論　文

ANISOTROPY AND STRAIN RATE DEPENDENCE OF TENSILE PROPERTIES ON AZ31 MAGNESIUM ALLOY SHEETS AT HIGH TEMPERATURE

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Tensile test have been performed to investigate anisotropy of strain and strength on AZ31 magnesium alloy sheet over a range of test temperatures (from room temperature to 220°C) and initial strain rates (10^{-4} to 10^{-1} s^{-1}). Tensile test specimens have been cut from a sheet 0.5mm thick at five different angles (the orientation:0,30,45,60,90 degrees) to the rolling direction, and some specimens were annealed at 400°C for one hour to compare the characteristic with as-rolled one. Microstructure, texture-elongation relationships have been analyzed by EBSP technique. There is a significant anisotropy of failure strain and maximum stress at room temperature, regardless of as-rolled or annealed conditions. The anisotropy of strain was also kept at each high temperature, although the anisotropy of stress is not found at higher temperature, 220°C. All failure strain decreased with increasing strain rate at room temperature, and the strain rate dependence on maximum stress was slightly found at only room temperature. The failure strain at 150°C has been showed the peak value at the strain rate of 10^{-2} order. In contrast with this, the failure strain at 220°C is the lowest level at the strain rate of 10^{-3} order. Elongation-to-failure of as-rolled sample is similar tendency to it of annealed sample. It is due to the texture formation and occurrences of dynamic recrystallization or twin during deformation.

Key Words : *AZ31 magnesium alloy, high temperature, tensile properties, failure strain, anisotropy*

1. INTRODUCTION

AZ31 alloy sheet has been using to produce many industrial components, and the deformation mechanism and formability have been studied to improve or enhance their performance[1)-4)]. The plastic formability of magnesium alloy is not superior at room temperature, due to have a restriction of slip system resulted from the hexagonal structure. Therefore, there are many study with behavior in high temperatures of magnesium alloy over 300°C, including with a research of superplasticity[5)]. For rolling sheets or extrusion bars, crystallographic textures cause anisotropy of both elastic and plastic properties. On the other hand, it is well known that dynamic recrystallization in magnesium alloy occurs easily and the fine grains are developed, when the alloy is formed at warm or hot working processes. The texture and grain size of magnesium alloy affect the ductility during deformation, and in particular, crystallographic texture also has a very large effect on yielding[6)]. The Schmid factor for basal slip varies with orientation from 0.5 to 0. As above mentioned, it is important to control the microstructures as a function of temperatures and strain rate during deformation, in case of sheet forming or press-forging process. The objective in this work is to investigate the effects of texture, or anisotropy on strain and strength at various temperatures (especially below 250°C for economical process) and strain rates with deformation mechanism.

2. EXPERIMENTAL PROCEDURE

2.1 Materials specifications

AZ31 magnesium alloy sheet was prepared and it has 0.5mm thickness. Table 1 gives chemical compositions of the alloy sheet used in this work. Tensile test specimens have been cut from the sheet at five different angles (the orientation:0,30,45,60,90 degrees from rolling direction; RD, to transverse direction; TD) to the final rolling direction. Some specimens were annealed at 400°C for one hour to compare the characteristic with as-rolled one. All specimens for tensile testing have been machined to the size with a nominal 20mm gauge length and 4mm width.

Table 1 Chemical compositions of the alloy sheet used in this work (mass%)

Al	Zn	Mn	Fe	Si	Cu	Ni	Ca	Mg
3.43	0.94	0.45	0.002	0.01	<0.01	0.001	<0.01	bal.

2.2 Tensile test

Tensile tests are performed to investigate anisotropy of strain and strength on AZ31 magnesium alloy sheet, at temperatures ranging from room temperature to 220°C and four levels of initial strain rates ranging from 10^{-4} to 10^{-1} s^{-1}. Fracture surface and microstructure were observed by a scanning electron microscope and an optical microscope, respectively. The elevated temperature tests were performed using an Instron type testing machine equipped with electrical resistance furnace. All tests were performed in air at atmospheric pressure, after 10 minutes hold at each temperature. The elongation-to-failure was obtained from the gauge length of the fractured specimens.

2.3 EBSP analysis

Microstructure, texture-elongation relationships have been analyzed by Electron Back Scattering Diffraction Pattern (EBSP) technique. The crystal orientation has been measured by EBSP or X-ray diffraction (XRD) both as-rolled and annealed specimens. Orientation mapping with a step size of 1.2μm was carried out over 300μm×300μm areas on the sheet surface.

3. RESULTS AND DISCUSSION

3.1 Microstructures

The average grain size under as–rolled condition is 9μm as shown in Fig. 1(a). The microstructure of annealed specimen is shown in Fig.1(b), and the average grain size is 19μm, determined by the linear intercept method. Fig.2 shows a high density of basal planes paralleled to rolling plane, and no concentration of the {10-11} plane is found. For sheets of many hcp metals, the texture can be approximately described as having the basal plane, parallel to the plane of the sheet. There was little change in the texture both as-rolled and annealed specimen as shown in Fig.2(a) and Fig.2(b) respectively, even though the grain growth occurs after annealing.

