Materials Letters 165 (2016) 5–8

Contents lists available at ScienceDirect

Materials Letters

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

Effect of cerium on the as-cast microstructure and tensile ductility of the twin-roll casting Fe–6.5 wt% Si alloy

Hao-Ze Li *, Hai-Tao Liu, Xiang-Long Wang, Guang-Ming Cao, Cheng-Gang Li, Zhen-Yu Liu *, Guo-Dong Wang

State Key Laboratory of Rolling and Automation, Northeastern University, Shenyang 110819, PR China

ARTICLE INFO

Article history:
Received 19 July 2015
Received in revised form
9 November 2015
Accepted 22 November 2015
Available online 23 November 2015

Keywords:
Twin-roll casting
Fe–6.5 wt% Si alloy
Microstructure
Cerium
Tensile ductility
Deformation and fracture

ABSTRACT

Fe–6.5 wt% Si alloy doped with cerium is fabricated by twin-roll casting. Ce_2O_2S precipitates in the melt and acts as the efficient nucleation agent, leading to a refined solidification microstructure. The tensile ductility of this as-cast strip significantly reaches up to 56.8% at 600 °C, which is superior to the 22.8% of the as-cast strip undoped with cerium. The much more uniform and finer solidification microstructure along with the strengthened grain boundary is inferred to result in the dramatic improvement in tensile ductility.

1. Introduction

Fe–6.5 wt% Si alloy which processes excellent magnetic properties [1,2] is suitable for manufacturing the iron core of the motors and generators operating at high frequencies. However, the intrinsically limited ductility and the obviously intercrystalline brittleness of the Fe–6.5 wt% Si alloy seriously impede its commercial application. The traditional rolling method is not qualified for the fabrication of the thin sheet of the Fe–6.5 wt% Si alloy due to the excessive rolling deformation. Alternatively, the twin-roll casting (TRC) technology which produces the as-cast strip directly from the melt with a thickness close to the final product seems to be potential.

The research on the TRC Fe–6.5 wt% Si alloy has been intensively concentrated on the optimizations of the microstructure, texture and magnetic properties [3–7]. Rare investigations are conducted to enhance the tensile ductility of the as-cast strip, even though cracks suddenly blow out once the rolling temperature droping down to the medium interval (500–600 °C) at the subsequent rolling stage. The limited formability of the as-cast strip results in the occurrence of the strip breakage and deteriorates the iron loss of the final product. The further development of the TRC Fe–6.5 wt% Si alloy is thus seriously impeded.

As is well known, rare earth elements (REMs) which act as the efficient deoxidizer and desulfurizer in the molten steel can enhance the hot ductilities of various steels [8–10]. Benefiting from the positive solidification microstructure refining, grain boundary strengthening and the inclusion modifying effects of the REMs, the hot ductilities of the Fe–36Ni alloy doped with Ti–Ce refiners [8], the 1Cr–0.5Mo low alloy steel and the 00Cr25Ni7Mo4N duplex stainless steel doped with cerium (Ce) [9,10] can be greatly improved. To some degree, the medium-temperature ductility of the TRC Fe–6.5 wt% Si alloy may be also significantly enhanced by the doping of Ce.

In this work, the as-cast strips of the Fe–6.5 wt% Si alloy doped and undoped with Ce are produced by TRC, respectively. The differences in the microstructure, medium-temperature ductility and fracture mode of the as-cast strip are compared to discover whether the doping of Ce can enhance the ductility of the TRC Fe–6.5 wt% Si alloy or not.

2. Experimental procedure

The as-cast strips of the Fe–6.44Si–0.0036N–0.005S and the Fe–6.48Si–0.023Ce–0.0048N–0.003S (wt%) alloys were fabricated by a vertical type twin-roll strip caster with internally water-cooled copper rolls, as reported in a previous literature [11], and then directly air cooled to the room temperature. The average rolling forces of the former (1#) and the latter (2#) as-cast strips

* Corresponding authors.
E-mail addresses: lhzqq83@163.com (H.-Z. Li), zyliu@mail.neu.edu.cn (Z.-Y. Liu).

http://dx.doi.org/10.1016/j.matlet.2015.11.100

were about 28 kN and 80 kN, respectively, while the corresponded casting speeds were about 0.6 m/s and 0.5 m/s, respectively. The thickness of the 1# and the 2# strip was 2.2 mm and 2.9 mm, respectively. Flat tensile specimens (25 mm in gauge length and 10 mm in width) were wire cut from both as-cast strips along the casting direction (CD). Tensile tests were performed on a screw-driven Suns machine equiped with a tube furnace. The tensile temperature and the initial strain rate was 600 °C and 0.02 s^{-1}, respectively. The tensile specimen was soaked at the target temperature for 1 h prior to each tensile test. Electron backscattered diffraction (EBSD) analyses were conducted on the longitudinal sections of the as-cast strips defined by CD and normal direction (ND) in a FEI Quanta 600 scanning electron microscope (SEM) equipped with a OIM 4000 EBSD system by operating at 30 kV. The EBSD samples were mechanically polished and then electro-polished in a solution of perchloric acid at 25 V for 30 s. The scanning steps for the 1# and 2# strips were 7 μm and 3 μm, respectively. Elements analysis of the inclusion in the 2# strip was conducted by electron probe micro-analysis (EPMA) in a JEOL JXA-8530F field emission electron probe. Fracture morphology was examined in the FEI Quanta 600 SEM.

