Chapter 2
Investigating Failure Characteristics of Metals at High Strain Rates Using Magnetically Driven Expanding Cylinders

Aaron Zaretzki, Zev Lovinger, and Daniel Rittel

Abstract Failure modes under dynamic tension vary for different materials and different loading conditions (e.g., strain rate, stress states, and stress history), with necking and tension, or shear localization as the dominant failure mechanisms. The actual reason for the appearance of one mode rather than the other is still poorly understood and inconclusive. Most of the reported data in the literature is limited to rates of 10∧3-10∧4 s∧-1, measured at the free-flight stage of expanding rings or cylinders. This work focuses on the study of failure characteristics of three metals, SS304L, Cu, and Ta, in expanding cylinder experiments at very high strain rates, ranging from 10∧4 to a few 10∧5 s∧-1. The experimental work was performed using a pulsed current generator (PCG) to drive the expanding cylinders using magnetic forces. The main diagnostic tool to examine the actual failure modes of the expanding cylinders was post-mortem analysis of the soft-caught fragments, using optical microscopy. Velocimetry, measuring the ring expansion, was used to capture the failure strain at breakup. Different failure modes of tensile and shear were determined for the three materials at different loading conditions, and analysis was conducted in relation to material properties and stress conditions at the macro and micro scales.

Keyword Expanding cylinders · Failure mode · High strain-rate · Dynamic failure · Behavior of Materials

Introduction

Strain rate is an important factor when characterizing the strength and failure properties of a material. The dynamic behavior of a material can be significantly different from its static behavior. In the dynamic regime, at high strain rates, as the macroscopic strain rate becomes comparable to the rate of microscopic plasticity mechanisms, significant changes in the material's strength are evident. A turn-up behavior in strength at a typical strain rate of 10^4 s^-1 is observed [1, 2]. The plasticity mechanisms, attributed to dislocation dynamics through slip and twinning systems, cannot respond in the same manner, resulting in higher strengths, and possibly affecting also the failure behavior. At very high strain rates, changes in the failure strain are observed in different materials, and for some, a ductile-to-brittle transition is evident. Failure of materials at high strain rates has been studied for over 100 years, led by a strong interest in the fragmentation of shells and munitions. The fundamental work of N. F. Mott in the 1940's has focused on the theory of rupture in metals. Much data was analyzed to understand the sizes of fragments, or in practice, the distribution of sizes in the rupture of bomb casings [3, 4]. Much of Mott's work was revisited by D. E. Grady, together with more recent studies, including the vast work by D. E. Grady [5]. Part of Mott's work has examined the tensile and shear fracture characteristics from the evident fragments in his study, most of which were related to metals used for munition casings. The two dominant characteristic failure mechanisms causing fragment rupture are tensile fracture and shear. The appearance of these mechanisms is affected by many factors, such as the deformation rate, stress conditions related to 2D or 3D curvature, the occurrence of geometric and material instabilities, and material ductility [5]. Other works identified triaxiality as a dominant factor in defining the actual failure mechanism [6, 7]. The occurrence of such failure mechanisms, especially when observing different types of materials, is still not well understood to enable their prediction. Furthermore, controlled data at very high strain rates is limited. This study aimed to explore the characteristics of failure at very high strain rates up to 10^5-10^6 s^-1 in three different

Aaron Zaretski · Zev Lovinger · Daniel Rittel
Technion – Israel Institute of Technology, Faculty of Mechanical Engineering, Haifa, 32000, Israel
e-mail: a-z@campus.technion.ac.il; z.lovinger@technion.ac.il; merittel@technion.ac.il

© The Author(s), under exclusive license to River Publishers 2026

Paul Allison et al. (eds.), *Dynamic Behavior of Materials, Volume 1, 2026*, Conference Proceedings
of the Society for Experimental Mechanics Series, https://doi.org/10.13052/rp-9788743816249

types of metals, Tantalum, Copper, and ss304L, to try and better understand the factors and conditions that control these mechanisms.

Results

An experimental setup was developed on a PCG (Pulsed Current Generator) to apply electro-magnetic driving forces for the expansion of cylindrical specimens, following previous work of some of the authors [8]. The expanding cylinder setup, is shown in Fig. 1 and is an assembly of coaxial cylinders: an inner cylindrical steel rod (D = 3.5 mm), a copper cylinder serving as the "pusher" (D_{in} = 5.0 mm, D_{out} = 6.0 mm) and the tested specimen, which is mounted on the pusher" cylinder (D_{in} = 6.0 mm, D_{out} = 7.0 mm). When the voltage is discharged, a current flows on both sides of the plastic isolator but in opposite directions, thus creating repulsive magnetic forces between them. The "pusher" cylinder is driven outwards by expansion, and the internal rod is compressed inwards. The 'pusher' carries the high current, transferring the load to the tested specimen, thus preventing the joule heating of the specimen, which would affect its properties. The tested cylindrical specimens included various thicknesses (0.25/0.5/1.0 mm) and heights (7/15mm), examining three types of materials: SS304L, Copper, and Tantalum. PCG Voltage allowed to control the loading rate of the specimens. The continuous ring expansion was recorded using PDV probes, and 3D printed rubber padding was placed at the perimeter to allow the soft catch of the fragments. The fragments were then mounted and polished to examine the failure modes, using optical microscopy.

