

CHANGE OF EFFECTIVE THICKNESS OF AUSTENITE GRAIN DURING SEVERE PLASTIC DEFORMATION

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ABSTRACT

Effective thickness of deformed austenite is analysed using Ni-30Fe alloy to discuss the change of ferrite grain size by severe plastic deformation of austenite in low carbon steel. It is found that the effective thickness of deformed austenite becomes almost constant over a certain level of plastic deformation due to the dynamic recrystallization or the geometric dynamic recrystallization, which is thought to set a limit of ferrite grain refinement.

KEYWORDS

Effective thickness, austenite, ferrite, grain refinement, severe plastic deformation

INTRODUCTION

Grain refinement of ferrite has attracted great interest for the improvement of strength and toughness of low carbon steels.[1-7] Severe plastic deformation (SPD) of austenite at high temperature combined with accelerated cooling is known to be effective against the grain refinement of ferrite because it drastically increases the number of nucleation site.[1-4] Recently, the advances in SPD at relatively low temperature, such as ECAP (equal channel angular pressing) or ARB (accumulated roll bonding), enable the severe warm or cold forming to obtain fine ferrite grains by recrystallization.[5-7] However, the severe warm or cold forming still has some difficulties in applying to mass production, SPD of austenite is thought to have more advantages from the industrial point of view.

The effect of plastic deformation of austenite on the final grain size of ferrite is well documented for low carbon steels.[1,2] The change of ferrite grain size according to the deformation of austenite is shown in Fig. 1. The grain size of ferrite is decreased with the increase of compressive strain applied to austenite at first and then remains almost constant over a certain level of compressive strain. It demonstrates that there are lower limits of grain size of ferrite, which can be refined by SPD of austenite. In addition, the limit is dependent on the deformation temperature. The earlier studies on the change of ferrite grain size by SPD of austenite, however, did not cover the origin of the limit of ferrite grain refinement.

The deformed structures of austenite are probably responsible for the change of ferrite grain size in Fig. 1 because the deformation of austenite significantly affects the configuration and distribution of nucleation sites for ferrite.[8] Among various nucleation sites for ferrite, the high angle grain boundary in austenite is known as the most potent one. However, there have been few studies investigating the configuration of high angle boundaries in austenite during severe plastic deformation and discussing its effect on the grain size of transformed ferrite.

In the present study, we examine the deformed structure of austenite, using a Ni-30Fe alloy. Since the austenite in Ni-30Fe alloy is stable at room temperature and its stacking fault energy is reported to be similar to that of low carbon steel, Ni-30Fe alloy is frequently adopted as a model alloy for the investigation of deformed structure of austenite.[9-12] Under various deformation conditions, the

high angle boundaries in deformed Ni-30Fe alloys are characterized, and the limit of ferrite grain refinement by severe plastic deformation of austenite is discussed with respect to the effective thickness of deformed austenite.

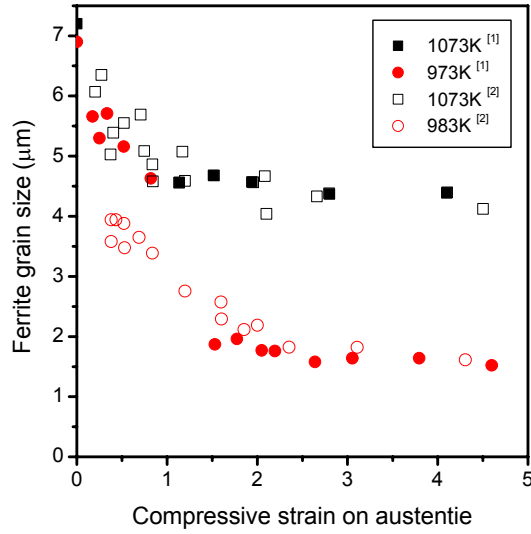


Fig. 1. Changes of ferrite grain size according to the deformation of austenite (initial grain size of austenite is 17 μ m)

EXPERIMENTAL

The chemical composition of prepared alloy is given in Table 1. The vacuum-melted ingot was hot-rolled to make homogeneous microstructure with the grain size around 20 μ m. The initial microstructure of Ni-30Fe alloy is given in Fig. 2.

