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Microscopic Surface Change of Polycrystalline Aluminum during Tensile Plastic Deformation

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Roughening on free surface of polycrystalline metal during plastic deformation is closely related to the inhomogeneous deformation in the respective grain at the surface. Uniaxial tensile tests are carried out on annealed pure aluminum sheet specimens with various averaged grain sizes. The roughening is measured by a 3-dimensional stylus instrument to examine the roughness change in both sides of specimen surfaces at each strain. The irregularities on one side are reversed on the backside, when the averaged grain size is as large as the thickness of the specimen. Discussions are made on the relation between the surface shapes of both sides adopting the cross correlation factor. The strains of respective grains are also measured from the grain boundary shape before and after plastic deformation. There are some deviations in the strains of the grains and their standard deviation increases with the applied strain.

1. INTRODUCTION

In recent years, highly precise products or ultra-small products are often needed, and the development of new precise processing methods and the improvement of the conventional processing methods are important problems. So, the study of roughening of free surface which influences the accuracy of plastic forming has been done analytically and experimentally [1]~[5]. Namely, when plastic deformation occurs in polycrystalline metal, minute unevenness is formed on the free surface and develops with plastic deformation. It was pointed out that such surface roughening is influenced by the averaged grain diameter or the strain path [2,6]. This is caused by the complicated deformation of grains in polycrystalline metals. Then, it is expected that the microscopic deformation behavior of polycrystalline metals is clarified by examining various characteristic of the surface roughening.

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The surface roughening during plastic deformation has the following characteristics: (a) The surface roughness is ε measurable parameter which reflects the non-uniform plastic deformation of polycrystalline metals. (b) The inhomogeneous deformation inside the material is estimated from the observation of the surface change, though there is quantitative difference between the deformation inside and that on the surface [7]. There are no means to measure the non-uniform deformation inside the material directly. (c) The surface roughness due to inhomogeneous deformation can be measured precisely within short time. (d) Averaged behavior of non-uniform deformation is measured on the surface, and the surface roughness is a parameter having various information on the inhomogeneous deformation.

In the present paper, experiments are done adopting four kinds of pure aluminum specimens with different grain size, to clarify the influence of the grain size on microscopic deformation behavior. The free surface shape after uniaxial tensile deformation is measured using the three-dimensional surface roughness measuring apparatus developed in recent years. Discussion is made on the change in various parameters obtained from the surface roughness.

Next, the in-plane strain of respective grains is measured from the shape change of the grains. Grain boundary lines are used as the measure of deformation before and after tension. Discussion is made on the non-uniform deformation behavior of polycrystalline metals based on the change of the above mentioned parameters.

2. EXPERIMENTAL PROCEDURES

2.1 Specimen and Tensile Test

The material used in the present study is polycrystalline aluminum sheet of 99.999% purity with 1mm thickness. The shape and dimensions of the specimen are shown in Fig.1. The specimen surface was polished with the abrasive paper up to #2000. The annealing of specimens was done using a box furnace to remove the residual stress and to get coarse grains. Specimen T_1 was annealed first at 743K for 18ks deformed in tension for 2% and then annealed again at the same condition and slowly cooled down in the furnace. Specimens T_2, T_3 and T_4 were annealed at 743K for 36ks, at 673K for 21.6ks and at 623K for 14.4ks, respectively, then slowly cooled down in the furnace. After electrolytic polishing was applied to the specimens for distinguishing grain boundaries, the surface of the specimens was observed with an optical microscope and the average grain size was determined (Electrolytic polishing liquid: phosphoric acid: ethanol: distilled water= 400ml: 380ml: 250ml). The obtained averaged grain diameters are 998μm (Specimen T_1), 527μm (T_2), 322μm (T_3) and 208μm (T_4). These values correspond to about 1 time, 1/2 times, 1/3 times and 1/4 times of the specimen thickness, respectively. It was also confirmed from the result of microscopic observation of the cross section of Specimen T_1 that the identical grain does not appear on the front and the back surfaces at the same time.

The indentation marks are placed on the corners of the observed area of 7×7mm^2 on the front surface (F-surface) as well as the same position of the back surface (B-surface) of the specimen, using the micro Vickers hardness testing machine. The marks were also used to measure the applied strain.

The tensile test of the specimen was done with the crosshead speed 0.5mm/min. up to a certain fixed amount of strain and then the specimen was taken out from the tensile testing machine (Shimadzu Co., DSS-5000) and the surface roughness was measured. The applied engineering strains were 0.03, 0.06, 0.09, 0.12, which correspond to the true strains of ε = 0.029, 0.058, 0.086, 0.113, respectively.

2.2 Measurement of Surface Profile

The surface shape before and after the tensile deformation was measured with the stylus surface roughness measuring instrument (Tokyo Seimitsu Co., SURFCOM 1400D, Fig.2). The tip of the stylus is a cone with 1μm radius and 90 degree angle. The stylus was run in the axial direction. The measuring interval was 20μm for both in the axial and in the transverse directions. The measuring length was 8.0~10.0mm and the traveling speed was 0.3mm/sec under the condition without cut-off (Profile).

