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Dual-phase hot-press forming alloy

H.L. Yi [a,*], S. Ghosh [a], H.K.D.H. Bhadeshia [a,b]

[a] Graduate Institute of Ferrous Technology, Pohang University of Science and Technology, San 31, Hyoja-dong, Nam-gu, Pohang 790-784, Republic of Korea
[b] Materials Science and Metallurgy, University of Cambridge, Cambridge CB2 3QZ, UK

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ABSTRACT

Hot-press forming steels are formed in a fully austenitic state followed by die-quenching in order to generate martensite and achieve strong steel. The ductility however, tends to be limited. We explore in this work a novel steel design in which the forming operation is in the two-phase austenite and ferrite field, so that the quenching results in a dual-phase ferrite and martensite microstructure at ambient temperature. It is demonstrated that better properties are achieved. The interpretation of the mechanisms of deformation during tensile testing indicates that the ductility can be further enhanced without compromising strength. The new steel also can be heated to temperature which is lower than that used for conventional hot-press forming steels, before transfer into the forming press.

1. Introduction

One application of strong steels in the context of automobiles is to enhance passenger safety by resisting damage to the passenger compartment during collisions. There are many varieties of such steels, for example those which are TRIP-assisted [1–6] or the dual-phase steels which are nicely reviewed in [7]. These steels have to be formable and that requirement is difficult to achieve when the strength exceeds about 1000 MPa. Strong steels also suffer from an exaggerated change in shape due to the relaxation of elastic stresses when the steel is removed from the forming press [8].

One solution to these difficulties was the invention in Sweden [9,10] of the process known as hot-press forming, in which a hot sheet of steel in its austenitic state, is fed into a forming press with water-cooled dies which quench the material into a martensitic state. Following austenitisation at about 900 °C [11,12], the steel is transferred to the press and the deformation occurs at high temperatures approximately in the range 800–600 °C [13] where the steel is soft and formability limitations insignificant. The quenching produces already-formed components with strength in the range 1200–1600 MPa. There is little or no change in shape when the component is removed from the press. The steels typically have a composition Fe–0.22C, 1–2 wt% Mn (depending on whether the steel also is alloyed with boron) and other trace elements to give a martensite-start temperature of about 400 °C [14]. The steel in its final condition after hot-press forming is fully martensitic and has a ductility (total elongation) of approximately 6–8%. One variant of the process is warm forming [15], where the maximum temperature to which the steel is heated can be as low as 600 °C in order to minimise springback and oxidation. However, the strength achieved in this case is much lower than in hot-press forming because the steel is not austenitic during the forming process.

The purpose of the present work was to explore another option with the hope of improving ductility in the press-formed condition whilst maintaining the strength. An alloy was designed so that it consists of a mixture of allotriomorphic ferrite and austenite at the forming temperature, so that subsequent quenching leads to a dual-phase steel. A potential advantage of this mixture of allotriomorphic ferrite and martensite could be that the latter phase occurs in a finer state than in fully martensitic steels; this in itself should improve the resistance of the martensite to cracking [16–18].

2. Experimental method

The steel studied has the chemical composition

$$\text{Fe} - 0.40\text{C} - 0.26\text{Si} - 2.02\text{Mn} - 2.50\text{Al} - 0.018\text{P} \quad ()$$

$$-0.0036\text{S} - 0.0048\text{N wt\%} \quad ()$$

and its calculated phase diagram is in Fig. 1a. The combination of alloying elements, especially the aluminium, ensures that the alloy has a large ferrite content at elevated temperatures. The alloy in fact was originally designed for a different purpose, the so-called δ-TRIP concept [19–21] where the allotriomorphic ferrite present in conventional TRIP-assisted steels [5,4] is replaced by δ-ferrite created during solidification. However, effects associ-

* Corresponding author.
E-mail addresses: hityihl@postech.ac.kr (H.L. Yi), hkdb@cam.ac.uk (H.K.D.H. Bhadeshia).

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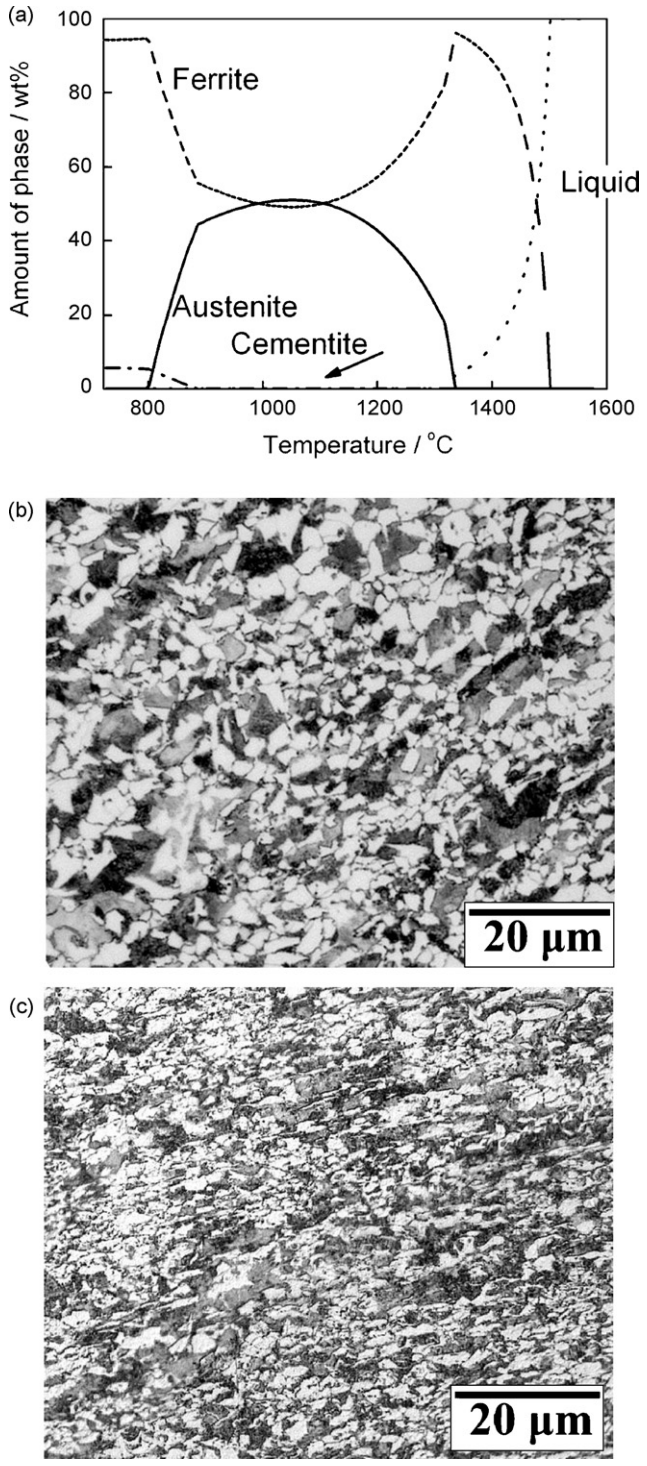

