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Perspective

Nanostructured steels for advanced structural applications

H J Kong, T Yang, T L Zhang, B X Cao and C T Liu*

Department of Mechanical Engineering, Department of Material Science and Engineering, Hong Kong Institute for Advanced Study, City University of Hong Kong, Hong Kong, People's Republic of China

Abstract

This vision summarizes the recent advancement of nanostructured steels for advanced structural applications, foresees possible challenges and pinpoints future directions as well as opportunities in this new era of industrial revolution 4.0.

Keywords: nanostructured steels, extreme environments, advanced manufacturing, shape memory

The recent advancement of steel metallurgy has pushed the yield strength of the conventional steels to over 2 GPa together with an extraordinary ductility and toughness, especially important for the automotive and advanced aerospace industries where a light weight often comes to the priority [1, 2]. As we step into the new era of industrial revolution 4.0, the conventional alloy production has started to transform into a smarter manufacturing system focusing on the decentralized production with emphases on digitization, automation, and man–machine integrations. The current 2 GPa grade steels are developed based on the conventional steel production methodologies with complex processing routes such as hot working and cold rolling which are essentially impractical in today's advanced alloy production through additive manufacturing. The development of novel advanced steel design strategies is thus necessary. Advanced steels should also possess good mechanical properties in applications involving extreme operating conditions such as the nuclear fusion power plants and space exploration. Advanced steels that demonstrate a shape memory effect are also important in smart structural applications particularly in anti-seismic dampers and self-adjusting turbine blades. The continual development of advanced steels is crucial in pushing the social economy forward.

Conventionally, ultrahigh strength steels rely on heavy carbon additions which often lead them brittle and non-weldable [3–5]. Steels with a superior weldability is important in nowadays modern laser-based additive manufacturing. In the case of high carbon steels, the rapid cooling during the laser printing process can result in cold cracking [3]. On the other hand, nanostructured steels strengthened by densely dispersed nanoscale precipitates are highly weldable due to their low carbon content [6, 7], especially suitable for the modern additive manufacturing and re-manufacturing of structural parts of complex geometries in automotive, locomotive, and marine industries. Nanostructured steels are defined as advanced steels consisting of nanoscale features with a large interfacial area to volume ratio over 0.04 nm^{-1} [8]. Traditionally, the development of nanostructured steels mainly focuses on the grain refinement such as the production of nanostructured steels with nanometer-sized grains through severe plastic deformation [5, 9].

* Author to whom any correspondence should be addressed.

Recently, by carefully tuning the chemistry of nanostructured steels, it is possible to develop a new class of 2 GPa grade low-carbon nanostructured steels with densely dispersed nanoscale precipitates [10–12]. Readers are advised to refer to the comprehensive reviews by Jiao *et al* [6] and Kong *et al* [7, 13] for the detailed processing, microstructure, and properties of this new class of nanostructured steels. Unfortunately, at this present stage, the precipitate strengthened steels produced by additive manufacturing have a relatively low yield strength in the range of ∼1000 MPa, possibly due to the formation of soft austenite or coarsening of microstructure due to the repetitive thermal cycling during the printing process [14, 15]. Besides, additive manufacturing does not involve the forging process as in the conventional manufacturing process, causing large grain sizes. Refined grain size is important in providing additional strengthening to nanostructured steels due to the Hall–Petch strengthening [16]. A new nanostructured steel recipe for advanced manufacturing is thus needed for an improved thermal stability and refined grain size.

Apart from the room temperature applications, nanostructured steels can be used in extreme environments, including the nuclear power plants and space vehicles that experience extreme temperature gradients. Literature indicates that highly disperse nanoscale precipitates in nanostructured steels can serve as vacancy traps and reduce swelling under irradiation conditions [17]. SpaceX has also started to shift to stainless steels for the construction of space vehicles for a cost reduction [18]. The current operating temperatures of nanostructured steels fall into around 400 °C–500 °C; above which the precipitates will start to grow or dissolutionize [13]. At high temperatures, dislocations can climb over the precipitates easily, resulting in softening and creep deformations [19]. For the successful use of nanostructured steels in extreme environments, the discovery of new precipitates that can resist growth, dissolution, and impede dislocation motion at elevated temperatures is highly important. Moreover, nanostructured steels have a low impact toughness at cryogenic environments due to the segregation of embrittling elements at prior austenite grain boundaries after peak aging at 400 °C–500 °C [20]. Grain boundary engineering to control elemental segregations at the prior austenite grain boundaries together with the grain refinement can be a possible solution for enhancing the cryogenic toughness of nanostructured steels [7, 21–23].

Steels are crystallographically complex and can transform into various structures such as pearlite, bainite, martensite, and ferrite depending on the steel chemistries and thermal histories. As demonstrated in the Fe–Mn–Al [24], Fe–Ni–Co–Ti [25], Fe–Pd [26], and Fe–Pt [27] alloy systems, thermoelastic or reversible martensitic transformation which leads to a super-elasticity in iron-based shape memory alloys is possible with a careful composition adjustment. Recent studies [24, 25] indicate that a 'right' chemistry can induce nanoscale precipitation of coherent ordered particles, resulting in thermoelastic martensitic transformation with a low thermal hysteresis. Recent researchers [25, 28, 29] believe that these ordered precipitates with a high coherency with the matrix enhance the tetragonality of the Body Centered Tetragonal martensite while strengthening the martensite and therefore discourage slip in martensite, leading to a reversible mobile austenite/martensite interface during the martensitic transformation. Tanaka *et al* [25] discovered that the additions of Ta is important for obtaining the super-elasticity in the Fe–28Ni–17Co–11.5Al–2.5Ta alloy system as Ta additions increase the volume fraction of the ordered γ'-(Ni,Fe,Co)$_3$(Al, Ta) precipitates. On the other hand, some researchers [30] argued that the precipitate size also plays an influential role in super-elasticity. A mechanistic understanding of the effects of alloying elements on the nanoscale precipitation and the resultant super-elasticity of various iron-based alloy systems is certainly needed for the development of low-cost shape memory alloys with enhanced properties for cost-conscious applications.

In essence, the development of the nanostructured steels is still in its infancy stage. Revolutionary design strategies for advanced manufacturing of nanostructured steels with exceptional properties are further needed to satisfy the stringent requirements of advanced structural industries.

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ORCID iDs

H J Kong https://orcid.org/0000-0003-3508-661X
T Yang https://orcid.org/0000-0003-4355-9210
T L Zhang https://orcid.org/0000-0002-1877-8238
B X Cao https://orcid.org/0000-0001-8221-1749
C T Liu https://orcid.org/0000-0001-7888-9725

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