# Fracture behavior of a tough bulk metallic glass at micrometer dimensions

A. Jelinek*, D. Kiener

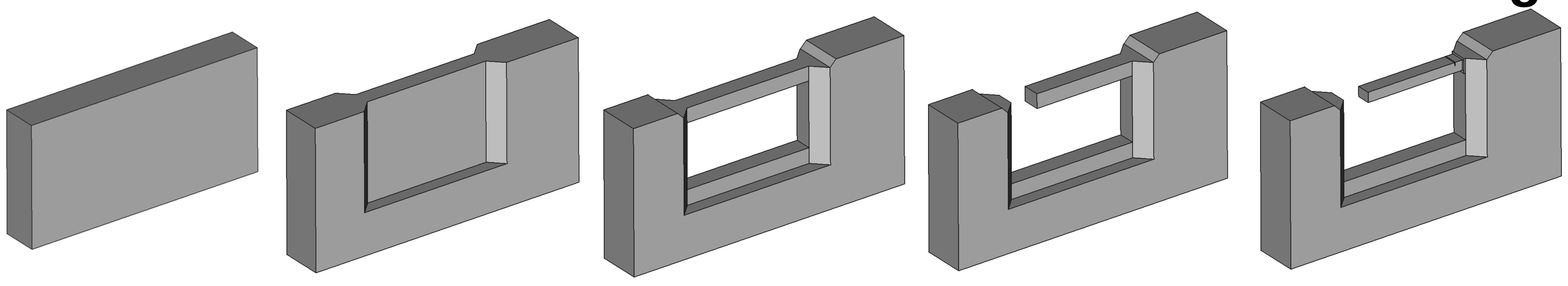
Department of Materials Science, Montanuniversität Leoben, Leoben, Austria

## Motivation

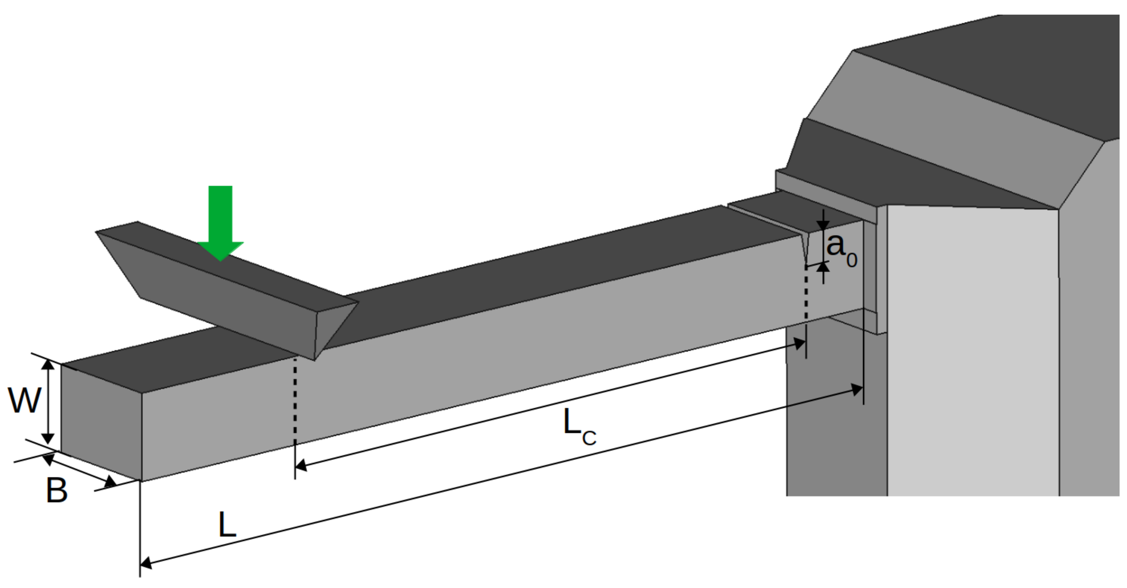
Bulk metallic glasses (BMGs) are a promising material group for applications in micro- and nano-electro-mechanical-systems due to their unique physical properties, such as a comparably high hardness and elastic limit, paired with amorphous structure and certain glass specific traits. Despite significant research efforts performed on BMGs, spare data is available for mechanical properties at the micrometer size regime, as required for the above mentioned usage. While glasses commonly suffer from shear localization, leading to macroscopic brittle behavior, inherently ductile metallic glasses exist, which show extraordinary high resistance to crack propagation under bending load [1]. This special case of crack tip plasticity poses an issue to the conventional description of fracture toughness and therefore further detailed investigation on the fracture process is required. The present work strives for a deeper insight into the deformation mechanism and fracture behavior of a strong and ductile BMG, namely $Pd_{77.5}Cu_6Si_{16.5}$, in the micrometer regime.

