fig. 1(a).

Revisiting this irregularity, we sought to examine the effects of early localization under possible conditions of stress concentrations. This phenomenon could be relevant when addressing engineering parts, including practical mechanical joint details for manufacturing or assembly considerations, that introduce localization sites. In this study, we conducted numerical simulations of collapsing TWC with specimens that included mechanical joint details to study the kinetics of such cases. We then conducted TWC experiments with Ti64 cylinders, representing a planar (gliding) mechanical detail, to compare the experimental results with the simulations. A good comparison was achieved, and the simulations revealed interesting insights into the kinetics succeeding the early localization.

Results

We first present 2D numerical simulations of two TWC specimens, one of which includes a step-like lap joint. The numerical simulations were carried out using a Lagrangian hydrocode previously described in [5]. The specimen material is Ti64, sandwiched between two copper cylinders. The specimen's outer and inner diameters are $D_{out} = 5$mm and $D_{in} = 3.5$ mm. The full geometry, material models, and the boundary pressure, which represents the magnetic load that is applied by the pulsed current generator (PCG), are detailed in previous work [3,5]. The comparison of the two cases at different time steps is shown in Fig. 2. Shear band patterns are well observed in plastic strain maps. While the whole cylinder shows no localization at $t = 1.5$ μs, the cylinder with the lap joint shows well-developed shear bands that evolved from the corners of the step-like detail, introducing localization sites. At later times, $t = 2.0$ μs and 2.5 μs, shear bands evolve in the whole-cylinder case in a homogeneous pattern, while for the joint cylinder, significant changes in the shear band patterns, away from the joint detail, are evident. The simulations reveal that the complex wave patterns, originating from the early developed shear bands, cause substantial shielding and suppression of developing shear bands around the joint. A noteworthy phenomenon was observed on the velocity maps. Figure 2 shows the simulation result at $t = 2.5$ μs, both with plastic strain and velocity maps. The simulation reveals that the kinetics of the early shear evolution cause a significant difference in the local velocity of the detaching mass between the shear bands. A relative velocity of 400-500 m/s in comparison with the bulk velocity is developed, causing significant changes in the deformation kinetics of the cylinder. In Figure 3, simulations with a planar joint (a slit) are shown, with a gap of 0.2 mm. This gap was chosen according to the actual details that we were able to

