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Effect of holding temperature and time on ferrite formation in dual phase steel produced by strip casting

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Abstract

Conventional dual phase (DP) steel (0.08C-0.81Si-1.47Mn-0.03Al, wt. %) was manufactured by the laboratory simulation of strip casting. The effect of holding temperature and time on microstructure evolution was studied using a quench-deformation dilatometer. Microstructures were observed using optical and scanning electron microscopy. The results showed that the nose temperature of ferrite phase field is around 650 °C. The kinetics of ferrite formation is fast within the first 100 s of holding at this temperature, and then formation of ferrite continues at a slower rate until it reaches the fraction corresponding to that defined by the lever rule. 70~80 % ferrite was obtained after holding at 650 °C for 100~900 s. Some Widmänstatten ferrite was also observed probably because of a large prior austenite grain size and quenching after holding. In addition, austenite-to-ferrite transformation kinetics is fitted well using Johnson-Mehl-Avrami equation. The Avrami exponent for ferrite formation was approximately 1 for both 650 and 670 °C holding temperatures, which means rapid ferrite transformation. It deduces that the ferrite formation obeys a linear growth behavior, which is associated with a decrease in amount of nucleation sites.

Keywords

effect, casting, holding, strip, temperature, produced, time, ferrite, formation, dual, phase, steel

Disciplines

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EFFECT OF HOLDING TEMPERATURE AND TIME ON FERRITE FORMATION IN DUAL PHASE STEEL PRODUCED BY STRIP CASTING

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ABSTRACT

Conventional dual phase (DP) steel (0.08C-0.81Si-1.47Mn-0.03Al, wt. %) was manufactured by the laboratory simulation of strip casting. The effect of holding temperature and time on microstructure evolution was studied using a quench-deformation dilatometer. Microstructures were observed using optical and scanning electron microscopy. The results showed that the nose temperature of ferrite phase field is around 650 °C. The kinetics of ferrite formation is fast within the first 100 s of holding at this temperature, and then formation of ferrite continues at a slower rate until it reaches the fraction corresponding to that defined by the lever rule. 70~80 % ferrite was obtained after holding at 650 °C for 100~900 s. Some Widmänstatten ferrite was also observed probably because of a large prior austenite grain size and quenching after holding. In addition, austenite-to-ferrite transformation kinetics is fitted well using Johnson-Mehl-Avrami equation. The Avrami exponent for ferrite formation was approximately 1 for both 650 and 670 °C holding temperatures, which means rapid ferrite transformation. It deduces that the ferrite formation obeys a linear growth behavior, which is associated with a decrease in amount of nucleation sites.

1. INTRUDUCTION

Dual phase (DP) steels are comprehensively researched due to their high strength and good ductility [1]. Compared to the hot-rolling and cold rolling paths, the strip casting is another potential route to produce DP steels in industry. Strip casting is a developing industrial process, which allows producing strip products directly from the melt [2-4]. Strip casting reduces energy consumption and emissions through a shorter processing line compared to hot rolling and cold rolling [3, 5]. Strip casting has already been used for manufacturing carbon, silicon and stainless steels in industry [2, 6]. However, production of DP steels by strip casting has not been researched so far [7]. In this work 0.08C-0.81Si-1.47Mn-0.03Al (wt. %) DP steel, having conventional chemical composition of DP steels [1], was produced by the laboratory simulation of strip casting. The effect of holding temperature and time on ferrite formation and microstructure evolution was investigated. Austenite-to-ferrite transformation was analysed using Johnson-Mehl-Avrami equation.

Table 1. Chemical composition of the DP steel (wt. %).

C	Si	Mn	Al	Cu	Cr	P	S	B
0.0768	0.805	1.47	0.0346	0.0126	0.233	0.0055	<0.00050	0.00091

2. EXPERIMENTAL DETAILS

As-cast specimens of 35 x 35 x 1.2 mm of the DP steel (Table 1) were produced at Deakin University by dip casting, which simulated rapid solidification during strip casting [8]. The microstructure after dip casting contained predominantly martensite with some bainite.

