

Amorphization-mediated plasticity

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Amorphization can be an additional mechanism to assist plastic deformation in crystalline materials, providing a strategy to improve the load-bearing ability of brittle materials.

Most materials can undergo permanent shape change when subjected to external loading, a property often termed as plasticity. The ability to mediate plastic deformation without fracture determines, to a large extent, the application of technological materials. Macroscopic plasticity can be mediated by various microscopic mechanisms, including dislocation slip or climb, twinning and martensitic phase transformations. In some extreme cases, such as severe plastic deformation, materials can also experience localized amorphization (crystalline-to-amorphous phase transition), which causes materials to suddenly lose their load-bearing ability and eventually leads to fracture¹. Therefore, amorphization is usually considered undesirable and should be avoided. Now, writing in *Nature Materials*², Xuanxin Hu and colleagues report that, in some intermetallic systems, directional amorphization can also drive plasticity with sustained work-hardening ability, suggesting that the susceptibility of deformation-induced amorphization may be a design parameter in the search for materials with enhanced mechanical properties.

Amorphous (or glassy) materials are typically realized by quenching liquids during solidification to prevent the long-range ordered arrangement of atoms. The amorphous phase is usually considered to be a metastable phase and is energetically less favourable compared with its crystalline counterparts. Besides quenching, in principle, the energy barrier between crystalline and amorphous phases can be overcome by supplying a sufficient amount of mechanical work during deformation^{3,4}. Deformation-induced amorphization has been observed in many materials systems including metals⁵, intermetallic compounds⁶, and covalently and ionic-bonded solids^{7,8}. It is also associated with other important phenomena across different length and time scales, such as deep-focus earthquakes⁸ and meteorite impacts⁹.

The amorphous regions produced by deformation are normally confined within a narrow band, displaying a similar morphology to that of a shear band – a phenomenon that marks heavily localized plastic deformation. The transformation from a crystalline to an amorphous phase results in a sudden volume change (usually dilatation), which may lead to the nucleation of voids and cracks. Moreover, the amorphous material is usually brittle because it lacks a slip system to accommodate shear deformation. All these suggest that amorphization may serve as the precursor to the fracture of materials.

Therefore, the discovery of Hu and colleagues that an amorphous shear band can also be the primary carrier of plasticity in nominally brittle materials is important. They investigated a unique Al–Sm binary system where multiple intermetallic materials with different stoichiometry exist. In particular, Al₂Sm and Al₃Sm were chosen, both of which exhibit deformation-induced amorphization during nanomechanical

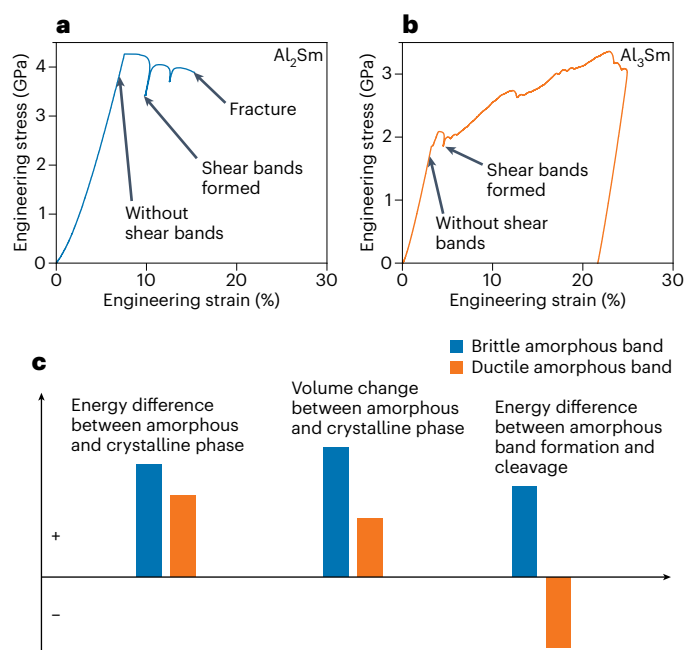


Fig. 1 | Brittle-to-ductile amorphous shear bands in the binary Al–Sm system.

a, b, Micropillar compression tests for Al₂Sm with brittle amorphous band (**a**) and Al₃Sm with ductile amorphous band (**b**). **c**, Schematic representation of the comparisons between brittle and ductile shear bands. Panels **a** and **b** adapted with permission from ref. 2, Springer Nature Ltd.

testing, which is confirmed by post-mortem transmission electron microscopy. However, micropillar compression tests suggest that the post-yield behaviours are quite different for the two materials (Fig. 1a,b). Al₂Sm shows a drastic drop in load upon the formation of the shear band, and the flow stress continues to drop rapidly until catastrophic fracture occurs, indicating brittle behaviour, whereas Al₃Sm displays a moderate drop in stress followed by a continuously increasing flow stress, suggesting ductile behaviour.

The authors further investigate the origin of the drastically different mechanical behaviours of the two intermetallics. Density functional theory calculations suggest that the energy gaps between the amorphous and the crystalline phases for the two materials are distinctive (Fig. 1c). The energy change is 0.2445 eV per atom for Al₂Sm and 0.1965 eV per atom for Al₃Sm. The smaller energy difference for Al₃Sm indicates that it is relatively easier for the material to undergo amorphization. Density functional theory simulations also illustrate that the density difference between the amorphous and crystalline phases is 6.73% for Al₂Sm and 3% for Al₃Sm. A smaller density mismatch would mitigate the stress concentration in the vicinity of the transformation zone and reduce the nucleation of voids and cracks. In addition, the authors also compute the formation energies of the

amorphous shear band and compare them with the cleavage energies of the close-packed planes in both materials. The results clearly show that the formation of the amorphous shear band is energetically more favourable than cleavage in Al_3Sm , and the opposite is true for Al_2Sm (Fig. 1c).


It is interesting to note that the formation of amorphous shear bands in both Al_2Sm and Al_3Sm does not seem to involve other deformation mechanisms, such as dislocation motion and twinning. This means that amorphization can be an independent ‘slip system’ to accommodate plastic deformation, which is in contrast to the traditional view of amorphization resulting from defect and damage accumulation. Intriguingly, the brittle-to-ductile behaviour of the amorphous shear band can be tailored by tweaking the stoichiometry in the binary Al–Sm system, providing insights into improving the ductility of brittle materials.

This work shows that there are still many aspects of solid-state amorphization that need further exploration. A deeper understanding of the amorphization mechanism is needed. For example, the mechanisms of nucleation and interaction of the amorphous bands and the stress–strain fields associated with them remain elusive. The mechanisms by which amorphous shear bands interact with other microstructures, such as grain boundaries, are unknown, and thus a theoretical framework that incorporates amorphization to accommodate polycrystalline plasticity is lacking¹⁰. The work of Hu and colleagues gives a clue that a small density change during this first-order crystalline-to-amorphous phase transition is the key to making amorphous shear bands ductile. A practical question is then how this rule can be used as a guiding principle to toughen brittle, crystalline

materials using ductile, amorphous bands, and whether it can be used in other materials systems. With the development of more advanced in situ experimental techniques and data-driven and physics-informed computational tools, we are on the verge of uncovering more details of this exciting phenomenon.

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Competing interests

The authors declare no competing interests.