3.2 Tensile properties

Fig.3 shows the engineering stress-strain curves of as-rolled and annealed specimens at each test temperature under the strain rate of 10^{-4}. The maximum stresses decrease with increasing temperature at both conditions. As-rolled specimen shows a higher maximum stress than annealed specimen at room temperature, however, the stress of annealed specimen is higher at 220°C. Furthermore, elongation-to-failure strain at as-rolled condition is superior to it of annealed one at 220°C. The work hardening during deformation is not found at high temperature of 220°C in both specimens. Dynamic recrystallization initiates after peak stress on these curves. Fig.4(a) shows strain rate dependence of yield stress in as-rolled and annealed specimens. The yield stress of as-rolled specimen from 0 degree is greater than the annealed one at room temperature under the strain rate of 10^{-4}, while the yield stress of as-rolled specimen from 90 degree is similar to the annealed one under all strain rates as shown in Fig.4(a). With effect on maximum stress of annealing treatment, there is a considerable difference in maximum stress between the specimens from 0 degree and 90 degree, although that is a little strain rate dependence as shown in Fig.4(b). It is indicated that anisotropy remains after annealing and occurrences of twins or other slip system during formation. Fig.5 shows the strain rate dependence on maximum stress of annealed specimens at room temperature and 220°C. Annealed specimen has little strain rate dependence at room temperature, compared with as-rolled specimen having slightly strain rate dependence. Anisotropy in stress is clearly observed as shown in Fig.5(a), and the stress of transverse direction, i.e. from 90 degree, is the greatest in all samples at all strain rates. There was a significant anisotropy of not only maximum stress but also failure strain at room temperature, regardless of as-rolled or annealed conditions. As shown in Fig.5(b), the maximum stresses increase with increasing strain rate at temperature of 220°C, and the anisotropy is not clear at all strain rates. Fig.6 shows microstructures of as-rolled specimen near fracture point after tensile test at room temperature. There are more twins in grains at higher strain rate of 10^{-1} rather than a lower strain rate of 10^{-4}. In generally, the twin occurs easily when subjected to the stress at low temperature or impact stress. It seems that the quantity of twin increase with increasing strain rate. In annealing specimen with same strain rate, as shown in Fig.7, more twins are also found at the specimen of 90 degree rather than 0 degree. The shear stresses required for pyramidal

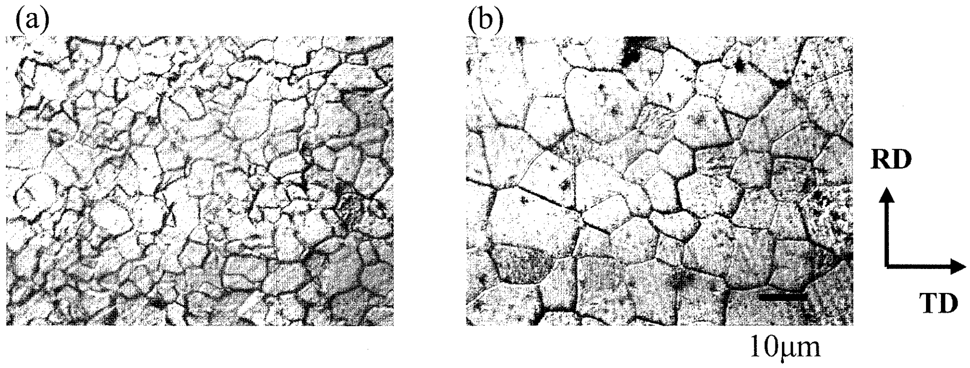

Fig.1 Microstructures of (a)as-rolled, and (b)annealed specimens.

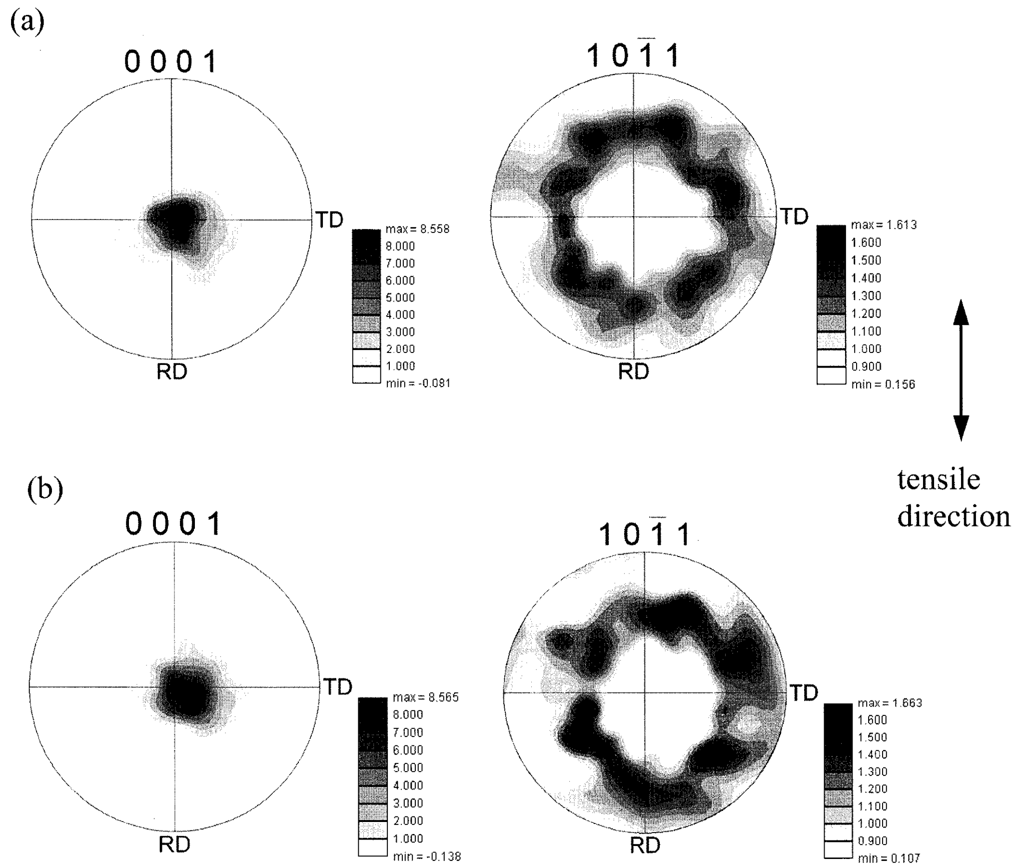

Fig.2 Pole figures of (a)as-rolled and (b)annealed specimen obtained from the rolling sheet surface. Before tensile deformation, $\varepsilon = 0\%$, 0 degree.

