Decomposition of Coarse Grained Austenite During Accelerated Cooling of C–Mn Steels

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The simulation of microstructural evolution of a range of C–Mn steels following high-speed continuous casting and controlled cooling was carried out using quench dilatometry. An initial coarse-grained austenitic microstructure (as expected during casting of low carbon steel strip) was produced by a high temperature austenitising treatment followed by cooling at rates up to 600°C/s. Continuous cooling transformation (CCT) diagrams for a range of cooling schedules were constructed. It was found that both cooling rate and steel composition produces a range of final microstructures from polygonal ferrite to martensite with a concomitant range in hardness. Coarse grained austenite was found to promote the formation of degenerate pearlite and bainitic microstructures. The role of alloying additions, in combination with cooling rate is discussed in the context of microstructural development and mechanical properties of as-cast low carbon steel strip.

KEY WORDS: CCT diagrams; C–Mn steels; dilatometry; strip casting.

1. Introduction

Conventional continuous casting (CCC) of steel into slabs, billets and blooms has developed in the past few decades into a maturing industrial technology.1,2) Most recently, direct strip casting (DSC) has attracted world-wide attention as this technology has the capability of producing sheet products at a greatly reduced cost compared with CCC and thermomechanical processing (TMP).1,2) Twin roll casting (TRC) is argued to be the favoured method of direct strip casting of steel.2) In this process, molten metal is introduced into a tundish connected with a nozzle or tip. The metal flows through the nozzle into the gap between two water-cooled rolls that rotate at a given speed to produce strip of thickness of 1–2 mm. The high rate of heat extraction from the melt results in rapid solidification and can produce as-cast microstructures radically different to that produced by CCC.1–7)

The entire process of TRC is under intense development and extensive research is required to characterise the broad range of microstructures and properties that are possible in this vastly different processing route. The viability of producing strip-cast low carbon steels in large tonnages is expected to compete with the CCC/TMP route.2) It is therefore necessary to develop a better understanding of the effect of strip casting variables on microstructural development of low carbon steels as one of the most critical challenges for TRC is to produce steel strip with the mechanical properties similar to those obtained via conventional strip production routes.7)

Following solidification of low carbon steel, such as by high-speed casting to produce thin strip2,7) or welding,8) solidification generally produces coarse-grained austenite of columnar morphology. Depending on (strip) casting variables, solidification produces austenite grains of width 100–250 μm and length 300–700 μm.7) While the production of this columnar microstructure under laboratory conditions is exceedingly difficult, recent work has shown that austenite grain width is a predominant factor during its decomposition.7) In the present work, quench dilatometry was used, on a range of C–Mn steels, to produce austenite with an average grain diameter of approximate dimensions to that of the grain width of austenite following casting. Specimens were subsequently cooled at rates up to 600°C/s in an attempt to simulate controlled cooling of steel strip following direct casting. The influence of alloying elements such as C and Mn, together with the rate of cooling on the mode of austenite decomposition, and the resulting hardness were the focus of this investigation. The information will provide important insight into microstructural control during DSC or welding, or other processes where a coarse austenite grain size is produced, followed by rapid cooling.

2. Materials and Experimental Program

Three grades of C–Mn steel, in the form of hot-rolled plate, were supplied by BHP Steel, Port Kembla. The chemical compositions of the steels are given in Table 1. The steels were prepared with the same general composition but with different concentrations of Mn ranging from 0.45 to...
1.0 mass%.

Samples were machined from as-hot-rolled plate to produce thin-walled cylinders of 4.5 mm external diameter, 3.5 mm internal diameter and length 10 mm. All experiments were carried out in a vacuum (10⁻⁴ torr) to limit possible decarburisation and/or oxidation of the samples during the heat treatment. The thermal cycle was controlled via a Type S thermocouple (0.13 mm wire diameter) spot-welded on the surface of each sample. Cooling of the samples was obtained by controlling the flow of the high-purity helium gas. To simulate the austenite microstructure that develops after solidification, an austenite grain size ~100 μm was produced by heating each sample at a rate of 5°C/s to a temperature of 1100°C followed by soaking for 185 s. This austenite grain size corresponds to a surface area : volume ratio (S/V) of ~20 mm⁻².¹⁰ Following isothermal holding, samples were cooled to room temperature at a constant rate of 1 to 600°C/s.

