Very Strong, Low–Temperature Bainite

Case for Support, Part I

Introduction

The addition of about 2 wt% of silicon to steel enables the production of a distinctive microstructure, consisting of a mixture of bainitic ferrite, carbon–enriched retained austenite and some martensite [1,2]. The silicon suppresses the precipitation of brittle cementite, and hence should lead to an improvement in the toughness. However, it is clear that the full benefits of this carbide–free bainitic microstructure have not been realised. This is because the bainite reaction stops well before equilibrium is reached, *i.e.* when the carbon concentration of the residual austenite reaches a point given by the T_0 curve, beyond which diffusionless growth is prevented. This leaves large regions of unreacted austenite which under stress decomposes to a hard, brittle martensite [3].

Bhadeshia & Edmonds [3] first presented the design procedure which avoids this difficulty in three ways: by adjusting the T_0 curve using substitutional solutes; by controlling the mean carbon concentration; and by minimising the transformation temperature. Steels were designed on this basis and when tested, revealed a reduction in the impact transition temperature of more than 100 K [3].

Fracture toughness measurements confirmed the remarkable levels of toughness that could be achieved, in some cases matching the expensive marageing steels [4]. Other aspects of the theory have been verified using a variety of advanced research techniques, reviewed in [2].

The first major commercial exploitation came with the development of a kinetic theory [2] to complement the three thermodynamic criteria, so that continuous cooling transformation which is typical in industry, could be dealt with. As described in part I, this led to the invention and large scale manufacture of a bainitic steel with outstanding wear and rolling–contact fatigue resistance. The steel transforms into the correct microstructure during the routine manufacturing process used for making rails.

The accumulated results to date are illustrated in Fig. 1, including our most recent research [5] in which gun barrel bainitic steels with the highest strength/toughness combinations ever recorded were designed theoretically and verified experimentally. Toughness values of nearly $130\,\mathrm{MPa\,m^{\frac{1}{2}}}$ have been obtained for strength in the range 1600–1700 MPa. We continue to match the critical properties of marageing steels which are at least thirty times more expensive. These alloys are the subject of patent applications.

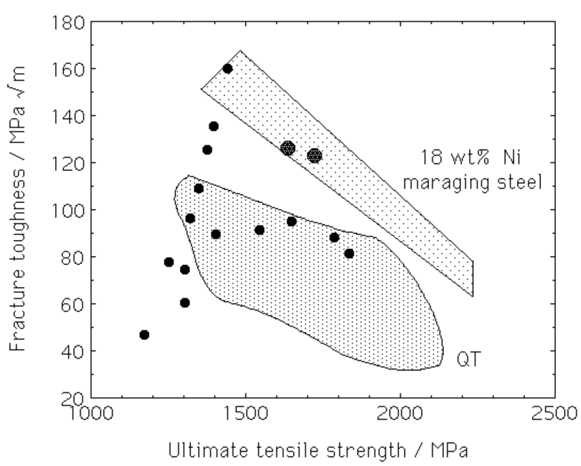

Fig. 1: Properties of mixed microstructures of bainitic ferrite and austenite, versus those of quenched and tempered (QT) low–alloy martensitic alloys and marageing steels. The two large points refer to the latest bainitic steels, which match the marageing steel but are much cheaper. [5]

During the course of our research on the design of steels [5], we made an exciting discovery, in which carbide–free bainite has been obtained by transformation at incredibly low temperatures, as low as 150 °C*. To put this into context, the random jump distance of an iron atom at that temperature is only* 10^{-17} *m over a period of three weeks. Preliminary experiments show the microstructure obtained is so refined that it is possible to achieve a strength of 2500 MPa with signs of considerable ductility. The discovery is the subject of a second patent application. An objective of the work proposed here is to understand and design this low–temperature bainite to achieve a novel class of incredibly strong, tough and cheap steels.*

The Discovery

The transformation to bainite occurs in a stepwise manner. The individual plates grow without diffusion, but the excess carbon then escapes into the residual austenite. Subsequent plates therefore have to grow from carbon–enriched austenite. This can continue until diffusionless transformation becomes impossible, when the composition of the austenite reaches the T_0 boundary of the phase diagram.

An important consequence is that the transformation can never go to completion. Substantial amounts of carbon–enriched austenite remain untransformed at the point where bainite ceases to grow in a silicon–rich steel. The carbon concentration of this austenite is substantially larger than that of the steel as a whole (typically 2 wt%). In order to particularly to study the mechanical properties of this high–carbon austenite, we manufactured an alloy replicating the chemical composition of the retained austenite (Table), but with a carbon concentration of about 1 wt%. The martensite–start temperature was expected to be below ambient, but the steel was observed to emit audible sounds at $T < 200\,°C$ during slow cooling from the austenitic state.

Table 1	C	Si	Mn	Cr	Mo	V
wt%	2-3	1.5	1.9	1.3	0.3	1

Systematic investigations revealed that bainite could be obtained by transforming at very low temperatures, *e.g.* 150 °C, the lowest temperature ever reported for this microstructure. The transformation can take many days to initiate and up to three weeks to complete.