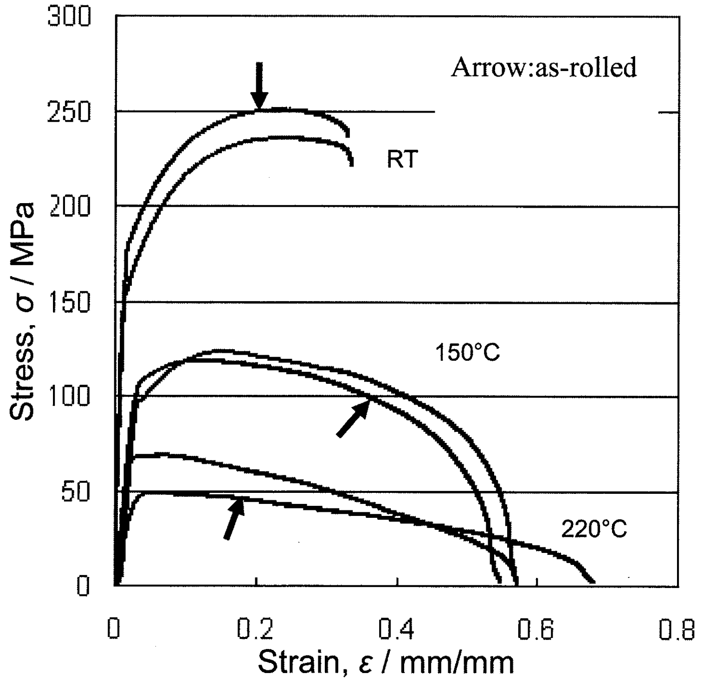

Fig.3 Engineering stress-strain curves of as-rolled and annealed specimens at each test temperature. 4.17×10^{-4} s^{-1}, 0 degree.

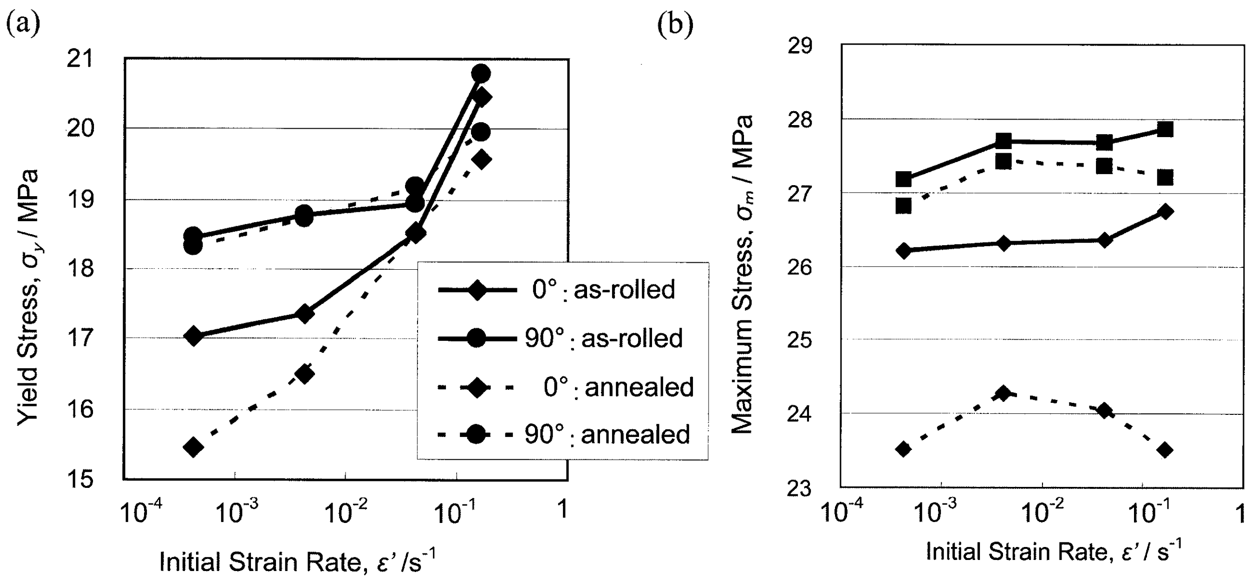

Fig.4 Effect of annealing on (left:a)yield stress and (right:b)maximum stress in the orientation angle of 0 degree and 90 degree. Solid line: as-rolled, Dashed line: annealed.

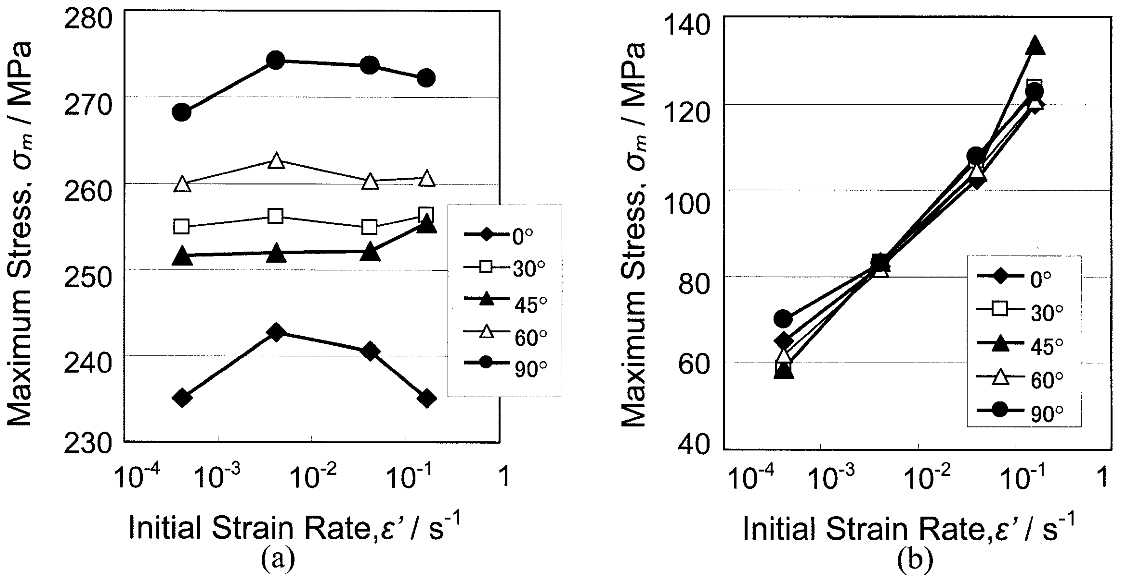

Fig.5 Strain rate dependence and anisotropy of maximum stress of annealed specimens at (left:a)room temperature and (right:b)220°C.