In order to clarify the relation between the surface roughness and the deformation of grains, the grain boundary map was drawn from the optical micrographs of the surface and superimposed with the contour map of the surface roughness pattern. As the measure of the surface roughness, the center line averaged roughness R_a has been widely used [4,5]. In the present paper, the three-dimensional surface roughness R_{a3} was employed, which is the extended measure of the surface roughness for a certain area. It is given by the averaged value of the difference between the observed height and the averaged height plane as follows.

$$R_{a3} = \frac{1}{A_0} \int_0^{y_l} \int_0^{x_l} \left| F(x,y) - z_0 \right| dxdy \qquad (1)$$

A_0 is the measured surface area. x_l and y_l are the measuring lengths in x- and y-direction, respectively.

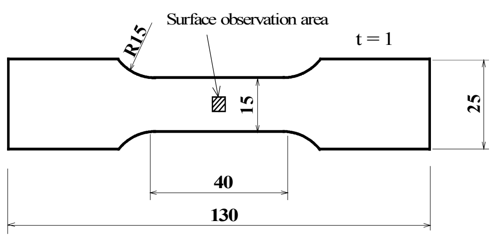


Fig.1 Aluminum specimen used for tensile test (unit mm).

Fig.2 Three-dimensional surface roughness measuring instrument.

$F(x, y)$ is the height of the point (x, y) and z_0 is the averaged height in z-direction.

It was reported [2] that the surface roughness R_a is proportional to the applied strain ε and the averaged grain size d and expressed as follows.

$$R_a = C \cdot d \cdot \varepsilon \tag{2}$$

In order to get more precise correlation between the surface roughness and the averaged grain size, we propose here the following relation between the surface roughnesses R_{a3}, the applied strain ε and the averaged grain size d.

$$R_{a3} = C' \cdot d^n \cdot \varepsilon = \alpha \cdot \varepsilon \tag{3}$$

$$C' = R_{a3} \big/ (\varepsilon \cdot d^n) \tag{4}$$

C' is a parameter depending on the deformation path and the kind of metal, α is the rate of increase of surface roughness and n is an exponent indicating the effect of grain size.

Next, to find the relation between the surface roughness and the averaged inclination angle, the averaged inclination angle $S\Delta q$ of surface profile is calculated from the following relations, considering the root mean square slope [5].

$$S\Delta q = \sqrt{\frac{1}{A_0} \iint_{A_0} \{z'(x,y)\}^2 \, dxdy} \tag{5}$$

$$z'(x,y) = \sqrt{\left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2} \tag{6}$$

$z'(x, y)$ is the slope of the surface roughness profile at the point (x, y). The averaged slope defined by Eqs. (5) and (6) is obtained from the following numerical equation for discrete experimental data [5].

$$S\Delta q = \sqrt{\frac{1}{(m-1)(n-1)} \sum_{i=2}^{m} \sum_{j=2}^{n} \left\{ \left(\frac{z(i,j) - z(i-1,j)}{\Delta x} \right)^2 + \left(\frac{z(i,j) - z(i,j-1)}{\Delta y} \right)^2 \right\}} \tag{7}$$

m, n : Total numbers of measurement in loading and in transverse directions
$z(i, j)$: Surface roughness data in measuring area
Δx, Δy : Measuring intervals in loading and in transverse directions

In the present numerical calculation, Δx and Δy are chosen as 4~20 μm..

A new method was proposed to estimate the wavelength of the surface roughness profile from the averaged surface roughness R_{a3} and the averaged slope, assuming that the surface roughness curve is sinusoidal [9]. Applying this method, the wavelength l can be estimated from the value of R_{a3} in Eq.(2) and $S\Delta q$ in Eq.(7) as follows.

$$l = 2\pi R_{a3} \big/ \tan(S\Delta q) \tag{8}$$

2.3 Cross-correlation Function R_c

In order to clarify the correlation between the surface roughness patterns on the front and the back surfaces of the specimens, the normalized cross-correlation function R_c is obtained from the following relation [10].

$$R_c = \frac{\sum_i \sum_j f(i,j) g(i.j)}{\sqrt{\sum_i \sum_j f^2(i,j)} \sqrt{\sum_i \sum_j g^2(i,j)}} \tag{9}$$

$f(i, j)$ and $g(i, j)$ are the height data at the same poison (i, j) of the front and the back surfaces, respectively. When the shape of the surface curves on the front and the back surfaces are proportional, $R_c = -1$ (Fig.10 (a)). Meanwhile, when they are reversely proportional, $R_c = 1$ (Fig.10 (b)). When they have no correlation, $R_c = 0$ (Fig.10 (c)). In general, the value of R_c lies between -1 and 1.