The microstructure is found to be ductile, whereas martensite in the same steel fails in a brittle manner. In a few compression tests, and in just one tension test, we have measured 0.2% proof strengths in the range 1960–2650 MPa. Limited transmission electron microscopy shows that the microstructure is indeed bainitic with substantial quantities of retained austenite.

Scientific and Technological Relevance

Bainitic microstructures with strength levels as high as those reported here are unprecedented. Furthermore, the microstructure shows evidence of ductility whereas martensite in the same steel does not. This is because the carbon, in the bainitic microstructure, ends up in the residual austenite where it does no harm.

We believe that the highly promising properties come from the fact that the microstructure is refined by the very low temperature of transformation. It is very surprising, at least on the basis of preliminary observations, that lower bainite has not been obtained in such a high carbon material. From a scientific point of view we need to understand both qualitatively and quantitatively, the development of bainite at very low temperatures, to characterise the microstructure, thermodynamic and kinetic behaviour. All of this will contribute new knowledge, not only on the mechanism of transformation but there is a possibility of creating a new class of very strong steels which can be obtained in bulk form in any shape by holding isothermally at very low temperatures, albeit for prolonged periods.

We believe that the length of the required heat treatment is not a problem because of the low temperatures involved, and for the components appropriate for this level of strength, *e.g.* gears, armour plate. Indeed, it is not necessary to cool rapidly to the transformation temperature because there are no transformations before bainite even during the air cooling of a 10 cm thick ingot.

The alloy (Table 1) was designed originally to determine the properties of high carbon austenite in isolation, not intentionally as a bainitic steel. To assess the true scientific and technological potential of the low–temperature bainite, we would like to begin again and design specifically for the purpose of achieving the enormous strength and toughness.

Relevance to Beneficiaries

The diffusion distance of an iron atom in three weeks at 150 °C is 10^{-17} m, an incredibly small distance. And yet, bainite has been obtained at such a low transformation temperature. We believe that a fundamental study of the microstructure, the shape deformation and kinetics will provide definitive evidence for the mechanism of transformation. Another advantage of the low transformation temperature is that the shape deformation may be largely elastically accommodated, in which case it may be possible to reveal the mode of the lattice–invariant deformation using atomic force microscopy.

The technological benefits to the UK defence industry in particular but to users of high strength steels in general could be enormous if this low alloy steel, which can be produced using a simple heat treatment, can be shown to have all the properties needed for reliable engineering applications. The cost reductions relative to marageing steels have already been highlighted.

Dissemination and Exploitation

It is intended to publish fundamental information in the open scientific literature, to present the information at conferences and to place any software that emerges from this research onto the Materials Algorithms Project world–wide web site for free access.

The Programme

The experimental data to date are very limited and do not form the basis for predicting alloys which are optimised for the stated purpose of low temperature transformation, high strength and toughness.

We shall begin with our existing theoretical models for the bainite transformation [6] in order to design a new experimental alloy, which may have a simplified chemical composition. This will involve the application of thermodynamic phase stability calculations including the T_0 concept [2], the calculation of time–temperature–transformation diagrams [7], the evolution of isothermal transformation [8], aspects of the scale of the microstructure [9] and the expected phase mixtures [10,11]. Given the very high strengths that are required, it is necessary to control chemical segregation during casting; we have alloy design procedures to minimise such segregation. The hardenability of the alloy will be controlled [7] to prevent any transformation prior to bainite and to avoid martensite at low temperatures. The overall aim is to promote the proportion of bainitic ferrite, and to ensure that the residual austenite is in the form of fine films and that it is stable to transformation under stress.

The alloy will then be manufactured as a 20 kg melt, homogenised at 1200 °C for two days to minimise chemical segregation effects and then forged to an appropriate shape and to break up the cast microstructure.

A series of isothermal transformation experiments over a calculated range of temperatures will help characterise the kinetics of transformation for comparison with theory (which has only ever been applied to high temperatures). A detailed transmission electron microscope characterisation will also be needed to establish the scale of the bainite sub-units, and the retained austenite films. One goal of the research is to confirm and understand why the steel does not seem to transform to lower bainite in spite of the very high carbon concentration [12]. X–ray analysis experiments will be used to measure the fraction of austenite, its carbon concentration and the extent of "strain" in the microstructure.

Bhadeshia proposed a theory in 1981 to rationalise the displacive transformations that occur in steels, *i.e.* Widmanstätten ferrite, bainite and martensite [11]. It was argued that the nucleation of Widmanstätten ferrite and bainite occurs by a mechanism which is similar to that of martensitic nucleation, except that the partitioning of carbon is essential to provide the necessary driving force at low undercoolings. The nucleus develops into Widmanstätten ferrite when the undercooling is not sufficient to sustain the diffusionless growth of bainite. For martensite both the nucleation and growth processes are diffusionless. An important prediction of the theory is that not all of the three displacive transformation products will necessarily occur in every steel. As the hardenability is increased, Widmanstätten ferrite is eliminated, followed by bainite, so that high–alloy steels only transform martensitically.

