

Properties of Fine–Grained Steels Generated by Displacive Transformation

H. K. D. H. Bhadeshia

University of Cambridge

Materials Science and Metallurgy

Pembroke Street, Cambridge CB2 3QZ, U. K.

hkdb@cam.ac.uk, www.msm.cam.ac.uk/phase-trans

Abstract

It has been possible in recent times to make large quantities of steels in which the controlling scale is 20 nm or less, *i.e.*, comparable to that of carbon nanotubes. The mechanical properties of such steels are abnormal. For example, in some cases the ductility vanishes as the strength increases, whereas in others the ductility almost entirely consists of uniform plastic strain. Some of the steels also can tolerate large fractions of brittle phases before fracture. These and other aspects of strong, nanostructured steels are critically assessed to arrive at a hypothesis which rationalises the odd observations.

Key words: mechanical properties, fine scale, martensite, bainite

1 Introduction

It has been possible for some time, to produce iron in which the space-filling crystals are just 20 atoms wide [1,2]. These samples were prepared from the

vapour phase followed by consolidation. Although of limited engineering value, work of this sort inspired efforts to invent methods of making large quantities of steels with similarly fine grain-structures. Many of the results have been disappointing in that the steels tend to lack ductility [3]. In contrast, ductile bainitic steels have been produced in which the controlling scale of the ferrite crystals is 20–40 nm [4]. The purpose here is to explain these contradictory observations and in the process, propose a theory for the strain to fracture for the novel bainitic steels. We begin by considering why ductility is lost when extremely fine grain structures are induced into ordinary metallic materials.

2 Fine Grains and Diminished Work–Hardening Capacity

Modern technologies allow steels to be made routinely and in large quantities with grain sizes limited to a minimum of about 1 μm by recalescence effects [5,6]. Limited processes, generally involving severe thermomechanical processing, have been developed to achieve nanostructured ferrite grains in steel, with a size in the range 20–100 nm. Experiments indicate that the Hall–Petch equation holds down to some 20 nm, confirming that enormous strengths can be achieved by refining the grain size. The equation begins to fail at grain sizes less than about 20 nm, possibly because other mechanisms of deformation, such as grain boundary sliding, begin to play a prominent role. The volume fraction V_B of material occupied by the boundaries is given by

$$V_B \simeq 2a/\bar{L} \quad (1)$$

where \bar{L} is the mean lineal intercept defining the grain size and a is the thickness of the boundary layer. Clearly, the fraction of atoms located at the grain

surfaces becomes very large as the crystal size reaches minute scales, facilitating diffusional processes such as grain sliding (Fig. 1).

Although the nanostructured steels are strengthened as expected from the Hall–Petch equation, they tend to exhibit unstable plasticity after yielding [3,7]. The plastic instability occurs in both tension and in compression testing, with shear bands causing failure in the latter case. It is as if the capacity of the material to work harden following yielding diminishes. The consequence is an unacceptable reduction in ductility as the grain size is reduced in the nanometer range. At very fine grain sizes, the conventional mechanisms of dislocation multiplication fail because of the proximity of the closely-spaced boundaries. It then becomes impossible to accumulate dislocations during deformation. Grain boundaries are also good sinks for defects. This would explain the observed inability of nanostructured materials to work harden.

The difficulty that very fine grains have in deforming by a dislocation mechanism is highlighted in recent experiments [8] where mosaics of minute crystals of ferrite were *forced* to deform in shear. Instead of the expected lattice-invariant deformation, the crystals underwent a shear transformation into austenite.

3 Austenite and Enhanced Work–Hardening Capacity

The loss of work hardening capacity in fine-grained ferritic-steels can in principle be compensated for by introducing retained austenite into the microstructure. Plastic deformation can induce the austenite to transform into harder martensite. The resulting enhancement of ductility is a complex combination

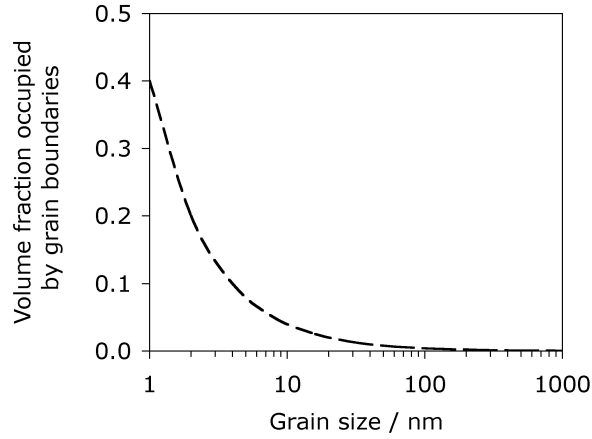


Fig. 1. The volume fraction of grain boundary as a function of the grain size.

