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Static recrystallisation of steels produced by direct strip casting – The effect of carbon and vanadium concentration

M. Ramajayam [a], N. Stanford [b,*]

[a] Institute for Frontier Materials, Deakin University, 3216, Australia
[b] Department of Materials Science and Engineering, Monash University, 3800, Australia

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ABSTRACT

Six steel alloys containing a range of carbon and vanadium concentrations have been prepared by simulated strip casting. The alloys were cold rolled and annealed to examine the recrystallisation behaviour. The annealing treatment resulted in three processes occurring concurrently: recrystallisation; spheroidisation of cementite, and precipitation of vanadium-enriched nano-precipitates. These nano-precipitates had a much higher concentration of Fe than would be expected from traditional processing methods, and this increased their maximum attainable volume fraction. In the two alloys that did not contain second phase particles, recrystallisation showed typical reaction kinetics, and the recrystallised grain size continued to increase with increasing time at temperature. However, in those alloys with second phase particles the recrystallised grains showed unusual behaviour, rapidly reaching an upper limit to their size. Continued time at temperature was not accompanied by an increase in the grain size. This growth limit has been attributed to Zener pinning, with the limiting grain size being proportional to the Zener pinning pressure. It has been proposed that the delayed recrystallisation that is typically observed in strip cast steels is likely to be the result of nano-scale precipitation which is unique to rapidly cooled materials, such as those produced by strip casting.

1. Introduction

Twin roll strip casting is a steel processing technology that solidifies liquid steel directly into thin sheet [1]. The energy savings associated with this direct approach make it of great technological interest [2]. Although the process has successfully been up-scaled to commercial size, very little information on the physical metallurgy of the strip cast sheet is available in open literature. From this small pool of information, there is a growing body of work indicating that during secondary processing, strip cast steels show unusual behaviours, particularly in respect to their static recrystallisation behaviours [3,4].

Ferry and Xu have shown that strip cast low carbon steels exhibit delayed recrystallisation compared to conventionally processed sheets [5]. For the case of strip cast stainless steels, significant delays in static recrystallisation have also been reported [3]. In both of these cases, the alloys were not precipitate hardenable grades, yet in the latter case the formation of small sulphide and nitride particles was concluded to be responsible for the retarded recrystallisation. These small particles are a result of the rapid solidification of the sheet during strip casting, and retention of elements in solid solution above equilibrium concentrations is now known to be a common feature of the strip cast microstructure [6].

The recrystallisation behaviour of precipitate hardenable grades such as high strength low alloys steels after strip casting have yet to be examined. It is known that Nb is retained in solid solution after strip casting [6,7]. What remains unclear is how the supersaturated microstructure will respond to annealing, and what impact the concurrent precipitation may have on recrystallisation. Since Nb is relatively well studied, in the present case Vanadium was chosen as the carbide forming element of interest. A range of steel compositions were studied in order to elucidate the effect of precipitation on the recrystallisation behaviour of strip cast steels.

2. Experimental method

2.1. Simulation of direct strip casting

Six steel alloys were prepared, and a summary of the alloy compositions are detailed in Table 1. The samples were prepared by a simulation technique designed by Strezov et al. [8], and a schematic diagram of the apparatus is shown in Fig. 1(a).

* Corresponding author.

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Table 1
Composition of the six alloys tested in the present work. Compositions are shown in wt% and were measured using ICP-OES.

	C	Al	Si	Mn	S	P	N	V	Fe
Pure Fe	0.02	0.002	0.01	0.11	0.02	0.02	0.01	–	Bal.
Fe – 0.1C	0.09	0.002	0.11	0.17	0.02	0.02	0.04	–	Bal.
Fe – 0.5C	0.46	0.002	0.01	0.13	0.02	0.02	0.01	–	Bal.
Fe – 0.1C – 0.04V	0.09	0.002	0.11	0.17	0.02	0.02	0.04	0.04	Bal.
Fe – 1V	0.02	0.006	0.01	0.11	0.02	0.02	0.04	0.95	Bal.
Fe – 0.5C – 1V	0.42	0.002	0.01	0.11	0.02	0.02	0.01	0.82	Bal.

Approximately 100 kg of high purity iron was melted in an induction furnace, and alloying elements were added successively to attain the desired steel composition. The melt temperature was monitored by an R-type thermocouple located ~45 mm below the melt surface. Two steel electrodes were placed along the paddle to sense the melt height. The paddle was programmed to immerse and retract at a velocity of 60 m/min, this resulted in an average residence time of the paddle in the melt of around 0.2 s. Molten steel solidifies on the copper substrates, and an example of the specimens obtained in the as-cast condition are shown in Fig. 1(b). The thickness of the specimens varied between 0.9 mm to 1.2 mm. The cooling rate of the solidified sample varied from 40 °C/s to 15 °C/s through the ferrite transformation temperature range of 800–500 °C, Fig. 1(c).

