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On the Roughening of Free Surface in Deformation Processes*

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Conditions governing the roughening phenomenon of free surface in deformation processes are investigated. It is shown that the surface roughness increases with strain, and the roughening rate is affected by the mode of deformation (tension and compression), and by the position of the surface. The effects of the deformation mode and the position of the surface are related with change of the surface area during deformation. It is also found that the roughening rate is affected by grain size and the lattice structure of the metal, i.e. the roughening is remarkable in the metal of large grain size and of small number of slip systems. Wave length of the roughness is about 10 times as large as the grain size. Theoretical analysis of the wave length is carried out on the basis of probability.

1. Introduction

In the metal forming processes such as swaging and sheet metal forming, a free surface, which is not in direct contact with the tool, becomes roughened with an increasing amount of deformation. This phenomenon prevents fine finishing of the product and is called "orange peel". Surface roughness of the deformed metal was studied in the past by O. Kienzle⁽¹⁾ and a few other investigators⁽²⁾. It is said that the surface roughening is remarkable in the metal of large grain size, and that the method or the mode of deformation has a significant effect on the surface roughness. To reduce the roughening which is induced by deformation, the metal sheets of small grain size have been used for press forming.

Because the roughening phenomenon is one of the main factors determining the fraction of true contact area between tool and work piece in the lubricated condition, the phenomenon has also been investigated in the studies of lubrication and friction in metal processing⁽³⁾⁻⁽⁶⁾.

Most of these studies, however, are qualitative investigations, and no theoretical treatment has been done. This paper is a quantitative and theoretical study of the roughening of free surface during deformation.

2. Effect of deformation mode

In order to examine the effect of deformation mode such as compression and tension, and the effect of the position of the surface depending upon whether the surface is situated at the side or the end of the specimen, compression and tension tests are carried out.

The material used is 52S aluminium containing magnesium as much as 5%, and the specimens are annealed for 1 hour at 360°C after machining. The surfaces of the specimens are polished to mirror surfaces with emery 06 paper, and the center line average roughness (H_{CLA}) is 0.05~0.1 μ m. The mean grain size of the specimens is 40 μ m. The tension and compression tests are carried out in a 30 ton universal testing machine.

In Fig. 1 are shown relations between logarithmic strain (longitudinal direction) and surface roughnesses of the specimens deformed under tension and compression. The measurements of roughness are carried out in parallel direction to the specimen axis for the side surface with Talysurf model 3. The free surface is also obtained at the end surface of compression specimen as follows.

Under high speed compression testing, a very thick film of (0.05~0.1 mm) liquid lubricant has been trapped between the tool and the specimen as shown in Fig. 2, and no direct contact between the tool and the specimen has taken place at the central part of the end surface⁽⁷⁾. Because the roughening of the surface is not prevented

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by the tool in this case, the end surface of the dynamically compressed specimen is considered to be a freely roughened surface, though hydrostatic pressure of the lubricant acts on the surface.

As shown in Fig. 1, the surface roughness increases with increasing strain in these three cases, but the rate of roughening differs in each case.

It is difficult to relate the difference of roughness directly with the stress state, because the deformation of the metal is controlled by shear stress, and the state of shear stress at the side surface of the tension specimen is same as that of the compression specimen.

The difference of roughness due to deformation mode is related to the amount of surface area change during deformation. For example, the area of side surface of compression specimen decreases with increasing strain, whereas the area of tension specimen increases. When the area increases, the roughness wave may be stretched and the height of the wave may become lower than that of the surface deformed to the same

Fig. 1 Effects of logarithmic strain, deformation mode, and position of the surface on roughness of 52S aluminium specimens

Fig. 2 Schematic illustration of lubricant trapping under high speed compression. The specimen contacts with the tool only at its periphery.

strain without area change. The degree of roughness change is treated theoretically on the basis of this conception.

Consider a trace of roughened free surface as shown in Fig. 3 (a). The center line average roughness is defined as follows:

$$H_{CLA} = \frac{1}{L} \int_0^L |f(l)| dl \quad (1)$$

where $f(l)$ is the distance from the center line to the trace. l and L are defined in Fig. 3 (a).

As the recorded trace is difficult to treat theoretically, a so-called "bearing curve" shown in Fig. 3 (b) is drawn from the recorded trace in the following manner. At first many straight lines are drawn in parallel to the center line on the record, and the fraction of the line within material side is calculated. The bearing curve can be obtained by plotting the fraction as the abscissa and the distance from the center line to the position of the line as the ordinate. The fraction of material side in the bearing curve can be considered to be the fraction of area at the depth.