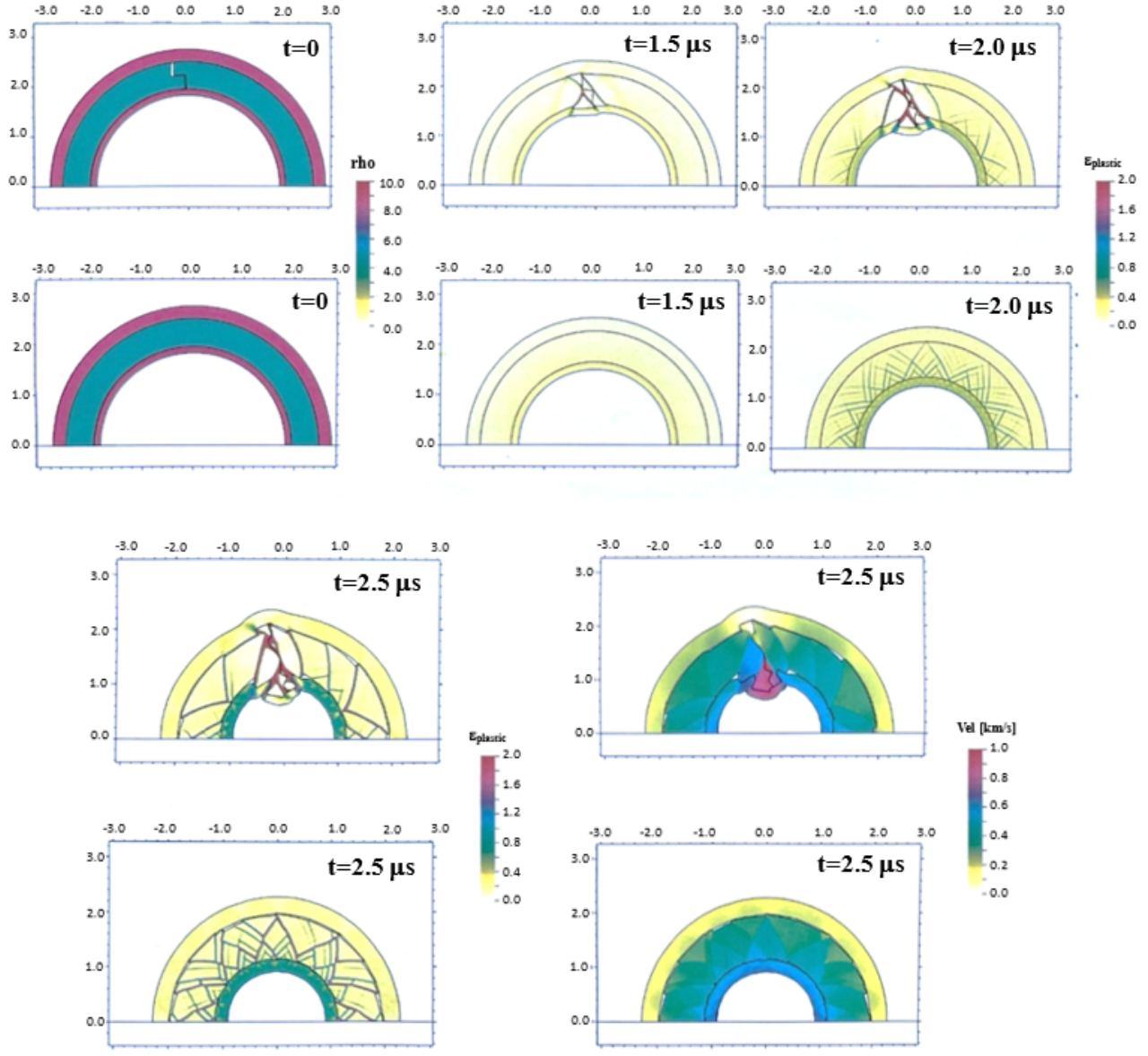

Fig. 2 Numerical simulations of collapsing Ti64 TWC with and without a mechanical step-joint: Density maps at t = 0,Plastic Strain maps at t = 1.5, 2.0, 2.5 µs and Velocity maps at 2.5 µs.

manufacture for the experimental work. Similar phenomena as for the step-joint case are achieved in the simulations, yet the specific geometrical details of the shear bands and the corresponding detaching mass differ.

The planar joint shows stress concentrations at the joint corners, yet upon the cylinder's collapse, an impact occurs between the two planes, and a focal point is created as an additional localization point, as can be seen in Figure 3.

Finally, we wanted to examine and validate these phenomena in experiments. To create a mechanical detail in the TWC specimen, we used EDM (Electrical Discharge Machining) to create a narrow slit in the mid-section of the cylinder. This allowed us to examine in the same experiment both a section with a mechanical joint and sections with the original full cross-section. Figure 4 shows micro-CT scans of the whole cylinder together with cross-sections of the original geometry and post-test results. Fig. 4a shows the slit at the center height of the cylinder together with a corresponding cross-section of the original geometry. Fig. 4(b) shows the post-tested specimen with two cross sections: above (CS#1) and below (CS#2) the machined slit. CS#1 shows a homogeneous SB distribution, similar to that obtained for this geometry and conditions in previous work [2]. CS#2 shows different geometrical details where the slit was present. Figure 5 shows a zoomed-in comparison with the numerical simulations. Significant resemblance of the localized details of shear bands and corresponding geometry is found.

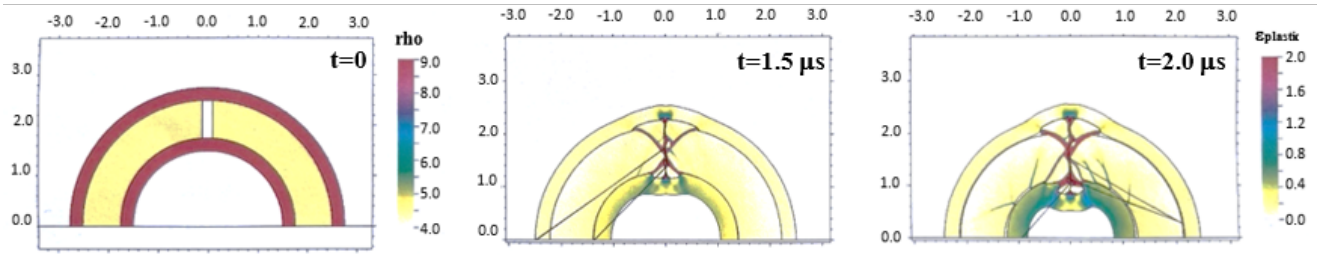

Fig. 3 Numerical simulations of collapsing Ti64 TWC with a mechanical planar (gliding) joint: Density map at t = 0 and Plastic Strain maps at t = 1.5, 2.0 µs.

