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Surface roughening and formability in sheet metal forming of polycrystalline metal based on *r*-value of grains

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ABSTRACT

The *r*-value is defined as the ratio of the width strain to the thickness strain. It was pointed out that the *r*-value can be defined for each grain in polycrystalline metal during plastic deformation. Based on *r*-value of grains, a model of plastic deformation of polycrystalline metal and surface roughening after plastic deformation is proposed in the present paper. Various experimental features of the surface roughening under uniaxial stress are well explained with the present first model.

Meanwhile, the *r*-value is also known as a measure of formability in the sheet metal forming process. Marciniak and Kuczynski proposed the so-called M–K model which gives the analytical estimation of the formability of sheet metal under biaxial stretching considering a certain irregularity of the thickness of the sheet metal. Yamaguchi et al. showed that the experimentally measured surface roughness may correspond to the surface irregularity suggested in the M–K model. In the present paper, the formability of sheet metal under biaxial stretching is analyzed based on the surface roughening model caused by the difference of the *r*-value in sheet metals.

1. Plastic deformation and surface roughening of polycrystalline metal based on *r*-values of grains

The *r*-value is well known as a parameter representing the formability of sheet metals. The *r*-value is suggested by Hill [1] and its importance in sheet metal forming verified experimentally by Lankford et al. [2]. When uniaxial stress is applied in 1-direction and the surface normal is in 3-direction, the *r*-value is defined as the ratio of the width strain to the thickness strain [1]

$$r = \varepsilon_2/\varepsilon_3 \quad (0 \le r \le \infty) \tag{1}$$

The relation between slip system and *r*-value is schematically shown in Fig. 1.

In general, the volume constancy is maintained for plastic deformation of metals

$$\varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0 \tag{2}$$

Then,

$$\varepsilon_3 = -(\varepsilon_1 + \varepsilon_2) \cong -\varepsilon_A, \tag{3}$$

where ε_A is the grain-area strain. ε_A is measurable from the experimentally obtained images of a certain grain on the surface of specimen before and after plastic deformation, hence ε_3 is determined for each grain.

Song and Abe [3] pointed out that by using instruments such as laser-scanning microscope, *r*-value can be defined for respective grains in polycrystalline metal from the changes of grain profile or grain area during plastic deformation using Eqs. (1)–(3). An example of the measured change in the grain area strain $\varepsilon_A = -\varepsilon_3$ with the applied strain ε_1 is shown in Fig. 2 [4] (the material is polycrystalline pure aluminum). It is seen that the strain ε_3 normal to the surface is quite different from grain to grain. This fact indicates that the surface roughening is closely related to the *r*-value of grains.

Based on the *r*-value of grains, a model of plastic deformation of polycrystalline metal and surface roughening after plastic deformation under uniaxial stress is proposed, which explains various aspects of experimental data on surface roughening qualitatively [5].

1.1. Experimental background of surface roughening after plastic deformation

A flat surface of polycrystalline metal is roughened after plastic deformation. Various experimental investigations have been done for the surface roughening of polycrystalline metal after plastic deformation. The characteristic features of the experimentally observed surface roughening are summarized as follows:

1. The surface roughness increases with plastic strain ε.
2. The surface roughness increases with the grain size d. Namely, the following relation was experimentally obtained [6]

$$Ra = cd\varepsilon \tag{4}$$

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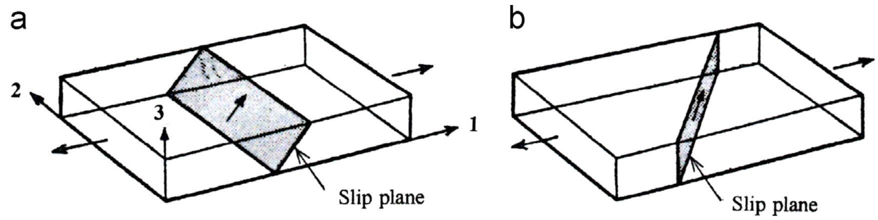

Fig. 1. Relation between slip system and r-value of sheet specimen under uniaxial stress in 1-direction.

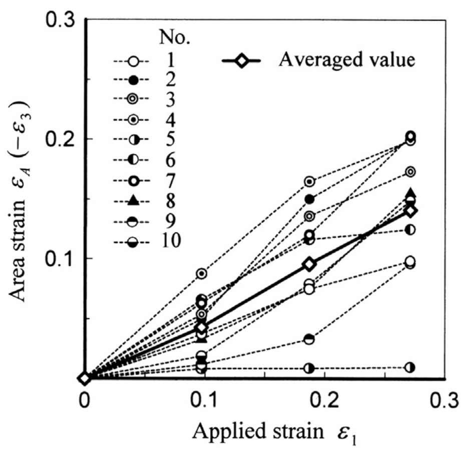

Fig. 2. Change in grain area strain ε_A , that is, strain $(-\varepsilon_3)$ normal to surface, with tensile strain ε_1 for various grains (nos. 1–10) [4].