2.4 Measurement of Strain of Grains

The deformation of about 20 grains in the surface measuring area was examined. After processing the image of the grain boundaries obtained from the optical microphotograph in a computer, the maximum lengths of respective grains in the loading direction and in the transverse direction, before and after the tension, were measured. Then, the change of plastic strain of respective grain was calculated from the following equation at each step of deformation.

$$\varepsilon_{gl} = \ln(l_{l1} / l_{l0}), \quad \varepsilon_{gt} = \ln(l_{t1} / l_{t0}) \tag{10}$$

ε_{gl}, ε_{gt} : Strains of grains in loading and in transverse directions
l_{l0} : Maximum grain length in loading direction before tensile deformation
l_{l1} : Maximum grain length in loading direction after tensile deformation
l_{t0} : Maximum grain length in transverse direction before tensile deformation
l_{t1} : Maximum grain length in transverse direction after tensile deformation

The standard deviation S of the strain of grains is given as follows.

$$S = \sqrt{\sum_{i=1}^{N} (\varepsilon_i - \bar{\varepsilon}_x)^2 \big/ (N-1)} \tag{11}$$

ε_i is the measured strain, $\bar{\varepsilon}_x$ is the averaged strain and N is the number of measurements.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Change in 3-D Surface Profile with Applied Strain

Figs.3 (a)~(d) show the superimposed figures of the grain boundary maps and the contour maps at the strain of ε = 0.029 and 0.113 for Specimen T_1. Figs.3 (e)~(f) show the overhead view of the surface roughness shape at the strain ε = 0.113. F surface and B surface in Fig. 3 represent the front and the back surfaces, respectively. The area PQRS on the front surface corresponds to the area P'Q'R'S' on the back surface.

Similarly, the combined figures for Specimen T_2, T_3 and T_4 at the strain ε = 0.113 are shown in Figs.4~6, respectively. The height of the surface roughness is divided equally into seven levels between the maximum and the minimum values. The white parts show mountains (higher value area) and the black parts show valleys (lower value area). The thick lines in the figure are grain boundaries.

It is seen from Figs.3~6 that the height difference of the surface roughness increases with the applied strain, while the relative position of the mountains and the valleys almost remain unchanged with respect to grain configuration. Furthermore, most of the peaks of the mountains lie near the grain boundaries. This implies that the observed surface roughness is strongly related to the non-uniform deformation of grains and resulted from surface inclination composed of several grains [7]. Many mountains lie along the grain boundaries and elongate in the direction of the loading axis with the increase of the applied strain.

In the case of Specimen T_1 with large grain size, the mountain on the front surface corresponds to the valley on the back surface. That is, the surface roughness pattern

