Effects of Rolling Texture upon the Cutting Mechanism of the Cold-rolled Material*

By Mototaro SATO**, Tsuneaki SAKAKI***, Yoshio KATO**** and Takao YAMAZAKI*****

In order to study the effect of rolling texture on the cutting mechanism, cold-rolled aluminum alloy and brass plates which have distinctive preferred orientations were used as materials to be cut. Orthogonal cutting was performed by changing the angle θ between the rolling direction and the cutting direction, and change in cutting phenomenon with θ was examined. Moreover, the obtained experimental results were analyzed by r -value and the anisotropic parameters which were determined from tensile tests of the same plates. The results showed that the effects of plastic anisotropy of the material appeared clearly at the cutting force, that is, cutting shear stress τ , was affected by the harmonic mean value r in shearing direction.

Key Words : Cutting, Cutting Mechanism, Rolling Texture, Anisotropy, Preferred Orientation, Anisotropic Material

1. Introduction

Completely isotropic materials for practical use are hardly obtained since they are somewhat subjected to plastic deformation in their manufacturing processes.

Moreover, such materials as heavily rolled magnetic materials or single crystals in semiconductor elements are widely applied for industrial use in recent years, taking advantages of anisotropic properties. Since mechanical properties are direction-dependent, plastic deformation mechanism in processing is expected to be closely related to the crystallographic orientation of the material. In the case of plastic processing, Lankford⁽⁴⁾, et al, (1950) already found that strain ratio r obtained by tensile tests is intimately related to press formability. At present, the r value representing plastic anisotropy is an indispensable factor in the discussion of the press formability⁽⁵⁾⁻⁽⁶⁾ of thin plates. On the other hand, in the case of cutting process, the cutting phenomena of heavily rolled plates or of single crystals are only analysed under isotropic assumption and few analyses are made taking anisotropy into account.

In particular, no analyses on cutting phenomena related to the crystallographic orientation of polycrystalline material have been performed so far. Firstly, the present investigation clarifies the effect of roll-

-ing reduction on the formation of aggregate structure of cold-rolled alloys, using aluminum alloy and brass as test pieces. Secondly, tensile test and orthogonal cutting tests were performed mainly on 90% aluminum alloy and 85% brass having clear aggregate structures, and effects of the structure and the plastic anisotropy on cutting mechanism were investigated in detail. The present report deals with the above results.

2. Experimental Procedure

2.1 Tensile test

1) Preparation of the specimen

Aluminum alloy and brass plates with a finished thickness of 15 mm by hot rolling and with a chemical composition shown in Table 1, were used as test pieces. After removing the prehydrogenation of the material by heat treatment at 540°C for 30 h in salt bath (for aluminum alloy) and at 500°C for 1 h in vacuum (for brass), cold rolling was performed by changing the rolling reduction from 0% to 90% by a two-high rolling mill.

Thus rolled plates with different aggregate structures were produced. Specimens were cut off from the above plate in three directions to the rolling direction, namely 0° (rolling direction), 45° and 90°, and they were machined into the JIS 6 type tensile test pieces.

Table 1 Chemical composition wt%

Aluminum alloy (5052)							
Si	Fe	Cu	Mn	Mg	Cr	Zn	Al
Si + Fe=0.45	0.10	0.10	2.4	0.2	0.2	R	

Brass (B5 P-1/4H)

Cu	Pb	Fe	Zn
58.0-62.0	<0.20	<0.20	R

* Received 19th February, 1982.

** Associate Professor, Faculty of Engineering, Shinshu University, 500, Wakasato, Nagano, Japan.

*** Associate Professor, Faculty of Engineering, Tokyo Metropolitan University, 2-1-1, Fukazawa Tokyo, Japan.

**** Professor, Faculty of Engineering, Shinshu University, 500, Wakasato, Nagano, Japan.

***** Junior Assistant, Faculty of Engineering, Shinshu University, 500, Wakasato, Nagano Japan.

2) Measurements of r values

Measurements of r values were performed on rolled plates of 90% aluminum alloy and 85% brass. Uniaxial tension was applied using an Instron type universal testing machine at the rate of 1 mm/min. The length and width of the plate which had 10% strain in the axial direction of the test piece were measured by differential transformer type displacement gauges and automatically recorded with an X-Y recorder to obtain r values.

