Materials Science & Engineering A 581 (2013) 39–47

Contents lists available at SciVerse ScienceDirect

Materials Science & Engineering A

journal homepage: www.elsevier.com/locate/msea

Static recrystallization of strip cast alloys in the presence of complex nano-sulfide and nitride precipitates

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ARTICLE INFO

Article history:
Received 11 February 2013
Received in revised form
17 May 2013
Accepted 28 May 2013
Available online 5 June 2013

Keywords:
Strip casting
Rapid solidification
Steel
Recrystallization
Zener pinning

ABSTRACT

The static recrystallization of three strip cast stainless steels including one ferritic stainless steel, one austenitic stainless steel and a 201 stainless steel was investigated in the present work. The samples were obtained from a laboratory scale strip casting simulator and were subjected to cold rolling and annealing. It is shown that the strip cast samples develop nano-precipitates which in the case of austenitic and ferritic stainless steels can significantly hinder the recrystallization kinetics. Two different precipitate species were identified: sulfides and nitrides. The sulfides are formed in the as-cast structure and hinder recrystallization. These can be coarsened by heat treatment to make recrystallization more rapid. The nitrides, however, are in solution in the as-cast condition and only retard the recrystallization after a heat treatment has been used to cause their precipitation.

1. Introduction

Strip casting is a continuous casting process with the capability of producing near net shape products allowing cost, energy and environmentally efficient steel production. Direct strip casting solidifies steel directly into thin sheet of ~2 mm in thickness, and the elimination of intermediate hot rolling steps can reduce energy consumption by up to 90% [1]. Strip casting subjects the steel to uniquely high cooling rates, many hundreds of degrees per second [1,2]. Consequently, strip cast steels have very different microstructures compared to conventional sheets produced by thermo-mechanical processing. The rapid cooling experienced during strip casting can produce super saturated solid solutions, and has also been reported to form nano-precipitates and solute clusters [3–7]. In the former case, fine particles are known to have a significant impact on the recrystallization of alloys due to Zener pinning of moving grain boundaries [8–10], and this is the topic of the present work.

Of interest in the present paper is the static recrystallization behavior of strip cast steels after cold rolling. There have been some reports of retarded recrystallization kinetics in strip cast steels compared to conventionally processed materials [6,11,12]. Xu and Ferry [11] reported delayed recrystallization after strip casting in a low carbon steel, and Arribas et al. [12] reported that TiN particles developed during rapid solidification were effective in retarding the static and dynamic recrystallization of a low carbon steel. Frawley et al. [6] have also reported the inhibition of austenite recrystallization in low carbon steel as a result of fine Mn and Cu sulfide particles developing during thin slab casting. From this limited number of published papers, there seems to be compelling evidence that, firstly, fine particles can develop during rapid solidification of low carbon steels and, secondly, that these particles are able to retard recrystallization. Although this has been found to be the case for plain carbon steel grades, there is no information about how these particles may affect other steel grades. Consequently, we present here a dedicated study on the effect of strip casting on the recrystallization behavior of three different stainless steel alloys: one ferritic steel, one austenitic steel, and a 200 series alloy that is duplex in nature after strip casting. Since we now know that particles can have a major effect on recrystallization, a significant part of this research will be to identify the different particles that develop and determine how they behave during processing.

2. Experimental work

Three different alloys were used in this study with the chemical composition given in Table 1. The samples were obtained from a laboratory scale strip casting simulator known as a dip tester.

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http://dx.doi.org/10.1016/j.msea.2013.05.070

Table 1
Chemical composition (wt%) of alloys used in this study.

Alloy type	C	Mn	Cr	Ni	Al	Si	N	S	P	Fe
Fe–18Cr–5Ni–6Mn (AISI 201 series)	0.11	6.0	17.7	4.8	0.15	0.77	0.20	0.017	0.007	Bal
Fe–15Cr–4Al (Ferritic stainless steel)	0.04	0.2	15.3	0.3	3.74	0.43	0.14	0.009	0.010	Bal
Fe–35Ni (Austenitic stainless steel)	0.02	0.3	–	35.2	0.03	0.19	0.10	0.014	0.015	Bal