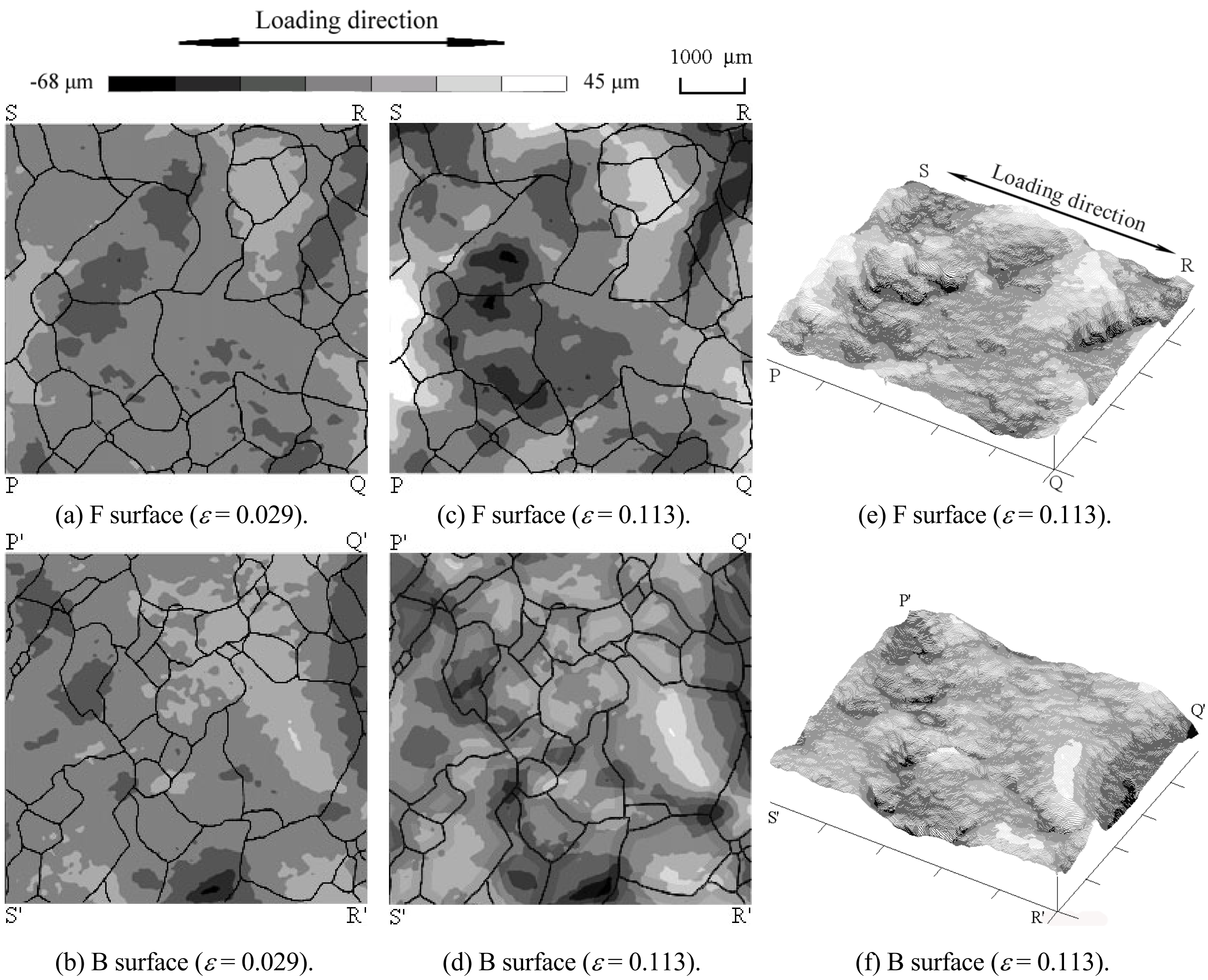
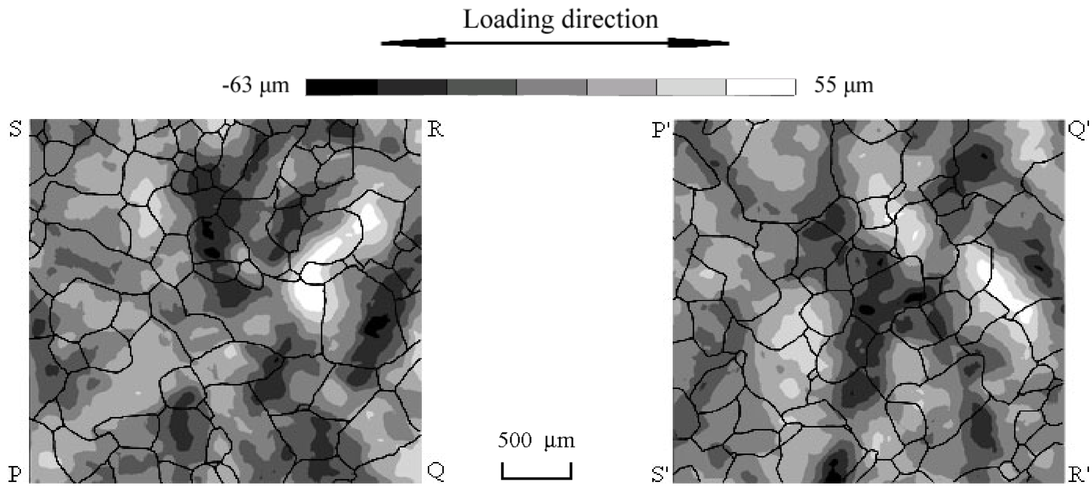
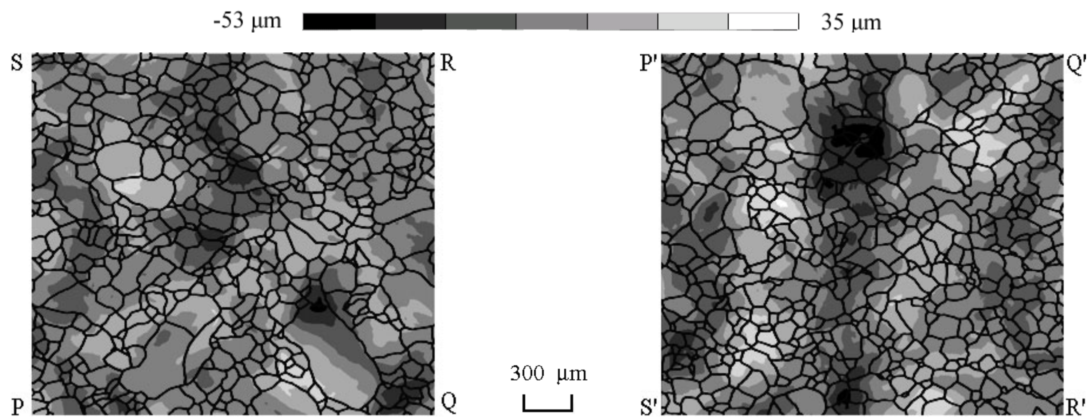


Fig.3 Change in 3-D surface shape of T_1 specimen (d = 998µm).