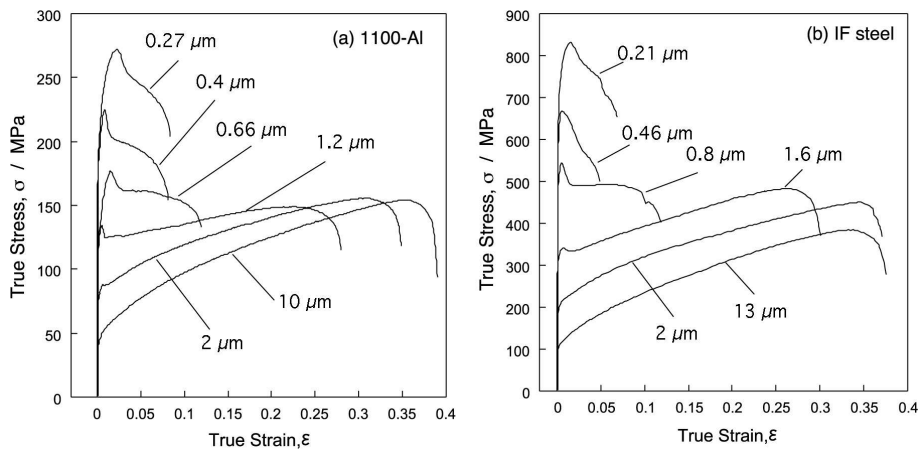


Fig. 2. Loss of ductility as the grain dimensions are dramatically reduced. The grain size is indicated in micrometers adjacent to each tensile curve. (a) Aluminium alloy, (b) iron alloy. Courtesy of Tsuji [7].

of the increase in work hardening capacity and the transformation strains due to the formation of martensite. These effects are often lumped together and described as transformation-induced plasticity, *TRIP*, [9]. Note that TRIP is not unique to martensite. Bainite [10] and Widmanstätten ferrite [11] also exhibit the phenomenon given their similar shape deformations. These transformations all are *displacive*, i.e., they are accompanied by a shape deformation which is an invariant-plane strain with a large shear component and hence show pronounced transformation-induced plasticity under appropriate

circumstances.

To appreciate the role of retained austenite it is necessary to distinguish between two kinds of steels – those which are initially in a fully austenitic state and others in which the retained austenite is a minor phase. The latter category is of particular relevance because it represents cheap alloys, often referred to as the TRIP–assisted steels [12,13]. In these steels, the average carbon concentration is low (0.15 wt%) but the austenite becomes enriched with > 1 wt%C by the partitioning of carbon when other phases grow. It therefore becomes stable at room temperature without the use of expensive solutes.

The transformation strain due to the formation of martensite in common TRIP–assisted steels makes only a minor contribution to the overall ductility. This is partly because the fraction of retained austenite tends to be < 0.2 but also because the exploitation of transformation strain requires variant selection [14,15]

On the other hand, the martensite that forms is very hard and through composite effects, raises the work hardening coefficient of the entire microstructure [16,17]. It is this which makes a major contribution to the extent of uniform ductility achieved by the composite microstructure. This conclusion is consistent with recent work by Jacques *et al.* [18] who argue that in certain steels containing only a small amount of retained austenite, the composite effect gives uniform elongation which is superior compared with commercial alloys with larger quantities of austenite.

To summarise, retained austenite makes an important contribution in enhancing the work–hardening rate during deformation, and can be exploited in the context of nanostructured steels, as will be described below.

4 Nanostructured Bainite

An unconventional, carbide-free steel has recently been invented which on close examination is found to contain bainitic-ferrite plates as thin as 20 nm, separated by carbon-enriched films of retained austenite [4,19–23]. This is the hardest ever bainite, which can be manufactured in bulk form, without the need for rapid heat treatment or mechanical processing. Many details have already been published but the structure is illustrated in Fig. 3. It is important to note that it consists only of two phases, slender plates of bainitic ferrite in a matrix of carbon-enriched austenite. We now proceed to discuss its mechanical behaviour.