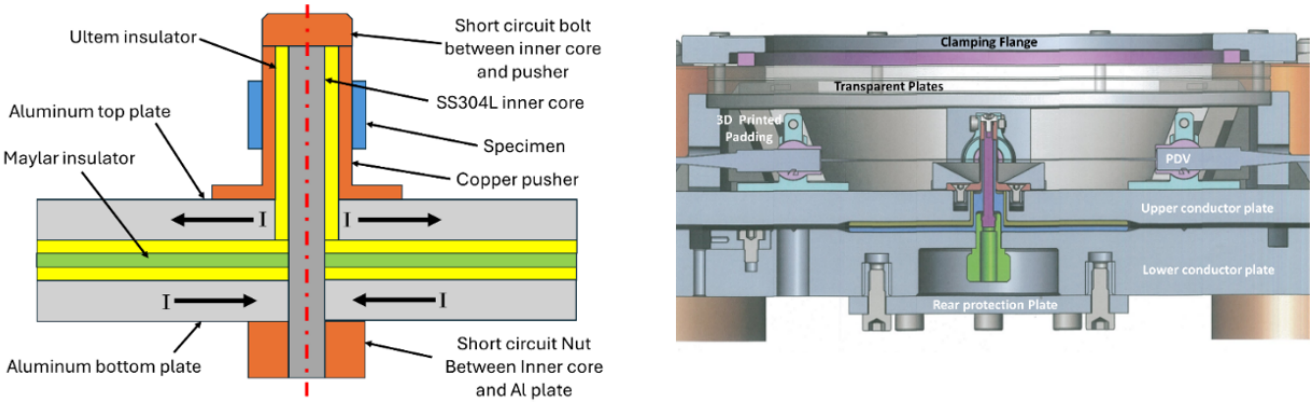

Fig. 1 Schematic description of the expanding cylinder set-up on the PCG and an overview assembly of the test chamber with soft catch padding and PDV probes.

Along with the dynamic setup, quasi-static tests were conducted with similar specimens, using a piston-like setup on an Instron machine. The axial load pressed a soft plastic disk between two hard rods, expanding the specimen, which was placed around the extruding plastic disk. The setup and a typical result are shown in Figure 2.

A total of 23 experiments were conducted (7 static and 16 dynamic expansion tests). Optical microscopy was conducted on metallurgical specimens of the fragments to characterize the failure modes. Representative fragments of each of the materials are shown in Figure 3. The main result we obtained was that for all tested parameters (geometry and loading conditions), the failure mode remained the same for each material, and no transition was observed. The resolved failure modes were: Tantalum – tensile failure, ss304L – shear failure, copper- showed a mixed mode of both tensile and shear failure modes.

The results have been examined from different perspectives to explore reasons for the preference of the failure mode for the three materials, and the observed sensitivities and trends in the failure strain. The following criteria were examined:

(1) Considère criterion – examining the onset of necking. Low values for this criterion refer to materials that tend to neck and fail under tension.

(2) Triaxiality – related to the different material properties and geometries.

(3) Plasticity mechanisms (Twinning) – as all three materials exhibit twinning, we examined their twinning energy, related to their SFE values, and examined the possible relation of the plasticity mechanism preference to the actual failure mechanism.