The r value was obtained from the following equation (1),

$$r = \frac{\ln(W_0/W)}{\ln(l_0/l)} = \frac{\ln(W_0/W)}{\ln(lW/l_0W_0)} \quad \text{.....(1)}$$

Where W_0 , t_0 , l_0 , W , t , and l are the values of width, thickness, length before and after test respectively.

2.2 X-ray diffraction test

Rolled plates of 60-90% aluminum alloy and 0-85% brass were subjected to X-ray diffraction, using Cu target at a voltage of 30Kv and a current of 10mA. Reflection and transmission method were employed.

2.3 Experimental cutting

1) Specimen

The specimen is cut off from the cold-rolled plates with various rolling reduction at an interval of 15° within a range from 0° to 90°. The shape of the specimen is like a narrow paper tablet with a size of 80x3.0 x1.5 mm.

2) Cutting test

Cutting was done by an orthogonal cutting method using the longitudinal feed of a vertical milling machine. The specimen fixed to a tool dynamometer on the table of the milling machine was cut and both the principal component and the thrust component of the cutting force were measured. The shear angle was calculated from cutting ratio.

Experimental conditions and orthogonal cutting model are shown in Table 2 and Fig.1 respectively.

3. Relation between Buildup of Rolling Texture and Rolling Reduction

Table 2 Cutting conditions

Tool dimensions	Rake angle α	30 (deg)
	Relief angle γ	9 (deg)
	Nose radius r	15 (μ m)
	Tool material	SKH 9
Cutting conditions	Cutting speed v	300 (mm/min)
	Depth of cut t	0.1 (mm)
	Cutting fluid	none
Cutting mode	Orthogonal cutting

Fig. 1 Schematic diagram of orthogonal cutting model

1) For aluminum alloy

Figure 2 (a) shows the (111) pole figure illustrating the rolling texture of a rolled 90% aluminum alloy. The buildup in the (112) [111] orientation counted 2000cps, while the buildups in other orientations were extremely weak. Therefore, it might be concluded that this is a preferred orientation. Then, the rolling reduction was varied in the range from 60% to 90% and the buildup intensities in the preferred orientation (112) [111] were measured as shown in Fig.2 (b). The figure noticeably indicates the effect of the rolling reduction on rolling texture formation, where a linear rise in the buildup intensity with an increase in rolling reduction is observed.

2) For brass

Figure 3 (a) and (b) show the (100) pole figure and the relation between the buildup intensities of the preferred orientation and the rolling reduction.

Fig.2 (a) (111) pole figure of Al-alloy after 90% reduction
(b) Relation between X-ray intensity and rolling reduction

The orientation (110) $\bar{1}\bar{1}3$ was obtained as the preferred orientation of brass from the above pole figure. Similarly to aluminum, the preferred orientation of the brass raised somewhat linearly its buildup intensity with an increase in the rolling reduction, the differences being the reduction of the slope, and the buildup of the preferred orientation at 60% rolling reduction is almost saturated showing that a preferred orientation at low rolling reductions is clearly observed.

4. Difference in Plastic Anisotropy of both Alloys

As it was made clear that both rolled plates of 90% aluminum alloy and 85% brass showed noticeable rolling textures, the difference in plastic anisotropy of both plates are considered in the present chapter.

Plastic anisotropies are represented with r_θ obtained through tensile tests, anisotropic constant C, and the harmonic mean value of r_θ and $r_{\theta+90^\circ}$.

1) Where r_θ is defined as the r value of the plate making angle θ with the rolling direction as shown in Fig.5 and expressed by the following equation.

$$r_\theta = \frac{4H + (2N - F - G - 4H)\sin^2 2\theta}{4(F\sin^2 \theta + G\cos^2 \theta)} \quad \dots\dots\dots (2)$$

F, G, H and N in equation (2) are anisotropic parameters according to Hill, which are related with the r values at $\theta = 0^\circ, 45^\circ$ and 90° , as follows.

$$\left. \begin{aligned} r_0 &= H/G, \quad r_{90} = H/F, \quad r_{45} = \frac{N}{F} + G - \frac{1}{2} \\ \text{または} \\ \frac{N}{H} &= \left(r_{45} + \frac{1}{2} \right) \left(\frac{1}{r_0} + \frac{1}{r_{90}} \right) \end{aligned} \right\} \quad \dots\dots\dots (3)$$

Fig.3 (a) (100) pole figure of brass after 85% reduction
(b) Relation between X-ray intensity and rolling reduction

Therefore, the ratios among F, G, H and N are obtainable by direct measurement of r_0 , r_{90} and r_{45} .