After thermal cycling, samples were sectioned and prepared for metallographic examination using conventional techniques. The microstructures were examined by both optical microscopy and scanning electron microscopy. For quantitative optical examination of the microstructure, dark-etching phases such as pearlite, bainite and martensite are referred to as secondary phases. Quantitative metallography was performed using image analysis where grain size measurements were based on mean linear intercept method.¹⁰ Hardness measurements were made using Lecco Vickers microhardness testing with a 200 g load. For a given cooling rate, the transformation start (Ar3, Bs and Ms) and transformation finish temperatures (Ar1, Bf and Mf) were measured for each steel by locating the temperature at which the dilatation–temperature curve showed a 2% deviation from linearity.¹¹ CCT diagrams were constructed using data obtained from dilatometry together with microstructural analysis. Scanning electron microscopy (SEM) was also used to identify the secondary transformation products and the phase nomenclature used here is based on the classification system proposed by ISIJ Bainite Committee.¹²,¹³ For C–Mn steels, it is expected that the transformed microstructure from austenite consists of different forms of ferrite and carbide aggregation, and so, quantitative metallography was used to locate the temperature of formation for each type of ferrite phase.

3. Results

3.1. CCT Diagrams

CCT diagrams for all steels are given in Figs. 1 to 3, with representative optical microstructures of the lowest and most highly alloyed steels given in Fig. 4. A comparison of the CCT diagrams shows that an increase in both the

| Table 1. Principal alloying elements (mass %) and steel designation. |
|------------------|------------------|------------------|
| Element | Fe-0.11C-0.45Mn | Fe-0.14C-0.74Mn | Fe-0.14C-1.0Mn |
| C | 0.11 | 0.14 | 0.14 |
| Mn | 0.45 | 0.74 | 1.0 |
| P | 0.004 | 0.014 | 0.018 |
| Si | 0.005 | 0.005 | 0.01 |
| Ni | 0.024 | 0.024 | 0.02 |
| Cr | 0.02 | 0.014 | 0.015 |
| Al | 0.038 | 0.032 | 0.03 |

Fig. 1. CCT diagram for Fe-0.11C-0.45Mn steel (dₐ=100 μm).
Fig. 2. CCT diagram for Fe–0.14C–0.74Mn steel ($d_p = 100 \mu m$).

Fig. 3. CCT diagram for Fe–0.14C–1.0Mn steel ($d_p = 100 \mu m$).
C and Mn content shifts the ferrite transformation nose to slower cooling rates and lowers the CCT diagrams with respect to temperature. For example, the ferrite transformation nose for Fe–0.11C–0.45Mn is located at \( \sim 30^\circ\text{C/s} \) (Fig. 1), while for Fe–0.14C–0.74Mn and Fe–0.14C–1.0Mn, it is between 10–30°C/s (Fig. 2) and \( \sim 10^\circ\text{C/s} \) (Fig. 3) respectively. An increase in C and Mn contents also causes the \( \gamma \rightarrow \alpha \) transformation to occur over a wider temperature range, which indicates slower transformation kinetics, that is, an increase in hardenability.

The influence of both cooling rate and composition on the transformation start and transformation finish temperatures are shown in Fig. 5. An increase in cooling rate lowers both these critical temperatures significantly and an increase in C–Mn content lowers them most significantly in the cooling rate range 30–300°C/s.

### 3.2. Microstructural Development

The effect of cooling rate on microstructural development is essentially consistent for all steels. For example, for Fe–0.11C–0.45Mn steel, it can be seen in Fig. 4 that, at cooling rates below 3°C/s, the secondary phase is lamellar pearlite but changes to a mixture of widmanstätten ferrite...
and granular bainitic ferrite at rates of 10–100°C/s, and finally at cooling rates greater than 300°C/s, a mixture of lathlike bainite/martensite is produced. The evolution of microstructure as a function of cooling rate and prior austenite grain size is shown in Fig. 6 for the Fe–0.14C–0.74Mn steel. It is evident from Fig. 6 that the room-temperature microstructure produced from coarse prior austenite differs significantly from that produced from fine prior austenite for all cooling rates. For example, at a cooling rate of 10°C/s, polygonal ferrite is produced from fine austenite whereas coarse prior austenite leads essentially to the formation of acicular ferrite. The consequence of these differences in terms of conventional processing and strip casting is discussed in Sec. 4.2.