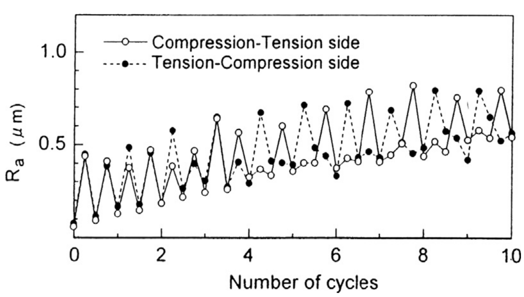

Fig. 3. Change in roughness Ra with the number of cycles during alternative straining in cyclic bending test [7].

Ra is the averaged surface roughness and c is a non-dimensional parameter determined by experiments. Usually, c takes the value around 0.1–0.3 for various polycrystalline metals.

3. The surface roughness during compressive deformation is larger than that during tensile deformation [6].
4. The surface roughness slightly increases after reversed tensile and compressive deformation. Fig. 3 shows an example of experimental data during alternative tensile and compressive straining in cyclic bending test [7] (the material is polycrystalline pure iron). Although the values of surface roughness increase or decrease according to the alternative plastic bending, their averaged value increases with the number of cycles.
5. The wavelength of the surface roughening curve is about 10 times of the averaged grain diameter [6].

1.2. Model of polycrystalline metal and surface roughening

We consider a simple model (Fig. 4) of plastic deformation of polycrystalline metal with different r-values for respective grains and surface roughening after plastic deformation. For the sake of simplicity, we assume the following for Model I [5]:

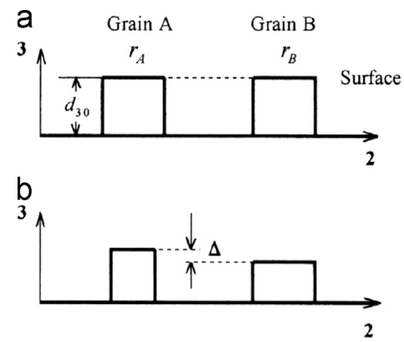

Fig. 4. Model I of plastic deformation of polycrystalline metal having different r-values for respective grains and surface roughening after deformation (uniaxial stress is applied in 1-direction).

1. The strain in the loading direction (1-direction) is equal for all grains.
2. The grains lie on a certain base plane which is parallel to the surface, as shown in Fig. 4.
3. Mutual constraint between grains is not considered.

The following relation is obtained from Eqs. (1) and (2):

$$\varepsilon_3 = -\frac{1}{1+r}\varepsilon_1 \tag{5}$$

When the r-values of grains A and B are denoted as r_A and r_B, respectively, the absolute value of the surface roughness Δ of the model shown in Fig. 4 is given by

$$\Delta = |(\varepsilon_3 d_3)_A - (\varepsilon_3 d_3)_B| = \left|\frac{r_A - r_B}{(1+r_A)(1+r_B)}\varepsilon_1\right| d_3 \tag{6}$$

Next, we consider the change in grain size in 3-direction after plastic deformation. Namely the grain size after plastic deformation is approximately given by

$$d_3 = d_{30}(1+\varepsilon_3) \tag{7}$$

where d_{30} is the initial grain size in 3-direction (Fig. 4). Then, from Eq. (6)

$$\begin{aligned}\Delta &= |(\varepsilon_3 d_3)_A - (\varepsilon_3 d_3)_B| \\ &= \left|\frac{r_A - r_B}{(1+r_A)(1+r_B)}\varepsilon_1 + \frac{(r_B - r_A)(2+r_A+r_B)}{(1+r_A)^2(1+r_B)^2}{\varepsilon_1}^2\right| d_{30}.\end{aligned} \tag{8}$$

It is considered that the mean average roughness Ra [Eq. (4)] obtained by experiments is a certain average of the roughness Δ given by Eq. (8) for various values of r_A and r_B, that is, for various grain orientations. Numerical simulation, however, might be necessary to discuss the relation between Ra and Δ in detail.

We assume here, without loss of generality, that $r_A \geq r_B$. We consider Δ^+ and Δ^- which denote the absolute value of the roughness under the applied tensile and compressive strains ε_{10} and $-\varepsilon_{10}$ $(\varepsilon_{10} \geq 0)$, respectively. The strain ε_{10} is usually small