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# Bauschinger effect in thin metal films

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**Abstract**

The Bauschinger effect in thin sputter-deposited Al and Cu films is studied by isothermally deforming the films alternately in tension and compression. Passivated films exhibit an unusual Bauschinger effect with reverse flow already occurring on unloading, while unpassivated films show little or no reverse flows when the film is fully unloaded.


*Keywords:* Bauschinger effect; Thin films; Compression test; Plastic deformation; Dislocations

## 1. Introduction

It is well known that the mechanical response of a metallic material depends not only on its current stress state but also on its deformation history. One of the most important examples is the observation that after a metal is deformed plastically in one direction, the yield stress in the reverse direction is often lower. Fig. 1 schematically shows a typical stress–strain curve for metallic materials. The stress $\sigma_f$ is the forward flow stress, and $\sigma_r$ at the start of reverse plastic flow is the reverse flow stress. If $\sigma_r$ is equal to $\sigma_f$, the material hardens isotropically. For many metals, however, the reverse flow stress is found to be lower than the forward flow stress. This anisotropic flow behavior was first reported by Bauschinger [1] and is referred to as the Bauschinger effect. The loss of strength due to the Bauschinger effect is of practical importance since the strength of a metal part may be impaired if the working stress acts in the reverse direction compared to the manufacturing stress. Furthermore, a good understanding of the physical origin of the Bauschinger effect may lead to more refined plasticity theories and may ultimately result in materials with superior mechanical behavior. Many experimental and theoretical efforts have been devoted to studying the Bauschinger effect in bulk metals since the phenomenon was first reported [2–15]. The physical origins are generally ascribed to either long-range effects, such as internal stresses due to dislocation interactions [6,7], dislocation pile-ups at grain boundaries [8,9] or Orowan loops around strong precipitates [10–14], or to short-range effects, such as the directionality of mobile dislocations in their resistance to motion or annihilation of the dislocations during reverse straining [10]. Satisfactory agreement has been achieved between models and experimental results obtained in various bulk metals and alloys [3–5,7–11].

Thin metal films are widely used in many advanced devices across a wide range of industries. Reliability problems encountered in these applications have motivated a strong interest in the mechanical behavior of thin films [16,17]. Besides this technological driving force, thin films also provide a unique opportunity to investigate fundamental problems in materials science. For example, at least one dimension of a thin film is comparable to the characteristic length scales associated with material defects such as dislocations; thus, free surfaces and interfaces are expected to play an important role in the mechanical behavior of thin films [18].

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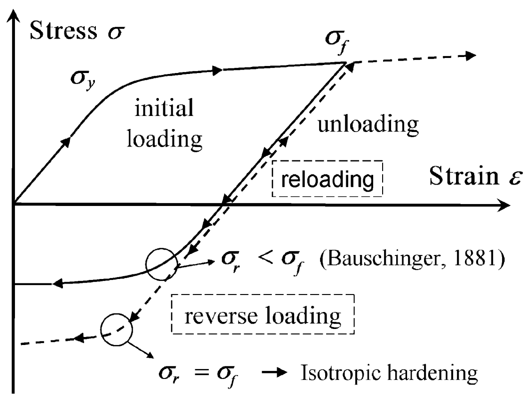


Fig. 1. A schematic of the typical stress–strain curve of a metallic material that exhibits the Bauschinger effect.

Furthermore, as a result of the special manufacturing techniques and the small materials dimensions, films often have unique microstructures. For example, thin films often have a columnar grain structure with an average grain size that is much smaller than in bulk materials; they are frequently highly textured [19]. As a result of these dimensional and microstructural constraints, many materials behave mechanically very differently in thin film form than in the bulk, especially in the plastic regime [18]. Various theoretical models and numerical simulations have been proposed recently to describe thin-film plasticity including strain-gradient plasticity theories [20,21], crystal plasticity theories [22], and discrete dislocation simulations [23,24]. The plasticity theories and the discrete dislocation models explain the strengthening effects associated with the film thickness and microstructure reasonably well; they predict, however, very different behavior in reverse loading. In the discrete dislocation simulations [22,25] and some crystal plasticity theories [25], passivated films show a distinct Bauschinger effect upon unloading after plastic pre-straining in tension. Reverse plastic flow starts early even though the overall stress in the film is still in tension. This type of Bauschinger behavior is not predicted in other models [20–22] and is also very different from that typically found in bulk materials. Up to date, however, there has been no direct experimental evidence of such a Bauschinger effect in thin metal films.

The most common experimental technique for revealing the Bauschinger effect in bulk material is cyclic or unidirectional testing where pre-straining in tension is followed by reverse loading in compression. This method cannot be directly applied to thin films because any compressive stress in the plane of a freestanding thin film causes it to buckle due to the large lateral dimension/thickness ratio in thin films. In this article, we report on a new experimental technique to deform thin metal films alternately in tension and compression and to measure the corresponding stress–strain curves. This technique allows us to quantitatively study the Bauschinger effect in thin metal film and has been applied to thin sputter-deposited Al and Cu films. The results provide for the first time unambiguous experimental evidence of a strong Bauschinger effect in thin metal films.

## 2. Experiment and results

The new experimental method is based on the plane-strain bulge test technique [26,27]. In this technique, the film of interest is deposited on a Si wafer and long rectangular membranes are fabricated using standard micromachining technology. Fig. 2(a) shows a perspective view of a typical bulge test sample. The as-prepared membrane is initially flat and under tension. It is then deflected by applying a uniform pressure to one side causing a state of plane strain in the film. The applied pressure, $p$, and corresponding membrane deflection, $h$, are measured and converted to a stress–strain curve using the following two simple formulae [26,27]:

$$\sigma = \frac{pa^2}{2ht} \quad \text{and} \quad \varepsilon = \varepsilon_0 + \frac{2h^2}{3a^2}, \tag{1}$$

where $t$ is the film thickness, $2a$ the membrane window width, as shown in Fig. 2(a), and $\varepsilon_0$ the residual strain

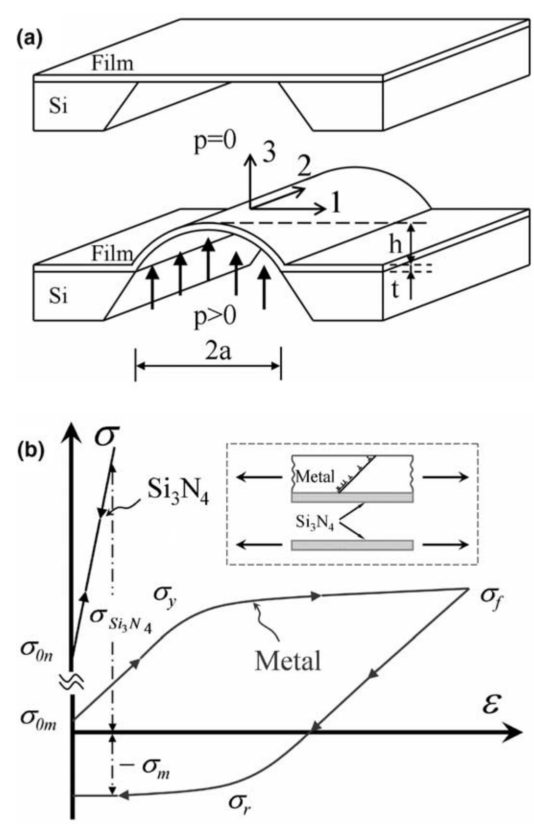


Fig. 2. A schematic of the compression test technique for thin metal films: (a) the plane-strain bulge test technique; (b) schematic of the stress–strain curve for each layer of the composite film.