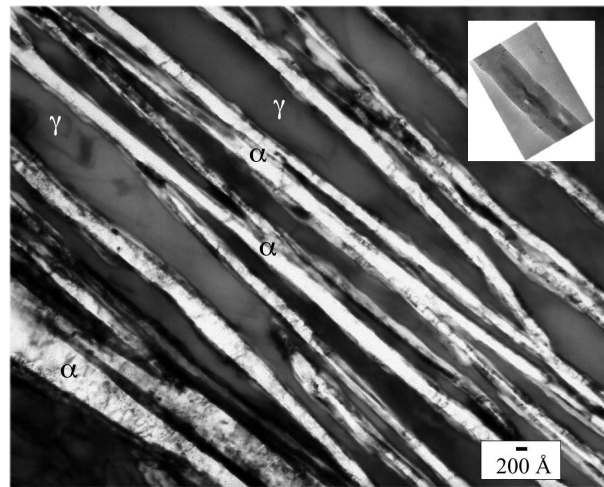


Fig. 3. Fe-0.98C-1.46Si-1.89Mn-0.26Mo-1.26Cr-0.09V wt%, transformed at 200°C for 5 days. Transmission electron micrograph [4,19,20]. The inset is of a carbon nanotube at the same magnification, courtesy of Ian Kinloch.

5 Nanostructured Bainite: Mechanical Properties

The hardness of the nanostructured bainite can be as high as 690 HV, with tensile strengths in excess of 2200 MPa, compressive strength in excess of 3000 MPa, ductility in the range 5–30% and K_{IC} values up to 45 MPa m^{1/2}. The original sources for these values can be found in a recent review [4]. The highest strength is achieved by forming bainite at the lowest transformation temperatures.

The reason for the high strength is well-understood from the scale of the microstructure and the details of the compositions and fractions of the phases. However, the stress versus strain behaviour is intriguing in many respects. There are two examples shown in Fig. 4 and corresponding details are summarised in Table 1.

The gradual yielding is as expected given the transformation plasticity and indeed the defect density of the microstructure generated by displacive transformation [15]. It is striking to see in Fig. 4 that virtually all of the elongation is uniform, with hardly any necking. Indeed, the broken halves of each tensile specimen could be neatly fitted together. It is not clear what determines the fracture strain.

It is now possible to estimate the change in the austenite content as a function of plastic strain and the driving force for martensitic transformation in TRIP steels [25]. Fig. 5 shows the expected variation in V_γ with strain for the three cases listed in Table 1. Also plotted are points which define in each case the strain at which the tensile samples failed. A prominent feature is that they all fail when the retained austenite content is reduced to about 10%. An

$T_I / ^\circ\text{C}$	V_γ	σ_Y / GPa	$\sigma_{UTS} / \text{GPa}$	Elongation / %
200	0.17	1.41	2.26	7.6
250	0.21	1.40	1.93	9.4
300	0.37	1.25	1.7	27.5

Table 1

T_I , V_γ , σ_Y and σ_{UTS} stand for isothermal transformation temperature, the volume fraction of retained austenite, the 0.2% proof and ultimate tensile strengths respectively [24].

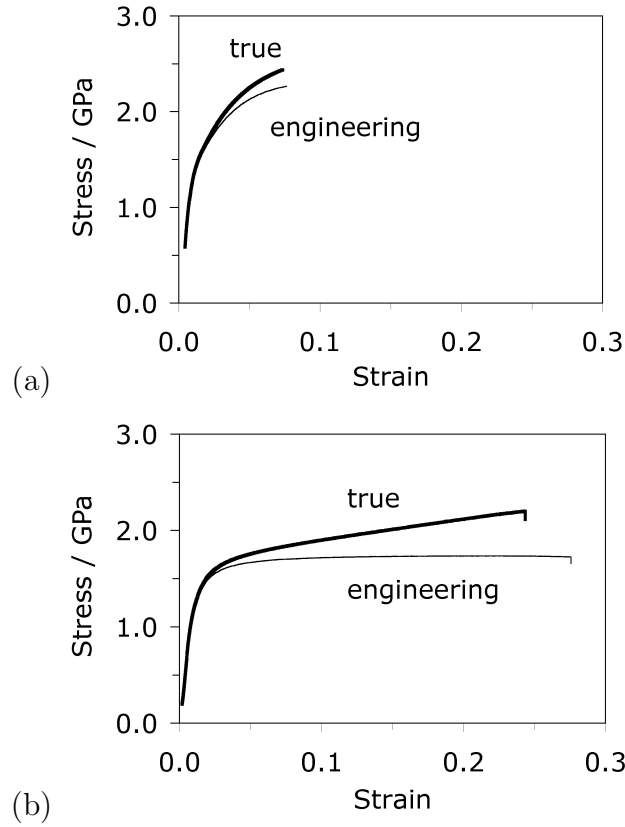


Fig. 4. Fe-0.79C-1.56Si-1.98Mn-0.24Mo-1.01Cr-1.51Co-1.01Al wt%. True and engineering stress-strain curves. (a) Bainite generated by transformation at 200°C. (b) Bainite generated by transformation at 300°C. Data from [24].

