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Application of equal channel angular extrusion on strengthening of ferritic stainless steel

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SUS430 ferritic stainless steel was subjected to equal channel angular extrusion (ECAE) at room temperature to a total strain of 2.3. It was shown that the sample processed by ECAE showed higher room temperature strength than the as-quenched sample. This is probably due to the heavily worked structure. On the other hand, annealing at 673 K and 773 K increased both strength and elongation of the ECAE processed sample. It is likely that higher strength is attributed to both the worked structure and fine substructures. It is also likely that higher elongation is attributed to the fine substractures. It is concluded that a combination of ECAE with annealing is available for improving the room temperature tensile properties of SUS430. © *2001 Kluwer Academic Publishers*

1. Introduction

Equal channel angular extrusion (ECAE) is a technique that provides the repetitive deformation and allows to high intensity of deformation. With this procedure, a sample is pressed through a channel that has an equal cross section but bent at an angle of Φ [1, 2]. Shear strain is introduced when a sample passes through the bending point of the channel. Repetitive processing is feasible because the cross-sectional dimension of a sample has no change during processing. To date, many reports have described that ECAE is available for the fabrication of fine-grained materials [3–11]. On the other hand, an ECAE processed sample can achieve high intensity of deformation through repetitive deformation. According to the equation given by Segal [2], a strain of about 1 is introduced in each pass through die if the angle Φ is 90 deg.

It is well known that high tensile strength can be achieved in metallic materials through work hardening [12]. It is also known that metallic materials with fine grain size show high strength [13, 14]. Hence, it is expected that ECAE is available for strengthening method in metallic materials. In the present paper, we will report the mechanical properties of the SUS430 ferritic stainless steel processed by ECAE. SUS430 has a bcc single-phase structure and shows no phase transformation, so that transformation strengthening cannot be applied. Hence, a heavy cold work such as ECAE may be effective for strengthening of SUS430 ferritic stainless steel. Annealing was conducted for the ECAE processed sample to vary its microstructure. Then, the effect of annealing on the strength of the ECAE processed sample was also investigated.

2. Experimental procedure

A commercial SUS430 stainless steel was used as the sample. The chemical composition of SUS430 is shown in Table I. The sample was solution treated at 1573 K for 10.8 ks and quenched into iced water. ECAE was carried out at room temperature and numbers of passes was 2. According to the equation given by Segal [2], total strain intensity for the sample was 2.3. The sample was rotated 180° about the extrusion axis after each pass because the microstructure strongly depends on the shear direction [2, 15, 16]. Some of the ECAE processed samples were annealed at 673 K or 773 K for 3.6 ks after ECAE. Annealed samples were quenched into iced water.

Microstructures were examined by both optical microscopy and transmission electron microscopy (TEM). The acceleration voltage of TEM is 200 kV (JEOL 200CX). Mechanical properties of the samples were examined by tensile test at room temperature, with an initial strain rate of 2×10^{-3} s^{-1}.

3. Result and discussion

3.1. Initial microstructure

Optical micrograph of he as-quenched SUS430 is shown in Fig. 1a. It is apparent from the micrograph that microstructure consists coarse equiaxed grains, whose

TABLE I Chemical composition of the sample (mass %)

	Cr	Ni	Si	Mn	Mo	C	N	O
SUS430	15.7	0.22	0.24	0.46	0.086	0.038	0.022	0.008

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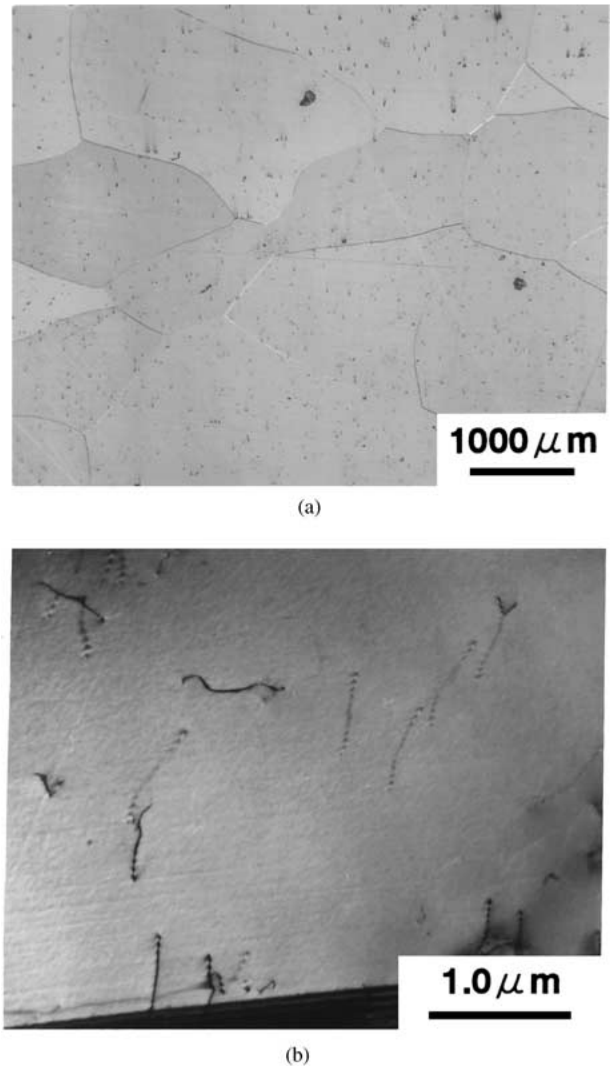