The heat treatment schedule (Figure 1a) for laboratory simulation of strip casting was carried out using a Theta Dilatronic III (Quenching and Deformation) dilatometer. The temperature was measured using an S-type (Pt/Pt-10%Rh) thermocouple spot-welded to the surface center of flat samples (Figure 1b). The heat treatment included: austenitising at 1300 °C for 180 s, in order to simulate the prior austenite microstructure inherent for as-cast condition (the average grain size of prior austenite is 117±44 μm), cooling at 90 Ks^{-1} to various holding temperatures T_F (600, 650, 670 and 700 °C) in austenite-to-ferrite two phase region, holding at these temperatures for various times t_F (60, 100,150, 180, 300 and 900 s) and then helium quenching at 140 Ks^{-1} to room temperature. Samples after heat treatments were cut through thickness in the centre and the centre of cross section was used for observation. The samples were etched with 2% nital for optical and scanning electron microscopy (SEM). Optical microscopy was carried out using a Leica DMRM microscope. SEM was carried out using a JEOL 7001F field emission gun scanning electron microscope (FEG SEM).

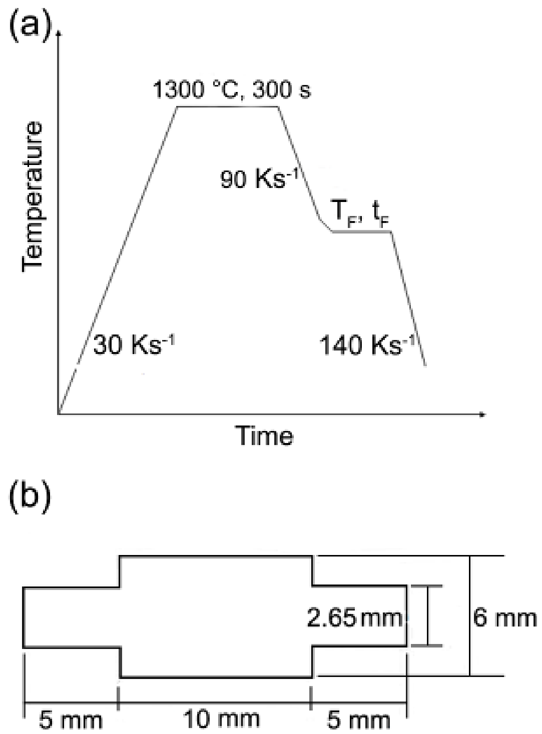

Figure 1. Schematic diagram of (a) heat treatment applied to the (b) samples to simulate strip casting.

3. RESULTS

3.1 Effect of holding temperature on ferrite formation

Table 2. Volume fractions of ferrite as a function of holding temperatures and times.

	600 °C	650 °C	670 °C	700 °C
60 s	-	25±4%	3±1%	-
100 s	-	70±2%	-	-
150 s	-	72±2%	-	-
180 s	28±5%	74±4%	-	16±4%
300 s	-	81±1%	75±1%	-
900 s		81±2%		

The volume fractions of ferrite obtained after holding at different temperatures and times are listed in Table 2. Some of corresponding microstructures are shown in Figure 2. The volume fraction of ferrite is higher after holding at 650 °C for 60 s than that after holding at 670 °C for 60 s (Figure 2). For 180 s holding time the volume fraction of ferrite is larger after holding at 650 °C than that after holding at 600 or 700 °C. Therefore, the nose temperature of ferrite field of the isothermal transformation diagram is around 650 °C.

