The effect of heat treatment on the microstructure of ECAP processed 316L stainless steel

S. H. Kang [a], H. Jin[a], J. Jang[a*], D. H. Kim[b], K. H. Oh[b], D. Foley [c], X. Zhang [c]
[a]*Nuclear Materials Research Division, Korea Atomic Energy Research Institute, Daejeon 305-353, Korea*
[b]*Department of Materials Science and Engineering, Seoul National University, Seoul 151-744, Korea*
[c]*Department of Mechanical Engineering, Texas A&M University, College Station, TX 77843*
[*]*Corresponding author: jjang@kaeri.re.kr*

1. Introduction

316L stainless steel (SS 316L) is a widely used structural material in various fields such as the nuclear power plants, petrochemical and fertilizer industries. SS 316L is different from other stainless steel grades due to the reduction of C (0.02 wt.%) and the addition of Mo (2.5 wt.%). The addition of Mo is known to improve both corrosion resistance and hot deformation (creep) behavior. Moreover, Mo in solid solution acts as a favorable element in reducing dislocation mobility [1,2]. It is related to the stacking fault energy (SFE) of the material and the magnitude of SFE controls the ease of cross-slip. Deformation twins are expected to form easily in SS 316L with low SFE, and play an important role instead of cross-slip in determining the subsequent microstructure during deformation process [3,4]. Coincidence site lattice (CSL) boundaries, especially twin boundaries have low grain boundary energy compared to random boundaries. It is generally accepted that low energy grain boundaries, as contrasted with high energy boundaries, are highly resistant to grain boundary deterioration [5,6]. A report suggested that the microstructure of SS 316L was stable in spite of the prolonged annealing at 700°C; the grain size and the fractions of the twin boundaries were similar for all annealing conditions [7]. From above investigations, it is deduced that once the microstructure is controlled to form high density of twin boundaries, the chemical, mechanical properties of material could be more enhanced than the material with random boundaries. Therefore, the way to generate high density of twin boundaries, their stability and effects on mechanical properties becomes great concern.

2. Experimental

Equal channel angular pressing (ECAP) is a well-known mechanical process which can develop fine grained microstructure of material by shear deformation. Previously, the method was only applied to relatively easy deformable metals, such as aluminum and copper. However, new applications are made for high strength materials, such as stainless steels or titanium alloys because of the increasing demand for advanced ultra fine sized grains. In this study, a 2.54 X 2.54 X 15.24cm sized SS 316L square bar was processed by ECAP to develop nano-sized microstructure and higher fraction of deformation twins. After the ECAP process, heat treatments at different temperatures have been conducted. Corresponding microstructure evolutions were studied by using electron backscattered diffraction (EBSD). EBSD band contrast has been identified as a possible indicator to provide characteristic information on plastic deformation. Local defects can distort crystal lattices, and deteriorate the uniformity of the EBSD patterns [8]. Thus, band contrast reflects the perfection of the lattice or degree of plastic deformation. band contrast is dependent upon many factors including the material itself (grain orientation and lattice strain), sample preparation (polishing and etching) and measuring system (SEM/EBSD working condition, such as beam conditions, geometrical set-up, material phases, video processing parameters used for the Hough transform [8]). Assuming the parameters are carefully fixed for the each measurement, however, the effect of measuring factors associated with microscope and EBSD system can be ignored. In order to ensure that all of the specimens had the same surface condition, specimens were finished by electrolytic polishing under the same conditions.

3. Results and Discussion

The microstructure variation of SS 316L during ECAP process is shown in Fig. 1. The grains with clear annealing twin boundaries are shown in Fig. 1(a), and the ECAP processed grains which is seen to be elongated along the shear band direction are in Fig 1(b). A high-density of deformation twins was observed in all grains. Extensively intersected twin boundaries constructed a network pattern in the heavily deformed grains.

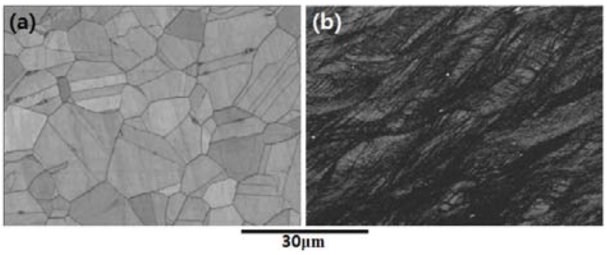

Fig. 1 Grain maps for (a) before and (b) after ECAP process. The band contrast variations of SS 316L microstructure are displayed.

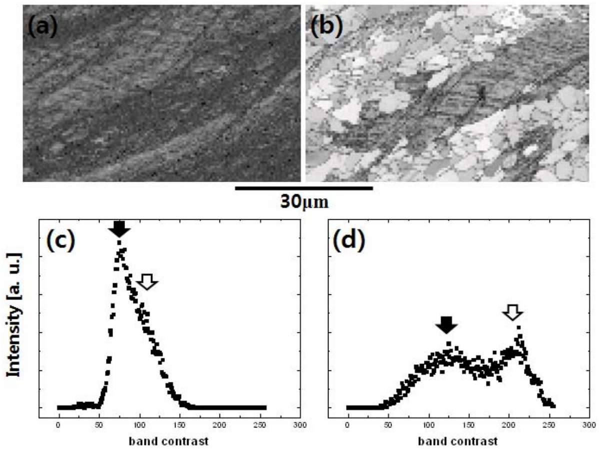

Fig. 2 Grain map for (a) ECAP processed, (b) recrystallized at 800˚C and corresponding band contrast histogram (c) ECAP processed, (d) recrystallized at 800˚C.