The volume fraction of secondary phases as a function of both cooling rate and composition is given in Fig. 7. It is evident from Fig. 7 that the room-temperature microstructure produced from coarse prior austenite differs significantly from that produced from fine prior austenite for all cooling rates. For example, at a cooling rate of 10°C/s, polygonal ferrite is produced from fine austenite whereas coarse prior austenite leads essentially to the formation of acicular ferrite. The consequence of these differences in terms of conventional processing and strip casting is discussed in Sec. 4.2.

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4. Discussion

4.1. The Controlled Decomposition of Austenite—Simulation of DSC

The control of as-cast microstructure in low carbon steel is important in several industrial processes such as direct strip casting (DSC) and welding. Solidification usually results in non-equilibrium conditions to produce both a wide range of microstructures (Fig. 4) and mechanical properties (Fig. 8). While the laboratory simulation used in this work does not produce the columnar prior austenite morphology found in as-cast strip, it is known that the austenite grain width is the important factor during transformation whereby preferential nucleation of diffusional products occurs at the faces of these columnar grains.7) Thus a prior austenite grain size of 100 μm was chosen to simulate the decomposition of austenite following DSC where it was shown that decomposition produces a final microstructure ranging from polygonal ferrite to bainite/martensite.

Elements such as Mn and C in steel are austenite stabilizers and hence affect its rate of decomposition. An increase in Mn content is argued to result in a decrease in the ferrite growth rate it affects the thermodynamic stability of austenite relative to ferrite14) Similar to previous work on microalloyed steels,15,16) increasing the Mn content retards both the onset (lowers Ar3, Bf and Ms) and progress (lowers Ar1, Bf and Mf) of transformation in the C–Mn steels (Fig. 5). The retarding effect of Mn on the rate of decomposition of austenite has been attributed to segregation of Mn atoms along the α/γ phase boundary causing a strong solute drag effect.17,18) The addition of Mn to steel also decreases the activity of C in austenite18) thereby promoting the formation of secondary phases, such as degenerate pearlite and MA (martensite–austenite island) constituents in preference to equilibrium lamellar pearlite.

4.2. Influence of Austenite Grain Size—Comparison with Conventional Hot-Band

For a given cooling rate, the microstructures produced from coarse γ were vastly different to those produced from fine γ after simulated hot rolling and accelerated cooling.11) Table 2 gives a summary of the effect of grain size on the critical cooling rates required to produce a given microstructure. It is clear from Table 2 that formation of lamellar pearlite from coarse γ is more difficult, which is probably due to the long diffusion paths involved. The polygonal ferrite nose is also shifted to slower cooling rates indicating the strong influence of coarse γ on the formation of bainitic microstructures. This is more clear when the bainitic nose temperatures are compared for the higher C–Mn contents, and the CCT diagrams in Fig. 9 shows that bainite forms from coarse γ at rates as low as −10°C/s. From a theoretical point of view, the main effect of coarse γ is a decrease in interfacial grain boundary area per unit vol-

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volume and an increased diffusion distance which subsequently restricts its propensity for diffusional decomposition and, hence, increases hardenability.

It is known that coarse γ is difficult to avoid during DSC without the addition of certain alloying elements such as sulphur or using textured copper rolls to control nucleation sites during solidification to δ-ferrite.7) Despite this increase in hardenability, the range of cooling rates used in this work, which are achievable by DSC,2,7) produces a wider range of microstructures and mechanical properties compared with CCC/TMP routes, but with a marked reduction in processing steps. Figure 10 shows, for a given steel and cooling rate, that grain size does not have a significant effect on hardness during slow cooling (<10°C/s), but coarse γ produces a greater range in hardness as cooling rate is increased. Overall, the relative ease of producing a wide range of microstructures and, hence, mechanical properties from coarse γ is significant as the final thickness (1–2 mm) of as-cast steel strip allows limited scope for major microstructural modification by secondary processing.

