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Perspective

Perspective on hetero-deformation induced (HDI) hardening and back stress

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ABSTR

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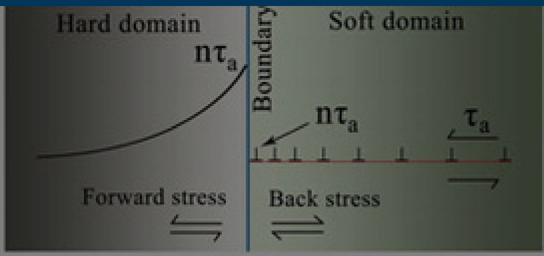

IMPACT STATEMENT

The 'back stress' hardening in the literature can be described more accurately as hetero-deformation induced (HDI) hardening and the measured 'back stress' should be renamed HDI stress.

KEYWORDS:

Heterostructured materials
strain gradient
back-stress
forward stress
hetero-deformation induced (HDI) hardening

Background

Heterostructured (HS) materials have recently attracted extensive attention from the
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Figure 1. [illegible] ed in recent
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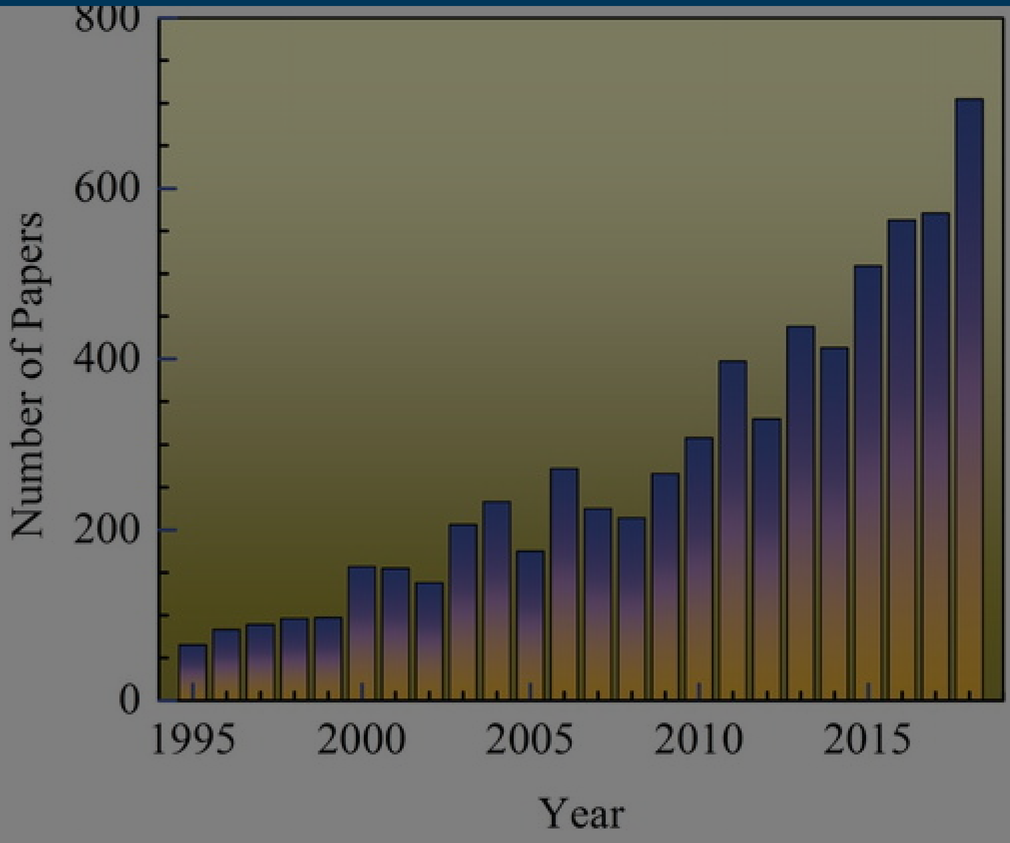

HS materials have very diverse microstructures [1], including heterogeneous lamella structure [2], gradient structure [3–8], laminate structure [9,10], dual phase structure [11–13], harmonic structure [14–16], bi-modal structure [17–20], metal matrix composites [21–26], etc. These apparently very diverse structures have a common feature: all of them consist of both soft domains and hard domains with dramatically different

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which in turn produces back-stress induced hardening, which helps with retaining ductility [1,2].