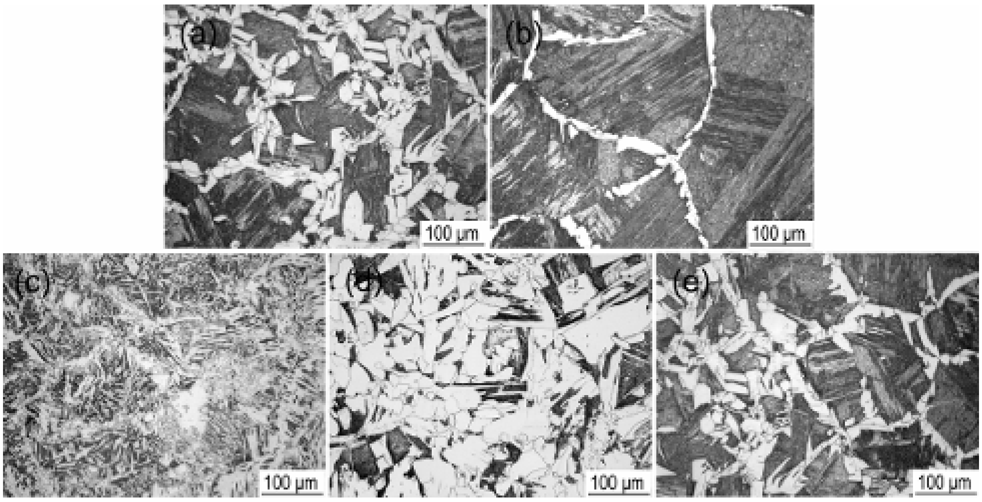

Figure 2. Microstructures after austenitising at 1300 °C for 180 s followed by holding at (a) 650 °C for 60 s, (b) 670 °C for 60 s, (c) 600 °C for 180 s, (d) 650 °C for 180 s and (e) 700 °C for 180 s.

3.2 Effect of holding time on ferrite formation

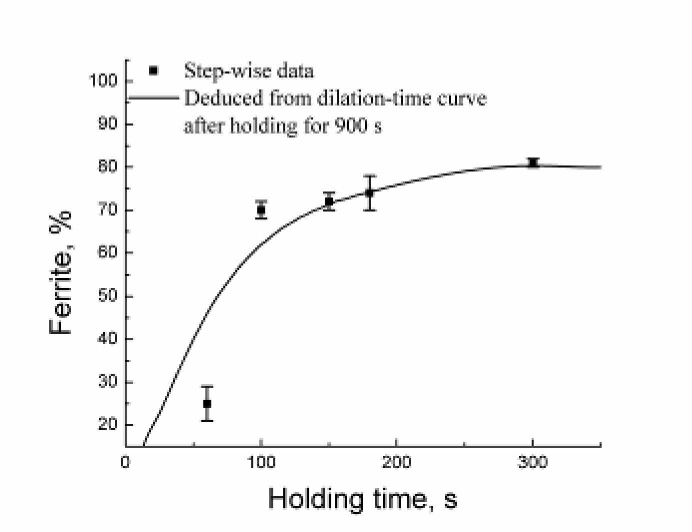

Figure 3. Variation in volume fraction of ferrite with time of holding at 650 °C.

Based on the previous section, the experiments with holding at 650 °C for different times were carried out (Table 2). Figure 3 shows the evolution of volume fraction of ferrite with increasing holding time. The line calculated from dilation-time curve after holding at 650 °C for 900 s has a good agreement with the step-wise data obtained using optical imaging, which means the dilation measurement is somehow reliable. Ferrite formation is fast within the first 100 s of holding at this temperature, and then formation of ferrite continues at a slower rate until it reaches 81±2%, the fraction corresponding to that defined by a lever rule.

4. DISCUSSION

4.1 Effect of ferrite formation temperature and holding time on microstructures

It is known that DP steels should contain 56~90% martensite in order to obtain a good combination of strength and ductility [9]. Figure 4 shows the microstructures containing 70~80% volume fractions of ferrite. Martensite forms as islands, which is similar to hot rolled DP steels [10].