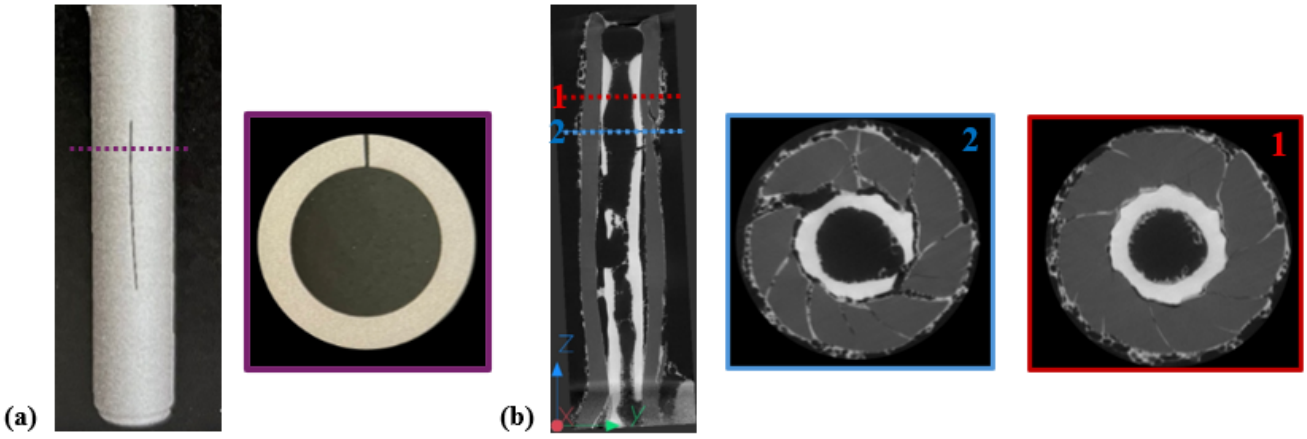

Fig. 4 Micro-CT scans of TWC specimen with a 0.2mm slit, representing a mechanical planar (gliding) joint: (a) original geometry with the corresponding cross-section, (b) post-test results of the cylinder with two cross sections (CS): CS#1 from area with no slit and CS#2 from area with slit.

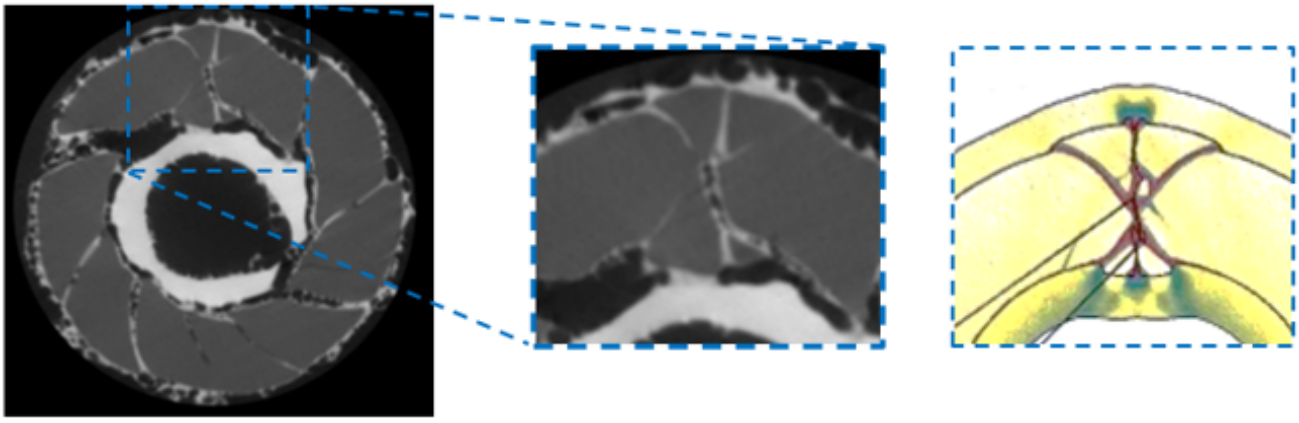

Fig. 5 Comparison of planar joint deformation in TWC experiment and the corresponding numerical simulation.

Conclusion and Future Work

This work has demonstrated the significant impact of mechanical details on the overall behavior of a collapsing TWC, due to the occurrence of early localization. The simulations highlighted the intricate influence on deformation kinetics as the cylinder undergoes large deformations. The successful comparison with designated TWC experiments sets a good basis for further study of this topic. This phenomenon could be relevant when addressing engineering parts, including practical mechanical joint details for manufacturing or assembly considerations, especially in materials that are susceptible to shear

banding, introducing early localization. Further exploration through numerical modelling is needed to examine the noted effects as a function of material susceptibility, geometrical scaling, and possible inertia effects.

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