To quantify the fracture toughness at micrometer dimension, procedures are required that may not fulfill all validity-requirements for standardized procedures, especially regarding sample dimensions. Since the fracture mechanical descriptions are based on fundamental considerations regarding crack and sample geometry, a deviation of such requirements should always be addressed with caution [2]. Nevertheless, the framework of fracture mechanics allows to study influences of e.g. size or load on the fracture process in terms of conditional fracture toughness, which may further be geometry dependent.

## Fabrication of micro cantilever with FIB and in-situ testing



- Rough cutting with a diamond wire saw
- Fabrication of a lamella through thickness-controlled grinding and polishing
- FIB milling of geometry with stepwise decreasing ion current (see above)
- Introduction of a notch via FIB




- 11 notched cantilever
- ligament sizes of 1, 2 and 5 µm
- dimension ratio W x B x L of 1 x 1 x 7
- $a_0$ / W ratio ranging from 0.3 to 0.4

in-situ testing:

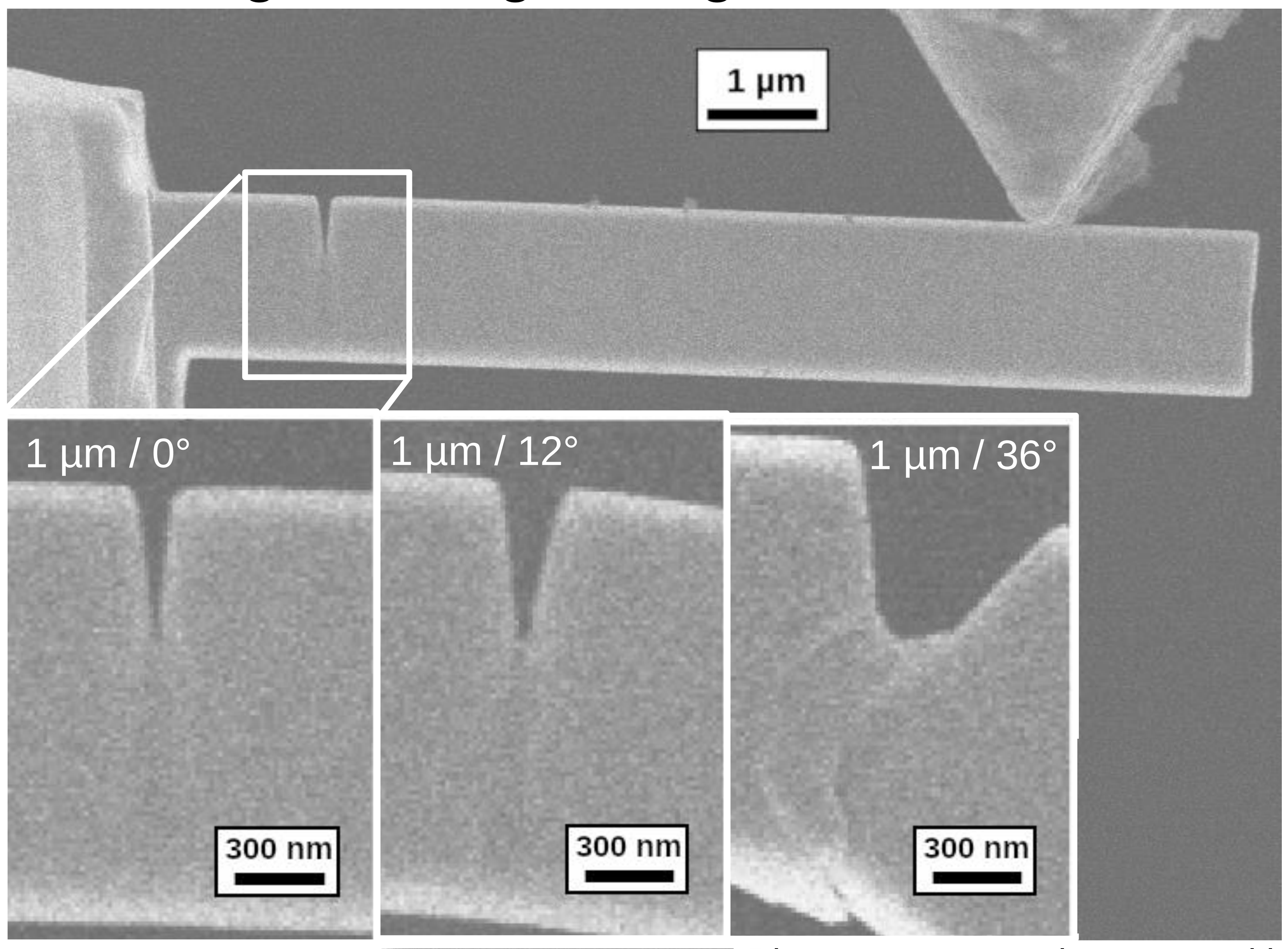
- Hysitron PI-85 Nanoindenter with a continuous stiffness measurement upgrade

