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Elastoplastic buckling as source of misinterpretation of micropillar tests

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Abstract

Microscopic compression tests (micropillar tests) are typically used to obtain stiffness and strength properties of materials at small length scales. In this work it is shown that structural effects, in particular instabilities, have implications on the resulting load–displacement diagram. Care has to be taken when the measured load–displacement path of a micropillar is interpreted as a stress–strain path of the material. Several structural effects are discussed by means of computational analysis.

Keywords: Compression test; Multilayers; Titanium aluminides; Finite element modeling; Micropillar

1. Introduction

Micropillar (MP) compression testing has been intensely used in the last several years to investigate the origin of size effects on the strength of miniaturized single-crystalline materials [1,2]. The "smaller is stronger" effect showing an increase in flow stress for decreasing material volumes is now to a large extent understood due to extensive experimental studies and modeling activities (see e.g. the reviews in Refs. [3–5]). This can be explained by considering the density and size distribution of available dislocation sources in the small material volumes as well as the loss (escape) of dislocations at free surfaces [6–8]. However, microcompression testing offers additional applications in materials testing as, with this method, the mechanical properties of individual microstructural features of the investigated materials can be probed with high spatial resolution.

Despite the capabilities that MP testing offers, the experimenter must be aware that the data obtained from the test represents a load–displacement relationship of a structure – the MP test set-up – rather than directly representing the stress–strain relation of the material under consideration. A careful distinction between true material properties and structural effects introduced by the testing procedure is required. It is the purpose of the present work to facilitate this distinction by discussing structural effects, in particular elastoplastic buckling phenomena, specific for the compression test of homogeneous and lamellar MPs.

Other publications [9,10] have already addressed structural properties of MP tests, such as the inhomogeneous stress distribution arising from pillar taper, the pillar aspect ratio and the clamping at the pillar base or loading device. The influence of the compliance of the surrounding

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material and misalignment of the loading device were also investigated. They used FE analysis and classical plasticity models.

Reference [9] also investigated elastoplastic buckling. However, deformation theory of plasticity was used, and therefore the post-buckling state, where path-dependent unloading becomes important, could not be represented faithfully. As a consequence of ignoring elastic unloading, the load displacement behaviour as calculated in Ref. [9] by deformation theory of plasticity is much too soft in the post-buckling regime. The present work focuses on extending the investigations mentioned above by a more detailed consideration of elastoplastic buckling for homogeneous MPs and MPs featuring a lamellar structure. Elastoplastic buckling is discussed from a theoretical point of view with regard to MP testing, and supplemented by numerical simulations. It will be shown how elastoplastic buckling affects data gathered from the test, how different MP properties influence the elastoplastic buckling load and the morphology of the deformed sample after the test, for both homogeneous and lamellar MP samples.

In the context of MP testing, the effect of structural instabilities, i.e. elastoplastic buckling, might be masked by material instabilities, e.g. the formation of shear band strain localizations, especially for homogeneous MPs. Such strain localizations are reported, for instance, in Fig. 2c of Ref. [11] for titanium aluminides. For metallic glasses, the formation of shear bands during MP tests is discussed in detail in Ref. [12]. In Ref. [13] an MP with only one active slip system is considered theoretically by finite element simulations using a higher-order gradient crystal plasticity theory in conjunction with a specific back stress model. In this case, the deformation state concentrates to a shear zone separating two nearly unstrained zones from each other. This deformation mode differs significantly from the one discussed in the present paper. For lamellar MPs, the formation of shear bands may be hindered both by the interfaces and by different glide systems in the individual material phases. Therefore, the effects of elastoplastic buckling may be recognized more clearly in lamellar MPs than in homogeneous MPs. It is for this reason that lamellar MPs are considered in detail in this work. Furthermore, displacement-controlled loading is assumed, thus strain bursts, as investigated, for example, in Ref. [14], in micro-compression tests of metallic glasses are not considered here.

2. Observations and motivation

The motivation for this work, and a demonstration of structural effects encountered in testing practice, are MP tests by Rester et al. [15]; these are discussed and serve as an example. It is important to note that the considerations presented in this work are of a general nature, and are not limited to this specific example.

Several MP tests were performed in the course of the investigations by Rester et al. [15] on lamellar titanium aluminide MPs. Multiple polysynthetically twinned titanium aluminide MPs consisting of two phases with different material properties, the α_2-phase (Ti_3Al) and the γ-phase (TiAl), were tested. The α_2-phase is distributed as thin lamellae inside a γ-phase matrix parallel to the axial direction (Fig. 1). The pillars considered are of square cross-section, have an aspect ratio of about three and no significant taper. Focused ion beam milling was used to manufacture the pillars. These were not milled from a solid block but, rather, from the tip of a 6 mm long needle with a cross-section of $0.5\,\text{mm} \times 0.5\,\text{mm}$ at the clamped end which tapers down to several microns at the tip, where the MP is located (Fig. 2a). This set-up introduces a large lateral compliance at the base of the pillar due to the length of the needle relative to the MP [16]. Compression is realized by a flat tipped micro-indenter punch, which moves the pillar tip in a displacement-controlled way.

Fig. 2 shows typical scanning electron microscope images of permanently deformed samples after unloading. From these images, bending ("S"-shape in Fig. 2b) and twisting (edge offset in Fig. 2c) were observed as modes of deformation as well as axial shortening. This is unexpected from axial compression alone. Possible explanations are discussed in the following subsections.

2.1. Bending

The sample shown in Fig. 2b exhibits clearly a "S"-like deformation shape resulting from bending and poses the question of the origin of the bending moment, which will be discussed below. Rotation is suppressed at the contact surface by the indenter punch and by the foundation of the MP on the needle at the pillar base. The MP bends by lateral movement of the needle.

The bending moment cannot have its origin in a non-symmetric axial stiffness distribution, e.g. due to a multiphase composition. Such a moment could arise if the position of the resultant of an arbitrarily applied external axial forces does not coincide with the center of stiffness of the MP, i.e. the resultant of axial stresses due to homogeneous strain. However, since the punch of the indenter suppresses rotation at the contact surface and imposes displacement control, loading is not arbitrary and its resultant coincides with the center of stiffness.

A non-zero bending moment in an axially compressed pillar-like structure exists only in the post-buckling state, prompting the investigation of instabilities encountered during MP tests. Because of the stocky proportions of the MP, the pure elastic (Euler) buckling load is far too high to be reached during the compression test. However, the compression test extends well into the elastoplastic regime, and elastoplastic buckling can occur at a much lower load. It will be shown in Section 4 that this explanation is backed by the results of the simulation.