Mesoscale Mechanical Testing: Possibilities for High Strain Rate Characterisation

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Abstract. Mesoscale mechanical testing provides a unique window into deformation and damage processes that are neither captured by bulk tests nor fully resolved by microscale methods. This work presents a mesoscale testing approach that enables controlled loading of mesoscale samples (50-500 μm) while limiting size effects. We identified a simple technique to manufacture and test specimens with gauge lengths below one millimetre. Further, as the specimen dimension reduces, high strain rate loading becomes possible with mesoscale specimens using conventional testing systems. Finally, we conclude the difficulties mesoscale testing needs to overcome to emerge as a necessary experimental regime for linking local deformation mechanisms to engineering-scale mechanical response.

Introduction

Progressive trend to manufacture ever smaller mechanical, optical and electronic devices and products has pushed the dimensions of structural components in micrometre scale. This created the need to characterise small-scale mechanical properties to ensure the applicability of the micro-components in service condition. The literature reveals a wide range of specimen sizes and geometries used for small-scale tensile testing, many of which deviates from ASTM standards without consistent terminology (small-scale, miniaturised, micro-scale, nano-scale). This lack of clarity is not just a semantic nuisance but originates on the challenges in manufacturing and testing samples at different length scale. Furthermore, there is a lack of clear interpretation to recover macroscopic mechanical behaviour to support engineering applications.

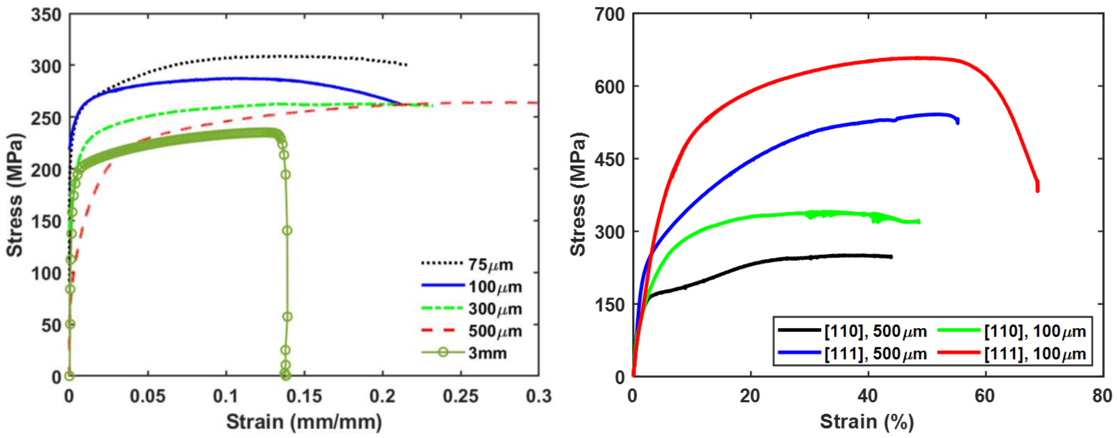
This work distinguishes the common terminologies literature referring to mechanical testing scales and proposes a taxonomy based on the required testing technology. We focus mesoscale tests, the lowest representation of bulk deformation behaviour, as a tool to facilitate mechanical testing of bulk properties. We demonstrate a cost-effective methodology to fabricate specimens and testing protocol which can further be extended to high strain rate testing.

Results and Discussion

We identified micromilling as an effective machining technique, which balances minimum achievable feature size and material removal rate. We used KERN Micromachining, following a two-stage process to fabricate specimens between 50-500 μm gauge widths, just under 45 minutes of fabrication time. This shows high dimensional tolerance and minimal damage from machining. Further we used Instron 5944 systems to deform the specimens ranging from single crystal Nickel to polycrystalline Copper and Nickel under quasi-static conditions first. Fig. 1 describes this as a schematic representation.

Fig. 1: Schematic of mesoscale mechanical testing followed in this work

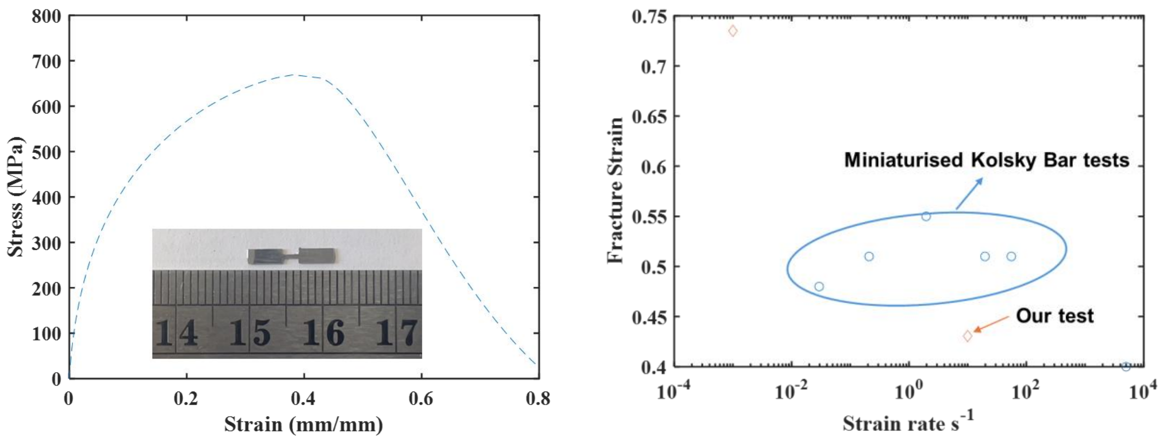
The results with polycrystalline copper show geometric size effect dominates below 500 μm gauge width (see Fig. 2a), which can be considered as the lowest representative size for macroscopic properties. Furthermore, single crystal Nickel with two different orientations and two different specimen sizes show orientation and geometric size sensitivity (Fig. 2b).



(a) (b)

Fig. 2: (a) Quasi-static tensile behaviour of polycrystalline Copper with different geometries. This reveals 500 μm gauge width as optimal mesoscale dimension without size effect. (b) Further extended to single crystal Nickel with different geometries and orientations.

We further extended this to high strain rate testing possibilities as an alternative to miniaturised Kolsky bar tests. We used mesoscale stainless-steel specimens for this case study. Following the methodology described earlier, we manufactured 500 μm gauge width specimens and tested it beyond quasi-static conditions. With present electronics, we only achieved a maximum of 10 s^{-1} strain rate. This is shown in Fig. 3a. Using fracture strain to compare between our method and miniaturised Kolsky bar tests, the results showed a good agreement.



(a) (b)

Fig. 3: (a) Tensile deformation of SS316 mesoscale specimen at 10 s^{-1} strain rate following our methodology. The specimen is shown at the inset. (b) A comparison of fracture strain with miniaturised Kolsky bar tests reveals comparable behaviour.

Conclusion

We developed a procedure for mesoscale mechanical tests, which can be easily adopted with traditional university testing systems. We demonstrated the mesoscale samples can be manufactured with confidence, but the main limitations are found on the testing technologies, which lack sampling speed and flexibility.