2) Anisotropic constant C is given in the following equation using an anisotropic parameter⁽⁷⁾.

$$C = 1 - \frac{N(F+G)}{2(FG+GH+HF)} \quad \dots\dots\dots (4)$$

Tabl 3 r-values and anisotropic parameters

	90 % Al-alloy	85 % Brass
Experimental r-values	$r_0 = 0.38$ $r_{90} = 0.51$ $r_{45} = 1.08$	$r_0 = 0.32$ $r_{90} = 0.89$ $r_{45} = 0.17$
Anisotropic parameters	$F = 1.09$ $G = 1.36$ $H = 0.55$ $N = 3.93$	$F = 0.64$ $G = 1.79$ $H = 0.57$ $N = 1.62$
Anisotropic constant	$C = -0.70$	$C = 0.22$
r-value of θ direction (Cal.v.)	$r_\theta = \frac{2.20 + 3.21\sin^2 2\theta}{4.36\sin^2 \theta + 5.44\cos^2 \theta}$	$r_\theta = \frac{2.28 - 1.47\sin^2 2\theta}{2.56\sin^2 \theta + 7.16\cos^2 \theta}$
Harmonic mean r-value (Cal.v.)	$\bar{r}_{\theta, \theta+90} = 0.45 + 0.66\sin^2 2\theta$	$\bar{r}_{\theta, \theta+90} = 0.47 - 0.30\sin^2 2\theta$
Mean r-value (Cal.v.)	$\bar{r} = 0.78$	$\bar{r} = 0.32$

3) As will be later stated, yielding on the anisotropic plates under the condition of plane strain directly depends on the harmonic mean value of r_θ and $r_{\theta+90^\circ}$.

Therefore, the harmonic mean value is defined by the following equation:

$$\bar{r}_{\theta, \theta+90^\circ} = \frac{2}{\frac{1}{r_\theta} + \frac{1}{r_{\theta+90^\circ}}} = \frac{4H + (2N - F - G - 4H) \sin^2 2\theta}{2(F + G)} \dots\dots\dots (5)$$

4) In addition, the mean value of r_θ and $r_{\theta+90^\circ}$ is calculated and expressed with $\bar{r}$, to recognize the average r value of the test piece.

$$\bar{r} = \frac{1}{2\pi} \int_0^{2\pi} \bar{r}_{\theta, \theta+90^\circ} d\theta = \frac{2N - F - G + 4H}{4(F + G)} \dots\dots\dots (6)$$

Table 3 give the calculated values of each parameter using r_0 , r_{45} and r_{90} values.

In order to distinguish the difference precisely in plastic anisotropy between aluminum alloy and brass, the dependence of r_θ and $r_{\theta+90^\circ}$ of both alloy on θ is shown in

Fig.4 using polar coordinates. Figure 4 (a) shows that the r_θ value of the 90% aluminum alloy is minimum at $\theta = 0^\circ$, maximum at $\theta = 45^\circ$, and medium at $\theta = 90^\circ$. In the strict sense, the dependence of r_θ on θ is two-fold symmetry type with the period of 180° , but, the proximity of r_0 and r_{90} values leads to an

approximation of four-fold symmetry type with 90° period. Also, the $\bar{r}_{\theta, \theta+90^\circ}$ values have

a distribution of four-fold symmetry type, which yields the minimum value at $\theta = 0^\circ$ and 90° , and the maximum at $\theta = 45^\circ$. These are the characteristics of the plastic anisotropy of materials with $C < 0$. In the case of rolled plates of 85% brass, r_θ in Fig.4 (b) is minimum at $\theta = 45^\circ$, maximum at $\theta = 90^\circ$, and medium at $\theta = 0^\circ$, being distributed in two-fold symmetry type with 180° period. $r_{\theta, \theta+90^\circ}$ shows

four-fold symmetry type, being maximum at $\theta = 0^\circ$, 90° and minimum at $\theta = 45^\circ$, but the phase angle is 45° displaced compared to that of aluminum alloy. These results are characteristic of plastic anisotropy of $C > 0$ materials. The mean $\bar{r}$ value is as high as $r = 0.78$ in the case of 90% aluminum alloy, whereas it is as low as $r = 0.32$ in 85% brass.