Fig. 1. (a) Phase diagram calculated using MTDATA [33] and the TCFE (version 1.2) database. (b) Optical microstructure in the hot-rolled state. (c) Optical microstructure in the cold-rolled state.

ated with non-equilibrium cooling prevented success [20] and a different approach was necessary in that application. Nevertheless, by serendipity, the alloy proved useful to explore the dual-phase hot-press forming studied here.

The alloy was manufactured as 34 kg ingot of 100 × 170 × 230 mm dimensions using a vacuum furnace. The ingot was reheated to 1200° C for rough rolling to make 25–30 mm slabs followed by air cooling. These slabs were then reheated to 1200° C and hot-rolled to 3 mm in thickness; 1.2 mm thick sheets were then produced by cold rolling. Optical microscopy samples were prepared using standard methods and etched in 2% nital. Higher resolution observations was done using a field-emission scanning electron microscope operating at 10 kV accelerating voltage. Heat treatments were conducted on a simulator, CCT-AY, made by ULVAC-RIKO. The cold-rolled sheets for tensile testing were heated in a nitrogen atmosphere at 840, 860, 880 and 900° C respectively for 3 min at the heating rate 20 °C s^{-1}, followed by quenching at −40 °C s^{-1} using nitrogen. The sub-size tensile specimens were machined according to ASTM standard E8M-00 with elongation recorded over a gauge length 10 mm and a strain rate of approximately 3.3×10^{-3} s^{-1}.

Table 1
Quantitative metallographic data, and the carbon content of the martensite as estimated by mass balance from the average concentration.

Heat-treatment T/°C	$100V_V^\alpha$	$C_{\alpha'}$/wt%	$\bar{L}_\alpha/\mu$m	$\bar{L}_{\alpha'}/\mu$m
840	38 ± 5	0.64 ± 0.05	1.2 ± 0.1	1.7 ± 0.3
860	34 ± 9	0.60 ± 0.07	1.1 ± 0.1	1.9 ± 0.1
880	32 ± 6	0.58 ± 0.05	1.1 ± 0.2	2.4 ± 0.2
900	26 ± 6	0.54 ± 0.05	1.0 ± 0.1	2.5 ± 0.4

Conventional hot-rolling was conducted between 1200 and 900 °C; the fact that ferrite coexists with austenite at all temperatures in this range leads to a significant refinement, a grain size of just 3.1 ± 0.2 μ m without using any thermomechanical processing (Fig. 1b). The phenomenon is well established in the field of superplasticity where two-phase mixtures can resist coarsening during deformation [22]. The cold-rolled structure is illustrated in (Fig. 1c).

3. Results and discussion

Metallographic observations confirmed the dual-phase ferrite (α) and martensite (α') microstructure obtained following heat-treatment at 840, 860, 880 and 900° C for 3 min followed by quenching, Fig. 2. Quantitative data are presented in Table 1, which show as expected from the phase diagram, that the fraction of ferrite decreases as the maximum heat-treatment temperature is increased. The size scales were characterised using standard metallographic theory [23], with the mean lineal intercepts ($\bar{L}$) in the two phases given by

$$\bar{L}_\alpha = \frac{LV_V^\alpha}{N^\alpha} \qquad \bar{L}_{\alpha'} = \frac{LV_V^{\alpha'}}{N^{\alpha'}} \tag{1}$$

where V_V and N represent the volume fraction and number of grains respectively of the phase identified by the superscript. The observed grain sizes of the ferrite and of the martensite islands are remarkably small given the simple heat-treatment and the absence of any thermomechanical processing, Table 1.

Tensile test results are illustrated in Fig. 3 together with a comparison against some published data. There are a number of features which are striking, first that the yield strength is quite low, around 400 MPa, followed by work-hardening. This kind of behaviour is expected in dual-phase steels [24–26] consisting of two phases which have quite different yield strengths. The application of stress at first causes yielding in the softer phase only, but because the ferrite does not occupy the entire specimen, it yields at a stress less than that of the ferrite isolation. This explains the very low macroscopic yield strength observed.

It is only after the ferrite has work hardened to be able to transfer sufficient load on to the stronger martensite that the latter begins to deform plastically. It is in this way that high-strength is achieved. However, fracture will occur when the martensite is no longer able to support plastic strain.

The surprising trend in the data illustrated in Fig. 3c is that the total elongation increases as the heat-treatment temperature