It is already shown⁽⁵⁾ that the roughened free surface can be represented by a straight line in the bearing curve as shown by Fig. 4 and that this simple model agrees well with the actual surface. For this model, the center line average roughness is written as follows from Eq. (1):

$$H_{CLA} = 0.5h \quad (2)$$

This means that the value of h increases when

(a) Surface trace (b) Bearing curve
Fig. 3 Recorded surface and bearing curve

Fig. 4 Model of freely deformed surface in the bearing curve

the roughness increases with strain.

Using this model, effect of change of surface area on the surface roughness is analyzed. The change of surface roughness and the change of surface area occur simultaneously in the actual deformation. But they are separated in this analysis for simplicity, i. e. the roughness change due to deformation without area change is treated at first, and then the roughness variation due to area change is considered.

It is assumed that the roughness increases linearly with logarithmic strain, when the surface area does not change, and written by

$$H_{CLA}^0 = \alpha \epsilon \quad (3)$$

where α is the roughening rate and subscript 0 designates the case of the deformation without area change. When the area change is considered subscript 1 is used.

The area change can be expressed in the bearing curve by plotting the area of the material side as the abscissa instead of the fraction of material side. In Fig. 5 is expressed the effect of area change on surface roughness. Volume of the material is assumed to be constant before and after area change in the layer from the peak to the bottom of the roughness wave.

Then

$$(\triangle A_0 O B_0) = (\triangle A_1 O B_1)$$

so that

$$\frac{H_{CLA}^0}{H_{CLA}^1} = \frac{h_0}{h_1} = \frac{S_1}{S_0} \quad (4)$$

where h_0 , h_1 , S_0 , and S_1 are defined in Fig. 5.

In Table 1 are listed the values of S_1/S_0 as

Table 1 Difference of S_1/S_0 by the mode of deformation and position of the surface

Deformation mode	Surface position	S_1/S_0
Tension	Side	$\sqrt{1+e}$
Compression	Side	$\sqrt{1-e}$
	End	$1/(1-e)$

Fig. 5 Illustration of effect of surface area change on surface roughness

a function of nominal strain e for the deformation modes and the positions of the surface.

Using Eq. (3) and Eq. (4), the surface roughness of tension and compression specimens are calculated and the results are presented in Fig. 6. The side surface of compression specimen becomes rougher than that of tension specimen, and the difference of roughness becomes remarkable with increasing strain. For the compression specimen, the side surface becomes rougher than that of the end surface. All these tendencies correlate well with those shown in Fig. 1.

The hypothetical surface roughness H_{CLA}^0 can be obtained from Eq. (4),

$$H_{CLA}^0 = H_{CLA}^1 \cdot \frac{S_1}{S_0} \quad (5)$$

where H_{CLA}^1 is the measured value of roughness.

In Fig. 7 is shown the relation between H_{CLA}^0 and logarithmic strain ϵ . All of the calculated points tend to lie on a straight line as predicted. This shows that the effects of deformation mode

Fig. 6 Theoretical result of effects of strain, deformation mode, and position of surface on surface roughness

Fig. 7 Relation between H_{CLA}^0 and logarithmic strain

and position of surface are attributable to the area change during deformation.

3. Effect of grain size and lattice structure

O. Kienzle⁽⁸⁾ indicated that the roughness of the free surface increases with increasing grain size. In this section, quantitative relation between α , the roughening rate in case of no area change, and grain size is investigated.

From Eq. (3) and Eq. (4), we have

$$\alpha = \frac{H_{CLA}^0}{\epsilon} = \frac{1}{\epsilon} \frac{S_1}{S_0} H_{CLA}^1 \quad \dots\dots\dots (6)$$

where α is calculated by substituting measured values of H_{CLA}^1 and ϵ and S_1/S_0 into the equation. In the former report⁽⁶⁾, the relation between H_{CLA}^1/ϵ and grain size* d is obtained for the end surface of a compression specimen of the 52S aluminium. By using the results in the reference (6), α is calculated and the results are plotted on the log-log scale in Fig. 8. Although little scatter due to the error of grain size measurement exists, the points tend to lie on the straight line showing that α is proportional to the grain size, and the relation is written by

$$\alpha = 0.35d.$$

This tendency that the roughening rate is proportional to the grain size suggests that the mechanism of surface roughening during deformation depends on the distortion of grain, and not on the smaller scale mechanism such as slip band. On this basis, the effect of lattice structure on the surface roughness is discussed.