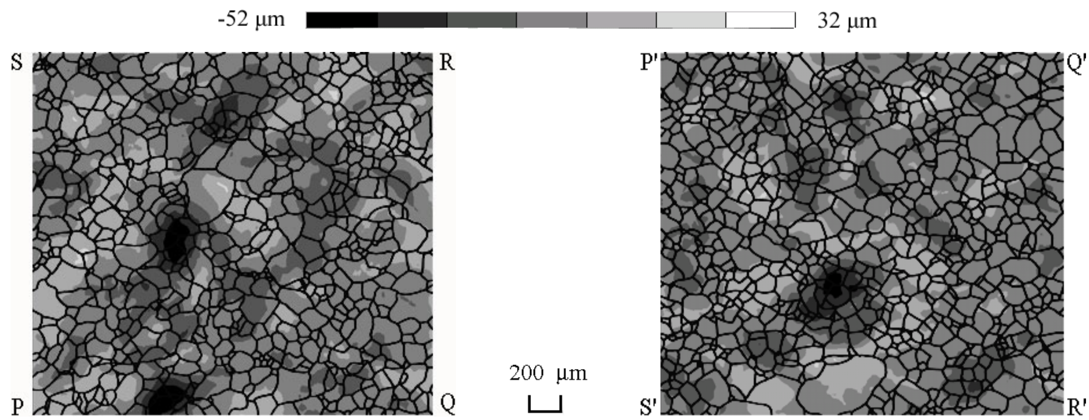
(a) F surface ($\varepsilon = 0.113$). (b) B surface ($\varepsilon = 0.113$).

Fig.4 Change in 3-D surface shape of T_2 specimen (d = 527µm).



(a) F surface ($\varepsilon = 0.113$). (b) B surface ($\varepsilon = 0.113$).

Fig.5 Change in 3-D surface shape of T_3 specimen (d = 322µm).



(a) F surface ($\varepsilon = 0.113$). (b) B surface ($\varepsilon = 0.113$).

Fig.6 Change in 3-D surface shape of T_4 specimen (d = 208µm).

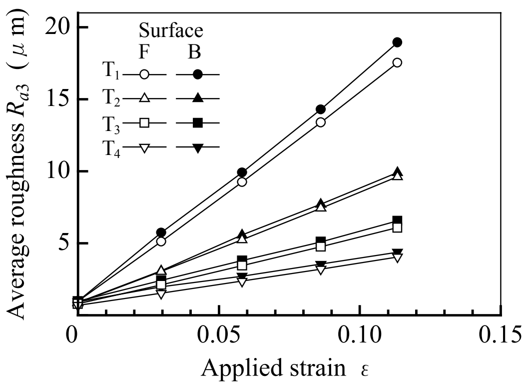


Fig.7 Change in averaged roughness with applied strain.

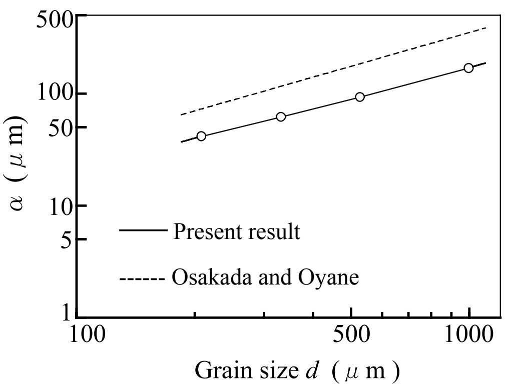


Fig.8 Relation between factor α and grain size.

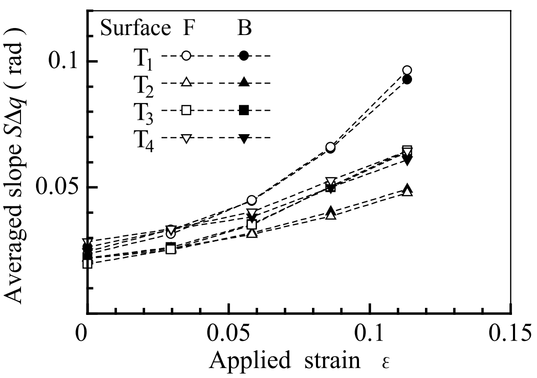


Fig.9 Change in averaged slope $S\Delta q$ with applied strain.

is almost reversed. Meanwhile, the correlation is hardly observed between the shapes of the front and the back surfaces for Specimens T_3 and T_4 having small grain size.