It is assumed that those network patterns of twin boundaries are thermo-mechanically stable because they have low energies than conventional random boundaries. In Fig. 2, microstructure variations during heat treatment at 800˚C are shown. The same area in the sample is observed before (Fig. 2(a)) and after (Fig. 2(b)) heat treatment. The results show that the region of high boundary density is relatively stable during recrystallization procedure. Excluding dark area (high density) in Fig. 2(a), grains are recrystallized, and changed to equiaxed grains (Fig. 2(b)). The histograms of band contrast in Fig 2(c) and 2(d) also suggest that the intensity count of low density region is lowered and the position of the peak moved to the higher band contrast value. Since '1' represent black and '256' represent white, the variation of brightness could be a ruler for measuring defect density, especially for boundary density in this study. In Fig. 2(c), two peaks are closely positioned, one is pointed by a black arrow, and the other one by a white arrow. They indicate high density and low density area, respectively. After recrystallization in Fig. 2(d), the peaks are separated into two distant profiles. The remained high density region is pointed by a black arrow and recrystallized regions by a white arrow.

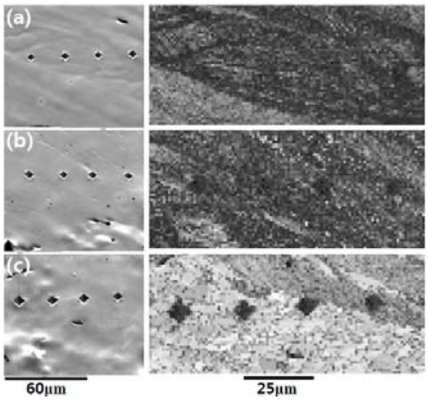

Fig. 3 Hardness measurement along the high and low boundary density region, (a) no heat treatment, (b) 700˚C, (c) 800˚C heat treated SS 316L

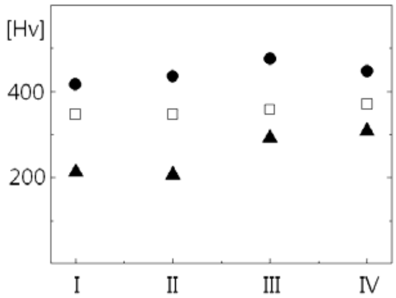

Fig. 4 Hardness values for each points in Fig. 3
● : no treat, □: 700˚C, ▲ : 800˚C

In Fig. 3, hardness profiles are measured for investigating mechanical properties of high and low boundary density region. The result describes that the region of high boundary density is harder than the rest regions. Same phenomenons have been observed at the samples of different temperature, while the hardness shows a decreasing tendency as the temperature increases. The measured hardness values are summarized in Fig. 4. The Hv value of recrystallized region is about half of the no-treated region. However, the remained high boundary density region is about 1.5 times harder than recrystallied region. This appears to be attributed to the stability of high boundary density region, especially, low energy of twin boundaries.

Acknowledgement

This research was supported by Nuclear R&D program through the National Research Foundation of Korea(NRF) funded by the Ministry of Education, Science and Technology (2009-0094107)

REFERENCES

[1] S. G. Chowdhury, S. Das, P. K. De, Cold rolling behaviour and textural evolution in AISI 316L, Acta Materialia, 53, pp. 3951–3959, 2005.

[2] J. W. Christian, S. Mahajan, Deformation twinning, Prog. Mater. Sci., 39, pp. 1–157, 1995.

[3] M. Michiuchi, H. Kokawa, Z. J. Wang, Y. S. Sato, K. Sakai, Twin-induced grain boundary engineering for 316 austenitic stainless steel, Acta Materialia 54, pp. 5179–5184, 2006.

[4] X. Fang, K. Zhang, H. Guo, W. Wang, B. Zhou, Twin-induced grain boundary engineering in 304 stainless steel, Materials Science and Engineering A, 487, pp. 7–13, 2008.

[5] V. Randle, Twinning-related grain boundary engineering, Acta Materialia, 52, pp. 4067–4081, 2004.

[6] H. Kokawa, Weld decay-resistant austenitic stainless steel by grain boundary engineering, Journal of Materials Science, Volume 40, Number 4, pp. 927-932, 2005.

[7] S. Downey II, P. N. Kalu, K. Han, The effect of heat treatment on the microstructure stability of modified 316LN stainless steel, Materials Science and Engineering A, 480, pp. 96–100, 2008.

[8] A. J. Wilkinson, G. Meaden, and D. J. Dingley, High-resolution elastic strain measurement from electron backscatter diffraction patterns: New levels of sensitivity, Ultramicroscopy, Volume 106, Issues 4-5, pp. 307-313, 2006.