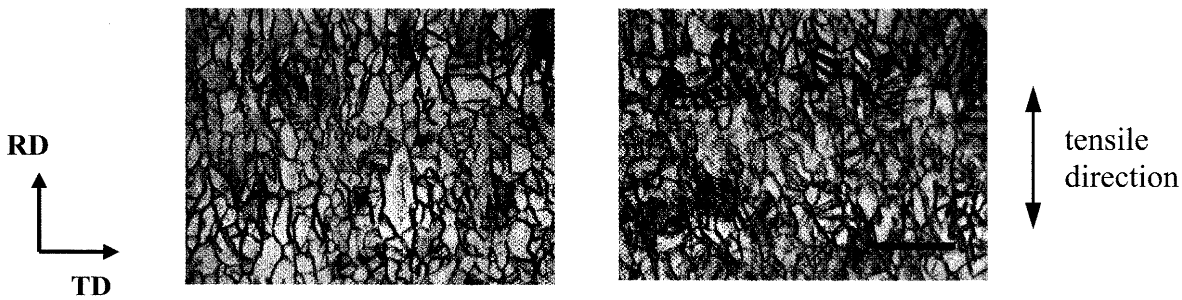

Fig.6 Microstructures of as-rolled specimen near fracture point after tensile test at room temperature. 0 degree. (left) 4.17×10^{-4} s^{-1} (right) 1.67×10^{-1} s^{-1} bar: 20μm

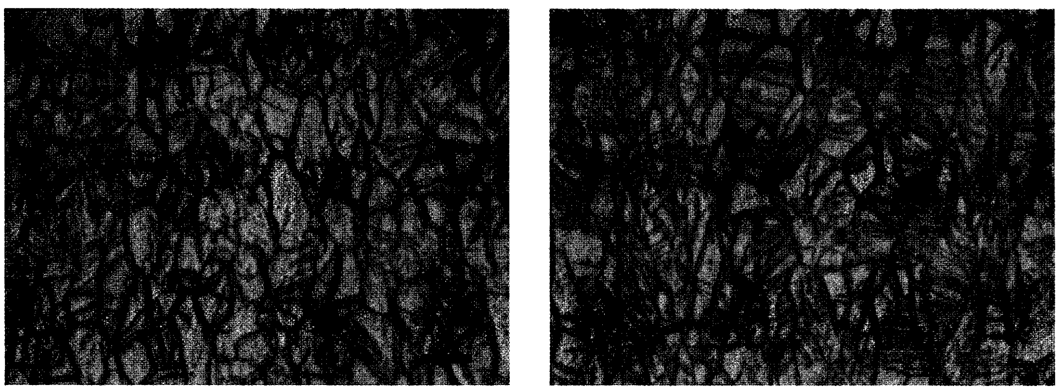

Fig.7 Microstructures of annealed specimens near break point after tensile fracturing at room temperature with same strain rate of 10^{-4}. (left) 0 degree, (right) 90 degree. bar: 10μm

slip are much higher than the stresses to cause basal and prismatic slip, while twinning unlike slip produces C-axis direction strains[6]. Deformation twinning is relation to anisotropy, and produces high stress and lower strain at room temperature. Anisotropy of strain is also kept at each high temperature as shown in Fig.8, although anisotropy of maximum stress is not clear at higher temperature, 150°C or 220°C. All failure strain decrease with increasing strain rate at room temperature, in spite of having no strain rate dependence on maximum stress, as shown in Fig.5. The failure strain at 150°C has showed the peak value at the strain rate of 10^{-2}. In contrast with this, the failure strain at 220°C has the lowest level at the strain rate of 10^{-3}. This tendency was also found under as-rolled condition. The decrease on strain rate of 10^{-1} order at 150°C is due to deform by twinning and/or non-basal slip resulted from subjected to higher stress. It seems that the decrease on strain rate of 10^{-3} order at 220°C is due to have the serrated boundaries resulted from dynamic recovery prior to dynamic recrystallization (DRX). Fig. 9 shows the variation in yield stress which has a strain of 0.2% as a function of strain rate at each temperature. The m-value(exponent of strain rate sensitivity) is approximately 0.15 at 220°C. The yield stress increase with increasing strain rate, and this tendency is found clearly when temperature has been elevated. In the other word, strain rate sensitivity increases with increasing the temperature. It was reported that the m-value was approximately 0.14 in the strain rates ranging from 10^{-4} to 10^{-2} at 250°C, examined for cast material, extruded material, and equal channel angular extruded material[7]. Fig.10 shows microstructures of specimen surface near fracture point after tensile test at high temperatures. DRX has been occurred on annealed specimen during tensile deformation at test temperature of 150°C in both strain rates, 10^{-4} or 10^{-2}. Elongated grains, some twins and small grains from DRX where has occurred at the boundaries between elongated grains are observed as shown in Fig.10(b). The serrated boundaries caused by dynamic recovery are also observed in Fig.10(c), and the microstructure in Fig.10(d) shows that mixture of many small grains resulted from DRX and original grains. It was reported by *Tan et al.*,[5] that the optimum DRX condition was found to be at 250°C and at a constant rate of 10^{-4} s^{-1}. In this work, the DRX is found at the limited condition as shown in Fig.10. In the necking region of tensile specimen after fracturing at test temperature of 220°C, fine equiaxial grains caused by DRX are observed at all strain rate as shown in Fig.11. These grains are finer when strain rate is increased. During DRX, subgrains initiate in the vicinity of the serrated grain boundaries and continue to form over the whole volume of the grain though the conversion of dislocation cell walls into subgrain boundaries[5]. These microstructure change correspond the results of strain behavior as shown in Fig.8. Table 2 shows the summary of characteristics of microstructures after fracturing near break point at high temperatures.