3.2 Change in Surface Roughness

Fig.7 shows the change in the averaged roughness R_{a3} with the applied strain ε. The value of R_{a3} increases linearly with the applied strain ε for all specimens. The increasing rate of the surface roughness R_{a3}, however, is large for Specimen T_1 with the largest grain size. This is in accordance with the previous report [2] that the increasing rate of the surface roughness becomes large with the increase of the averaged grain size. Fig.8 shows the relation between the rate of increase α (= R_{a3}/ε) of surface roughness and the averaged grain size *d*. The result of Fig. 8 is considered to support Eq. (3). When the value of *n* in Eq. (3) is calculated with the least square method from the data obtained by Osakada and Oyane [2] for 52S-Aluminum, $n \fallingdotseq 0.88$ is obtained. The value of *n* calculated from the present experimental data is the same, that is $n \fallingdotseq 0.88$. The value of C' in Eq. (4) calculated from the present data is given as follows.

$$C' = 0.386 \tag{12}$$

It is considered that, if $n = 1$, the surface roughening is caused by the inhomogeneous deformation totally depending on the grain size, such as grain rotation [9][10]. Meanwhile, if $n = 0$, the surface roughening is considered to be caused by a factor independent of the grain size. Therefore, it may be said that $n \fallingdotseq 0.88$ means that small part of surface roughness is caused by the factors independent of the grain size, such as slip bands.

Fig.9 shows the change in the averaged inclination $S\Delta q$ obtained from Eq. (7). It is seen that the averaged inclination increases with the increase in the applied strain for all specimens. The changes in the surface roughness and the averaged inclination with respect to the applied strain are similar, and the increase in the averaged inclination angle is large for Specimen T_1 having the largest grain size. The ratio of the surface roughness R_{a3} for Specimen T_1 to that for Specimen T_4 is about six (Fig.7). On the other hand, the ratio of the averaged inclination of Specimen T_1 to that of Specimen T_4 is only about two (Fig.9). That is, the change shown in Fig.9

Table1. Wavelength of surface roughness curve ($\varepsilon = 0.113$)

Specimen	Grain diameter *d* (μm)	Surface roughness *Ra* (μm)	Averaged slope $S\Delta q$ (deg)	Wavelength *l* (μm)	Relative wavelength *l/d*
T_1	998	18.24	5.42	1212.5	1.21
T_2	527	9.76	2.78	1261.8	2.39
T_3	322	6.32	3.69	616.5	1.91
T_4	208	4.22	3.59	422.7	2.03

may be resulted from the combined effect of both the surface roughness increase with the grain size and the wavelength increase with the grain size.

Table1 shows the estimated wavelength obtained from the experimental data and Eq. (8). It was pointed out [2] that the relative wavelength with respect to the grain size is l/d = 5~7 for the aluminum specimen with small grain size [2]. Meanwhile, for the present specimens with large grain size, the relative wavelength is small, i.e. l/d = 1.2~2.3. This may be due to the independent deformation behavior of grains in the specimen with large grain size, which is in contrast with the mutually constrained deformation behavior of grains in the case of small grain size.

3.3 Change in Cross-correlation Function R_c

Fig.10 shows models of non-uniform deformation and shapes of the front and the back surfaces. Model A shows the case where the valleys are produced at the same position of the front and the back surface, and corresponds to the value of the cross-correlation function $R_c = 1$ (Eq. (9)). Model B shows the case where the valley on the front surface corresponds to the mountain on the back surface, vice versa, and $R_c = -1$. Model C is

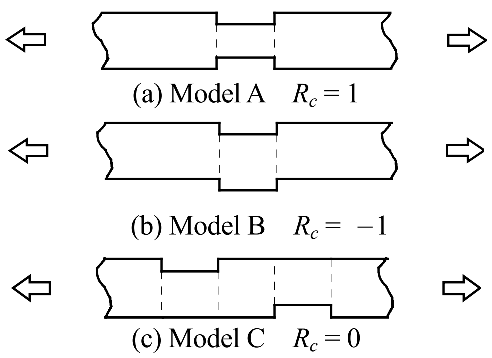


Fig.10 Models for explanation of cross-correlation function.

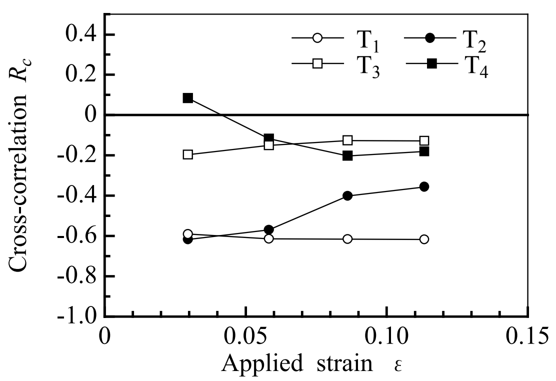


Fig.11 Relation between cross-correlation function and applied strain.

the case the shape of the front surface has no special correlation with that of the back surface, which corresponds to $R_c = 0$.