Figure 1 Microstructure of the as-quenched SUS430. (a) An optical micrograph and (b) a transmission electron micrograph.

size is about 2000 μm. TEM observation shows that dislocation density is very low in the as-quenched sample as shown in Fig. 1b.

3.2. Mechanical properties

The nominal stress strain curves at room temperature of the ECAE processed sample is shown in Fig. 2. For comparison, the curve of the as-quenched sample is also shown in this figure. The sample processed by ECAE shows higher strength than as-quenched sample. This result shows that ECAE is available for strengthening SUS430 ferritic stainless steel.

The nominal stress strain curves of the ECAE processed samples followed by annealing at 673 K and 773 K are shown in Fig. 3. It is of interest that the annealed samples show both higher strength and higher elongation than the non-annealing (only ECAE processed) sample. In addition, both strength and elongation of the ECAE processed sample annealed at 773 K are higher than those of the sample annealed at 673 K. Table II summarizes the results of the tensile tests for the ECAE processed samples. By annealing at 773 K, the strength of the ECAE processed sample reached 783 MPa and the elongation is 43%. That is, the room temperature tensile properties of the ECAE processed sample are improved by annealing.

TABLE II Summary of tensile tests

	U.T.S. (MPa)	Elongation (%)
Before ECAE	547	59
ECAE 2	627	30
ECAE 2 followed by annealing at 673 K for 3.6 ks.	717	38
ECAE 2 followed by annealing at 773 K for 3.6 ks.	783	43

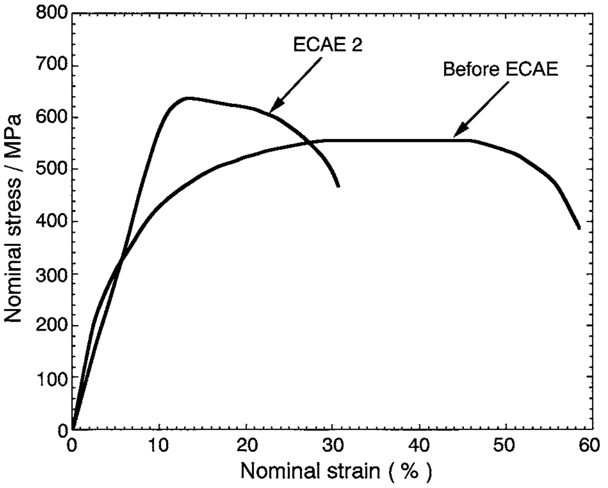


Figure 2 Nominal stress strain curves of the ECAE processed SUS430 and the as-quenched one. Number of ECAE passes is 2.

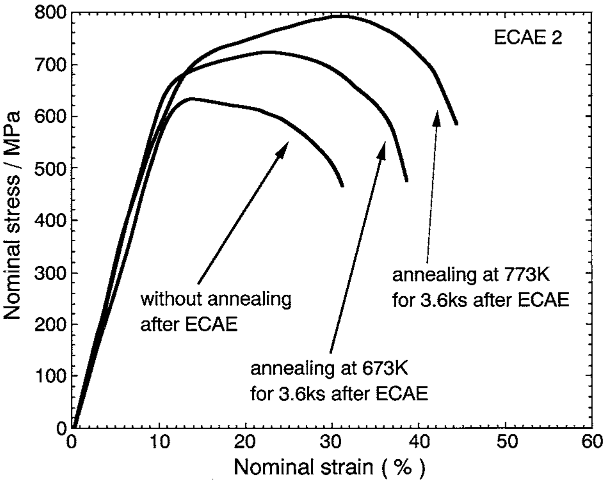


Figure 3 Nominal stress strain curves of the ECAE processed SUS430 followed by annealing. Annealing temperatures are 673 K and 773 K. In each annealing temperature, annealing time is 3.6 ks.