This theory currently forms the basis of all physical microstructure calculation models for steels. It is intended to apply this model to discover the lowest temperature at which bainite can be obtained in reasonable periods of time and then to use it to design an appropriate high–carbon steel with a fine microstructure generated at the lowest possible transformation temperature. This will represent the first ever test of the theory to discriminate accurately between the variety of displacive transformations in steels, and will at the same time help think of steels with the lowest conceivable bainite transformation temperatures.

Mechanical Property Model

The microstructural measurements will be used to understand how the high–carbon steel develops its remarkable strength. The strength of each phase will be calculated from its calculated composition, size and defect density as described in [13]. The overall deformation will then be modelled using Tomota's model [14].

Collaboration

Our major collaboration will be with DERA scientists, who will deal with the characterisation of the properties associated with ballistic requirements and will conduct tests on alloys designed by us. Our contribution of basic research on the mechanisms of microstructural development and mechanical property modelling will be vital to the DERA programme.

Management and Resources

Funding is requested for a post–doctoral research assistant, Dr Caballero, to conduct the alloy design and characterisation work on the high–carbon steels. She is an outstanding researcher who has been working on bainite with the principal investigator for two years and has the necessary theoretical and experimental skills to get the work underway. She was instrumental in the discovery of this low–temperature carbide–free bainite.

The work has a large experimental component including optical and TEM specimen preparation, mechanical testing, maintenance of our group atomic force microscope, routine machining, sample sealing and heat treatment. Hence the request for 75% of the time of a technician, John Street, who is highly qualified for these tasks.

The programme of research will require three dedicated furnaces because the heat treatments are lengthy in time. We do not at the moment have adequate facilities in this respect. Funding is requested for the preparation of four alloys, to be prepared by design at different stages in the project as we gain knowledge. Reasonable costs of sample preparation and transmission electron microscopy are also incorporated.

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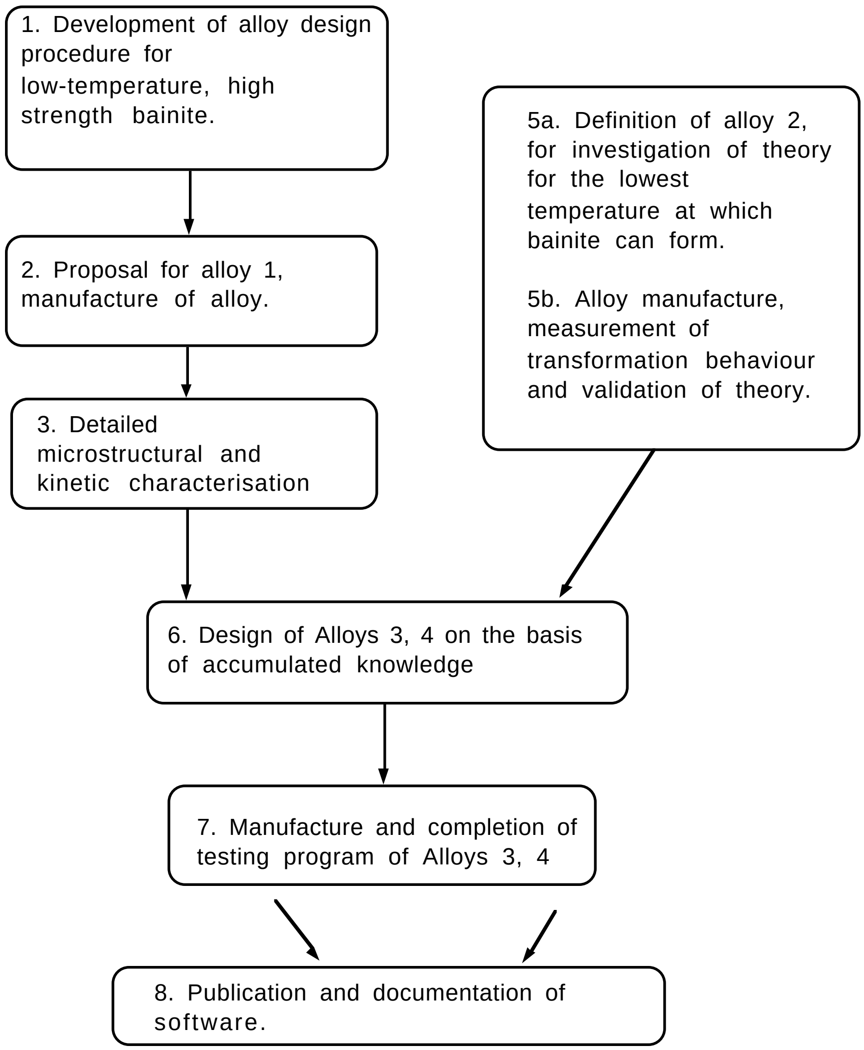

Milestones

6 months: Design of alloy 1, manufacture of alloy1
12 months: Testing of alloy 1, design of alloy 2
18 months: Manufacture of alloy 2, lowest Bs temperature?
24 months: Design of alloys 3, 4
30 months: Testing of alloys completed
36 months: documentation of software, publication

Fig. 1: Diagrammatic project plan. Flow chart illustrating the plan of work, Milestones and elements of the collaboration.