Table 1. Chemical composition of alloy (wt%)

C	Mn	Si	P	S	Ni	Fe
0.002	<0.002	0.008	0.002	0.001	69.8	bal.

To examine the deformed structures of austenite at various strain levels, compression tests were conducted with hot deformation simulator. The dimension of compression test specimen was 12mm(T) $\times$ 15mm(W) $\times$ 20mm(L). The specimens were heated at a rate of 5K/s up to 1073K, 1023K or 973K by resistance heating. They were held at each deformation temperatures for 5 seconds, and then compressed at a strain rate of 10/s. The deformed specimens were quenched to room temperature by water jet.

Deformation is usually concentrated on the centre of the hot compressed specimen due to the friction between the specimen and the tool. To quantify the inhomogeneous strain distribution along the compressive axis in deformed specimen, a screw-embedded specimen was used.[11] The peak compressive strains of the deformed specimens with the nominal reduction ratio of 50% and 75% were evaluated to be 2.1 and 4.9, respectively, at half-thickness point of deformed specimen along the compressive axis. The high angle boundary spacing in deformed austenite corresponding to various compressive strain levels were observed with light microscopy and high resolution scanning electron microscope with an attachment for orientation mapping using an electron back-scattered

diffraction (EBSD). For detailed investigation on the restoration process during hot deformation, a transmission electron microscopy was also used.

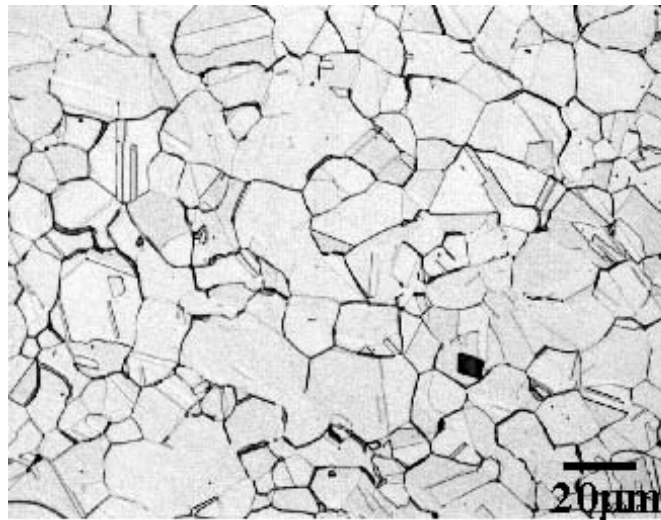


Fig. 2. Initial microstructure of Ni-30Fe alloy (grain size is around 20 μ m)

RESULTS AND DISCUSSION

(1) Deformation structures

Light micrographs and TEM micrographs in Figs. 3 through 5 show the deformation structures of Ni-30Fe alloy for compressive strain of 2.1 and 4.9 at each deformation temperature. At a deformation temperature of 1073K, a partially recrystallized structure starts to appear as compressive strain increase, and then fully recrystallized structures are evolved at compressive strains of 2.1 and 4.9 as shown in Figs. 3 (a) and (b). TEM micrograph of the deformation structure for compressive strain of 2.1 is shown in Fig. 4. The equiaxed grains with grain size of 2~5 μ m are observed. The substructures in the recrystallized grains indicate that dynamic recrystallization (DRX) is dominating restoration process during the deformation. When the deformation temperature decreases to 1023K, the deformed structures mainly consist of equiaxed grains even though the characteristics of the equiaxed grains cannot be clearly examined with the light micrographs in Figs. (c) and (d). A more detailed microstructural feature is given by TEM micrograph in Fig. 5. The polygonal grains (indicated with arrows) are observed in the upper and lower parts of the TEM micrograph. The polygonal grains have a few dislocations within themselves. This substructure denotes that the polygonal grains are evolved by DRX. Actually, the fraction of polygonal grains in the examined area with TEM is relatively small. On the other hand, considerable portion of the examined area with TEM is covered by dislocation cell structures that can be observed in the middle part of Fig. 5. It is well known that the dislocation cell structure is a characteristic feature of the recovery structure. However, recovered elongated grains are hardly found in the light micrograph in Figs. 3 (c) and (d). The TEM micrograph suggests that lots of equiaxed grains in Fig. 3 (c) and (d) have the recovery structure within themselves, and the grains are probably evolved by geometric dynamic recrystallization (geometric DRX). The geometric DRX results from the fragmentation of elongated grains due to the impingement of serrated boundaries, and thus the recovery structure can be retained in the equiaxed grains. The equiaxed grains by geometric DRX have been commonly observed during the severe plastic deformation of Al alloys.[13-15] The present authors also reported that the grain boundary serration was evolved in Ni-30Fe alloy during hot deformation, so it could give rise to the geometric DRX at sufficiently high compressive strain.[11,12]