experimental study by Sherif [26] on an aluminium-free alloy which is otherwise identical to the steel considered here, is consistent with this conclusion. His X-ray studies also indicated that tensile failure in nanostructured bainite occurs when the retained austenite content is diminished to about 10%.

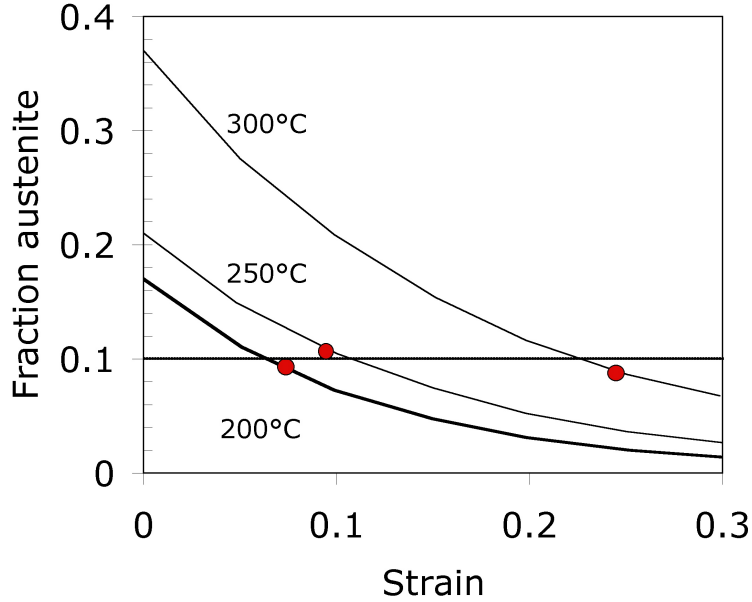


Fig. 5. Calculated variation in the fraction of austenite as a function of plastic strain for the samples listed in Table 1. Data adapted from [24].

This observation can be understood if it is assumed that failure occurs when the austenite, which is the toughest of all the phases present, becomes geometrically isolated, *i.e.*, it loses percolation, leading to fracture. Garboczi *et al.* have developed a numerical model for the percolation threshold when freely overlapping objects (general ellipsoids) are placed in a matrix [27]. Since the austenite is subdivided roughly into the form of plates by the bainite, it can be represented by oblate ellipsoids with an aspect ratio r of between about 1/10 and 1/100. The percolation threshold is then found to be $p_c \simeq 1.27r$, *i.e.*, $0.127 \geq p_c \geq 0.0127$. This is consistent with the observation that tensile failure occurs when $V_\gamma \simeq 0.1$.

This inference is in one sense surprising since the transformation of austenite leads to the formation of very hard, untempered, high-carbon martensite which should be highly susceptible to fracture. The carbon concentration of the retained austenite before it transforms is between 1–2 wt%. However, a study of Fig. 5 shows that large amounts of this potentially brittle martensite (7→27%) can be tolerated in the microstructure before the fraction of austenite reaches the percolation threshold and fracture actually occurs. The question then arises as to why this is the case.

The solution to this query lies in the fact that the tendency of the martensite to crack in a mixed microstructure of austenite and martensite depends on its absolute size [28]. In these mixtures, it is more difficult to crack fine martensite. It is the fine scale of the retained austenite in the nanostructured bainitic steels that permits the martensite to be tolerated without endangering their mechanical properties.

A fine plate size makes it difficult to transfer load on to the martensite when the composite mixture is strained. It has also been demonstrated that there is an exaggerated tendency to form long plates of martensite, which are most prone to cracking, when the austenite grain size is coarse [28].

6 Summary

Steels with very closely spaced grain boundaries generally suffer from a lack of ductility due to the loss of work hardening capacity. This problem can be remedied by introducing retained austenite in the microstructure. The strain- or stress-induced martensitic transformation of this austenite enhances the

work-hardening coefficient, making it possible to get substantial ductility in nanostructured bainitic steels. However, the amount of austenite must then be above the percolation threshold, which is estimated to be about 10 vol.‰.

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