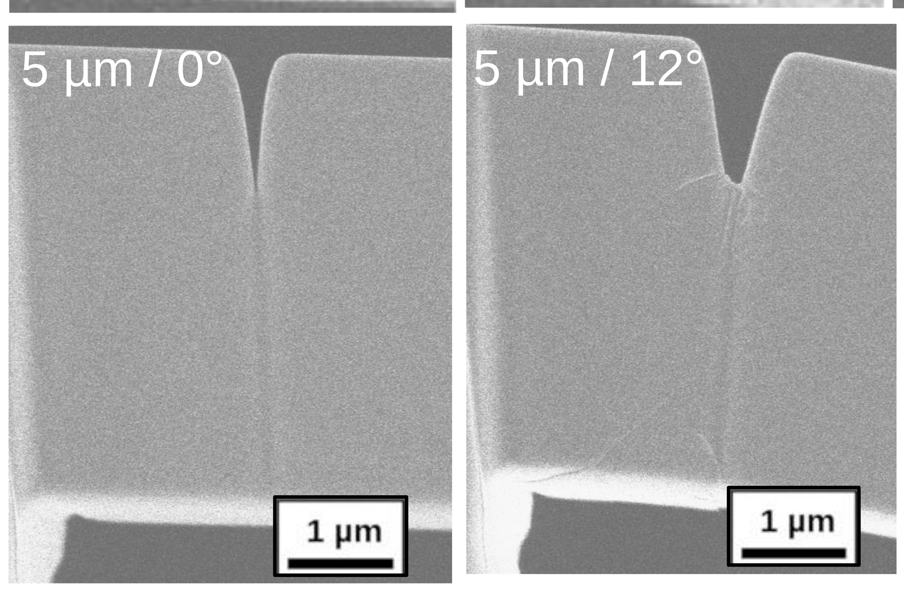
Test procedure:

- displacement of 5 µm applied at Individual bending length $L_C$ of about 5 x W
- collection of visual, force and displacement data

FIB: Auriga, Carl Zeiss AG, Oberkochen, Germany
SEM: LEO 1540XB, Carl Zeiss AG, Oberkochen, Germany