Let us consider a grain in a polycrystalline metal deforming under compression. If there exists only one slip system in the metal, the grain can not be deformed in the same way as

Fig. 8 Effect of grain size on roughening rate α for 52S aluminium

* grain size(mm) = $\sqrt{1/\text{number of grains in } 1\text{mm}^2}$,

the macroscopic deformation, and the grain is distorted as shown in Fig. 9 (a). But when the number of slip systems available is large enough as shown in (b), the grain can be deformed in conformity with the macroscopic deformation. Therefore, it can be considered that the roughening tendency is noted in the metal having a small number of slip systems.

In the actual metals, however, 5 degrees of freedom of deformation is necessary to prevent gaps between grains. Besides, twin deformation takes place in some metals. Because of such complexity, the quantitative analysis of the effect of number of slip systems is difficult to perform, but it is thought that qualitative comparison is valid.

The main slip systems for each lattice structure are as follows:

For the close packed hexagonal lattice metals, the principal slip system is $\{0001\} \langle 11\bar{2}0 \rangle$, and the number of the slip systems is 3. Sometimes twin deformation occurs and another system is active.

For the face centered cubic lattice metals, the slip system is $\{111\} \langle 110 \rangle$, and the number of the systems is 12.

The slip planes of Fe, the body centered cubic lattice metal, are $\{110\}$, $\{112\}$ and $\{123\}$, and the direction of slip on the planes is $\langle 111 \rangle$. The number of the slip systems is 48. In the special case, Fe containing 4% Si has only a slip system of $\{110\} \langle 111 \rangle$, and the number of systems is 12.

It can be said that the number of slip systems is largest in b.c.c. metals and smallest in c.p.h. metals.

In order to examine the effect of lattice structure on roughening of free surface, compression tests are carried out on the specimens of Mg, Zn (c.p.h.), Cu, 70-30 brass, 18-8 stainless steel (f.c.c.), Fe containing 0.03% C, and ferritic 13Cr stainless steel (b.c.c.). The surface roughnesses are measured on the side surfaces of the specimens. To avoid the effect of Lüders band, the experiments on Fe specimens

Fig. 9 Schematic illustration of distortion of grain during deformation

are carried out after prestraining the specimens in advance about 10% under compression. The other specimens are tested in the annealed condition. The values of α/d are calculated using Eq. (6), and the results are listed in Table 2. The result for the 52S aluminium obtained in Fig. 7 is also included in the Table. The values of α/d are around 1.0 for the c.p.h. metals, 0.5 for the f.c.c. metals, and 0.25~0.2 for the b.c.c. metals. The roughening tendency is strongest in the c.p.h. metals and weakest in the b.c.c. metals as predicted. Thus the surface roughness of the metal is affected by the lattice structure.

4. Distortion of grain in internal region

Distortion of an internal grain situated in deep region from the surface is not restricted by tool like the free surface. Though a grain is surrounded by the neighbouring grains, the constraint by them may not be so strong as by the rigid tool. This suggests that the distortion of a grain might occur also in the internal region, and so an imaginary flat plane within the metal is roughened by deformation.

In order to observe roughening of an inner flat plane, a compression specimen is split into two, and all the surfaces are polished to mirror surfaces ($H_{CLA}=0.05\sim0.1\mu\text{m}$). They are piled

Table 2 α/d for various metals

Lattice	Metal	Grain size $d \mu$	$\alpha \mu$	α/d
c.p.h.	Zn	137	115	0.84
	Mg	45	52	1.15
f.c.c.	Cu	45	22	0.49
	52S-Al	—	—	0.35
	70-30 Brass	12	6	0.50
	18-8 stainless steel	35	17	0.48
b.c.c.	Fe (0.03%C)	20	4.4	0.22
	13Cr stainless steel	70	16	0.23

Fig. 10 End surface and internal plane in a specimen deforming under high speed compression

up again as shown in Fig. 10, and the specimen is compressed in a high speed hammer using mineral oil as lubricant. As mentioned in section 1, the end surfaces do not come in contact with tool at the central part and are roughened freely during deformation, while the internal plane is completely surrounded by the grains. In Fig. 11 are shown the roughnesses of the end surface and the internal plane. No significant difference between two cases is found. From this result, it is thought that the constraint by the neighbouring grains at the free surface is almost the same as that at the internal plane situated in deep region from the surface.