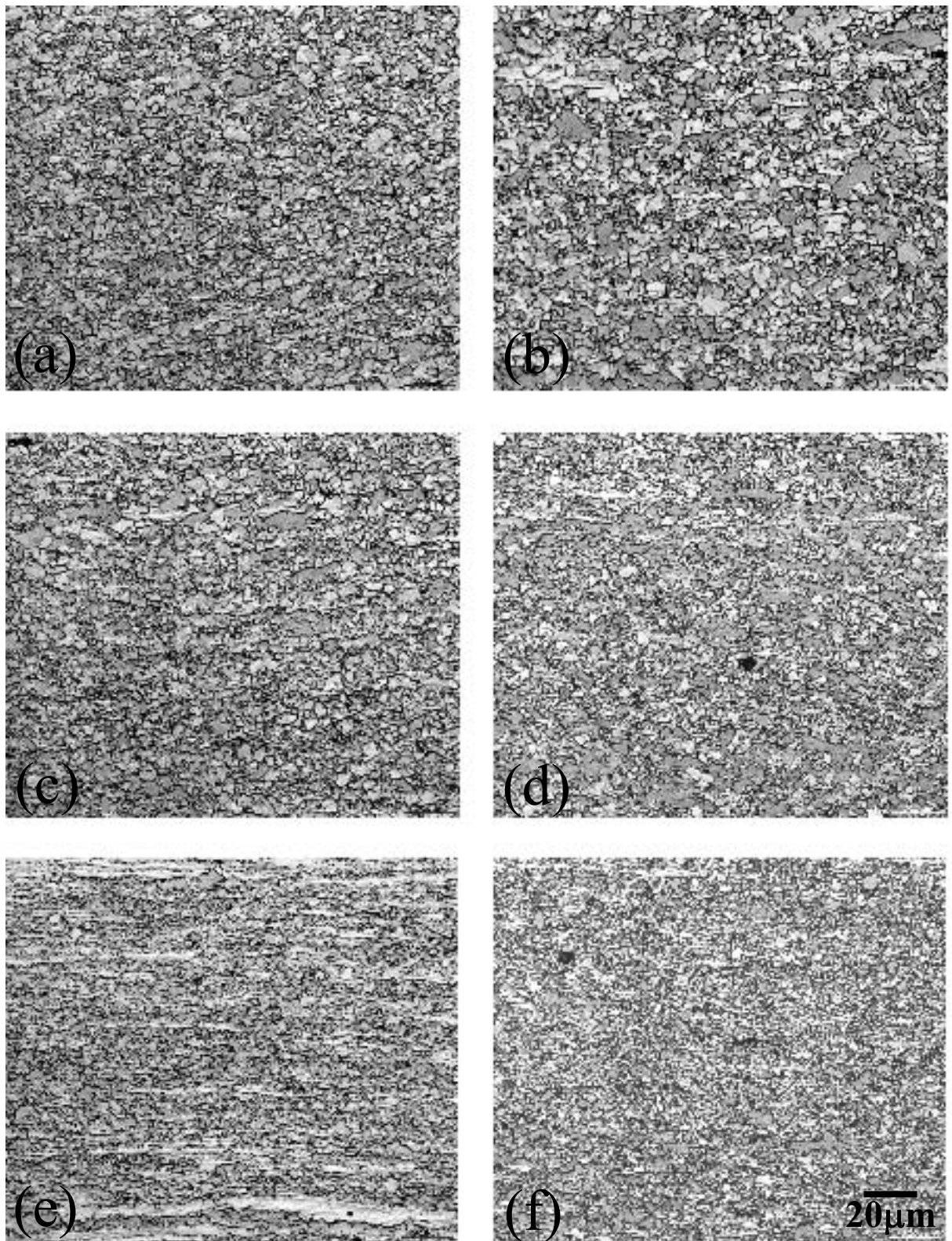


Fig. 3. Microstructural evolution of deformed specimen (T: deformation temperature, ϵ : compressive strain)

(a) T=1073K, ϵ =2.1, (b) T=1073K, ϵ =4.9, (c) T=1023K, ϵ =2.1, (d) T=1023K, ϵ =4.9, (e) T=973K, ϵ =2.1 and (f) T=973K, ϵ =4.9

Figs. 3 (e) and (f) show the deformed structures of Ni-30Fe alloys at 973K. The elongated grain structures gradually change into the geometrically recrystallized structures according to the increase of compressive strain. In particular, one can see the elongated grains, which are nearly fragmented by the impingement of grain boundaries, indicating the occurrence of the geometric DRX

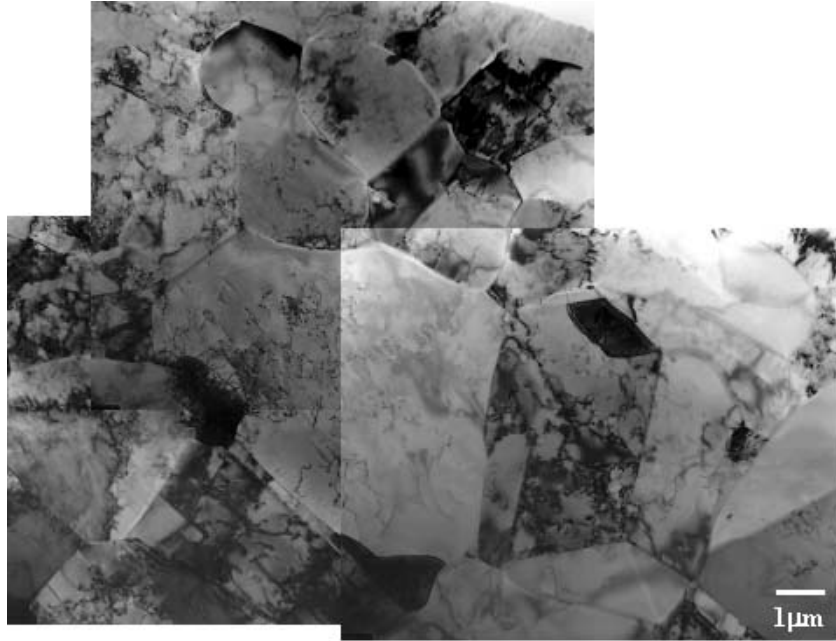


Fig. 4. TEM micrograph of specimen deformed at 1073K with compressive strain of 2.1 showing DRX grains