4.3. Mechanical Properties of Strip-cast Low Carbon Steels

Perhaps the most critical challenge for strip casting processes such as TRC is to produce low carbon steel strip with the mechanical properties similar to those obtained via

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**Fig. 6.** Development of microstructure as a function of cooling rate and prior austenite grain size in the Fe–0.14C–0.74Mn steel. (scale bar represents 10 μm). Etchant: 2.5% Nital (8 μm prior austenite grain size from Ref. 11).
conventional production routes. With reference to the CCT diagram in Fig. 2 (Fe–1.1C–0.45Mn), continuous cooling results in a range of microstructures from polygonal ferrite to martensite (Fig. 4) as well as a range in hardness from 125–425 HVN depending on cooling rate and composition (Fig. 8). If a more formable sheet product is required, then cooling at a given rate and isothermal holding in the temperature range 700–740°C, which simulates high temperature coiling, will produce a microstructure of polygonal ferrite and pearlite. Such a microstructure is amenable to further cold rolling and annealing operations and is expected

Table 2. Influence of steel composition and prior austenite grain size on critical cooling rates for specified transformation products.

| Steel            | Critical Cooling Rate (°C/s) |
|------------------|-----------------------------|
|                  | \(d_a = 8\mu m\) | \(d_a = 100\mu m\) |
| **Pearlite nose**|                            |
| Fe-0.11C-0.45Mn  | 30-100                     | 3-10                      |
| Fe-0.14C-0.74Mn  | 30-100                     | ~3                        |
| Fe-0.14C-1.0Mn   | 30-100                     | ~3                        |
| **Polygonal ferrite nose**|                              |
| Fe-0.11C-0.45Mn  | 300-600                    | ~30                       |
| Fe-0.14C-0.74Mn  | 100-300                    | 10-30                     |
| Fe-0.14C-1.0Mn   | 30-100                     | 10-30                     |
| **Bainite nose** |                            |
| Fe-0.11C-0.45Mn  | > 600                      | 300-600                   |
| Fe-0.14C-0.74Mn  | 300-600                    | 100-300                   |
| Fe-0.14C-1.0Mn   | 300-600                    | 30-100                    |

Fig. 7. Effect of cooling rate and steel composition on the volume fraction of secondary phases (\(d_a = 100\mu m\)).

Fig. 8. Effect of cooling rate and steel composition on the hardness of transformation products (\(d_a = 100\mu m\)).

Fig. 9. Comparison of CCT diagrams of Fe–0.11C–0.45Mn generated from coarse (100 \(\mu m\)) and fine (8 \(\mu m\)) austenite.

Fig. 10. Comparison of hardness of steels following transformation from coarse (100 \(\mu m\)) and fine (8 \(\mu m\)) austenite. Unbroken lines denote coarse austenite.
to produce an adequately formable final sheet product.\textsuperscript{19)} Unlike CCC/TMP, which usually produces a fine-grained polygonal ferrite hot-band, DSC in combination with controlled cooling and coiling generates a very wide range of microstructures with mechanical properties suitable for a specific application such as high-strength sheet through to more formable strip. For example, Mukunthan et al.\textsuperscript{7)} recently demonstrated that a wide range of strength/ductility combinations are possible in a low carbon strip-cast steel by minor alterations in composition and controlled cooling following solidification. These workers also showed that a similar range in properties in conventional low carbon steel hot-band requires a much broader range of alloys and alloying additions. Such variation in properties of strip-cast low carbon steel is remarkable and is expected to make a significant impact on the conventional flat products market. A limitation of DSC alone is the relatively small processing window available to modify the as-cast microstructure.\textsuperscript{2)} However, the incorporation of secondary processing steps such as hot direct rolling (HDR)\textsuperscript{20)} or cold rolling and annealing (CRA)\textsuperscript{19)} present opportunities for further modification of microstructure and thus control the mechanical properties of the strip-cast product to meet a particular application in the marketplace.

5. Conclusions

Experiments using quench dilatometry to produce coarse-grained austenite were carried out to simulate the effect of cooling rate on the microstructure and mechanical properties of strip-cast low carbon steels. The results of the simulation have shown that:

- A coarse austenite grain size enhances the development of a range of microstructures in combination with accelerated cooling.
- For a given steel, accelerated, continuous cooling results in a significant increase in hardness, together with the development of secondary phases such as quasi-polygonal ferrite, degenerate pearlite, acicular bainite and martensite.
- An increase in Mn content retards the rate of transformation to ferrite and causes a significant increase in hardness associated with an increase in volume fraction of secondary transformation products.

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