Internal stresses in a 15%Cr ferritic stainless steel after large strain unidirectional processing

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Abstract. An interstitial free ferritic stainless steel was cold worked to a total strain of 4.6. The largely strained steel is characterized by a submicrocrystalline structure consisting of elongated grains/subgrains with the transverse size of about 210 nm; and the fraction of high-angle grain boundaries is about 0.6. Following a rapid rise at an early processing stage, the dislocation density in (sub)grain interiors unusually decreased after total strains of above 2. Nevertheless, the samples are characterized by high residual stresses that result in complex elastic distortions of the crystal lattice within the elongated crystallites. Such internal stresses are shown to be originated from deformation grain boundaries including low-angle subboundaries.

1. Introduction

An interest in nano- and submicrocrystalline structural materials is motivated by a beneficial combination of their mechanical properties. Metallic materials with grain size of tens to hundreds microns were shown offering a lot of superior properties like a high strength with sufficient ductility, enhanced impact toughness, superplasticity at relatively low temperatures and high strain rates, etc. [1-3]. One of the most promising methods for production of submicrocrystalline metals and alloys is based on large strain deformation [4, 5]. Commonly, largely deformed materials are characterized by high residual stresses that affect deformation behavior and mechanical properties. The development of high internal stresses was discussed as a result of non-equilibrium grain boundaries in largely strained materials [5, 6]. However, the sources of high internal stresses in submicrocrystalline metals and alloys have not been studied in sufficient detail. The effect of crystallographic parameters of grain boundaries on the values of internal stresses and their relaxation is still unclear. The aim of the present work is to clarify the origin of high residual stresses and their relationship with dislocation densities and strain-induced grain/subgrain boundaries in a submicrocrystalline ferritic stainless steel processed by large strain plastic working.

2. Experimental

A ferritic stainless steel (Fe – 0.003C – 0.01Mn – 0.001P – 0.001S – 15.0Cr – 0.003N, all in weight%) was used as the starting material. The steel was homogenized and hot forged at 1200°C followed by a hot rolling at 700°C. The large strain deformation was carried out at an ambient temperature by calibre rolling/swaging to a total strain of 4.6. Structural investigations were carried out on longitudinal and transverse sections using a JEM-2100 transmission electron microscope (TEM). Grain/subgrain sizes were measured on the TEM micrographs by the linear-intercept method, counting the all clear defined (sub)boundaries. The dislocation densities were evaluated by counting the individual dislocations in grain/subgrain interiors. Misorientations across deformation (sub)boundaries and local curvatures within the submicrocrystallites were analyzed by the converged beam Kikuchi diffraction technique. The strain hardening was studied by Vickers hardness tests with a load of 3 N.

3. Results and discussion

Typical cold worked microstructures are shown in figure 1. Unidirectional cold working results in the development of elongated grains/subgrains that aligned along the deformation axis. The deformation (sub)boundaries that arranged parallel to the rolling direction in the sample strained to 2.0 can be considered as dense dislocation walls [7], which separate the cell blocks with high density of interior dislocations. The spacing between the longitudinal (sub)boundaries decreases with increasing the total strain, leading to the formation of lamellar microstructure after a large strain of 4.6.

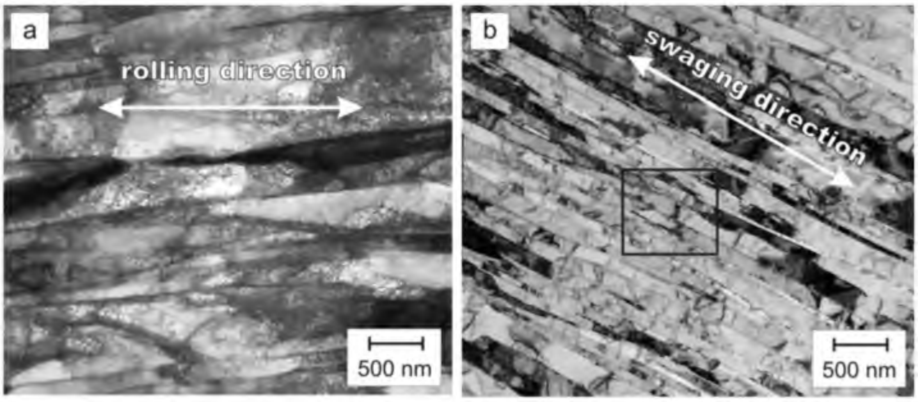

Figure 1. Deformation microstructures in Fe-15%Cr steel after cold working to a total strain of 1.0 (a) and 4.6 (b).

