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Perspective

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

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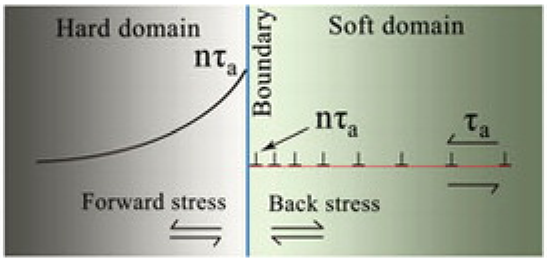
ABSTRACT

Heterostructured materials have been reported as a new class of materials with superior mechanical properties, which was attributed to the development of back stress. There are numerous reports on back stress theories and measurements with no consensus. Back stress is developed in soft domains to offset the applied stress, making them appear stronger, while forward stress is developed to make hard domains appear weaker. The extra hardening in heterostructured materials is resulted from interactions between back stresses and forward stresses, and should be described as hetero-deformation induced (HDI) hardening and the measured 'back stress' should be renamed HDI stress.

GRAPHICAL ABSTRACT



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.

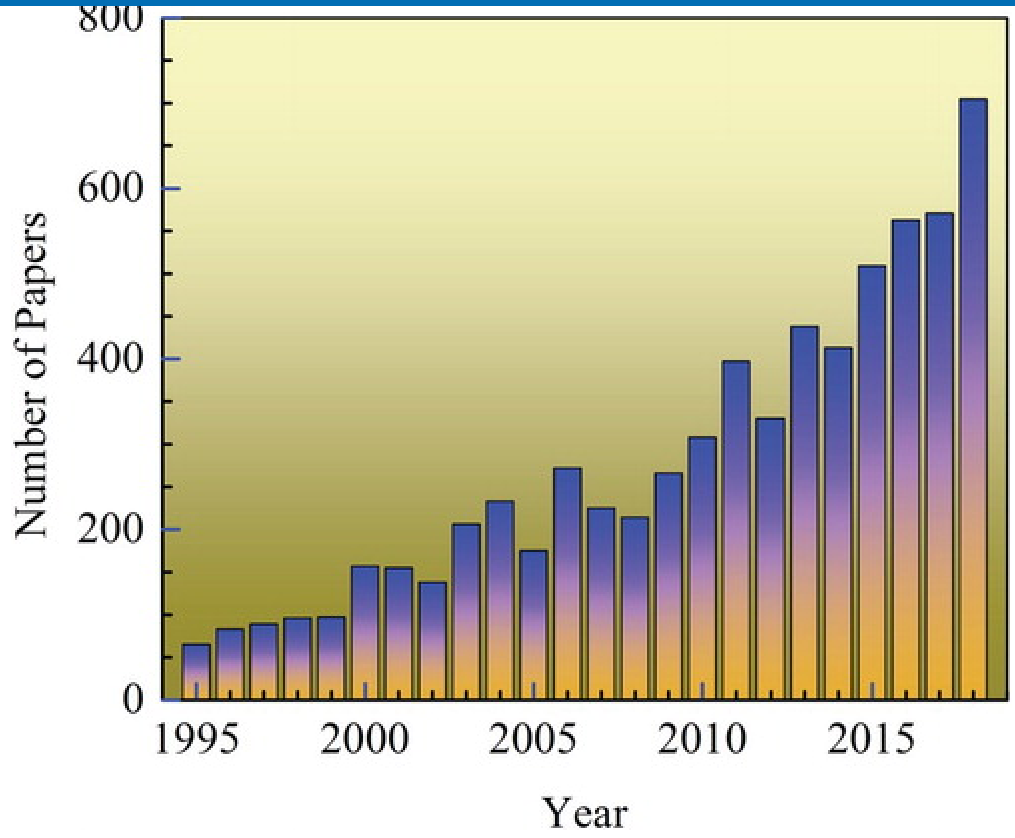
KEYWORDS:

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

Background

Heterostructured (HS) materials have recently attracted extensive attention from the materials community, as evidenced by the increasing number of international conferences and publications in recent years. For example, a symposium entitled ‘Heterogeneous and Gradient Materials III’ was held in the TMS Annual meeting in March 2019. A Gordon Research Conference on Heterostructured Materials will be held in June 2019. A symposium on Nanostructured, Heterostructured & Gradient Materials will be held in the Chinese Materials Conference in July 2019. Figure 1 shows that the number of papers on HS materials has been increasing exponentially. It is anticipated that HS materials will become a major research field in the post nanostructured-materials era.

Figure 1. The number of papers on heterostructured (HS) materials published in recent years.