## SEM images during testing



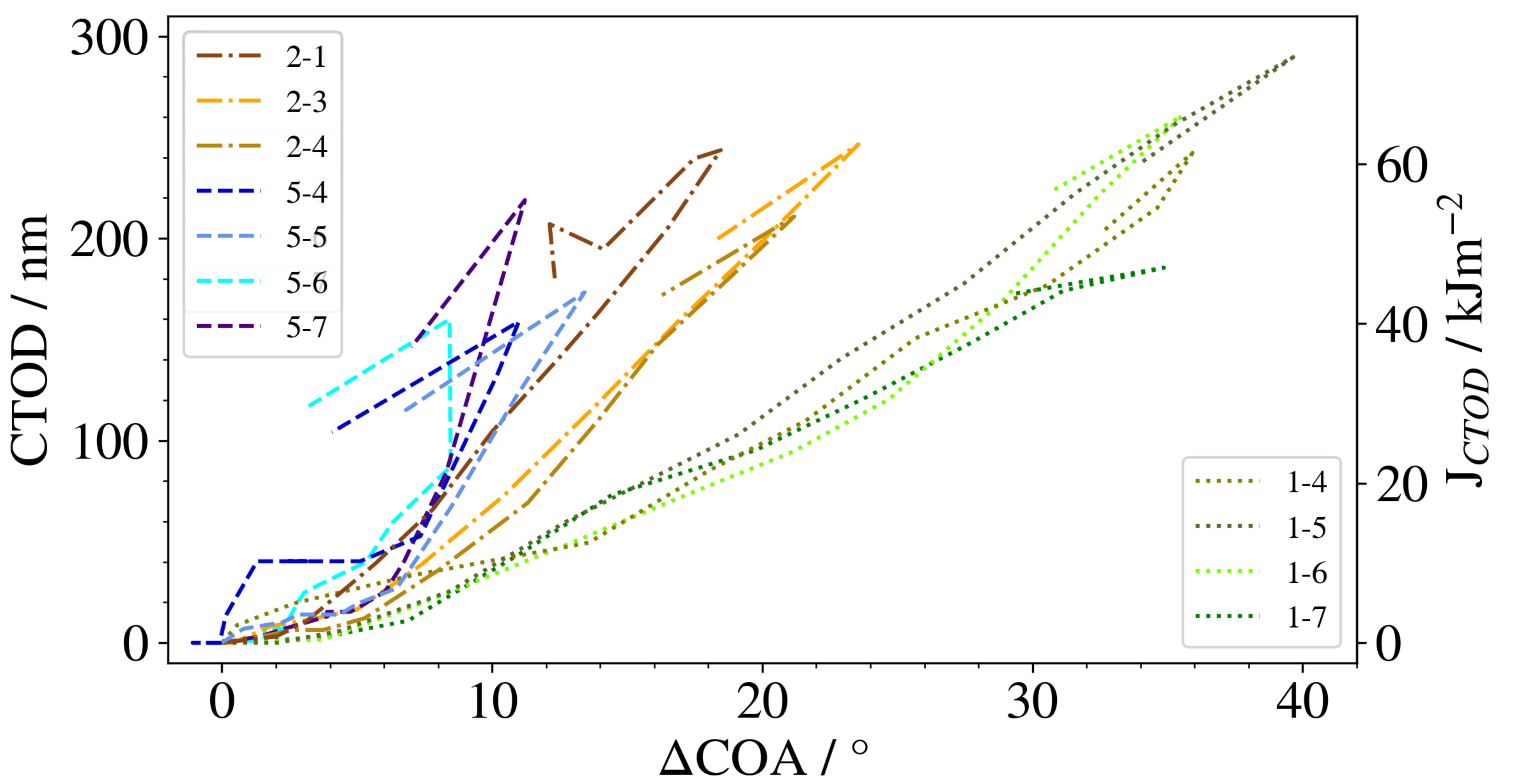

Direct comparison with normalized bending angle, Cantilever with 1 µm sized ligament compared with a 5 µm sized at testing stages of: 0°, 12° and 36°. Plastic deformation in the shape of shear bands, originating from the notch ground near the crack tip trough tension and the opposing face trough compression.

## Visually blunting characteristics and interpretation in terms of elastic-plastic fracture mechanics

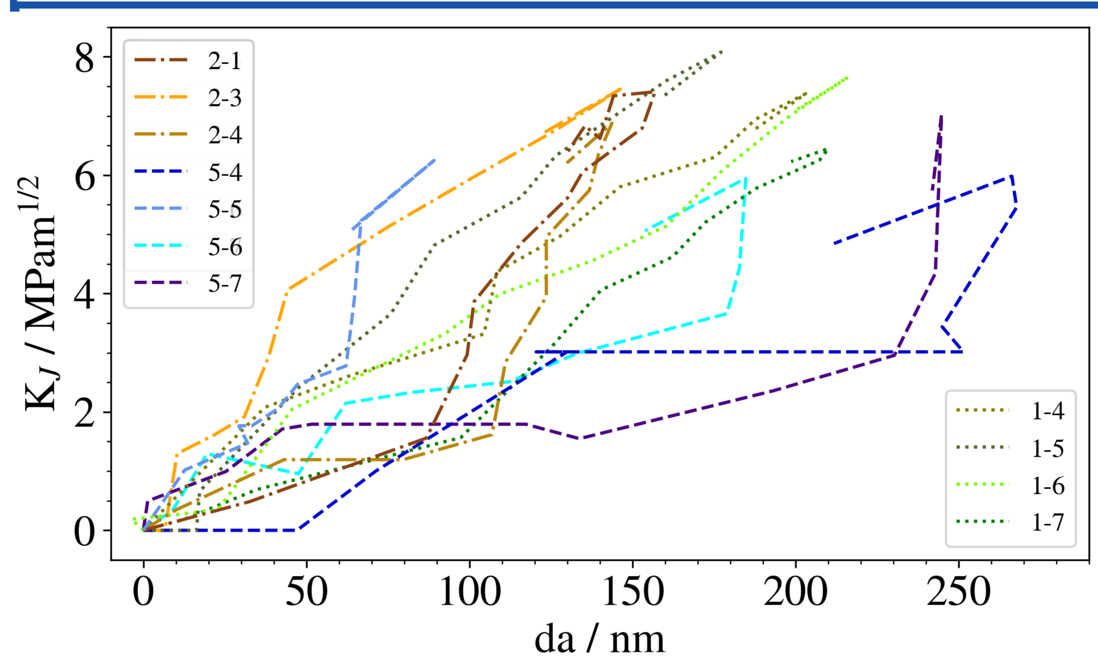
- excessive blunting (trough shear band formation) dominated over crack initiation and propagation
- application of linear elastic fracture mechanical concept impeded → elastic-plastic approach applied