The above results indicate a distinct difference in plastic anisotropy between the two alloys, and it is well anticipated that dependence on the cut-off angle θ of the resistance of cutting or that of the shear stress would differ between the two alloys.

Fig.4 θ dependence of r_θ and $\bar{r}_{\theta, \theta+90^\circ}$ in Al-alloy and brass

5. The Yielding Shear Stress of the Anisotropic Material under the Condition of Plane Strain

5.1 Relation between the dependence of the yielding shear stress on θ and r value of test piece.

Fig.5 Correlation between coordinate of material and coordinate of specimen

Fig.6 Relation between rolling direction and cutting direction in cutting

Two coordinate systems are placed on the rolled plate with orthogonal anisotropy as shown in Fig.5. The coordinate system X_1 of the test piece corresponds to a clockwise rotation of the coordinate system X_1 of the original material by θ degrees. Let the stress expressed by the coordinate system of

the test piece be σ'_{ij} . The following equation⁽⁷⁾ gives the yielding conditions of the plate at yielding with slip line in the X'_1 and X'_2 axes directions under plane strain condition.

Fig.7 The influence of cut-off orientation and the rolling reduction upon the specific cutting force, angle of R to cutting direction, shear stress and shear angle (Al-alloy)

Fig.8 The influence of cut-off orientation and the rolling reduction upon the specific cutting force, angle of R to cutting direction, shear stress and shear angle (brass)

$$\sigma'_{12} = (1 - C \sin^2 2\theta)^{1/2} \cdot T \quad \dots\dots (7)$$

$$\sigma'_{11} - \sigma'_{22} = \frac{C \sin 4\theta}{(1 - C \sin^2 2\theta)^{1/2}} \cdot T \quad (8)$$

Where T is the shear yield stress related to X_1 and X_2 axes, and C is an anisotropic constant defined by equation (4).

Equation (7) is transformed as follows by using the harmonic mean value r given by equation (5):

$$\sigma'_{12} = (P + Q \bar{r}_{\theta, \theta+90'})^{1/2} \cdot T \quad \dots (9)$$

Where P and Q are given by the following equations.

$$\begin{aligned} P &= \frac{2NFG - (FG + GH + HF)(F + G)}{(FG + GH + HF)(2N - F - G - 4H)} \\ Q &= \frac{\{N(F + G) - 2(FG + GH + HF)\}(F + G)}{(FG + GH + HF)(2N - F - G - 4H)} \end{aligned} \quad \dots\dots\dots (10)$$

The plus or minus of P, Q and C , the angle θ which maximizes or minimizes the $\bar{r}_{\theta, \theta+90'}$, and the relation between $\phi'_{1,2}$ and $\bar{r}_{\theta, \theta+90'}$ are determined by the size relation among N, F, G , and H .

5.2 The shear stress τ_s on the shear plane at cutting

Specimens were set as shown in Fig.6. The cutting direction CD was taken θ degrees clockwise from the rolled direction of the plate X_1 . ϕ , β and α indicated in Fig.6 represent the shear angle, friction angle and rake angle of cutting tool respectively. Let τ_s be the shear stress on the shear plane at cutting. τ_s equals to θ substituted by $\theta + \phi$ in equations (7) and (9).

$$\begin{aligned} \tau_s &= \{1 - C \sin^2 2(\theta + \phi)\}^{1/2} \cdot T \\ &= \{P + Q \bar{r}_{\theta + \phi, \theta + \phi + 90'}\}^{1/2} \cdot T \quad \dots\dots\dots (11) \end{aligned}$$

6. Effects of Plastic Anisotropy upon the Deformation Process in Cutting

6.1 The influence of cut-off orientation and the rolling reduction upon the specific cutting force, angle of R to cutting direction, shear stress and shear angle.