3.3. Microstructure after processing

The microstructure of the ECAE processed sample is shown in Fig. 4. Many dislocations are introduced into the sample during the processing. In addition, dislocations form tangles and dense dislocation wall structure. Hence, it is likely that the higher strength of the ECAE processed sample is attributed to the heavily worked structure.

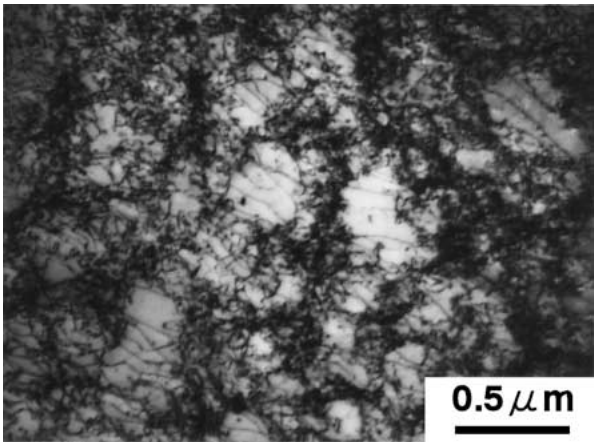
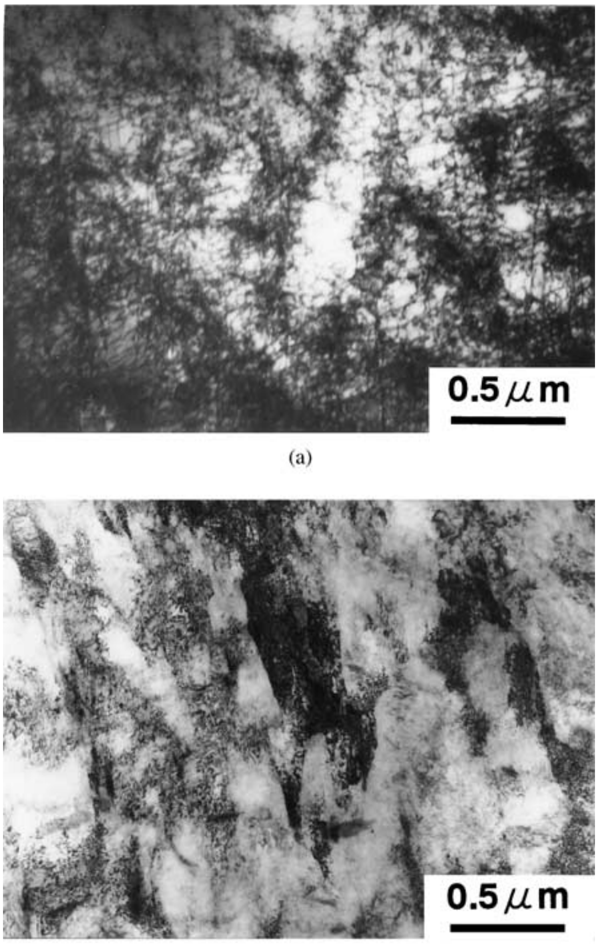


