



# Multiphase microstructures via confined precipitation and dissolution of vessel phases: Example of austenite in martensitic steel

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Received 2 July 2014; revised 14 November 2014; accepted 14 November 2014

**Abstract**—We present a novel method to locally control the constitution, morphology, dispersion and transformation behavior of multiphase materials. The approach is based on the targeted, site-specific formation and confined dissolution of precipitated carbides or intermetallic phases. These dispersoids act as “vessels” or “containers” for specific alloying elements forming controlled chemical gradients within the microstructure upon precipitation and subsequent (partial) dissolution at elevated temperatures. The basic processing sequence consists of three subsequent steps, namely: (i) matrix homogenization (conditioning step); (ii) nucleation and growth of the vessel phases (accumulation step); and (iii) (partial) vessel dissolution (dissolution step). The vessel phase method offers multiple pathways to create dispersed microstructures by the variation of plain thermomechanical parameters such as time, temperature and deformation. This local microstructure design enables us to optimize the mechanical property profiles of advanced structural materials such as high strength steels at comparatively lean alloy compositions. The approach is demonstrated on a 11.6Cr–0.32C (wt.%) steel, where by using  $M_{23}C_6$  carbides as a vessel phase, Cr and C can be locally enriched so that the thus-lowered martensite start temperature allows the formation of a significant quantity of retained austenite (up to 14 vol.%) of fine dispersion and controlled morphology. The effects of processing parameters on the obtained microstructures are investigated, with a focus on the dissolution kinetics of the vessel carbides. The approach is referred to as vessel microstructure design.

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**Keywords:** High strength steels; Multiphase materials; Microstructure design; Carbides

## 1. Introduction

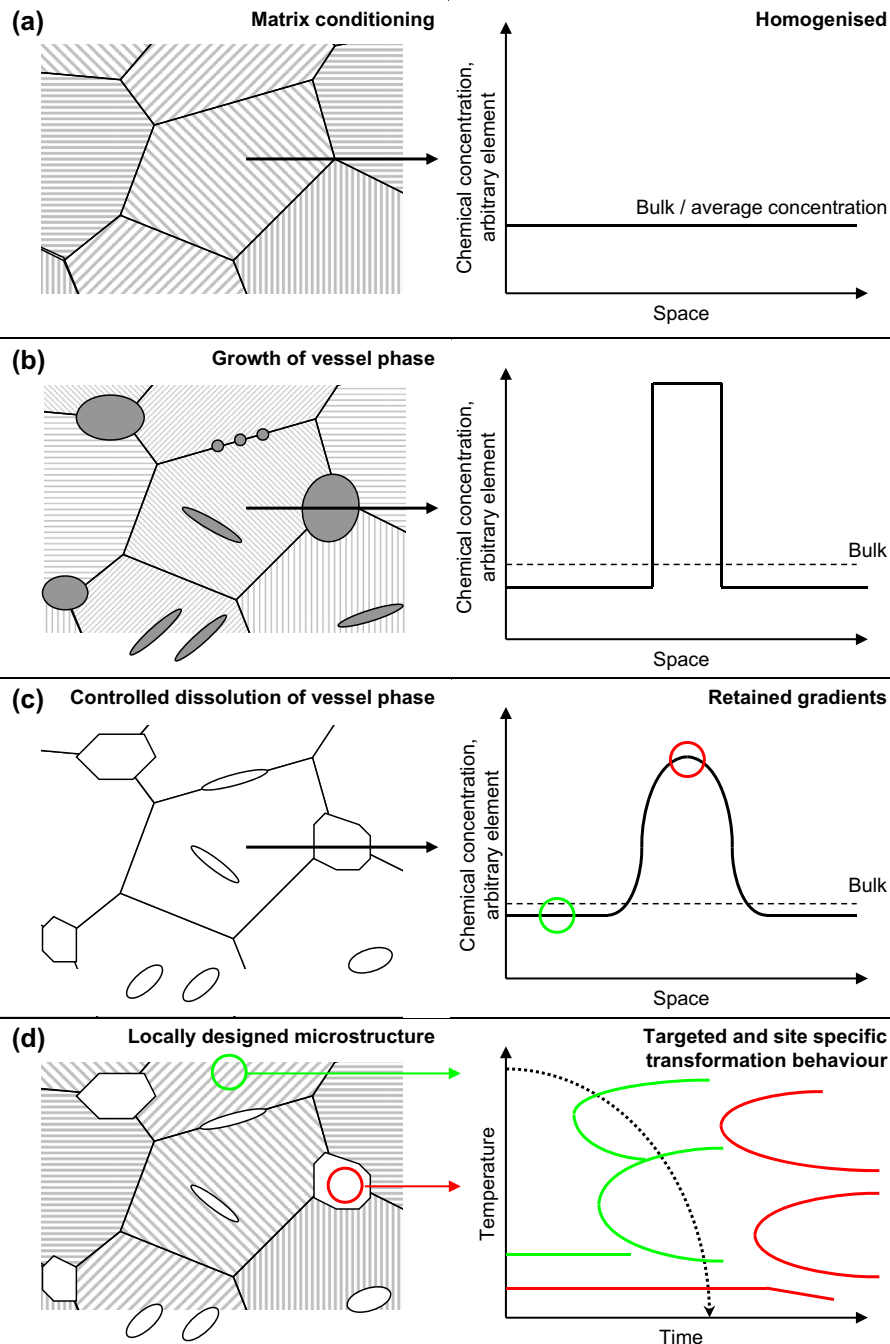
Advanced high strength steels derive their superior mechanical properties from the synergetic effects associated with precisely tuned multiphase microstructures, achieved by blending soft and ductile phases, such as ferrite or austenite, with hard and strong constituents, like martensite or bainite [1–3]. This is utilized for example in dual-phase (DP) steels, where finely dispersed martensite of 5–30 vol.% strengthens a ferritic matrix while retaining good formability [4–7], or in ultra-fine bainite, which consists of hard cementite aggregates within nanostructured bainitic ferrite [8,9]. For the design of ultra-high-strength steels, carbon-based (C) martensite and austenite are especially attractive microstructure constituents, as the former offers very high inherent strength, and the latter good ductility [10,11] coupled with additional work-hardening potential during deformation via the transformation induced plasticity (TRIP) mechanism [12,13].