3. Results and discussion

Both as-cast strips were fabricated at a relatively low melt super heat of about 30 °C so as to obtain a completely equiaxed structure (Fig. 1). The average grain size is about 258 μm and 127 μm, respectively. The grain size of the 1# strip is very non-uniform along ND (Fig. 1a), whereas that of the 2# strip is much more homogeneous (Fig. 1c). The heterogeneous distribution of the nucleation substrates in the melt pool is inferred to be responsible for the inhomogeneous solidification microstructure of the 1# strip (Fig. 1a). The rough surface of the casting rolls can provide sufficient nucleation substrates in the margin of the melt pool at the early stage of solidification. However, the interior of the melt pool, which is far from the rough surface of the casting rolls, is inevitably lack of sufficient nucleation substrates in the absence of the extrinsic nucleation agents. Hence, much finer equiaxed grains are formed near the surface of the 1# strip, whereas coarser grains appear in the strip interior (Fig. 1a).

Interestingly, the 2# strip demonstrates inclined dendrites with a tilt angle of about 40° towards CD in the outer layer of the strip (Fig. 1c). Similar phenomenon is common when the twin-roll casting is conducted at a high melt super heat [11]. In that case, the occurrence of the fluid flow during twin-roll casting, which is caused by the rotated casting rolls, makes the growing direction of the columnar grain deviating from the thermal gradient [11]. However, the formation of the tilted dendrites in the present work may be attributed to an alternative mechanism. The accompanied rolling deformation which occurs if the solidification end point is located above the roll nip point during twin-roll casting plays a critical role. As shown in Fig. 1d, large amounts of low angle grain boundaries, mainly in the form of sub-grain boundaries (red color), are found in the tilted dendrites of the 2# strip. Surprisingly, the length fraction of the sub-grain boundaries exceeds over 40%. The formation of the sub-grain boundaries mainly results from the accompanied rolling deformation and the subsequently static recovery of the dislocation structures at the air cooling stage. However, this accompanied rolling deformation is not capable of permeating the whole thickness in view of the absence of the sub-grain boundaries in the center layer of the 2# strip. By comparison, the length fraction of the low angle grain boundaries is much lower (~18%) in the 1# strip (Fig. 1b), indicating a smaller rolling deformation subjected by this strip. Hence, the solidification dendrites through the thickness of the 1# strip and at the center layer of the 2# strip, which undergo a much smaller rolling deformation, do not exhibit a tilting phenomenon. In summary, the 2# strip is inferred to possess a higher solidification end point with respect to the roll nip point and thus undergoes a larger rolling deformation during twin-roll casting, even though a similar melt super heat is adopted during the fabrications of the two strips.

Coarse and hexagonal precipitates with an average diameter of about 2μm could be detected in the grain interiors of the 2# strip (Fig. 2). The area fraction of the precipitates was quite low and was estimated to be around 0.03% based on multiple EPMA analyses on different sections of the 2# strip. Higher concentrations of Ce, oxygen (O), and sulfur (S) are detected in the precipitate (Fig. 2). According to the standard free energies of formation of the rare

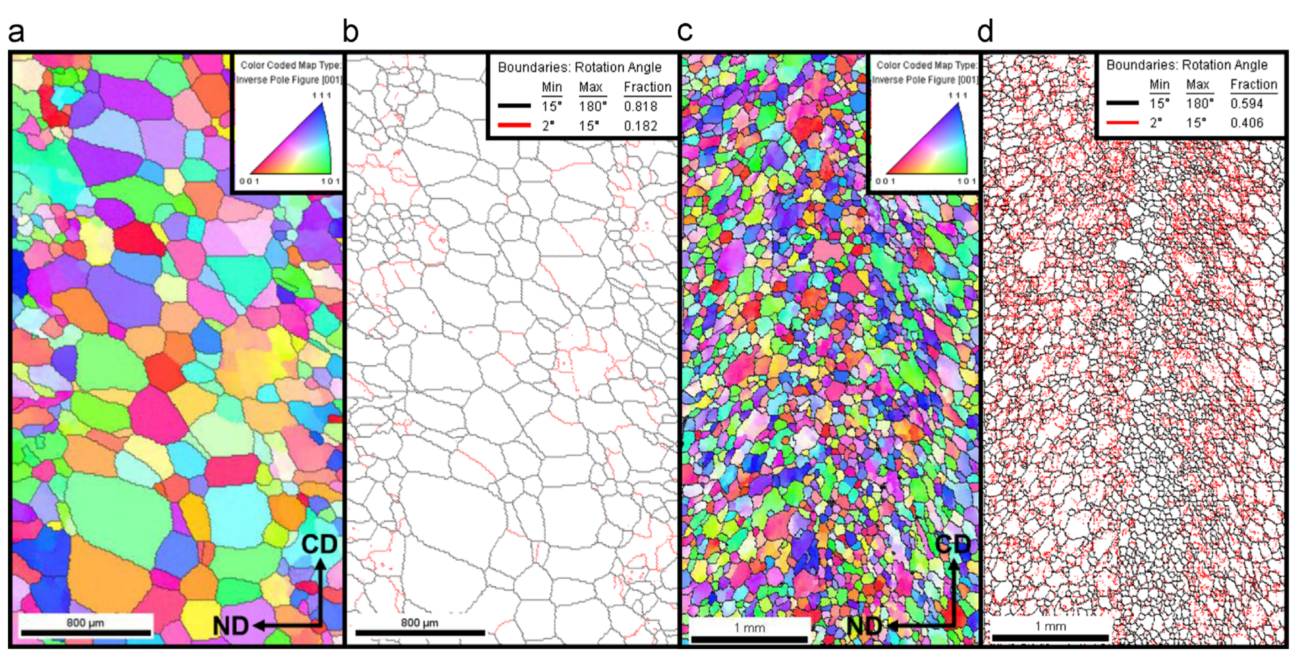

Fig. 1. Orientation image and the correspondingly grain-boundary maps of the 1# (a), (b) and 2# strips (c), (d). (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)