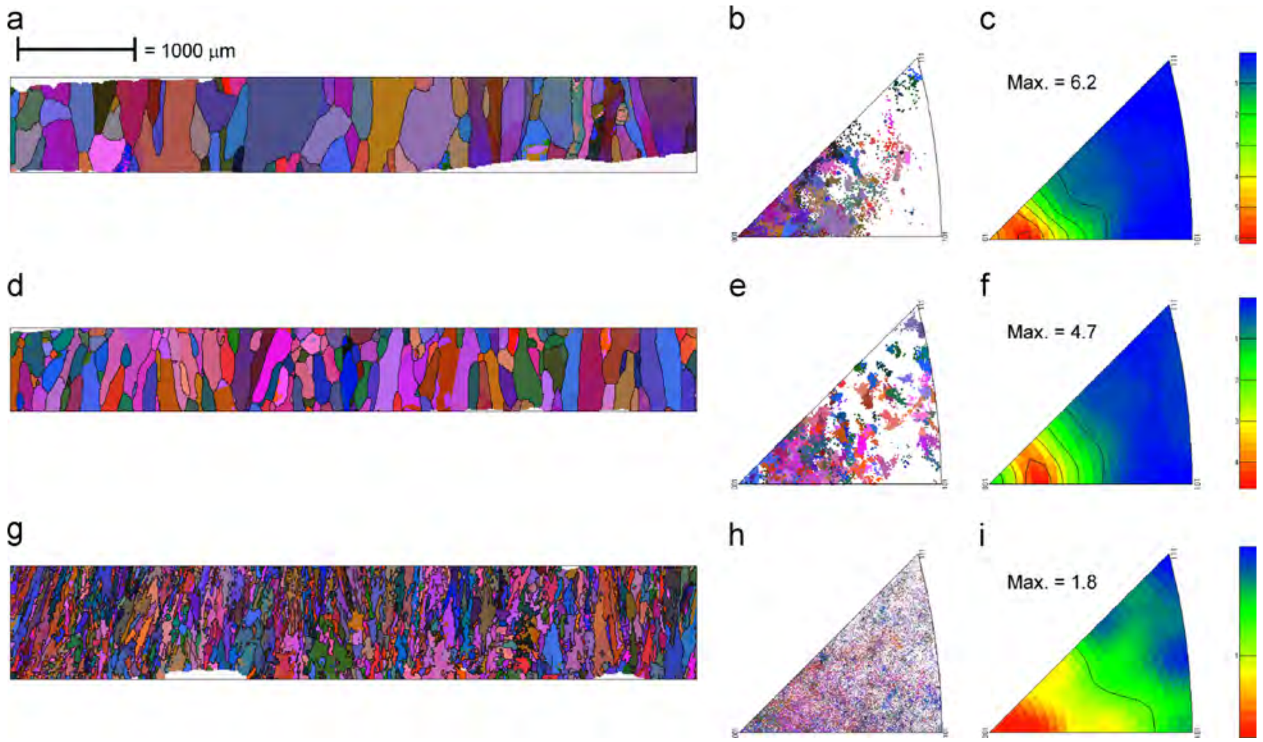

Fig. 1. Microstructural images and corresponding inverse pole figures of as cast. (a–c) Ferritic stainless steel, (d–f) Austenitic stainless steel, (g–i) 201 stainless steel. The black arrows show the solidification direction and the upper surface is the substrate surface.

This design has been described in detail previously [13] and will only briefly be described here. The dip tester is a rapid solidification simulator which is used to immerse a copper substrate into molten steel for a short and controlled period of time. The substrate is immediately retracted from the furnace and the sample removed from the substrate. The samples have dimensions of 35×35 mm^2, and a thickness that varies between 0.5 and 1 mm depending on the alloy, melt temperature and residence time of the substrate in the liquid steel. The specifics of the melt practice for each of the three materials tested here can be found in Refs. [14-16].

The cast samples were cut into strips approximately 10 mm wide, and then cold rolled to ~60% reduction in 5–8 passes. To study the recrystallization kinetics the cold rolled samples were subjected to annealing at 850 °C in a fluid bed furnace. The holding time varied between 5 s and 1800 s. For the 201 stainless steel samples, the recrystallization kinetics were also studied at 750 °C due to rapid recrystallization at 850 °C.

To effectively compare the recrystallization behavior of the strip cast samples to that which would be expected from a conventionally cast sample, a second set of samples were subject to simulated coiling. The purpose of this treatment was to simulate the temperatures and times that may be used during hot rolling and coiling of conventional product, processes which modify the carbides, sulfides and nitrides that may be present in the steel. The simulated coiling procedure was a 1 h hold at 1000 °C followed by slow cooling to 550 °C for an additional 3 h hold.

The microstructural investigations were performed using a LEO 1530, Supra 55 VP and Quanta FEG scanning electron microscopes (SEM). SEM was used to characterize the microstructure using angular selective back-scatter (AsB) imaging and electron backscatter diffraction (EBSD). Recrystallization fraction was calculated utilizing images obtained by AsB and point counting method. Transmission electron microscopy (TEM) was carried out with a 2001F field emission gun TEM equipped with a JEOL energy dispersive spectroscopy (EDS) system for compositional mapping.

3. Results

3.1. As cast microstructure

The microstructure of the as-cast samples are shown in Fig. 1. For the ferritic and austenitic steels, which do not undergo a solid state phase transformation during cooling, the as-cast structure is retained at room temperature. The grains nucleate on the copper substrate, and grow toward the melt during the immersion. The grains are in the range between 60–150 μm wide and 500–1000 μm long, and are typical for this kind of alloy [17]. The corresponding inverse pole figures are shown in Fig. 1b and c, and show a preference for 001 poles to be aligned in the solidification direction. This is consistent with this being the preferred growth direction of solid from liquid [18]. The austenitic stainless steel is also a composition that does not undergo a