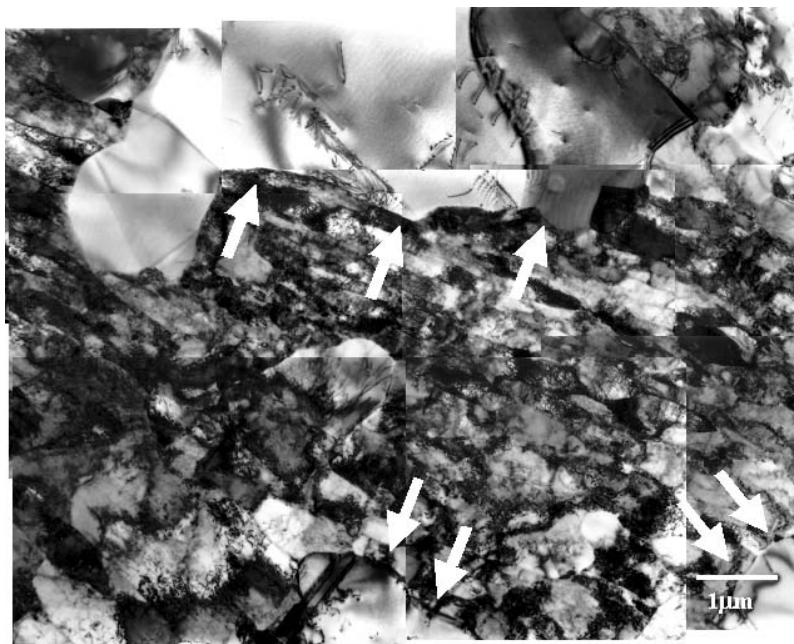


Fig. 5. TEM micrograph of specimen deformed at 1023K with compressive strain of 2.1 showing DRX grains (indicated with arrows) and dislocation cell structures

(2) Change of effective thickness of austenite during hot deformation

The deformed structure of Ni-30Fe alloy shows that the restoration process plays an important role in microstructural evolution of austenite during the severe plastic deformation. The light and TEM micrographs demonstrate that the DRX or the geometric DRX occurs during the deformation and thus the austenite grains are not monotonously elongated with the increase of the compressive strain. This microstructural evolution is possibly related with the change of ferrite grain size in Fig. 1, which shows the lower limit of ferrite refinement by SPD of austenite. The occurrence of DRX or geometric DRX can affect the configuration and distribution of nucleation site for ferrite, especially the high angle boundary of austenite. Through the light or TEM micrographs, however, it is difficult to investigate the high angle boundary configuration because the complicated microstructural evolution accompanying the dynamic restoration process hinders the quantitative characterization of high angle boundary in deformed austenite. In the present study, it is attempted to analyse the high angle boundary by orientation mapping using electron back-scattered diffraction. Fig. 6 shows the configuration of high angle grain boundary in austenite for Ni-30Fe alloy deformed at 1073K and 973K. The black solid line indicates that the misorientation of the boundary between adjacent pixels is larger than 15° .