Fig.11 shows the relation between the cross-correlation function R_c of the surface roughness, the applied tensile strain and the averaged grain size d. In the case of Specimen T_1 with the largest grain size, the value of R_c is about -0.6, which indicates the surface shapes of the front and the back surface are mostly reversed. For Specimen T_2, the value is $-0.36 \sim -0.62$, which indicates the degree of reversal of surface shape decreased. For Specimens T_3 and T_4, the values of R_c are $-0.13 \sim -0.20$ and $0.08 \sim -0.20$, respectively, which show that they are not reversal.

At every step of deformation, the value of R_c for reported to be about -0.7 for the tensile deformation of specimen with large grain size is small. The value of R_c is pure iron polycrystalline sheet specimen with 1.7mm thickness, whose averaged grain size is 2.9mm [11]. Then, it may be concluded that, when the averaged grain size is nearly equal to the specimen thickness, the surface roughness pattern of the front surface is almost reversed to that of the back surface. On the other hand, when the averaged grain size is smaller than the specimen thickness, little correlation is present between the surface roughness patterns of the front and the back surface.

It is considered that such reversal of roughness is similar to that caused by colony formation of the crystal orientation distribution (collection of the crystal grain of similar orientation) and the ridging phenomenon (occurrence of wrinkles) in the sheet metal forming of ferritic stainless steel sheets [12]. Namely, the ridging is supposed to be caused by the colony formation. Although the average grain size is small in the case of ferritic stainless steel, its deformation behavior is considered to be similar to the metal with large grain size, because of the colony formation.

3.4 Strain of Grains

Next, according to the method described in Section 2.4, the deformation behavior of grains on the surface plane of polycrystalline metal was examined by measuring strain of grains ε_{gl} in the axial direction and ε_{gt} in the transverse direction. Fig.12 (a)~(d) show the change in the strain of grains for Specimen T_1~T_4, respectively. The averaged value of strain of grains in the axial direction increases almost linearly with the applied strain ε, though the rate of increase is fairly different for respective grain. Similarly, the averaged value of strain of grains in the transverse direction decreases almost proportionally with the applied strain, though the decreasing rate of grains is different for respective grain. It is also seen that the increasing rate of some grains changes at respective step of the applied strain, which may be partially attributed to