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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 flow stresses (or strength) [1].

During tensile deformation of HS materials, the soft domains will start plastic deformation first while the hard domains remain elastic. In this elastic-plastic deformation stage, geometrically necessary dislocations (GNDs) will be blocked by and pile up against domain boundaries, which produces long-range internal stress, i.e. back stress, in the soft domain. The back stress is directional and offset some applied shear stress, making the soft domain appear stronger to sustain higher applied stress. It is this back stress that is believed to make the heterostructured materials stronger [2,27]. When both soft and hard domains are deforming plastically, the soft domains will sustain higher plastic strain than the hard domains, producing strain partitioning. Since the plastic strain needs to be the same at the domain boundaries to maintain continuity, there has to be strain gradient near the domain interface to accommodate the strain partition. The strain gradient needs to be accommodated by GNDs [28,29],

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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 mechanical testing, and the back-stress reported in the literature can be more accurately described as hetero-deformation induced (HDI) stress. We'll also briefly discuss the current fundamental issues that need to be investigated.

Brief history of back stress

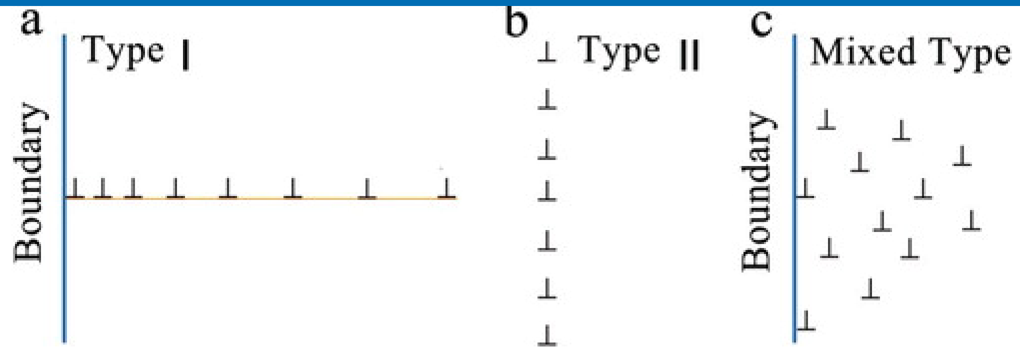
In the following, we will present a brief history of the back stress concept, instead of a comprehensive review. Back stress is often related to the Bauschinger effect because they have the same physical origin [36–39]. In 1886 Bauschinger found that after an alloy was deformed plastically in tension, it exhibited a compressive yield strength lower than its tensile yield strength, and vice versa [40]. This phenomenon has been referred to as the Bauschinger effect. In 1947 Orowan [41] proposed that dislocation pile-up against second-phase particles produced internal stress to resist the slip of following dislocations. In 1953 Fisher [42] proposed that the yield strength 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, which is hereafter referred to as the Type I GND arrangement. These GNDs have the same Burgers vector, and can be produced by dislocations emitted from a Frank-Read dislocation source. The GND pile-up produces a stress concentration of $n\tau_a$ at the boundary (the piling-up head) [55,56], where n is the number of GNDs in the pile up and τ_a is the applied shear stress on the slip system. Such a GND pile-up will bend slip plane and exert a long-range internal stress with a direction that is opposite to the applied stress. This long-range internal stress is named back stress [1,2,43,57]. It acts to repel more dislocation emissions from the Frank-Read source, which makes the soft domain appear stronger in HS materials.

Figure 2. Types of GND arrangements. (a) Type I: GNDs piled up on a slip plane against a boundary. Most effective in producing back stress. (b) Type II: GNDs aligned up vertically to form a low-angle grain boundary. It does not produce back stress. (c) The mixed type. Less effective than Type I in producing back stress.



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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 [36,38,47,50]. However, neither back stress nor Bauschinger effect has been regarded as a major player in strengthening metallic materials by the general materials community. For example, in the literature and textbooks [58], listed mechanisms for strengthening metallic materials include strain (work, dislocation) hardening, grain boundary hardening, solution hardening, and precipitation (dispersion) hardening. Back stress is not on the list. It should be noted that the precipitation (dispersion) hardening is explained by the blocking of gliding dislocations instead of the back stress. In other words, back stress is usually not considered as a mechanism for improving mechanical properties. One of the reasons is that back stress is usually very small in conventional homogeneous polycrystalline materials, and the observed mechanical properties can be adequately explained with the listed mechanisms from textbooks. The back stress in homogenous materials was indeed measured to be very low [35,59]. This is why back stress has been ignored by the majority of researchers in the materials community.

