Materials Characterization 123 (2017) 178–188

Contents lists available at ScienceDirect

Materials Characterization

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

Evolution of grain boundary character distributions in alloy 825 tubes during high temperature annealing: Is grain boundary engineering achieved through recrystallization or grain growth?

Qin Bai [a,b], Qing Zhao [a,b], Shuang Xia [a,b,*], Baoshun Wang [c], Bangxin Zhou [a,b], Cheng Su [c]

[a] School of Materials Science and Engineering, Shanghai University, Shanghai 200072, China
[b] State Key Laboratory of Advanced Special Steel, Shanghai University, Shanghai 200072, China
[c] Technical Department, Jiuli Hi-Tech Metals Co., Ltd., Huzhou 313008, China

ARTICLE INFO

Article history:
Received 1 August 2016
Received in revised form 31 October 2016
Accepted 14 November 2016
Available online 16 November 2016

Keywords:
Grain boundary engineering
Electron backscatter diffraction
Grain boundary character distribution
Recrystallization
Grain growth
Nickel-based alloy 825

ABSTRACT

Grain boundary engineering (GBE) of nickel-based alloy 825 tubes was carried out with different cold drawing deformations by using a draw-bench on a factory production line and subsequent annealing at various temperatures. The microstructure evolution of alloy 825 during thermal-mechanical processing (TMP) was characterized by means of the electron backscatter diffraction (EBSD) technique to study the TMP effects on the grain boundary network and the evolution of grain boundary character distributions during high temperature annealing. The results showed that the proportion of $\sum 3^n$ coincidence site lattice (CSL) boundaries of alloy 825 tubes could be increased to >75% by the TMP of 5% cold drawing and subsequent annealing at 1050 °C for 10 min. The microstructures of the partially recrystallized samples and the fully recrystallized samples suggested that the proportion of low $\sum$CSL grain boundaries depended on the annealing time. The frequency of low $\sum$CSL grain boundaries increases rapidly with increasing annealing time associating with the formation of large-size highly-twinned grains-cluster microstructure during recrystallization. However, upon further increasing annealing time, the frequency of low $\sum$CSL grain boundaries decreased markedly during grain growth. So it is concluded that grain boundary engineering is achieved through recrystallization rather than grain growth.
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1. Introduction

Nickel-based alloy 825 is widely used for chemical and petrochemical industrial applications due to the combination of good mechanical properties and corrosion resistance. However, intergranular corrosion (IGC) is one of the serious problems for alloy 825 exposed to aggressive environments, which could result in unexpected failures and lead to huge losses. The grain boundary structure, which can partly be described by coincidence site lattice (CSL) model, can influence the grain boundary chemistry and the susceptibility to intergranular corrosion. The research field of 'grain boundary engineering' (GBE) [1–3] has been developed a lot over the last three decades since the concept of "Grain Boundary Design" [4] was proposed by Watanabe. The aim of GBE is to enhance the grain-boundary-related properties of materials by increasing the frequency of low $\sum$CSL grain boundaries ($\sum \leq 29$) and tailoring the grain boundary network. It was reported that in some face centered cubic materials with low stacking fault energy, such as Ni-based alloys [5–8], lead alloys [9,10], austenitic stainless steels [11–14] and copper alloys [15,16], the frequency of low $\sum$CSL grain boundaries can be greatly increased by using proper thermo-mechanical processing (TMP), and as a result the grain boundary related properties were greatly enhanced.

GBE is usually applied though thermo-mechanical processing which includes different combinations of strain and annealing. Many researchers have studied the effects of thermo-mechanical processing on the low $\sum$CSL grain boundary population and gain boundary network. The high proportion of $\sum 3$ boundaries and twin-related higher-order $\sum 3^n$ ($n = 2, 3\ldots$) boundaries are formed during GBE processing. Multiple twinning [17,18] is the basic process of $\sum 3^n$ boundaries formation. Regarding to the changes of grain boundary character distribution (GBCD) during GBE processing, different models were proposed to understand the grain boundary network evolution. Randle [19,20] proposed the "$\sum 3$ regeneration model". The two newly recrystallized grains with the same crystallographic texture and containing twins impinged to produce more mobile boundaries. These boundaries migrate to interact with the pre-existing grain boundaries. A large number of $\sum 3^n$ boundaries were formed. Kumar et al. [21] proposed the "boundary decomposition mechanism". They thought that a small deformation during GBE processing was not sufficient to create the general conditions for conventional nucleation of recrystallization. They

* Corresponding author at: P.O. Box 269, 149 Yanchang Road, Shanghai, zip code 200072, China.
E-mail addresses: xs@shu.edu.cn, xiashuang14@sohu.com (S. Xia).

http://dx.doi.org/10.1016/j.matchar.2016.11.016
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Table 1
Thermomechanical treatments of the alloy 825 tube specimens.