3.3 The texture change during deformation

Fig.12 shows anisotropy and temperature dependence in failure strain of annealed specimen obtained at each test temperature. All failure strains increase with increasing temperature, however, anisotropy remains some extent. Fig.13 shows pole figures of annealed specimens after giving tensile pre-strain at room temperature. Fig.2 and Fig.13 also mean the texture change during deformation as a function of strain, 0, 9.51, and 11.38%. It is found that the concentration to {10-11} depends on the magnitude of strain, like from random at strain of 0% to a completely concentration of {10-11} plane at strain of 11.38%, via the rotation around C-axis. It has been reported that magnesium and some aluminum alloys occur the rotation recrystallization which new grains are formed by the continuous rotation of subgrains during deformation[8]. The concentration of {10-11} plane is revealed on the tensile direction as priority direction. Fig.14 shows the orientation imaging microstructures of annealed specimen which has a strain of 0, 9.51, and 11.38% at room temperature. These mapping corresponds to Fig.13. There are very small grains after giving pre-strain, and the fraction of low angle grain boundaries is higher when strain has been given. The fraction of low angle grain boundaries which includes the angle from 2 to 15 degree has approximately 9% before deformation, but the fraction is over 38% after giving strain. In AZ61 magnesium alloy sheets, it has been found that a uniform deformation appears when a major slip system acts by non-basal dislocation slip[9]. The <10-10> alignment to tensile axis leads a non-basal slip as a major slip system. As resulted from this behavior, the better ductility which caused by uniform strain was obtained. The tilting of basal planes to tensile axis also affects ability to the basal slip. Anisotropy of failure strain depends on an initial alignment and tilting of basal planes. Fig.13(a) shows that the {10-11} planes on 0 degree specimen is sharply concentrated, and it is indicated to have a non-basal slip as a major slip and better ductility. In

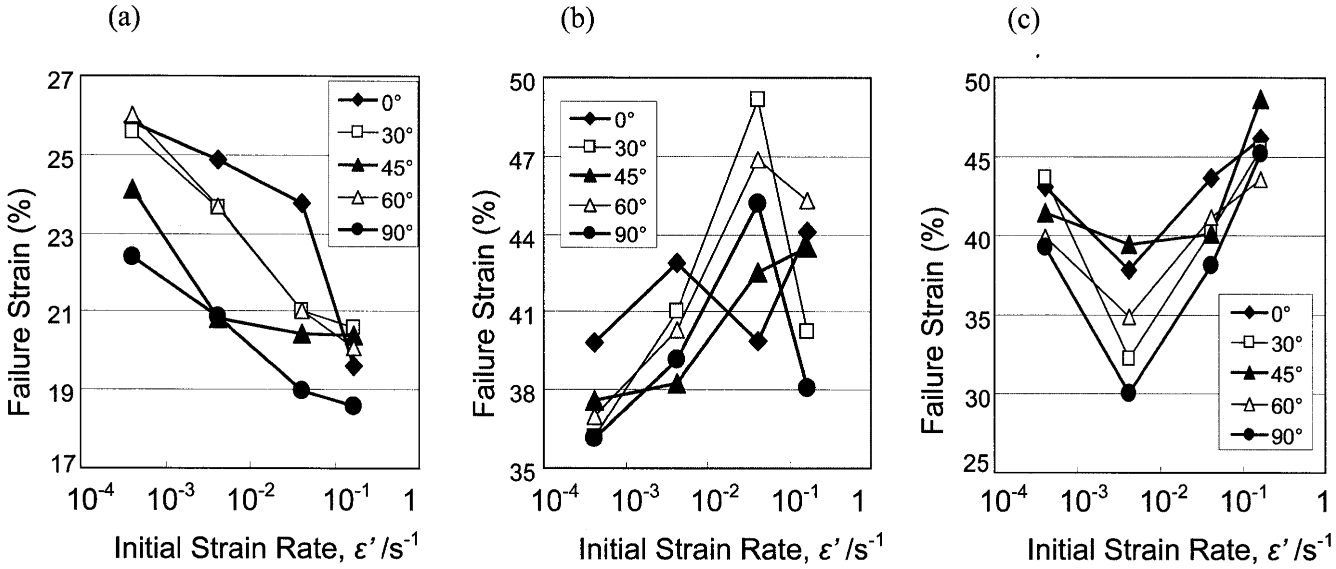

Fig.8 Strain rate dependence of failure strain of annealed specimens at (a)room temperature, (b)150°C , and (c)220°C.

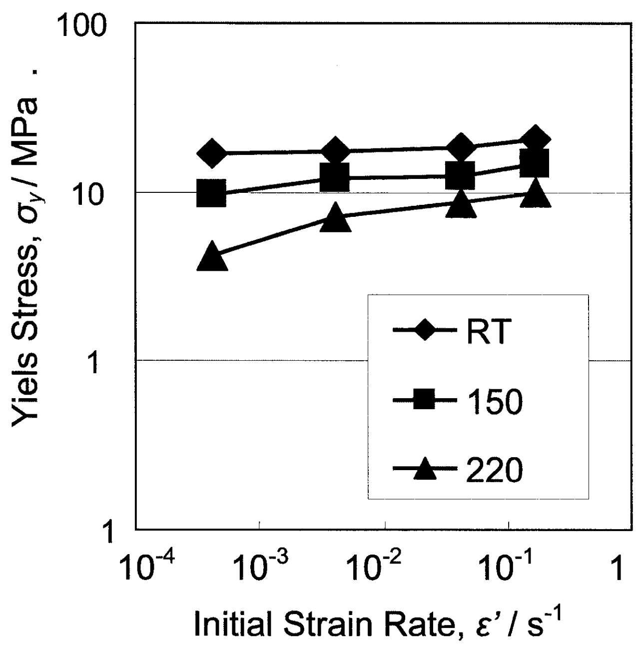

Fig.9 The variation in yield stress as a function of strain rates at each temperature.

