
High-Strain-Rate Nanoindentation: Revisiting the Hardness Upturn in Metals

Lalith Kumar Bhaskar*^{†1}, Dipali Sonawane¹, Hendrik Holz¹, Jeongin Paeng¹, Jing Rao¹, Bárbara Bellón¹, Damian Frey², László Pethő³, Johann Michler³, Jakob Schwiedrzik⁴, Gaurav Mohanty⁵, Gerhard Dehm¹, and Rajaprakash Ramachandramoorthy^{‡1}

¹Department of Structure and Micro-/Nano- Mechanics of Materials, Max-Planck-Institut für Nachhaltige Materialien GmbH, 40237 Düsseldorf – Germany

²Alemnis AG – Switzerland

³Laboratory of Mechanics of Materials and Nanostructures, Empa Swiss Federal Laboratories for Materials Science and Technology, Feuerwerkerstrasse 39, 3602 Thun, Switzerland – Switzerland

⁴Laboratory for High Performance Ceramics, Empa Swiss Federal Laboratories for Materials Science and Technology, Ueberlandstrasse 129, 8600 Dübendorf, Switzerland – Switzerland

⁵Materials Science and Environmental Engineering, Faculty of Engineering and Natural Sciences, Tampere University, 33014 Tampere, Finland – Finland

Abstract

The Fourth Industrial Revolution has ushered in rapid advancements in high-speed transportation, machining, and miniaturized electronics, exposing materials to extreme conditions, including high strain rates. While macroscale techniques like split-Hopkinson pressure bars, Kolsky bars, and gas gun experiments can reach strain rates of up to 10^4 s⁻¹, maintaining a constant strain rate during testing remains challenging. These methods require extreme actuation speeds, often in the range of several hundred meters per second, which can introduce shock propagation and complicate post-deformation analysis. Instrumented nanoindentation offers a promising alternative, in which one could achieve very high strain rates of up to 10^4 s⁻¹ with actuation speeds as low as ~ 100 mm/s over indentation depths up to ~ 1 μ m. Additionally, nanoindentation using exponential displacement profiles allows for a constant strain rate, which is advantageous for post-deformation analysis and generating reliable load-displacement curves. Despite these benefits, current limitations in hardware and protocols restrict the highest reported constant strain rate nanoindentation to only 10^2 s⁻¹. This presentation will provide an overview of a highly specialized, high-speed piezoelectric-based micromechanical setup designed to achieve constant strain rate nanoindentation up to an unprecedented strain rate of 10^4 s⁻¹. Key aspects of the custom-modified electronic hardware and essential experimental protocols for capturing precise load-displacement data during high-strain-rate indentations and accurately extracting hardness values will be discussed. The presentation will also examine the material behavior of two different materials: single-crystalline BCC molybdenum and nanocrystalline FCC nickel. Notably, a significant hardness upturn was observed in these materials beyond strain rates of 10^3 s⁻¹ and 10^4 s⁻¹.

*Speaker

[†]Corresponding author: l.bhaskar@mpie.de

[‡]Corresponding author: r.ram@mpie.de

for nanocrystalline nickel and molybdenum, respectively. This upturn, linked to strain-rate-dependent microstructural changes, resulted in a threefold increase in strain rate sensitivity for both materials. The observed hardness variations and underlying deformation mechanisms will be supported by transmission electron microscopy (TEM) analysis and thermal activation studies.