Figures 7 and 8 illustrate the influences of cut-off orientation and the rolling reduction on the cutting mechanism of aluminum alloy and brass, respectively. The values of annealed material (regarded to be isotropic) are also given for comparison. In Fig. 7, the specific cutting resistance K_s , shear stress τ_s , and shear angle ϕ of aluminum alloy vary regularly with 90° period when the rolling reduction exceeds 70%, while the periodicity is disturbed in rolling reduction below 60%, and that of the annealed material is completely constant.

The interesting feature is that the

above mentioned fluctuation period is concordant with previously obtained fluctuation period of r_θ or that of harmonic mean value r . The orientation dependence of the value in the direction of resultant force of resistance to cutting ($\beta - \alpha$) and the influence of rolling reduction were not noticeably observed. Figure 8 giving the values of K_s , τ_s and ϕ in brass similarly indicates a noticeable fluctuation period and the above values fluctuate with 90° period as was the case in aluminum alloy. This is obviously different from the 180° fluctuation period of r_θ in brass and is rather close to the 90° fluctuation period of harmonic mean value r .

The value in the direction of resultant force of resistance of cutting ($\beta - \alpha$) is poorly influenced by the cut-off orientation and rolling reduction as was the case with aluminum alloy. The difference between the alloys is summarized as follow. The fluctuation period of K_s , τ_s and ϕ in alloys show the 45° phase discrepancy to that of brass. Moreover, it is fact that the periodicity of the values in brass continue in even low rolling reduction (50%). The fact that rolling textures of rolled brass plates begin to change from the proximity of 50% rolling reduction explains the above phenomena.

6.2 Relation between the shear stress τ_s and harmonic mean value r

The relation between the shear stress at cutting τ_s' (denoted as experimental value hereinafter) and the angle between the rolling direction and the shear plane $\theta + \phi$ was calculated based on the data given in Figs. 7 and 8 of rolled plates of 90% aluminum alloy and 85% brass, and the are shown in Fig.9. The calculated values of τ_s using the yield stress Y ($T = \sqrt{(G+H)/2N} \cdot Y$) obtained through uniaxial tensile tests in the

Fig.9 Relation between shear stress τ_s (τ_s') and $(\theta + \phi)$. ($(\theta + \phi)$ is angle between the rolling direction and shear plane)
 τ_s' : Experimental values
 τ_s : Calculated values

rolling direction X_1 in combination with equation (11) and the harmonic mean value r of the $\theta + \phi$ direction are also given.

Figure 9 shows fluctuation of $\tau_s'(\tau_s)$ with approximately 90° period, which is in agreement with the fluctuation period of harmonic mean value r . This relation clearly expresses the meaning of equation (11) i.e., the practical data well define the elevated shear yield stress in the directions of high harmonic mean values r due to depressed shear deformation.

Of particular interest is the fact that aluminum alloy and brass are 45° displaced in the directions which attain the maximum $\tau_s'(\tau_s)$. This corresponds to the 45° displacement of the phase angles in the fluctuation of harmonic mean values r shown in Fig.4. In addition, considering the fact that plastic strain is extremely pronounced at cutting and that might induce strain hardening, τ_s and τ_s' are supposed correspond to each other.

7. Conclusion

Previous studies emphasized the effects of plastic anisotropy of cold-rolled materials on plastic processing. However, the present study has revealed that plastic anisotropy greatly affects the resistance of cutting.

That is to say, the harmonic mean value r of the shear direction dominates the shear stress at cutting, and high shear stresses occur in the direction of high harmonic mean value r .

References

- (1) Matsuo, Y., Science of Machine, (in Japanese), Vol. 33, No.2, (1981), P.233.
- (2) Kasai, T., and Ida, I., Journal of the Institute of Electronics and Communication Engineers of Japan, (in Japanese), Vol.58, No.5, (1975), P.515.
- (3) Kuniyoshi, M., Science of Machine, (in Japanese), Vol.28, No.1, (1976), P.207.
- (4) W.T. Lankford, S.C. Snyder and J.A. Bausher, Trans., ASM, Vol.42, (1950), P.1195.
- (5) R.S. Burns and R.H. Heyer, Sheet Metal Ind, Vol.35, (1958), P.261.
- (6) Nagashima, S., Aggregate Structure, (in Japanese), Kinzokugaku-Shinsho, (1966). Edited by Japan Institute of Metal.
- (7) R. Hill, The Mathematical Theory of Plasticity, Oxford, (1950).