Multiple alloying strategies and thermomechanical processing routes have been developed to achieve suitable microstructure blends, for example partially stabilizing

different phases chemically against quenching or transformation by introducing phase-specific alloying elements. As utilized in welds of duplex (ferritic/austenitic) steels [14], for example, the type of phases formed, as a function of the respective alloy concentrations, can be predicted using Schaeffler-type diagrams [15]. While this approach typically relies on rather high bulk alloying contents, as for example in stainless steels, the much leaner DP and TRIP-assisted steels widely used in automotive applications are produced by annealing in a two-phase (austenitic/ferritic) region, before cooling to room temperature following different time–temperature profiles [16,17]. This approach exploits the partitioning of alloying elements taking place during this intercritical holding, especially that of C, which leads to pronounced deviations in composition of the individual phases from the bulk values. This effect is aimed at tuning the local phase stabilities [18,19]. More complex processing, such as quenching – to above or below the martensite start ( $M_S$ ) temperature – coupled with subsequent tempering, may lead to precipitation and additional phase transformations, for instance yielding retained or reverted nanoscaled austenite in a tempered martensitic matrix [10,11,20–23].

All the aforementioned processes can be very effective in controlling the type and fractions of the blended phases. However, at least equally important for the

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**Fig. 1.** Sketch illustrating the proposed vessel microstructure design approach; (a) step 1, matrix conditioning, exemplified by homogenization; (b) step 2, accumulation of alloying elements in “vessel” precipitates nucleating under conditions imposed by the matrix conditioning; (c) step 3, dissolution of the vessel phase leads to chemical gradients, creating a chemically inhomogeneous matrix, constituting local alloying; (d) result: local changes in composition locally modify phase stability and morphology.

mechanical properties, especially ductility and toughness, is the local microstructure build-up in terms of dispersion, morphology and size of the constituents. Examples are the size and morphology of martensite islands as important factors governing crack initiation in DP steels [4,24] or the size dependence of austenite stability against its transformation in ultra-high-strength steels [19,25,26]. To further optimize such complex alloys in this regard the established processing and alloying routes are limited, as they offer only restricted and indirect control over the site-specific nucleation and stability

conditions of a given phase which may be desired for the local mechanical response. It thus becomes clear that in order to more effectively design innovative structural materials, it is of great interest to be able to control not only which types of phases are formed, but also simultaneously design their morphology, dispersion and stability.

The local phase stability and transformation behavior are determined by the local chemical concentration. As sketched in Fig. 1a, bulk alloying defines phase composition and hence stability, only in case of ideal

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