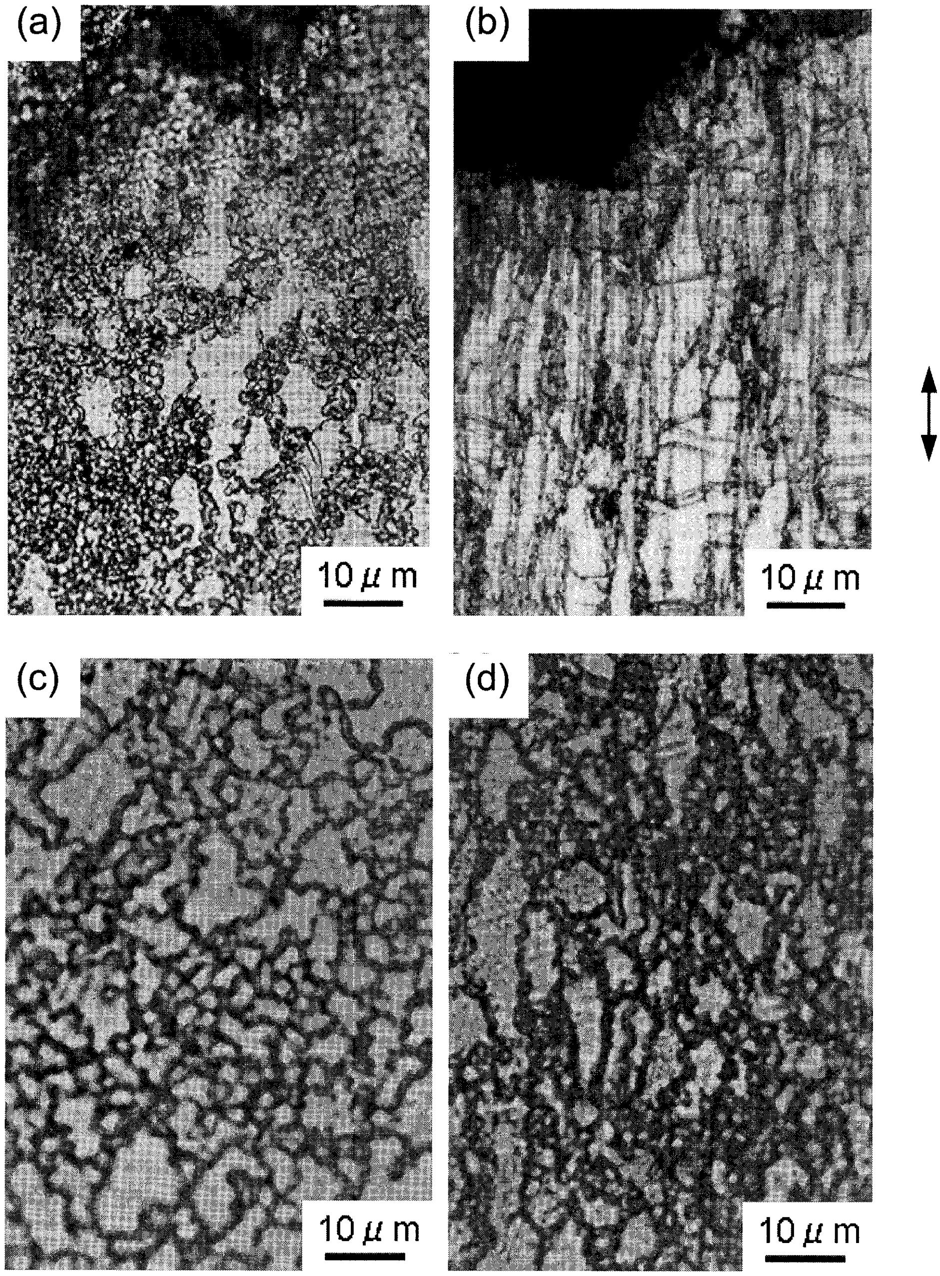

Fig.10 Microstructures of specimen surface near fracture point after tensile test. (Arrow: tensile direction)
(a) 150°C, annealed, 0 degree. 4.17×10^{-4} s^{-1}
(b) 150°C, annealed, 0 degree. 4.17×10^{-2} s^{-1}
(c) 220°C, as-rolled, 0 degree. 4.17×10^{-3} s^{-1}
(d) 220°C, as-rolled, 0 degree. 1.67×10^{-1} s^{-1}

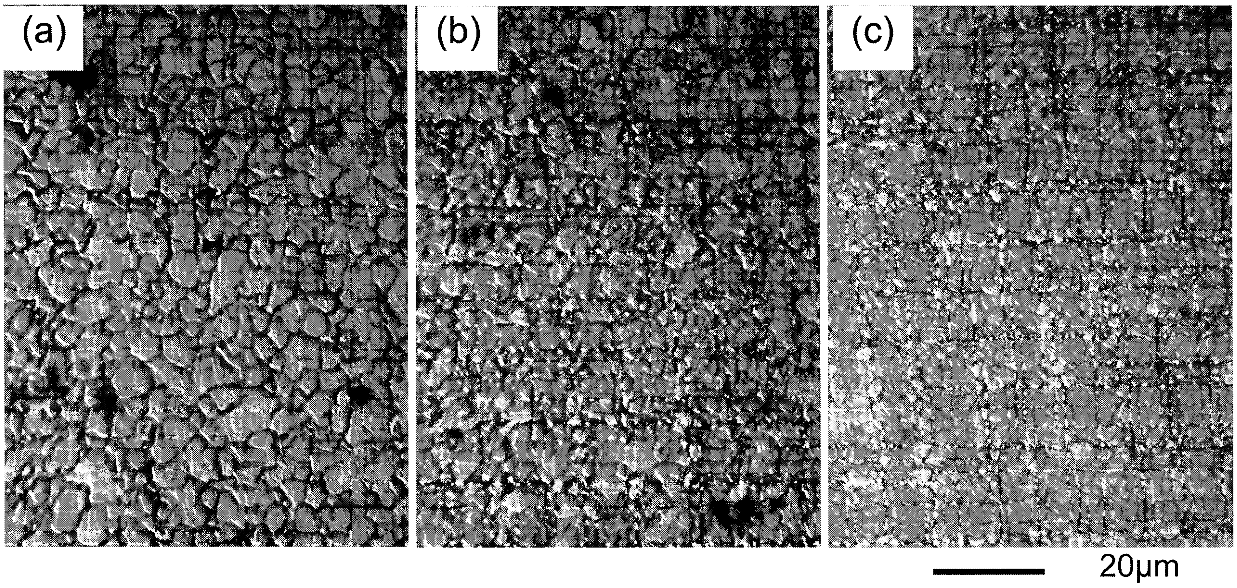

Fig.11 Microstructures in necking region of as-rolled tensile specimens(0 degree) after tensile fracturing at 220°C. (a) 10^{-4} s^{-1} (b) 10^{-2} s^{-1} and (c) 10^{-1} s^{-1} . Tensile direction: horizontal

