Editorial

Atomic Scale Characterisation of Steels

Steel is frequently the ‘gold-standard’ against which emerging structural materials are compared. What is often not realised is that this is a moving standard, with notoriously regular and exciting discoveries being made in the context of iron and its alloys. This progress is why steel remains the most successful and cost-effective of all materials, with more than a billion tonnes being consumed annually in improving quality of life. One reason for the overwhelming dominance of steels is the variety of microstructures and properties that can be generated by solid-state transformation and processing. All these processes are driven by the diffusion and redistribution of atoms in the iron matrix. It is, therefore, of technological importance to understand the underlying mechanism of such atomic movement in steels. This special issue focuses on the recent advances of characterisation made possible by the development of new measurement science with atomic-scale precision. Using state-of-the-art scanned probe techniques, we explore a diverse set of research areas including nano-sized nitrides in plasma-nitrided Fe–M (M=Al, Cr, Ti, V) alloys; oxide dispersion strengthened Fe–Cr alloys for nuclear applications; and interstitial-free and high strength steels for automotive applications.

Multiple characterisation techniques, and modelling and simulation tools, are used to investigate phase transformations at the atomic scale, the effects of friction stir welding on microstructural stability of oxide dispersion strengthened steels and the nature of nano-sized precipitates. The complementary nature of these experimental techniques, as well as the combination of experimental techniques with modelling and simulation, provide powerful synergies in these investigations. The papers included in this special issue emphasise studies where multiple techniques and/or computational materials science tools have been coupled for the study, at the atomic scale, of complex process related to precipitation/cluster formation and alloying effects on phase transformations in steels.

Three of the papers included in this special issue relate to nanostructured and oxide dispersion strengthened ferritic alloys. The new concept of nanostructured ferritic alloys (NFAs) shows great promise for use in high temperature energy systems, especially advanced fission and future fusion
reactors. Along with reduced-activation ferritic/martensitic and ferritic steels strengthened by a dispersion of oxide nanoparticles, NFAs are considered viable structural materials for fusion applications above 550°C and overcome one of the most important shortcomings of actual structural material considered for fusion reactors, i.e. enhanced resistance to radiation damage and to activation under the high neutron fluxes experienced in fusion applications. Accelerated development of these materials is crucial if they are going to be used in future power reactors. Therefore, it is essential to understand the microstructural stability and mechanical behaviour of these steels when subjected to the aggressive operating conditions of advanced fusion reactors, which currently are not well characterised. It is in this context that the atomic scale evolution of NFAs under high temperature and irradiation conditions is paramount. In this sense, De Castro et al. report on the successful application of a combination of transmission electron microscopy (TEM) and three-dimensional atom probe tomography (3DAPT) to characterise these steels at the near-atomic scale, to reveal the nano-particle structure, grain boundary chemistry and void distribution.

Etienne et al. address the technological problem of the joining of NFAs, which must be achieved by solid-state methods such as friction stir welding (FSW). The paper discusses the key question of the effect of FSW on the ultrahigh density of nanoscale features that imbue NFAs with their outstanding properties, including remarkable resistance to radiation damage. 3DAPT measurements suggest that the number densities of the nanoscale features are qualitatively similar before and after FSW, but they appear to be redistributed, resulting in a high degree of alignment along boundary and dislocation structures.

Miller and Parrish review the roles of the alloying elements in three NFA ferritic alloys (14YWT, MA957 and Eurofer 97) which have been established through the characterisation of the microstructure by 3DAPT and spectrum imaging in the TEM. Cr, W, Mo, Ti and Y were found to contribute to solid solution hardening in the ferrite matrix. Ti, Y, C, O, and N were found in the high number densities of precipitates and nanoclusters formed both in the grain interior and on grain boundaries, and thereby contributed to precipitation hardening. Cr, W and Mo were enriched at the intraparticle regions of the grain boundaries. The authors also describe how this solute segregation and precipitation pin the grain boundaries to contribute to the excellent creep properties of the alloys.
The evolution of clusters and fine precipitates during the annealing of ultrahigh strength steels widely used in the automotive industry has also been studied by 3DAPT. Pereloma et al. examine the microstructural evolution of severely deformed interstitial free steel. No dissolution of pre-existing Ti4C2S2 and FeTiP precipitates occurred during room temperature equal channel angular pressing (ECAP) and subsequent cold rolling. Ti-rich clusters in the matrix may serve as precursors to further precipitation at longer annealing times. While all fine precipitates detected by 3DAPT exhibited a variety of non-stoichiometric compositions, near-equilibrium composition was found in the order of magnitude coarser precipitates observed by TEM.

Furthermore, Timokhina et al. discuss the mechanisms of strengthening in steels consisting of ferrite and bainite. They conclude that the formation of Nb–C clusters in ferritic steels is the main cause of strengthening; meanwhile the formation of Fe–C clusters and fine particles in the bainitic steel is responsible for the outstanding strength levels achieved in this steel grade. Carbon segregation on dislocations in bainitic ferrite has also been observed by means of 3DAPT.

Finally, Miyamoto et al. investigate the nature of nano-sized alloy nitrides or alloying element–nitrogen (M–N) clusters formed in plasma nitriding of Fe–M binary alloys by means of high resolution TEM. The specimen surface of the Fe–Cr alloys was hardened by the formation of disc-shaped CrN precipitates of NaCl structure, approximately $2\pm$nm thick and $10\pm$nm in diameter. In nitrided Fe-Al specimens, two kinds of AlN nitrides (metastable NaCl-type and stable wurtzite-type) were formed near the specimen surface. Both of these nitrides were much larger in size than the CrN discs. In contrast to these specimens, nitriding of Fe–Ti and Fe–V alloys produced a high density of M–N clusters, a few nanometres in diameter, many of which were mono-layered, lying on \{001\}_\alpha planes, leading to a greater hardness increase than nitriding of the Fe–Cr and Fe–Al alloys. The authors also explain the formation of M–N clusters in nitriding by the thermodynamic analysis of phase separation between M/N poor and M/N rich bcc phases.

Readers are strongly encouraged to read the full text of these stimulating articles.

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*Guest Editors*