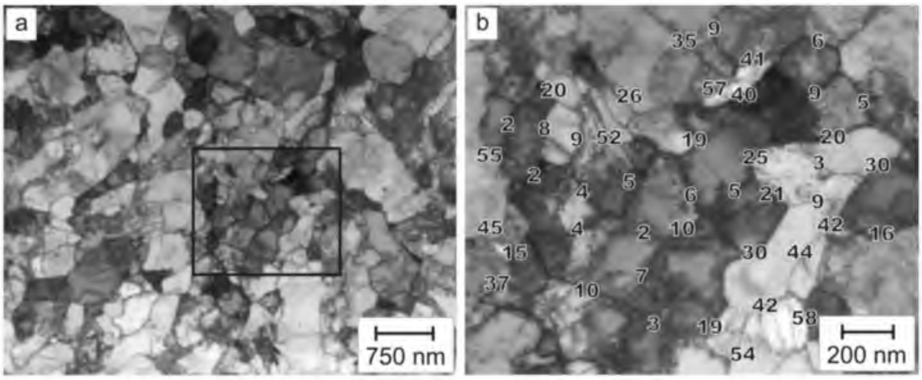

Figure 2. Deformation microstructure in Fe-15%Cr steel after cold working to a total strain of 4.6. Numbers in (b) indicate the (sub)boundary misorientations in degrees.

The decrease in the transverse size of structural elements is accompanied with increase in the (sub)boundary misorientations. Figure 2 presents the cross section microstructure that evolved in the sample processed to a strain of 4.6. The cross section of highly elongated grains/subgrains looks like almost equiaxed microstructure composed of irregular network of (sub)boundaries with different misorientations. The fraction of high-angle grain boundaries comprises about 0.6. Therefore, the deformation microstructure in largely strained sample consists of rod-shaped grains/subgrains separated by various boundary types, i.e. from low-angle dislocation subboundaries to conventional high-angle grain boundaries.

The transverse grain/subgrain size rapidly reduces to about 250 nm in early straining to about 1.0 followed by gradual decrease to 210 nm during further deformation to a strain of 4.6 (figure 3). Correspondingly, the hardness quickly increases at relatively small strains, then, the hardening rate decreases and results in a gradual hardening with increasing the total strain. The structural refinement and the strain hardening at strains of $\varepsilon < 2$ are accompanied with an increase in the dislocation density within grain/subgrain interiors. However, the further straining leads to unusual decrease of the interior dislocation density down to the level comparable to initial state (figure 3).

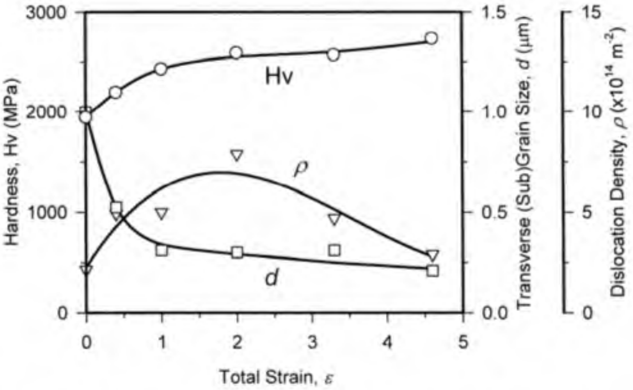

Figure 3. Effect of strain on the hardness, the transverse (sub)grain size and the interior dislocation density.

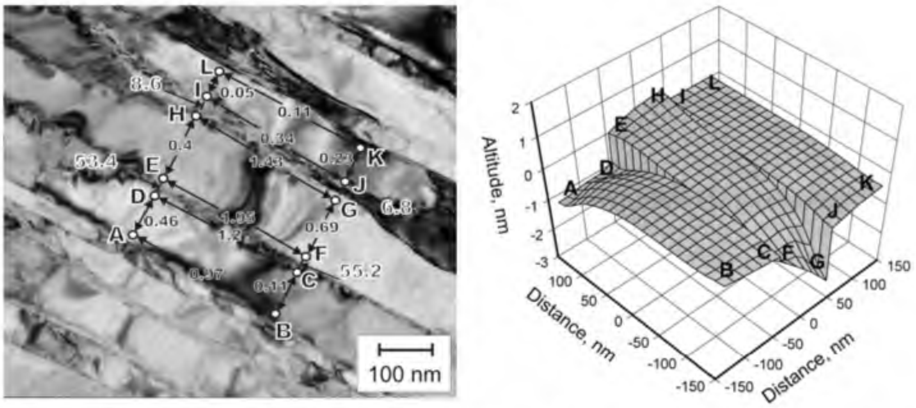

Figure 4. Enlarged portion of fine structure in figure 1b. Numbers indicate the local disorientations in degrees between the pointed micro-regions.