Table 2 Characteristics of microstructures after fracturing beneath break point at 150°C, or 220°C

Temp.	ε'	Near break point	
150℃*	10^{-4}	Grains + DRX	
	10^{-3}	Elongated grains + DRX	
	10^{-2}	Elongated grains + less DRX + twins	
	10^{-1}	Elongated grains + less DRX (at boundaries) + more twins	
Temp.	ε'	Near break point	(Necking region)
220℃**	10^{-4}	Grains	(whole DRX:SG)
	10^{-3}	Grains with the serrated boundaries (dynamic recovery)	(whole DRX:SG)
	10^{-2}	Grains + DRX	(whole DRX:FG)
	10^{-1}	Elongated grains + DRX	(whole DRX:FG)

* annealed specimen, 0 degree
** as-rolled specimen, 0 degree
SG: small grains, FG: finer grains

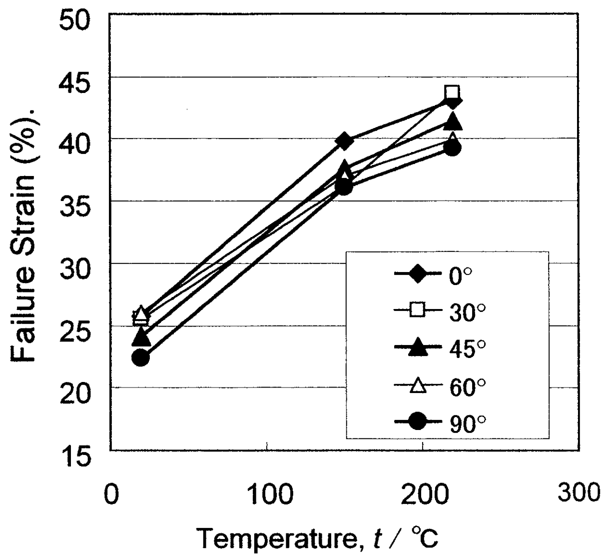

Fig.12 Anisotropy and temperature dependence in failure strain of annealed specimen obtained at each test temperature. $\varepsilon' = 10^{-4}\ s^{-1}$.

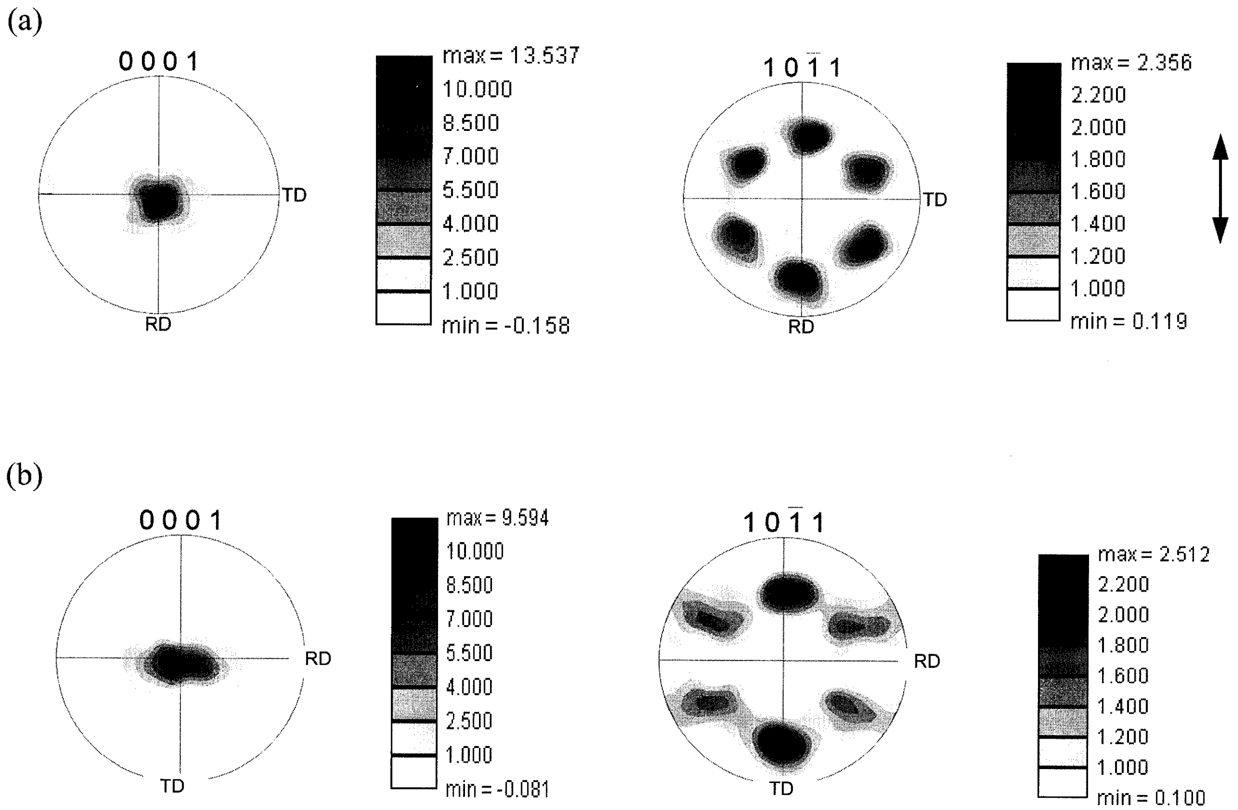

Fig.13 Pole figures of annealed specimens after giving pre-strain (near maximum stress).
(a) RT, 0 degree, $\varepsilon = 11.38\%$, $4.17\times10^{-4}\ s^{-1}$ (b) RT, 90 degree, $\varepsilon = 9.51\%$, $4.17\times10^{-4}\ s^{-1}$
Arrow: tensile direction