GBE				Partially recrystallized processing		
The initial state	Cold-drawing/%	Annealing	Sample ID	Cold-drawing/%	Annealing	Sample ID
Solution annealed	3	1050 °C × 10 min	A1	5	1050 °C × 60 s	A6p
		1075 °C × 10 min	A2		1050 °C × 90 s	A9p
		1100 °C × 10 min	A3		1050 °C × 120 s	A12p
		1125 °C × 10 min	A4		1050 °C × 150 s	A15p
	5	1050 °C × 10 min	B1		1050 °C × 180 s	A18p
		1075 °C × 10 min	B2		1050 °C × 210 s	A21p
		1100 °C × 10 min	B3		1050 °C × 240 s	A24p
		1125 °C × 10 min	B4		1050 °C × 420 s	A42p
	7	1050 °C × 10 min	C1		1100 °C × 60 s	B6p
		1075 °C × 10 min	C2		1100 °C × 90 s	B9p
		1100 °C × 10 min	C3		1100 °C × 120 s	B12p
		1125 °C × 10 min	C4		1100 °C × 150 s	B15p
	10	1050 °C × 10 min	D1		1100 °C × 180 s	B18p
		1075 °C × 10 min	D2		1100 °C × 210 s	B21p
		1100 °C × 10 min	D3		1100 °C × 240 s	B24p
		1125 °C × 10 min	D4		1100 °C × 420 s	B42p

attributed the enhancement of the $\sum 3^n$ boundaries to the decomposition of high energy boundary during strain-induced boundary migration. Wang [22] proposed that the nuclei of recrystallized grains had incoherent $\sum 3^n$ boundaries with the deformed microstructure. The migration and interactions of these grain boundaries played a significant role on the evolution of the grain boundary network. Our previous work [23,24] showed that the GBE was a recrystallization process which was featured by the formation of large grain-clusters with a large number of inner-connected $\sum 3^n$ type triple junctions. The grain-cluster was formed by multiple twinning starting from a single nucleus during the recrystallization process.

The development of multiple twinning can affect the microstructural evolution that results in different proportions of $\sum 3^n$ boundaries. However, it is not clear that the phenomenon of multiple twinning is occurred more dominantly during the process of recrystallization or grain growth. Chen et al. [25] have reported an investigation on the evolution of annealing twins in a cold rolled high-purity nickel as a function of annealing temperature. It is revealed that the fraction of $\sum 3$ boundaries increases rapidly with increasing annealing temperatures during recrystallization process; while during grain growth after full recrystallization, the fraction of $\sum 3$ decrease significantly with further increasing temperature. Jin's research work [26] on 304L austenitic stainless steel has also shown that the annealing twins are generated mostly during the recrystallization regime and determined by the interaction, the propagation or the disappearance of the existing twins in the grain growth regime. However, Horton et al. [27] have proposed that the percentage of twins increase in impure nickel during grain growth. The study of Gindraux et al. [28] on copper has revealed that twins are progressively annihilated during grain growth. Moreover the investigation of Randle et al. [29] on nickel has presented that if a certain value of $\sum 3$

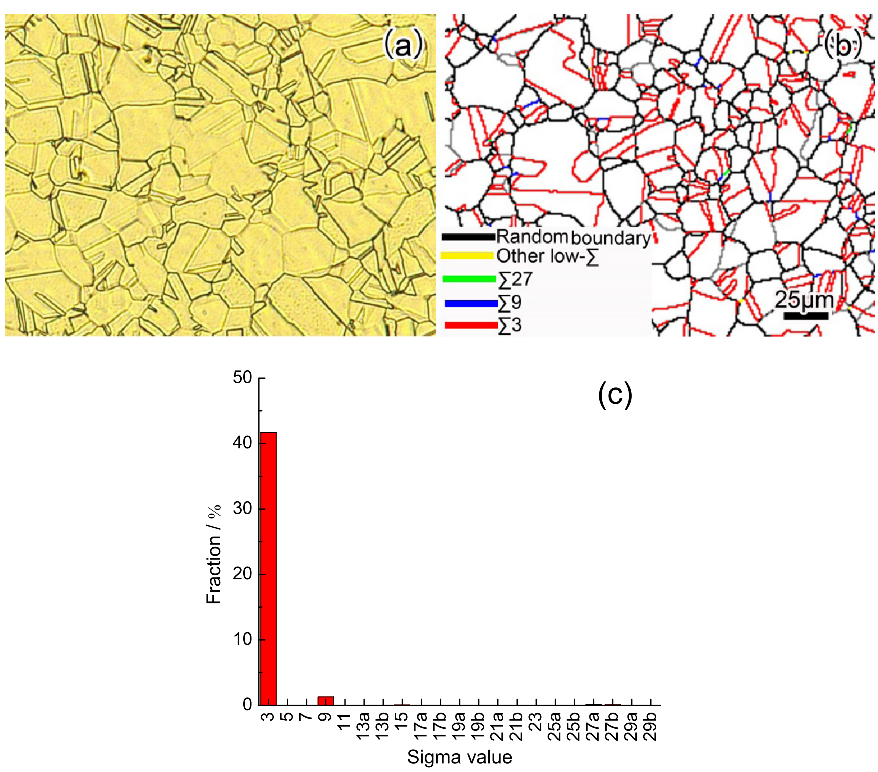

Fig. 1. OM map (a), distributions of the types of grain boundaries (b) and histogram of grain boundary character distribution (c) of the solution annealed starting material.

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