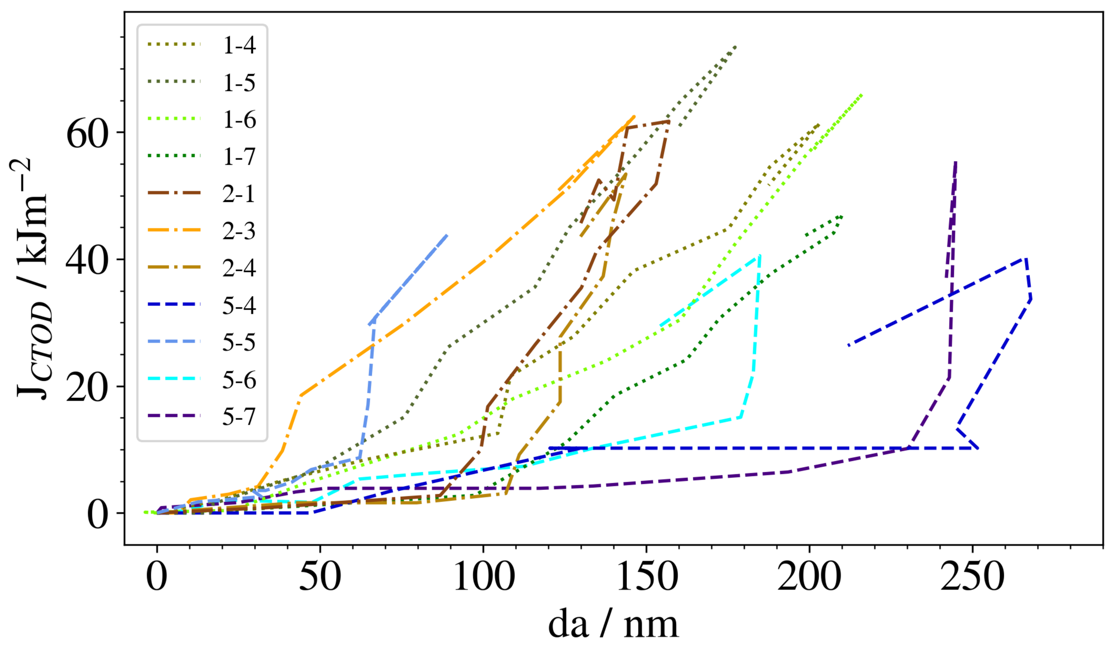
elastic-plastic quantified through visual measurement:

- crack tip opening displacement (CTOD) the crack driving force
- change in crack opening angle (ΔCOA), measured between the crack flanks, as normalized strain




Trendlines of individually sized specimens grouped by size and color, associated label consists of size regime of the cantilever ligament (1, 2, 5 µm) followed by a sample number.




Estimation of other crack driving forces:

- JCTOD - J-Integral (via the Shih-relation)
- $K_J$ - stress intensity factor (via the standard plain stress K-J-Relation)
- da - crack propagation (by crack tip blunting)

## Summary & Outlook

- lack of significant crack propagation → standardized fracture toughness models could not be applied
- size dependence in blunting behavior quantized → further experiments required to clarify origin
- experiments underline the results reported in [3], where the exact same material was investigated
- behavior of $Pd_{77.5}Cu_6Si_{16.5}$ , according to sharp notches, were visually quantified
  → important for application in micro- and nano-electro-mechanical-systems

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*alexander.jelinek@unileoben.ac.at