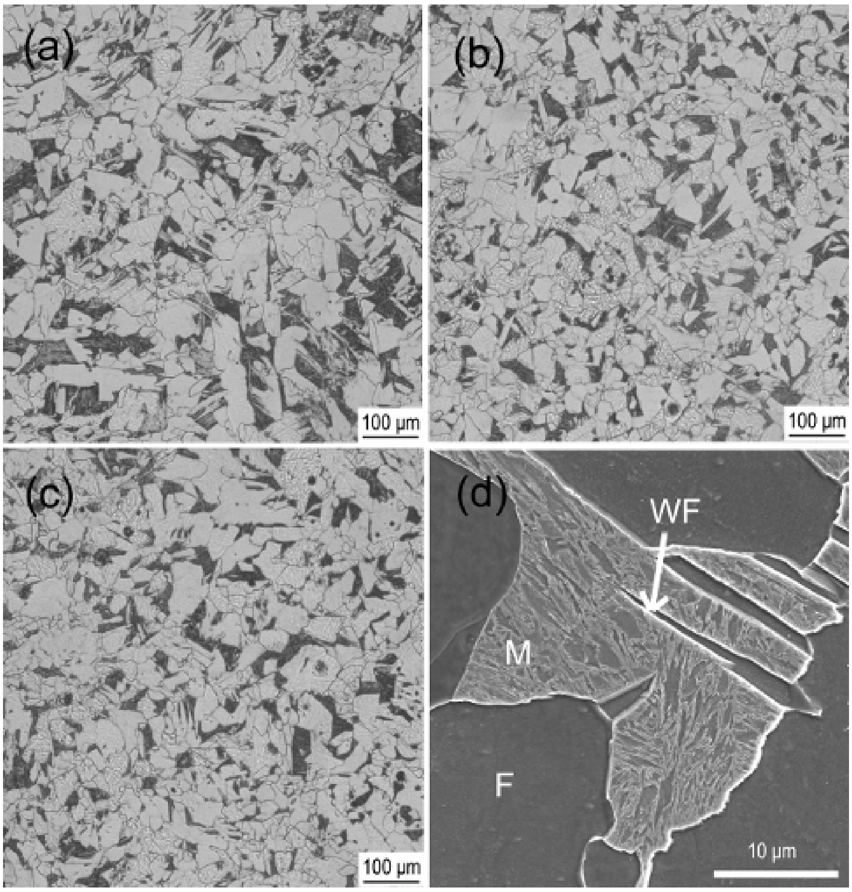

Figure 4. Microstructures and martensite distribution after holding at 650 °C for (a) 100 s and (c, d) 300 s, and holding at (b) 670 °C for 300s: *F* ferrite, *M* martensite, *WF* Widmanstätten ferrite.

With increasing volume fraction of ferrite, microstructures become more homogeneous. Some Widmanstätten ferrite was observed (Figures 4) probably because of large prior austenite grain size and rapid cooling after holding in the temperature region of austenite-to-ferrite transformation. Widmanstätten ferrite is harmful to mechanical properties, especially to toughness [11]. Although it can enhance the yield stress and tensile strength, it decreases ductility [12, 13]. Thus, Widmanstätten ferrite should be reduced or even avoided. With increasing holding time and ferrite formation temperature, the amount of Widmanstätten ferrite is expected to decrease.

4.2 Kinetics of austenite-to-ferrite transformation

Austenite-to-ferrite transformation kinetics is a critical factor affecting the final microstructures of DP steels. Therefore, it should be thoroughly understood. The ferrite fraction increasing with an increase in holding time can be described using Johnson-Mehl-Avrami (JMA) equation [14, 15]:

$$f(t)=f_e(1-\exp(-kt^n)),$$

where f_e is the equilibrium ferrite fraction at a certain holding temperature, k is the rate parameter related to the growth rate of a new phase and to the density of active nuclei, n is the Avrami exponent and t holding time.

The dilatometric data (such as the line in Figure 3) was used to fit the JMA equation. For this, the JMA equation was presented in the following form $Y=f(t)/f_e=(1-\exp(-kt^n))$, and then the curve $\ln(-\ln(1-Y))$ vs $\ln t$ was fitted against the experimental data as shown on Figure 5 (a, c). Parameter n

can be determined from the line slope, while ln*k* is the intercept of the line with Y axis. Parameter *n* was determined to be 0.89 and 1.07, while ln*k* was -3.35 and -4.07, at 650 and 670 °C respectively. It is a good agreement with other researches that Avrami exponent for ferrite formation is approximately 1, which means rapid ferrite transformation [16, 17]. Parameter n being in the range of $1 \leqq n \leqq 2$ means the ferrite formation obeys a linear growth behavior [18]. On the other hand, the Avrami exponent can be expressed as $n=a\times b+c$, where the parameter *a* represents growth dimension (*a*=1 is for linear, *a*=2 is plate-like, *a*=3 is polyhedral), the parameter *b* is determined by the mode of growth (interface-controlled or diffusion-controlled), and the parameter *c* is related to the type of nucleation [19]. In our material the parameter *a* equals to 1 because the ferrite growth obeys a linear type [20], while *b* equals to 0.5 because the ferrite growth is diffusion-controlled under the paraequilibrium condition [19]. The parameter *c* was deduced to be 0.394 and 0.567 at 650 and 670 °C respectively, which means the ferrite nucleation rate decreases, because the parameter *c* is between 0 and 1 [19]. In summary, the austenite-to-ferrite transformation in the studied DP steel produced by strip casting proceeds with a decreasing nucleation rate, by the linear type of growth and according to the diffusion-controlled mode.