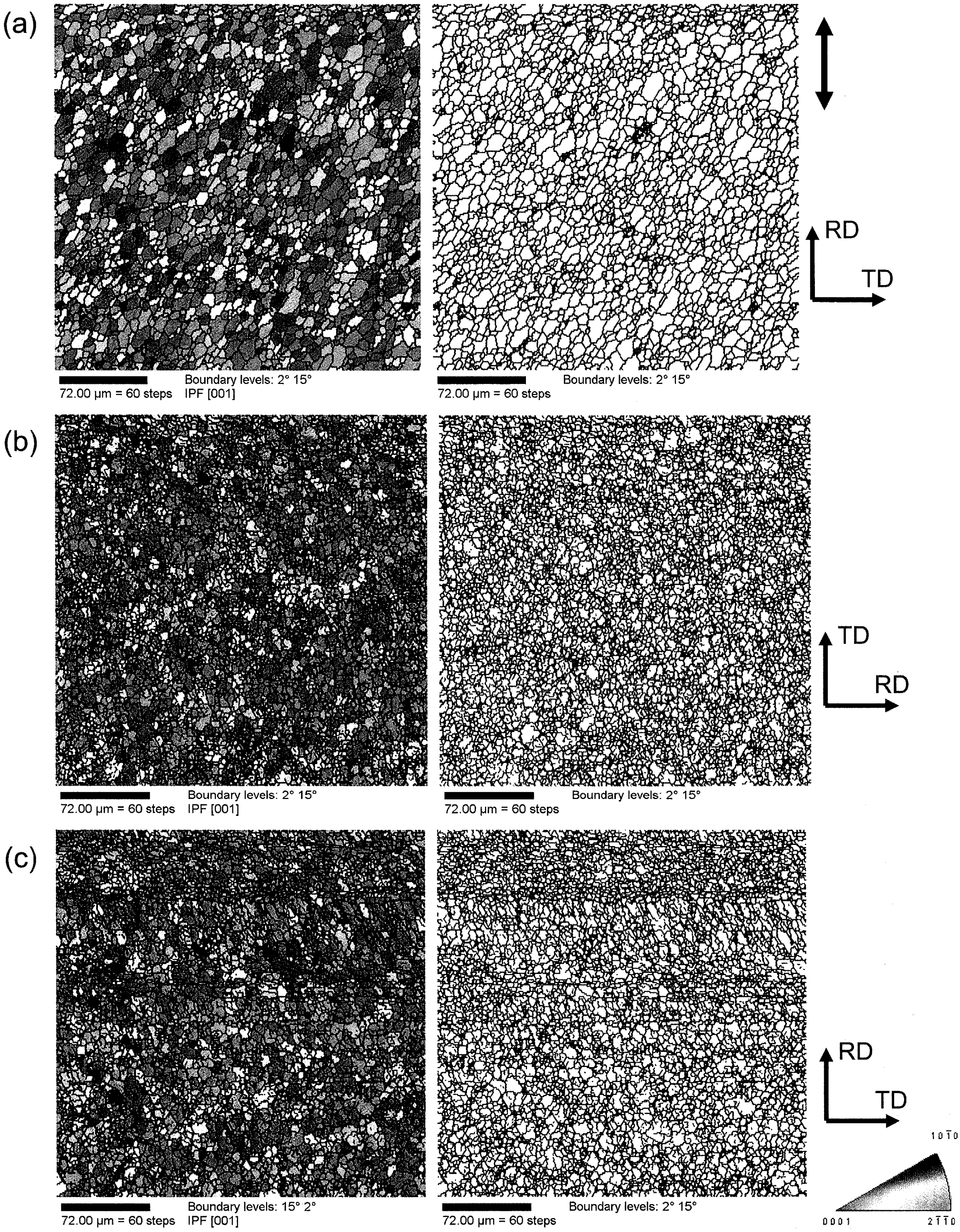

Fig.14 The orientation mapping microstructure of annealed specimen which has a strain of (a)0%, 0 degree (b)9.51%, 90 degree and (c)11.38%, 0 degree at room temperature. Low angle (blue line), High angle (black line). Arrow: tensile direction

comparison with this, the 90 degree specimen in Fig.13(b) has a concentration to only just tensile direction, even though Fig.13(a) and Fig.13(b) are not same strain correctly. However, it seems that alignment of {10-11} planes during deformation controls the failure strain and leads to anisotropy.

4. CONCLUSIONS

Fundamental relationships of anisotropy, texture and strain rate during deformation have been investigated.

(1) For strain rate dependence, strain rate dependence on maximum stress is a little found, in contrast with this, the failure strain strongly depends on the strain rate at room temperature. The failure strain decreases with increasing the strain rate. At higher temperatures of 150℃ or 220℃, maximum stress increases with increasing the strain rate. The failure strain at 150℃ shows a peak value at strain rate of 10^{-2}, and the failure strain at 220℃ shows the lowest level at strain rate of 10^{-3}. Twinning is found at the condition of higher strain rate and the orientation of 90 degree at room temperature.

(2) With effects of anisotropy on tensile properties, there is a significant anisotropy both maximum stress and failure strain, at room temperature. At higher temperatures, no anisotropy is found on maximum stress, regardless of anisotropy of the failure strain remains.

(3) There is some difference of properties between annealed and as-rolled specimen. Maximum stress of as-rolled specimen is higher at room temperature, and the failure strain of as-rolled specimen is lower than that of annealed one. Especially, at the orientation of 0 degree and the strain rate of 10^{-4}, yield stress of as-rolled specimen is also higher than that of annealed specimen. However, at all of temperatures and strain rates, the tensile properties have been showed a same tendency in both conditions.

(4) DRX or twin occurs during deformation at higher test temperatures, and it affects the elongation-to-failure. The dynamic recrystallization which resulted fine grain structure gives a increase of failure strain. At 150℃ with strain rate of 10^{-1}, more twins have appeared on perpendicular to tensile direction.

(5) During tensile deformation at room temperature, the texture changes with increasing strains. It is found the concentration of {10-11} plane increase with increasing strain, as priority to tensile direction. Fraction of the low angle boundaries increase when the strain has been given.

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