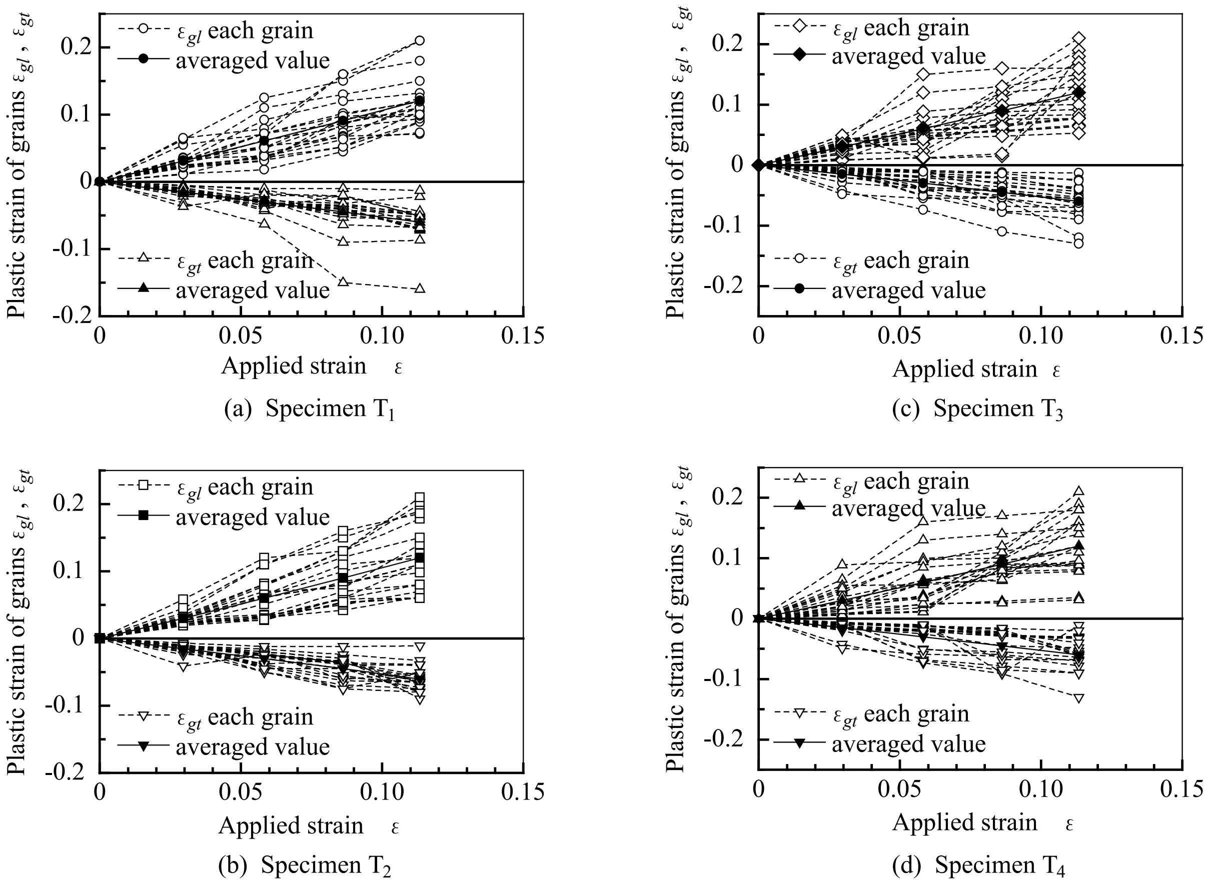


Fig.12 Relation between grain strains and applied strain. ε_{gl} and ε_{gt} correspond to grain strains in loading and transverse directions, respectively.

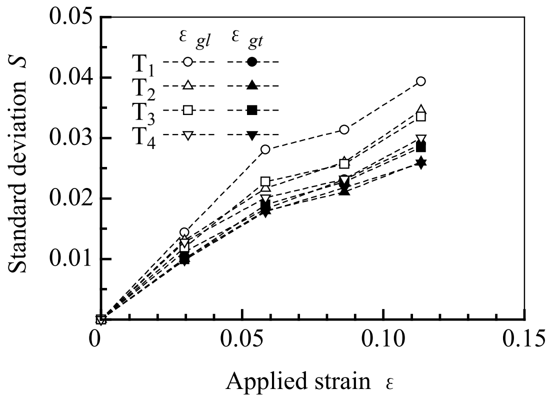


Fig.13 Change in standard deviation S of grain strains with applied strain.

the rotation of grains and the change in the active slip systems.

Fig.13 shows the change in the standard deviation S calculated from the measured strain of grains and Eq. (11). The standard deviation S also increases with the applied strain and the rate of increase is large for the specimen with large grain size. This may also suggest that the mutual constraint of grains is small for the specimen with large grain size, so that the deviation of the strain of grains becomes large.

4. CONCLUSIONS

Tensile tests were performed on polycrystalline pure aluminum sheet specimens with different grain size and the change in microscopic surface profile was examined in detail. By using the three-dimensional surface roughness measurement apparatus, the correlation between the deformation of grains on the front surface and that on the back surface was examined. The main results are summarized as follows.

(1) The surface roughness increases with the applied plastic strain, and the increase is high for the specimen with large grain size. The height difference of the surface profile increases with the applied strain, while the position of the surface wave with respect to the grain configuration remains nearly unchanged.
(2) The averaged inclination angle of the surface roughness wave increases with the applied strain.
(3) The profile of the front surface is nearly reversed with that of the back surface for the specimen with large grain size. This is also confirmed numerically by calculating the cross-correlation function from the profile data of the both surfaces.
(4) In the case of present polycrystalline aluminum with large grain size, the ratio of the wavelength to the grain size is about 1.2~2.3, which is fairly smaller compared with that of the aluminum specimen with small grain size.
(5) Strain of grains on the surface plane is obtained from the change in the grain boundary shape. The strain of grains, as well as the standard deviation of the strain, increases with the applied strain. The value of the standard deviation is large for the specimen with large grain size.

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REFERENCES

[1] M. Oyane and K. Osakada, Trans. Japan Soc. Mech. Eng., **35** (1969), 673.
[2] K. Osakada and M. Oyane, Trans. Japan Soc. Mech. Eng., **36** (1970), 1017.
[3] T. Abe, Bulletin JSME, **19** (1976), 1420.
[4] T. R. Thomas, Rough Surfaces, (1982), Longman.
[5] T. R. Thomas, Rough Surfaces, 2nd.ed (1999), Imperial College Press.
[6] A. Azushima and M. Miyagawa, J. Japan Soc. Tech. Plasticity, **27** (1986), 1261.
[7] T. Abe, T. Nosho, Y. Z. Tai, M. Matsuzaki and I. Shimizu, Trans. Japan Soc. Mech. Eng., **A-61** (1995), 1562.
[8] T. Abe, I. Shimizu and T. Nishiyama, Trans. Japan Soc. Mech. Eng., **A-57** (1991), 2587.
[9] H. L. Song, T. Abe and N. Tada, submitted to J. JSMS.
[10] T. Abe, I. Shimizu, T. Nosho and S. Nagaki, Advances in Engineering Plasticity and Its Applications, eds. B.Y. Xu and W. Yang, Int. Academic Pub., (1994), 191.
[11] T. Abe, S. Okada, I. Shimizu, S. Tomosada, E. Iizuka and T. Kobayashi, Key Eng. Mat., **Vols. 177-180** (2000), 141.
[12] S. Sato, T. Ujiro and K. Ishii, Kawasaki Steel Giho, **31** (1999), 28.