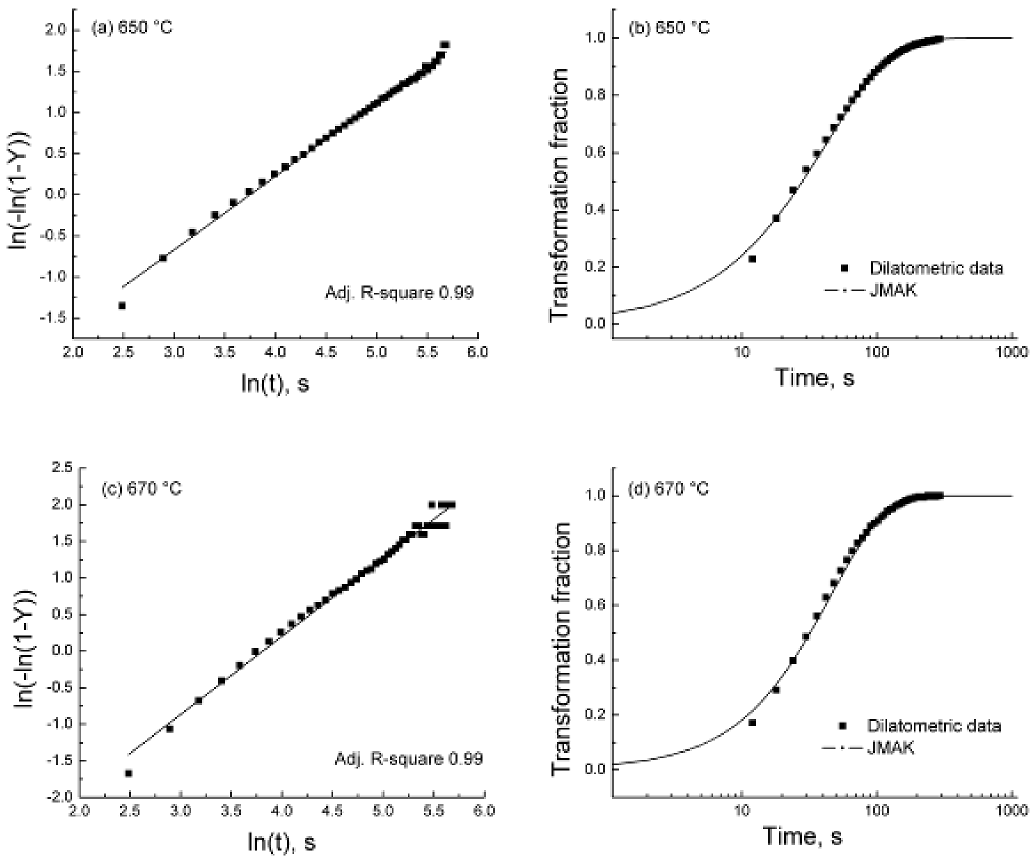

Figure 5. ln(-ln(1-Y)) as a function of holding time at (a) 650 °C and (c) 670 °C; the fittings of Avrami equation at (b) 650 °C and (d) 670 °C.

The experimental data are fitted well by JMA equation, but a little deviation still exists (Figure 5b, d). The JMA equation assumes homogeneity of the grain structure [14], under which condition the overall transformation is the fastest [20]. However, the prior austenite grain size in our steel varies, which leads to a variation in the ferrite nucleation rate. In the areas with larger austenite grains the nucleation rate is slower than predicted by the JMA equation due to a decreased area of grain boundaries; thus the ferrite transformation kinetics is slower in these areas than the predicted by

JMA equation. After all small austenite grains have transformed to ferrite, the grain size of remaining austenite is large but homogeneous; and these areas of larger grains control the ferrite transformation kinetics at the latter stage [15].

5. CONCLUSIONS

The microstructural investigation of a 0.08C-0.81Si-1.47Mn-0.03Al (wt.%) dual phase steel produced by the laboratory simulation of strip casting has shown the following:

1. The nose temperature of ferrite field of the transformation diagram was identified to be ~ 650 °C. The ferrite formation is fast within the first 100 s of holding at this temperature, and then formation of ferrite continues at a slower rate until it reaches the fraction corresponding to that defined by a lever rule.
2. Higher holding temperatures and longer holding times are beneficial to avoid Widmanstatten ferrite and also result in a homogeneous distribution of martensite.
3. Austenite-to-ferrite transformation kinetics was fitted well by the Johnson-Mehl-Avrami equation. Austenite-to-ferrite transformation takes place at a decreasing nucleation rate, via a linear type of growth by the diffusion-controlled mode. Large prior austenite grain size hinders the ferrite formation at an early stage.

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