As described above, back stress is believed responsible for the strengthening and extra strain hardening observed in HS materials. Furthermore, various schemes to measure back stress from mechanical testing have been proposed [27,30,31], most equations for calculating back stress are based on concepts and assumptions instead of fundamental dislocation-based derivations. Back stress is also often associated with kinematic hardening, a term extensively used in the field of mechanics [32], which describes the mechanical phenomenon without addressing its physical origin. The concept and term of back stress are themselves still under debate in the materials community, with some researchers prefer to call them long-range internal stress [33,34]. Although back stress is usually small in homogeneous metals [27,35], it becomes significant for HS materials [1,2]. Therefore, it is of critical importance to understand the relationship between back stress and the mechanical behavior of HS materials.

In this perspective, we will briefly delineate the history of back stress, analyzing the development of back stress and forward stress in HS materials. We will show the inadequacy of using back stress to describe the strengthening and extra strain hardening in HS materials. In addition, back stress cannot be measured from mechani ... ore accurate ... briefly discuss t...

Brief h...

In th... nstead of a comp... t because they hav... t after an alloy wa... trength lower th... has been referred ... slocation pile-up a... slip of followin... of a internal stress exerted on the matrix by precipitates. The internal stress proposed by Orowan and Fisher was later named back stress in a dislocation model by Ashby [43].

The back stress concept was later used by many groups to explain the strengthening of a metal matrix by second-phase particles in the 1970s [44–46]. More recently, back stress has been used to explain the hardening behavior and Bauschinger effect in TRIP steels [47], the transient plastic flow during creep [48], the Bauschinger effect in thin films [38], the hysteresis loop under cyclic loading [49], the extra strain hardening of HS materials [1,2,27,50,51], etc. These reports show that the back stress concept has been widely, if not fully, accepted by the materials community.

Dislocation models for back stress

Several dislocation models on the formation of back stress have been proposed [1,33,43,52–54]. The back stress is produced by geometrically necessary dislocations (GNDs). It is believed that GNDs are needed to accommodate the strain gradient in the gradient plasticity theory [28,29]. GNDs create lattice bending or misorientation, depending on their geometric pattern of arrangement. As shown in Figure 2, there are two basic types of GND arrangements. Figure 2(a) illustrates a pile-up of GNDs on a slip plane against a segment of the grain boundary, phase boundary, or domain boundary,
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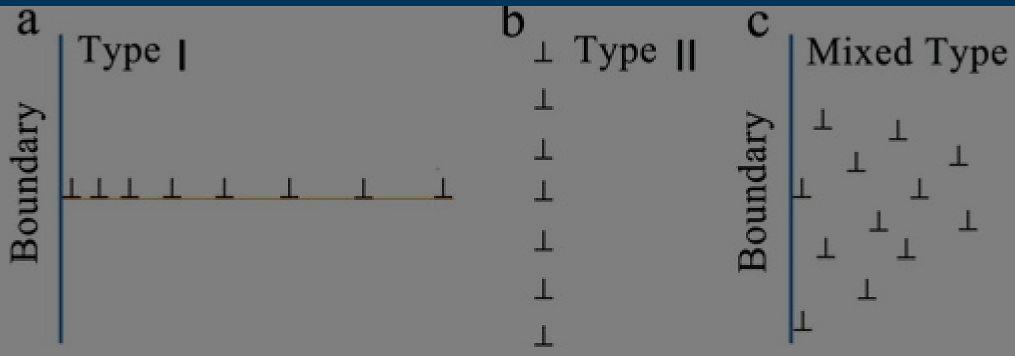

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Another basic type of GND arrangement is shown in Figure 2(b), which is essentially a tilt low-angle grain boundary. It is hereafter referred to as the Type II GND arrangement. It does not produce long-range internal stress, i.e. back stress [57]. However, internal stress exists in short range close to the tilt low-angle grain boundary. In a real situation such as bending of a crystal, a mixed type may exist [29], as shown in Figure 2(c), which does produce back stress but is not as effective as the Type I GND arrangement.

Back stress and mechanical properties

Back stress has been considered playing a critical role in the strengthening of metal matrix composites [44–46]. It is also often associated with Bauschinger effect
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is because the HS materials have great variation in flow stress from one domain volume to the next, which makes the back-stress induced strengthening and work hardening the primary players in the mechanical behavior. For example, an HS lamella Ti was found to have the strength of the ultrafine-grained Ti and uniform elongation higher than that of the coarse-grained Ti [2]. In addition, it also has strain hardening that is higher than the coarse-grained Ti. These mechanical behaviors cannot be explained by the conventional mechanisms in the textbooks. Therefore, back stress strengthening and work hardening have been used to explain the extraordinary mechanical properties of HS materials [1,2,27,60].