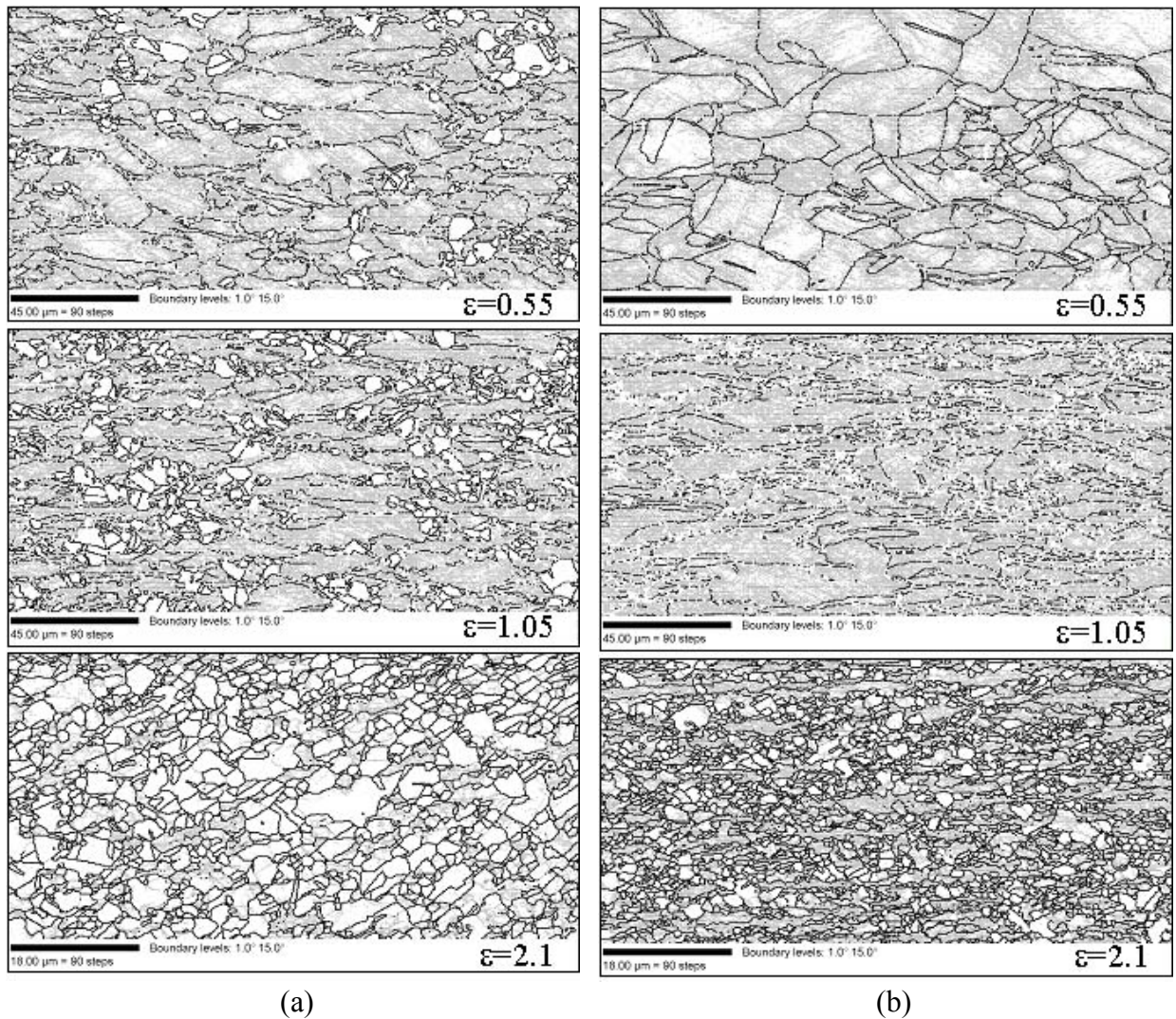


Fig. 6. High angle boundary in deformed specimen: (a) deformation temperature of 1073K and (b) deformation temperature of 973K

At deformation temperature of 1073K, it is apparent in Fig. 6(a) that the DRX austenite grains are evolved at grain boundaries of deformed austenite with the increase of compressive strain. Full

DRX structure is found at a compressive strain of 2.1. The grain size of DRX austenite is around $2.5\mu\text{m}$, which is well consistent with the grain size from TEM micrograph in Fig. 4. At deformation temperature of 973K, as shown in Fig. 6(b), DRX grains are hardly found at compressive strains of 0.55 and 1.05, although the microstructure consists of fine equiaxed grains at a compressive strain of 2.1. As mentioned, the fine equiaxed grains at a compressive strain of 2.1 are evolved by geometric DRX. The high angle boundary spacing in geometric DRX structure is around $1.2\mu\text{m}$. Once the geometrically recrystallized structure is evolved, the high angle boundary spacing is not changed significantly by additional deformation.