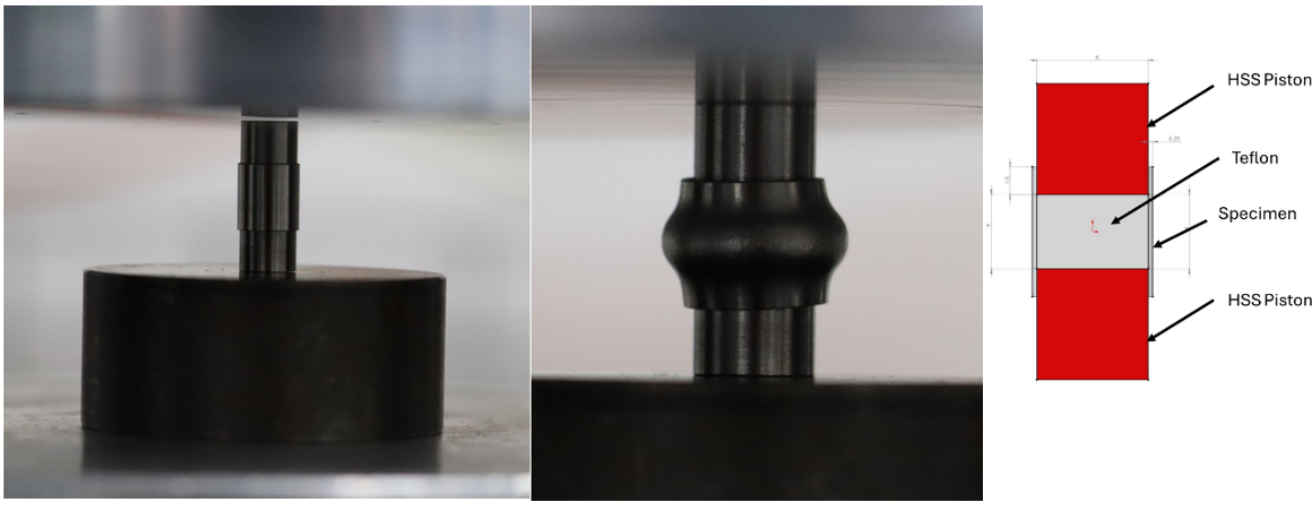

Fig. 2 Quasi-static expanding cylinder set-up using hard steel (HSS) pistons and soft Teflon undergoing expansion.

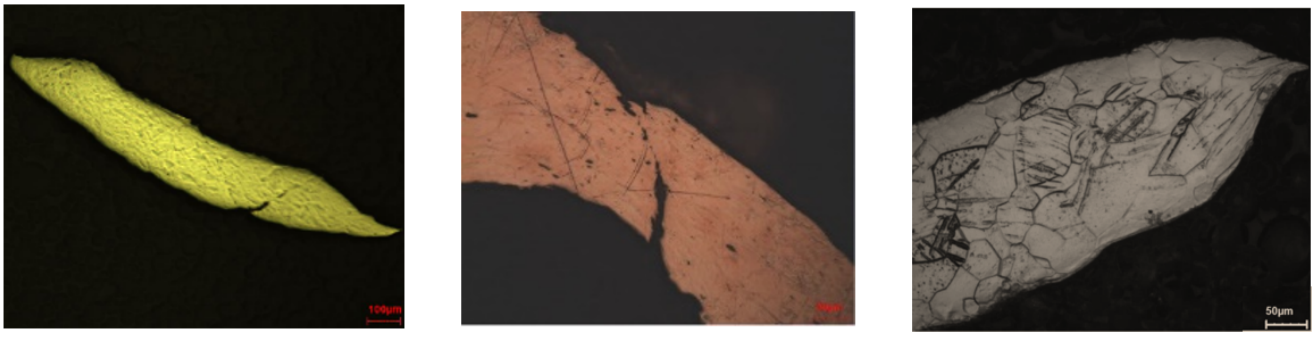

Fig. 3 Representative fragments (left to right) for ss304L (shear failure), Cu (mixed mode failure), and Tantalum (tensile failure).

Conclusions and Future Work

The collective behavior of the failure modes in the three materials was examined through three different perspectives and corresponding criteria: Considère criterion for necking, propensity to twinning, and triaxiality effects. The overall analysis suggests competition between the two failure modes, where the 3 examined perspectives are complementary factors to one another. Higher tendency to necking (with a low strain by the Considère criterion) will lead to ductile tensile failure like Ta, while higher tendency to twin over slip will encourage shear failure, as for ss304L. These two factors match well with the experimental results. For copper, the 'close' competition results in a mixed mode, finding sometimes necking and tensile failure, and in some cases, shear failure. Triaxiality, which was suggested in the literature to be related to the failure mode, seems to be in a limited range in our experiments and thus is not a dominant factor in this research. Inertia effects were also expected to affect the failure results, but no significant phenomena in failure modes were noted under dynamic conditions; thus, they were not part of our analysis. Future work will examine the validity of these findings with additional materials and examine a parametric numerical study for some of the parameters that were limited through our experimental setup, such as cylinder geometry and the range of triaxiality.

References

1. F. J. Zerilli and R. W. Armstrong (1992), "The effect of dislocation drag on the stress-strain behavior of fcc metals", Research and Technology Department, Naval Surface Warfare Center.
2. P. S. Follansbee, U.F. Kocks (1988), "A constitutive description of the deformation of copper based on the use of the mechanical threshold stress as an internal state variable", Acta Metal. Vol. 36, pp. 81-93

3. Mott, N.F. (1948), Fracture of Metals: Theoretical Considerations, Engineering, 165, 16–18.
4. N.F. Mott (1945) “Fragmentation of shell cases”, Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, Volume 189, Issue 1018, pp. 300-308.
5. D. E. Grady (2006), “Fragmentation of Rings and Shells”, Springer, Berlin, Heidelberg.
6. Y. Bao & T. Wierzbicki (2004), “On fracture locus in the equivalent strain and stress triaxiality space”, Int. J. of Mech. Sci. 46, pp. 81 – 98.
7. Y. Bao & T. Wierzbicki (2008), “A Comparative Study on Various Ductile Crack Formation Criteria”, J. Eng. Mater. Tech., Vol. 126, pp. 314-324.
8. E. Avriel, Z. Lovinger, R. Nemirovsky, D. Rittel (2018) “Investigating the strength of materials at very high strain rates using electromagnetically driven expanding cylinders”. Mech, of Mat. Vol. 117, pp. 165-180.