5. Pitch of roughness wave

In Fig. 12 is shown a recorded surface trace for the side surface of a magnesium specimen deformed under compression. The grain size is $45\mu\text{m}$ and the amount of deformation is 2%. It seems that small waves superpose on the waves of comparatively long pitch. The half pitch of the small wave is about $50\mu\text{m}$ and nearly equal to the grain size. But it is obvious from the

Fig. 11 Roughnesses of end surface and internal plane of 52S aluminium specimen deformed under compression

Fig. 12 Surface record of side surface of magnesium specimen compressed to 2%

figure that the controlling factor of roughness is the wave of long pitch.

In order to measure the mean length of roughness waves, a center line is drawn in the figure and the number of the points where the trace intersects the center line is counted. The half wave length is determined by dividing the whole length by the number of intersections. The value of the half wave length is about 250 μm for the magnesium specimen under consideration. Because the grain size is 45 μm , the pitch of the wave is about 10 times as large as the grain size. The same tendency is observed in other metals.

For the analysis of the pitch of roughness wave, some models are proposed. The simplest model is shown in Fig. 13. Each grain has a tilting angle of $+\theta$ or $-\theta$ alternatively. In this case, the wave length is twice as large as the grain size. But it is unnatural that the grains have angles alternatively.

It would be more natural to assume that each grain has a probability level of 1/2 to have an angle of $+\theta$ and also 1/2 of $-\theta$. This problem can be solved by analogy to the random walk problem in the mathematic statistics. Namely, as shown in Fig. 14 the displacement from the center line to the position of the surface changes as much as $+a$ or $-a$ for each grain size d . The probability level for $+a$ or $-a$ is 1/2.

Let us define that the half wave length is the distance from the starting point to the first intersection with the center line. Each wave length is integral times of $2d$, and has a certain

Fig. 13 A model for wave length of roughness-1

Fig. 14 A model for wave length of roughness-2

probability level to become the length. For example, the probability level is 1/2 for the half wave length of $2d$, 1/8 for $4d$, 1/16 for $6d$, 5/128 for $8d$,... Generally, the probability P for the half wave length $2nd$ (n is integer) is written by

$$\left. \begin{aligned} P &= \frac{1}{n} \binom{2n-2}{n-1} \frac{1}{2^{2n-1}} \\ \binom{l}{m} &= \frac{l!}{m!(l-m)!} \quad (l > m) \end{aligned} \right\} \dots\dots\dots (7)$$

and the mean value of the half wave length ($\omega/2$) is

$$\frac{\omega}{2} = \frac{\sum (2ndP)}{\sum P} \dots\dots\dots (8)$$

If the wave length becomes too large, it is adequate to recognize it not as roughness, but as waviness. In ordinary metals the grain size is 20~50 μm , and maximum length of roughness wave (cut off length) is several millimeters. Therefore the maximum value of n may be less than 50.

Calculations are carried out assuming maximum values of $2nd$ from $20d$ to $80d$ ($n=10\sim40$)

$$\left. \begin{aligned} \omega_{20}/2 &= \frac{\sum_{n=1}^{10} (2ndP)}{\sum_{n=1}^{10} P} \div 4.3d \\ \omega_{40}/2 &\div 5.7d \\ \omega_{60}/2 &\div 6.8d \\ \omega_{80}/2 &\div 7.8d \end{aligned} \right\} \dots\dots\dots (9)$$

The calculated values of wave length exist in a range from about $9d$ to $15d$, and agree with the observed value.

From the microscopic view point, distortion of a grain is affected by the crystal direction of the grain, and the local stress resulting from the deformation of neighbouring grains. As the direction of a grain is random in the isotropic metal, it is considered reasonable to treat the distortion of a grain on the ground of probability.

6. Conclusions

(1) The free surface, which does not contact with tool, is roughened with increasing amount of strain. The roughening rate is affected by the mode of deformation, position of the relevant surface, grain size and the lattice structure of the metal.

(2) Effects of the mode of deformation and the position of the surface are theoretically explained taking account of the variation of surface area during deformation.

(3) The roughening rate is proportional to the grain size and the roughening is remarkable in the metal having a small number of

slip systems. For the engineering metals, the rate is highest in the close packed hexagonal metals, and lowest in the body centered cubic metals.

(4) The hypothetical plane within the metal is also roughened with increasing strain, and the roughening rate of the plane is same as that of the free surface.

(5) The length of the roughness wave is about 10 times as large as grain size. An analysis of the wave length is carried out on the ground of probability. The analytical result agrees with the experimental result.

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