From the orientation mapping in Fig. 6, the change of effective thickness of austenite grain according to the compressive deformation is evaluated. Here, the effective thickness of austenite grain means the high angle boundary spacing measured along the compression axis. Fig. 7 shows the changes of effective thickness of austenite grain with increasing the compressive strain. Fig. 7 indicates that the effective thickness of austenite grain remains almost constant over a certain level of compressive strain due to the dynamic restoration process. This result demonstrates that the geometric DRX as well as DRX is responsible for the change of high angle boundary configuration during severe plastic deformation. Even at a deformation temperature where DRX cannot be occurred, the effective thickness of austenite grains cannot be reduced over a critical value due to the geometric DRX.

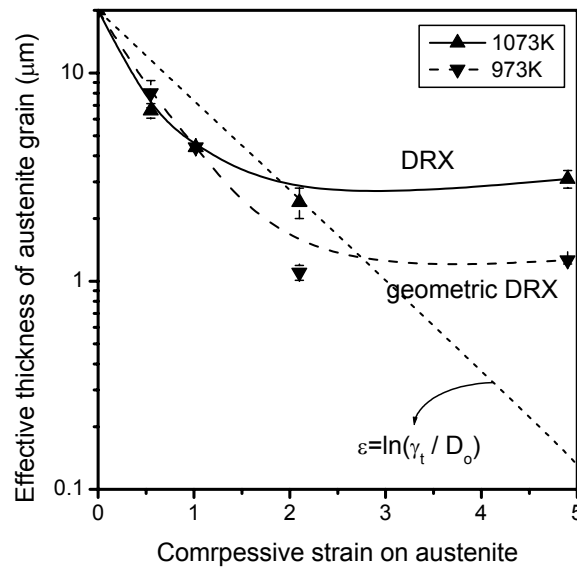


Fig. 7. Change of effective thickness of austenite grain according to the compressive strain