In spite of apparently low density of interior dislocations after large strains, the deformed sample is characterized by high residual stresses. The precise evaluation of local crystallographic orientations revealed large elastic distortions of the fine grains/subgrains. The lattice curvatures attain about 2 over a distance of 300 nm within the (sub)grains, which are free of any interior dislocations (figure 4). The lattice curvatures between the analyzed points are represented more clearly by the bent surfaces in figure 4. The relative altitudes of the surfaces were plotted as deviations of the central electron spots in Kikuchi maps from those of the grain centers, the relative altitudes of which were taken as zero. It is clearly seen that the large elastic distortions are maintained by both the high-angle grain boundaries (misorientation of about 55° between C and F) and low-angle subboundaries (misorientation of about 7° between G and J). This suggests that low-angle subboundaries in largely strained materials serve as effective barriers for dislocation motion, playing a similar role in strengthening as conventional grain boundaries.

The strengthening caused by dislocation substructures should follow a power law function of subgrain size with the exponent of -1.0, while the exponent of -0.5 is attributed to the grain size strengthening mechanism [8, 9]. Figure 5 illustrates the strain hardening as a function of transverse (sub)grain size in various cold rolled/swaged stainless steels. The Hv_0 of 1800 MPa was taken for Fe-18%Cr-7%Ni and Fe-22%Cr-3%Ni [6] and that of 1200 MPa for fully annealed Fe-15%Cr [10]. The size exponent of -0.5 is obtained for all the worked steels. Therefore, the strengthening of largely strained steels obeys the Hall-Petch-type relationship, irrespective of rather large fraction of low-angle subboundaries in strain-induced submicrocrystalline structures.

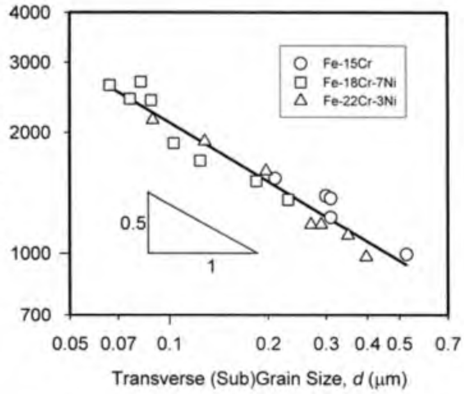

Figure 5. Relationship between the transverse (sub)grain size and the hardening (ΔHv) for bar rolled/swaged steels.

4. Summary

An Fe-15%Cr stainless steel subjected to large strain cold working by bar rolling/swaging is characterized by high residual stresses resulting in complex elastic distortions of strain-induced submicrocrystallites. The internal stresses are maintained by the submicriocrystalline boundaries including low-angle deformation subboundaries. The strain hardening during cold working follows the Hall-Petch-type relationship in spite of wide distribution of grain/subgrain boundary misorientations.

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References

[1] Wang Y, Chen M, Zhou F and Ma E 2002 *Nature* **419** 912
[2] Musin F, Kaibyshev R, Motohashi Y and Itoh G 2004 *Scripta Mater.* **50** 511
[3] Kimura Y, Inoue T and Tsuzaki K 2008 *Science* **320** 1057
[4] Humphreys F J, Prangnell P B, Bowen R J, Gholinia A and Harris C 1999 *Phil. Trans. R. Soc. Lond.* **357** 1663
[5] Valiev R Z, Islamgaliev R K and Alexandrov I V 2000 *Prog. Mater. Sci.* **45** 103
[6] Belyakov A, Kimura Y, Adachi Y and Tsuzaki K 2004 *Mater. Trans.* **45** 2812
[7] Bay B, Hansen N, Hughes D A and Kuhlmann-Wilsdorf D 1992 *Acta Metall. Mater.* **40** 205
[8] Young C M and Sherby O D 1973 *J. Iron Steel Inst.* **211** 640
[9] Kimura Y, Hidaka H and Takaki S 1999 *Mater. Trans JIM* **40** 1149
[10] Belyakov A, Tsuzaki K, Kimura Y and Mishima Y 2007 *J. Mater. Res.* **22** 3042