Issues with the back stress concept

As discussed above, back stress strengthening and work hardening have been believed responsible for the superior combination of strength and ductility of HS materials [1,2,39,61] as well as the Bauschinger effect [36,38,47,50]. With the fast development of the field of HS materials, it is of critical importance to clarify and understand how the back stress affects the mechanical behavior. Specifically, methods and equations have been proposed and developed to experimentally measure back stress from mechanical testing. Most of these methods and equations are not well anchored in deformation physics, … measured
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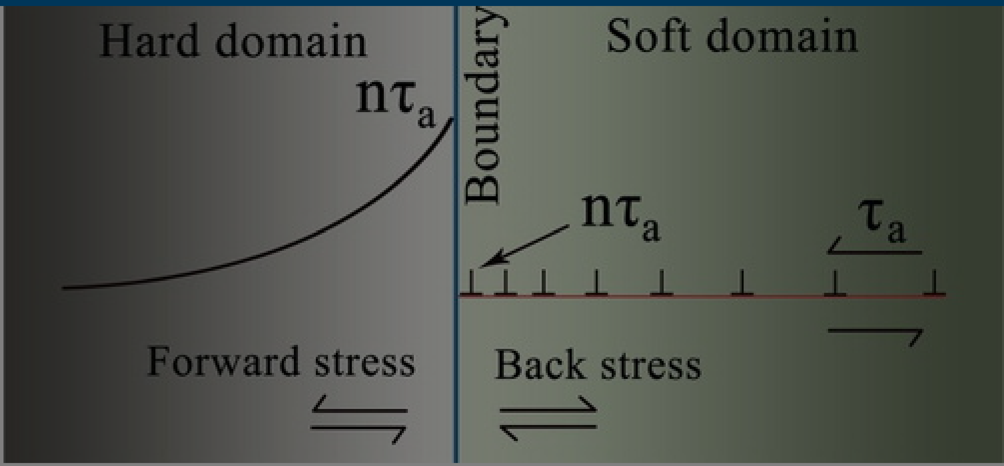

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Under the forward stress, the hard domain may behave in three different ways. Note that the forward stress in the hard domain near the domain boundary can be many times higher than the applied stress. First, if the hard domain is not much stronger than the soft domain, the leading dislocation at the head of a pile-up may be pushed into the domain boundary, which may lead to the emission of another dislocation from the boundary into the hard domain. In such a scenario, the buildup of back stress and forward stress is limited, and their influence on the mechanical behavior is also limited, as in the case of GND pile-ups at grain boundaries in conventional homogeneous materials. Second, if the hard domains are much stronger than the soft domains, the domain boundary will be much more effective in blocking GNDs, and the hard domain will rema

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suggests that it is logically not appropriate to attribute the unique mechanical behavior of HS materials to the back stress alone.

In the literature, back stress is measured by unloading-reloading curves in a tensile test [27], or from the unloading curves alone [30]. As shown in Figure 3, during unloading-reloading both the back stress and forward stress will be affected because they are coupled. Therefore, the unloading and reloading curves are affected by the interaction of the back stress and forward stress, instead of back stress alone. In other words, the back stress is not measurable from the mechanical testing curves, and the measured ‘back stress’ is not the real back stress in a physical sense. It should be noted that since the forward stress is induced by the back stress, we can logically regard the unique mechanical behavior of HS materials as induced by back stress. However, such a description can be misleading, since it may imply that the forward stress does not play a role.

New definition

As discussed above, a new term is needed to describe how the heterostructure affects the mechanical behavior and properties, because the current term, back stress, cannot represent the full physical process. At the fundamental level, the heterostructure leads
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Outstanding issues

The definitions of HDI hardening and HDI stress raise some scientific issues for future study. First, the back stress and forward stress are coupled and act in opposite directions. It is not clear how they interact with each other to produce the HDI hardening and HDI stress. Recently, it has been observed that local shear bands are formed across domain boundaries [62]. This might be caused by local interactions between local back stresses and forward stresses. Second, the HDI stress (measured 'back stress' in the literature [2,27]) appears to increase quickly in the elastic-plastic deformation stage, but slows down during the plastic deformation stage, which need to be investigated. Third, GND pile-ups lead to the development of back stress, which in turn induces forward stress. It is also believed that GNDs are needed to accommodate strain gradient near domain boundaries. The relationships among back stress, forward stress, strain gradient and HDI stress need to be studied. Understanding these issues will help us with understanding the fundamental physics as well as the heterostructure-mechanical properties of HS materials.

Disclosure statement

No poten

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