2.2. Secondary processing

Samples were cold rolled using a hand-rolling mill to 50% reduction in thickness in multiple passes. To study the recrystallisation kinetics, static annealing was performed in a muffle furnace at 650 °C. This temperature was chosen because it is low enough to be within the ferrite phase field, but high enough to make the recrystallisation rates practicable. Depending on the chemical composition of the steel, the annealing time varied from 100 s to 172,800 s (48 h). After annealing, the samples were quenched in cold water to arrest the recrystallisation.

2.3. Sample preparation

All microstructural analysis was conducted along the through thickness direction, unless otherwise mentioned. The mounted samples were ground through a series of successively finer grades of silicon carbide paper: 240, 600 and 1200 grit. Three different diamond suspensions 9 μm, 3 μm and 1 μm were used in polishing the samples. The final stage of polishing was carried out using OPS solution. This preparation was sufficient for scanning electron microscopy (SEM) which was carried out with a Supra VP FEG SEM at 20 kV. Images were taken using a backscattered detector. For optical microscopy, the samples were then etched using 3% Nital solution (nitric acid: ethanol, 3:100).

Thin foils for transmission electron microscopy (TEM) analysis were prepared by grinding selected specimens to a thickness between 50 and 70 μm using 1200 grit silicon carbide paper. Discs of 3 mm diameter were punched from the foil and these were then ion polished until a small hole appeared in the centre of the disc. Ion polishing was carried out using a GATAN precision ion polishing system (PIPS) with an accelerating voltage of 5 keV.

2.4. X-ray diffraction

For X-ray diffraction (XRD) analysis, 15 mm × 15 mm × 0.5 mm samples were cold mounted in an epoxy resin parallel to the casting or rolling direction. The mounted samples were metallographically prepared for X-ray analysis by the same methods as described in Section 2.3. X-Ray measurements were made with a Panalytical X'pert PRO using Cu Kα radiation and a Ni filter. Peak profiles of {110}, {200} and {112} planes corresponding to Bragg

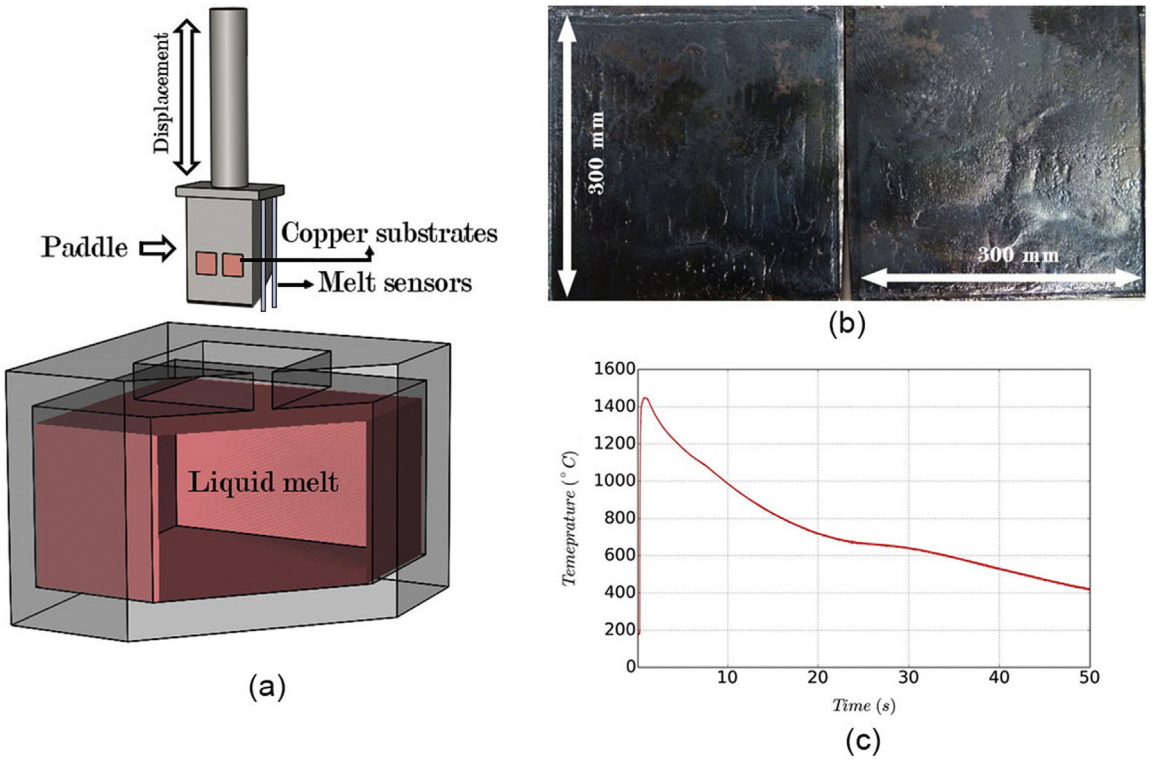

Fig. 1. (a) Schematic representation of immersion apparatus that simulates strip casting conditions. (b) Photograph of strip cast steel. (c) Typical cooling curve for the steel.