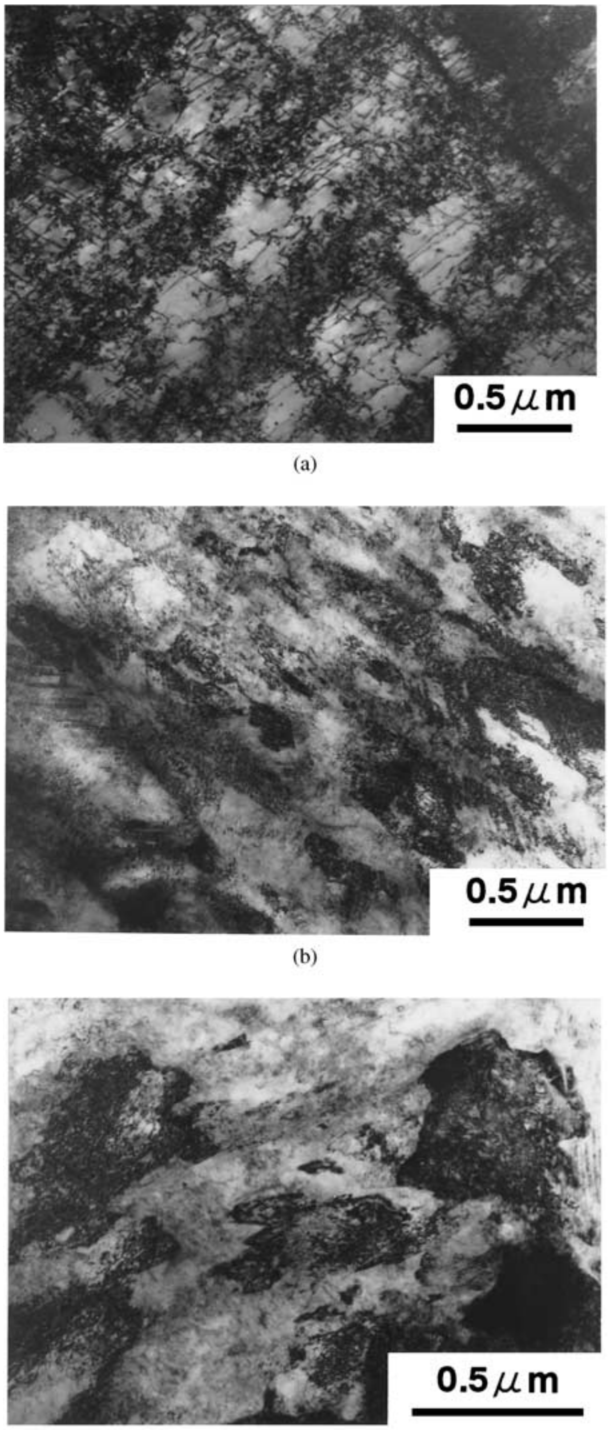
Figure 4 Transmission electron micrograph of the ECAE processed SUS430. Number of the ECAE passes is 2.



(a)

(b)

Figure 5 Transmission electron micrograph of the ECAE processed SUS430 followed by annealing at 673 K. (a) Dense dislocation wall structure and (b) fine dislocation cell structure.



(a)

(b)

(c)

Figure 6 Transmission electron micrograph of the ECAE processed SUS430 followed by annealing at 773 K. (a) Dense dislocation wall structure, (b) fine dislocation cell structure and (c) fine subgrains.

The microstructures of the ECAE processed sample after annealing at 673 K are shown in Fig. 5a and b. Dense dislocation wall is still present in the sample even after annealing. In addition, dislocations form fine dislocation cell structure as shown in Fig. 5b. The formation of the dislocation cell structure suggests that recovery occurred during annealing. However, recrystallization did not occur at this annealing temperature. That is, the microstructure of the ECAE processed samples after annealing consists of both worked structures and recovery structures. Hence, it is likely that the higher strength of the ECAE processed sample after annealing is attributed to both the worked structure and the fine dislocation cell structure. It is also likely that higher elongation of the sample is attributed to the fine dislocation cell structure.

The microstructure of the ECAE processed sample after annealing at 773 K is shown in Fig. 6a, b and c. Microstructure of the sample consists of dense dislocation wall and fine dislocation cell structure as well as the sample annealed at 673 K. In addition, fine subgrains, whose size is about 0.5 μm, are formed by annealing at 773 K shown in Fig. 6c. This micrograph suggests that recovery proceeds as compared to the ECAE processed sample annealed at 673 K. Recrystallization, as well as the ECAE processed sample annealed at 673 K, did not occur in this sample annealed at 773 K. As described earlier, both strength and elongation of the ECAE processed sample annealed at 773 K are higher than those of the sample annealed at 673 K. Although precise discussion cannot be made, it is likely that higher strength is attributed to both the worked structure and fine substructures, e.g. fine dislocation cell structure and fine subgrains. It is also likely that higher elongation is attributed to the fine substructures.

4. Conclusions

Equal channel angular extrusion was carried out at room temperature for SUS430 stainless steel. The following results were obtained.

1. The sample processed by ECAE at room temperature showed higher strength than the as-quenched sample. This is likely due to the heavily worked structure formed by ECAE.
2. Annealing increased both strength and elongation of the ECAE processed sample. It is likely that higher strength is attributed to both the worked structure and fine substructures. It is also likely that higher elongation is attributed to the fine substructures.
3. A combination of ECAE with annealing is available for improving the room temperature tensile properties of SUS430.

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