Fig. 8 shows the effective thickness of deformed austenite for Ni-30Fe alloy overlapped with the grain size of ferrite in Fig. 1. Fig. 8 demonstrates that the changes of ferrite grain size show almost the same behaviour as the changes of the effective thickness of austenite during severe plastic deformation. The lower limit of grain size of ferrite refined by severe plastic deformation of austenite is around $4\mu\text{m}$ at a deformation temperature of 1073K and around $1.5\mu\text{m}$ at a deformation temperature of 973K. This is close to the effective thickness of severely deformed austenite for Ni-30Fe alloy, which is around $2.5\mu\text{m}$ at 1073K and $1.2\mu\text{m}$ at 973K. Besides, it is noted that the grain size of ferrite remains almost constant over a certain compressive strain at which the effective thickness of austenite also remains constant due to DRX and geometric DRX.

As mentioned before, since the high angle boundary in austenite is the most potent nucleation site for ferrite, the effective thickness of austenite will play a major role in determining the grain size of

ferrite. It is believed that ferrite grains cannot be further refined by additional deformation of austenite once the DRX or geometric DRX occurs because of the little change in the effective thickness of austenite over a critical strain level. Therefore, it can be suggested that the constant high boundary spacing in austenite due to the DRX or the geometric DRX is responsible for the limit of ferrite grain refinement by severe plastic deformation of austenite.

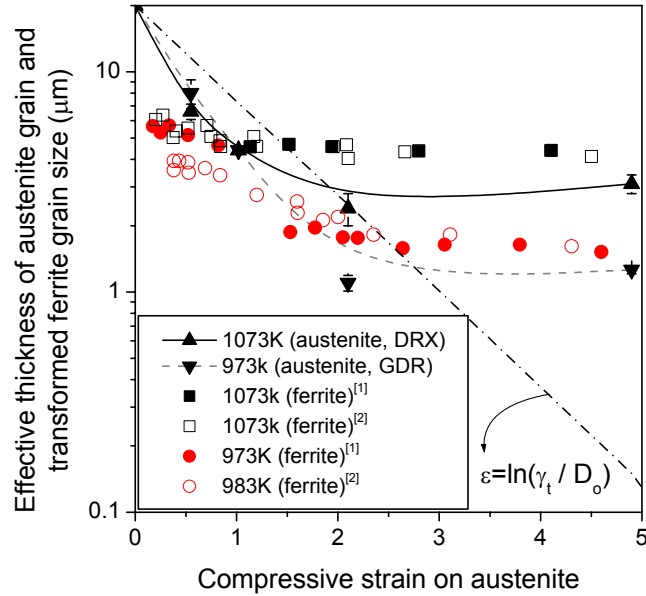


Fig. 8. Effective thickness of austenite during compressive deformation compared with the final grain size of ferrite

CONCLUSION

The deformed structure of Ni-30Fe alloy was characterized to discuss the change of effective thickness of austenite during severe plastic deformation and the following conclusions can be drawn.

- (1) The deformation structure of Ni-30Fe alloy indicates that DRX or geometric DRX occurs with increasing the compressive strain. The deformation temperature is associated with the type of restoration process.
- (2) DRX or geometric DRX plays an important role in microstructural evolution during severe plastic deformation. High angle boundary spacing given by orientation mapping reveals that the effective thickness of austenite grain is not changed significantly by additional deformation once DRX or geometric DRX occurs.
- (3) The change of ferrite grain size according to the deformation of austenite shows consistent behaviour with the change of effective thickness of austenite, which indicates the high angle boundary configuration in austenite given by DRX or geometric DRX set the limit of ferrite grain refinement.

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