Opinion

The strengthening mechanisms of materials are well-known to be primarily governed by the interactions of dislocations with solutes, precipitates, short-range order and various defects. Nevertheless, there are many issues related to the mechanical properties of materials which these mechanisms cannot account for, such as yield drops, dynamic strain aging, and age hardening, among others. We suggest that the destruction of short-range order by moving dislocations causes a sudden drop in strength due to the generation of tensile stresses by disordering, which is contrary to Fisher’s bond cutting mechanism.

In 1954, for the first time, Fisher [1] suggested that short-range order (SRO) gave an important contribution to the strength of highly alloyed solid solutions. His theoretical assumption was that as moving dislocations destroyed SRO and created an interface of positive energy $\gamma$, an additional stress $\tau=\gamma/b$ was required to force the dislocation along the slip plane. In contrast, one year later, Ardley [2] found experimentally that an appreciable drop in strength arose as an alloy passed from the ordered to the disordered state. Considering that the destruction of SRO leads to disorder formation, the so-called bond cutting mechanism [3] proposed by Fisher [1] cannot account for Ardley’s observations [2], indicating that Fisher’s bond cutting mechanism is invalid. In other words, the strengthening mechanism of short-range order remains elusive even though it is well known that SRO will increase the strength of materials. The aim of this work is to understand the strengthening mechanism of SRO in materials.

Given that materials consist of atoms, the occurrence of ordering and disordering cannot be avoided in materials like gravity. Despite a great number of published research papers in association with atomic ordering, the effects of ordering and disordering have never been fully appreciated in the strengthening mechanism of materials. Currently, the strengthening of materials is known to be governed by dislocation mobility which is primarily determined by interactions of dislocations with solutes, precipitates and various defects. As major strengthening mechanisms, not only Fisher’s bond cutting mechanism but also Cottrell’s locking and Suzuki’s pinning mechanisms [2] have been suggested to be viable. Given observations [4,5] that yield drops were observed only in ordered specimens and that the amount of yield drop increased with the increasing degree of order, however, Smallman and his workers maintained that ordering locking was responsible for the strengthening mechanism of SRO in materials. However, what all of the strengthening mechanisms proposed thus far have ignored is the spontaneous generation of compressive or tensile stresses by either ordering or disordering. For example, when dislocations start moving upon yielding, either of two processes can occur by moving dislocations: ordering [6,7] or disordering [8]. Solid evidence is presented in Figure 1 [9] where the martensite phase showed lattice expansion and contraction, respectively, upon deformation at room temperature (RT) in 304 stainless steel (SS) samples without and with charged hydrogen. Considering that lattice contraction and expansion imply ordering and disordering, respectively [7-10] depending upon if charged hydrogen is present or not, either ordering or disordering occurred in the 304 SS during plastic deformation. Specifically, when disordering is dominant over ordering as with furnace-cooled materials with SRO, the SRO formed decays into disorder due to moving dislocations. The effect of this disordering transformation is to spontaneously generate tensile stresses [7-10], and thereby lattice expansion upon yielding in materials [8,9]. Direct evidence is provided by Smith’s observations [11] that the lattice spacing of a mild steel with 0.1 wt.% carbon underwent an abrupt expansion upon yielding. These tensile stresses autogenously generated by disordering cause a sudden drop in the applied stresses upon yielding, referred to as a yield drop. Thus, the higher the degree of SRO is, the higher
the magnitude of the yield drop becomes [4,5]. In other words, no yield drops should occur in materials with disorder. Note that this claim differs from Cottrell’s dislocation theory [12,13], which holds that yield point phenomena are related to the interactions between dislocations and solute atoms. This is further evidenced by observations [14-17] that the yield point phenomena always occur in furnace-cooked materials with SRO but not in water-quenched materials with disorder, irrespective of their crystal structure. In contrast, for water-quenched materials with disorder, ordering may become dominant over disordering due to moving dislocations upon yielding the rate of which is determined by strain rate and temperature. If the strain rate is slow and the temperature is high enough to cause ordering (or strain-induced ordering) to dominate disordering (or strain-induced disordering) during deformation, then SRO is nucleated after yielding. Considering that SRO has a smaller lattice spacing than disorder [8,18], ordering leading to SRO formation generates compressive stresses [19,20]. As a result, increased tensile stresses should be macroscopically applied during straining sufficiently to offset the compressive stresses generated spontaneously by ordering. This leads to a higher strain hardening rate and can account for why yield drops do not occur in water-quenched materials. Wilson [21] also suggested that an initial rapid rise in the yield stress was related to the local ordering of the interstitial solute atoms because a rise in the yield stress during strain aging occurred too rapidly to be accounted for by the long range diffusion of carbon and nitrogen to dislocations. Consequently, considering that SRO formed in materials transforms into disorder due to dislocations, SRO cannot contribute to an increase in the strength of materials but instead causes a rapid drop in the strength, which is evidenced by Ardley’s observations [2]. However, this is contrary to Fisher’s bond cutting mechanism. This sudden drop in strength, leading to a yield drop upon yielding, is attributed to tensile stresses generated by disordering.

This claim is new and therefore may be controversial. However, compelling evidence is found in changes in the activation volume during plastic deformation in materials. Although plastic deformation by shear cannot produce changes in the volumes of materials, the changes in the activation volume due to plastic deformation have been frequently observed in materials but their cause is yet to be clarified. Given that ordering and disordering spontaneously generate compressive and tensile stresses, respectively, leading to changes in volume [8,9,19-21], changes in the activation volume during plastic deformation imply the occurrence of ordering or disordering by moving dislocations, which is termed strain-induced ordering or disordering. In other words, the changes in the activation volume are compelling evidence of the occurrence of ordering or disordering in materials when they undergo plastic deformation. For example, a decrease in the active volume with strain was observed in aluminum alloys such as Al-Ti-Mn [22] and Al-Mn [23] during their plastic deformation at RT, indicating that ordering accompanied RT plastic deformation. In contrast, an increase in the activation volume with strain at RT was observed in a CoCrFeMnNi high-entropy alloy (HEA) [24], indicating that disordering was dominant over ordering during RT plastic deformation in a HEA. Therefore, it is evident that ordering or disordering occurs in materials during plastic deformation, leading to decreases or increases in their activation volume, depending on whether ordering or disordering is dominant. Consequently, the strengthening mechanism of SRO is related to compressive stresses induced by the formation of SRO by ordering, but neither to the bond cutting mechanism proposed by Fisher, nor to the interactions of dislocations with solutes, precipitates, SRO and various defects. Yield drops are ascribed to tensile stresses spontaneously generated by the destruction of SRO by moving dislocations upon yielding, or strain-induced disordering, which differs from Cottrell’s dislocation theory. Consequently, we suggest that the mechanical properties of materials are governed by ordering and disordering occurring, respectively, during plastic deformation but not by the interactions of dislocations with solutes, precipitates, short-range order and other defects.

![Figure 1: (a) disordering and (b) ordering accompanied during RT plastic deformation in the martensite phase of 316 stainless steel samples without and with charged hydrogen, leading to lattice expansion and contraction, respectively [9].](image)

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Conflict of Interest

The authors declare no conflict of interest.

References