For HS materials, the enhancement in strength and strain hardening can be so dramatic

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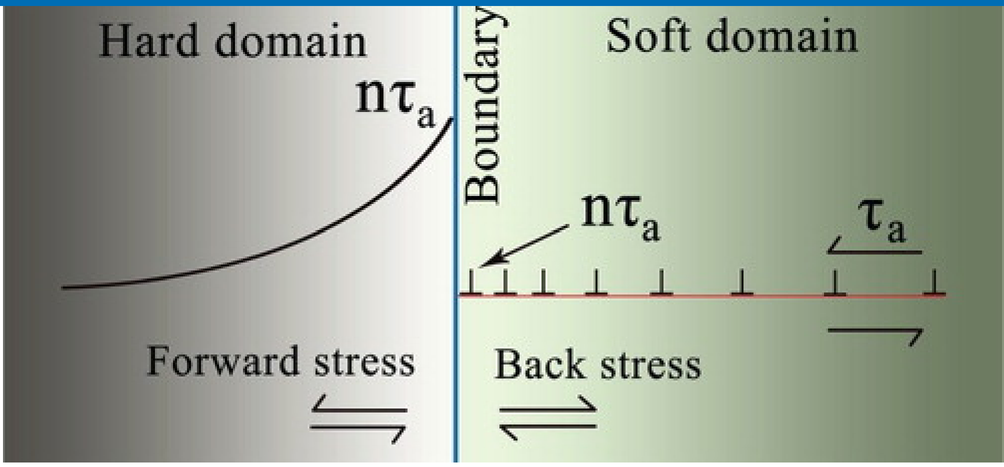
is because the HS materials have great variation in flow stress from one domain volume to the next, which makes the back-stress induced strengthening and work hardening the primary players in the mechanical behavior. For example, an HS lamella Ti was found to have the strength of the ultrafine-grained 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, i.e. dislocation mechanisms. A question arises on what is actually measured and if the measured ‘back stress’ is physically the global back stress in the materials.

To analyze this issue, let’s look at the dislocation model of GND pile-up at an HS domain boundary in Figure 3. As shown, there is a GND pile-up against the domain boundary in the soft domain under an applied shear stress τ_a. As discussed earlier, this dislocation pileup would produce back stress in the opposite direction of the applied shear stress in the soft domain to make it appear stronger. At the head of the pile-up, there is a stress concentration of $n\tau_a$, where n is the number of GNDs in the pile-up. This stress concentration is applied to the hard domain across the domain boundary, which is in the same direction of the applied stress, and is therefore named forward stress. In other words, the back stress in the soft domain induced the forward stress in the hard domain, as schematically represented by the curve in the hard domain.

Figure 3. Schematics of a GND pile-up, inducing back stress in the soft domain, which in



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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 remain elastic until the back stress is very high in the soft domain. This will increase the global yield stress and result in extra work hardening when both domains are deforming plastically, especially when the soft domain is fully constrained by the hard domain, as reported in the heterogeneous lamella Ti [2]. Third, if the hard domain is not plastically deformable, as in the case of metal matrix composites reinforced by second phase particles, the domain interface may fail when the stress concentration is too high, and voids may form around the particles, which leads to sample fracture. The is the case for most particulate reinforced metal matrix composites.

As discussed above, the back stress and forward stress are coupled at the domain (or grain) boundary and acted in opposite directions. The back stress makes soft domain appear stronger and the forward stress may make the hard domain appear weaker if it is deformable. Logically, both back stress and forward stress should affect the mechanical behavior and their interaction is not a zero-sum game, as indicated by the unique mechanical behavior and superior mechanical properties of HS materials. This 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 to hetero-deformation among HS domains [1]. First, after the soft domains start yielding, the hard domains will remain elastic, which is a hetero-deformation scenario that produces back stress in the soft domain to raise the global yield strength. After the sample starts yielding, hetero-deformation is produced by partitioning of plastic strain between the hard and soft domains [2], which will produce back stress in the soft domain and forward stress in the hard domain. This consequently produces extra strain hardening as observed in the HS lamella Ti [2]. In other words, it is the hetero-deformation that leads to the development of back stress and forward stress, which collectively produces the strengthening and extra work hardening. Therefore, the extra hardening in the HS materials can be described more accurately as the hetero-deformation induced (HDI) hardening, and the 'back stress' measured from the mechanical testing can be defined as the HDI stress. The HDI stress is kinematic, directional, and associated with GND pile-up. It is also called kinematic stress in the field of mechanics.

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 potential conflict of interest was reported by the authors.

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