Deformation-induced phase transitions, a playground for tailored mechanical properties of Fe-based engineering alloys

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Since decades, the future of structural engineering alloys has been mostly dictated by the quest for continuously higher levels of strength. While stronger steels, titanium or aluminium alloys were required, for example in transport applications for structural lightweight or crashworthiness improvement, (de)formability was also required to be kept at an increasing (or not too shortened) level. Different ‘classical’ strengthening mechanisms (solid solution, precipitation, grain refinement, in situ composite, …), all showing globally the same reverse trend between strength and ductility, that means the same work hardening rate, were successively tested, optimised and successfully used in numerous applications.

The concept of ‘dynamic’ microstructure with deformation-induced mechanisms, i.e. martensitic transformation or mechanical twinning that bring larger levels of work hardening when it is needed was then considered. It is worth emphasising that improvement of the work hardening results from (positive) interactions between these deformation-induced transitions and the basic mechanisms related to dislocation glide. Indeed, large dislocation activity remains a mandatory condition for the improvement of the work hardening without substitution or compensation (like in hard-to-deform hcp alloys).

Metallurgy of Fe-based alloys is a good example of this story of successive mechanisms to continuously improve the combination of strength and ductility. Starting from solid solution strengthening, mostly by carbon and manganese, precipitation hardening and grain refinement were developed in the sixties as a response to the development of welding, while Dual Phase steels constituted the answer to the oil crisis in the 1970s. Since the 1990s, more continuous developments based on phase transitions appeared in order to answer to the constant urgency of greenhouse gas decrease and improvement of crashworthiness.

It is well established now that deformation-induced phase transitions is an effective strategy to avoid the decrease with strain of the work hardening rate, bringing about unprecedented levels of work hardening in steels, and more recently in titanium alloys or high entropy alloys. Specific grades, designed owing to more or less established theories and criteria, exhibit levels of work hardening close to the theoretical limit.

While much efforts are still devoted to characterise the microstructure – properties relationship in these alloys, better understanding and potential future improvements would rely on the full and complete consideration of the role of the work hardening rate. It is definitely of primary importance to highlight the role of the microstructure modifications brought by these deformation-induced phase transitions on the net balance between the sources and sinks of dislocations and to identify the storage mechanisms. A huge number of specific interfaces are created either by the martensitic transformation or the mechanical twinning. These interfaces strongly interact with dislocations in a way that sometimes still needs to be understood. On the other hand, both martensite and mechanical twins exhibit different mechanical behaviour from the matrix, so that mechanical contrast and intrinsic composite effect are activated during straining. Finally, future prospects for these ultra-high strength engineering alloys could be based on the analysis of potential interactions with the damage and fracture mechanisms. While on the one hand, the levels of strength that are reached are so high that damage is prone to dramatically appear, such a large work hardening rate could on the other hand heal early occurring damage.