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Some Considerations on the Mechanics of Aluminium Machining*

By Shigeo ZAIMA** and Kanji TAKIMIZU***

A commercial pure aluminium (2S) plate is orthogonally cut by the shaping machine and the peculiarity in machining aluminium is studied. The results obtained are as follows;

In cutting O-materials of aluminium, if the depth of cut is not so large, a pair of large and small cutting resistances are measured alternately when the deformed layer is cut by pre-machining and when the deformed layer is not cut. According to that fact, the chip in the case of large cutting resistance has a larger compression factor than in the case of small cutting resistance, and the cut surface becomes poor with stick-slip. In cutting H-materials, the above mentioned alternate change in the cutting resistance, the chip formation, the cut surface and others are not so clear and, in cutting $\frac{1}{2}$ H-materials, the change is transitionary between them. And it is observed that the structure of the part near the cut surface is a sort of machined fibre structure and has directionality revealed by etching-pit process.

1. Introduction

Aluminium has good properties such as small gravity and good anticorrosion resistance, but offers many problems in machining. Aluminium is very soft and a large plastic flow on the surface layer is observed during machining, so it is difficult to obtain a good finished surface. Since the front part of cutting tool is compressed and the back part is pulled, the flow occurs on the surface layer of soft materials like aluminium. When the depth of cut increases, the change becomes complicated. The deformation of forming chips occurs not on a single shear plane but in a sheared region which has a certain width, the deformed part reaches the lower than planned cutting surface⁽¹⁾. Therefore aluminium is plastically much deformed by machining, and this effect is large on the machine-finished surface and deformed layer.

In this paper, a commercial pure aluminium sheet was orthogonally cut and some points on the machining of aluminium such as the changes of machining resistance, the formation of chips and the condition of deformed layer were studied. And some reference data on the suitable conditions for aluminium machining were obtained.

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** Professor, Faculty of Engineering, Shizuoka University, Hamamatsu.

*** Graduate Student, Postgraduate Course, Shizuoka University.

2. Experimental procedure

Specimens were prepared as follows: Commercial pure aluminium (2S), 7 mm thick, whose chemical compositions are shown in Table 1, is cold-rolled to 3.9 mm (reduction ratio 45%), cut in a shape of 120 mm × 50 mm and annealed at 500°C for four hours. Mechanical properties of specimens used are shown in Table 2.

A sheet specimen was set to an orthogonal cutter shown in Fig. 1 (cutting apparatus was a shaping machine), and dry cutting was performed. The tool used was a high speed steel (SKH 4) plain cutting tool (19 mm □), its clearance angle was 8° and the rake angle α was changed from 0° to 30°. The cutting tool was finished to about 0.6 μ of maximum roughness, and the radius of tip curvature was made equal to about 10 μ using a tool grinding machine (WA-60 L wheel used).

The cutting condition used was the low speed

Table 1 Chemical compositions of specimen used

	Cu %	Si %	Fe %	Mg %	Mn %	Zn %	Al %
2S	0.12	0.35	0.30	0.02	0.03	0.02	Bal.

Table 2 Mechanical properties of specimen used

Tensile strength kg/mm ²	Yield strength (0.2%) kg/mm ²	Elongation %	Vickers hardness H_v (Load 10kg)
9.5	3.8	38	21.3

light cutting and the cutting speed being $V=4.3 \sim 16.8$ m/min, and depth of cut in the range of $t=25 \sim 200 \mu$. To measure the cutting force, a strain gauge was set in a fixed disk type tool dynamometer. To measure the fluctuating cutting force, the follow of the measuring apparatus is important, and in this case, the characteristic frequency of the tool system was about 1.7 kc/sec and the amplifier and the recorder used satisfactorily followed the motion.

3. The fluctuation of cutting force

The authors have studied the cutting mechanism of aluminium alloys. The cutting force increased at the early stage and reached a maximum value, then decreased to a constant value, and an overrunning of the cutting force was observed. During the period from the maximum to the constant value, the built-up edge grew and stuck to the rake surface of the tool. In the period of the cutting force being constant, the formation of stable built-up edges without growth and falling off was observed⁽²⁾. Similar studies were performed on aluminium alloy sheets with different cold reduction ratios. As the cold reduction ratio increases, the overrunning of cutting force in the early stage decreases, and the built-up edge without growth and falling off becomes small⁽³⁾. With 1S or 2S pure aluminium sheets, the overrunning of the cutting force was observed, but the changes of cutting resistance were slightly different for different cuttings even

Fig. 1 Orthogonal cutting apparatus

Fig. 2 Aspects of chips and finished surfaces

under the similar cutting conditions. The same amount of overrunning did not occur and the reproducibility was poor⁽⁴⁾. In aluminium machining, the machining mechanism was quite different from pure shear. A pulsation like a stick-slip in the formation of chips was observed. When the cuttings was repeated, the change of cutting force seemed to be the same for every other cutting. These are characteristic behaviors of pure aluminium machining. If the cutting was performed under the same cutting conditions, while the depth of cut was small (up to about 100μ), a partial periodicity was observed in machining phenomena. For example under the conditions of the rake angle of $\alpha=0^\circ$ and the cutting speed $V=4.38$ m/min, depth of cut of $t=50 \mu$, short and thick chips, with chip compression factor $r_c=(\text{the thickness of the chip})/(\text{the depth of cut})=16.4$ and long thinner chips with a constant thickness, $r_c=2.8$, were produced alternately, as shown in the left side of Fig. 2. The stick-slip like rough finished surface was obtained under the former condition for $r_c=16.4$ and considerably good finished surface was obtained for $r_c=2.8$. The changes of the cutting resistance were large for the former case and small for the latter case as shown Fig. 3.

When the depth of cut changes to $t=200 \mu$,

Experimental conditions: $V=4.38$ m/min, $\alpha=0^\circ$, $t=50 \mu$
Fig. 3 Fluctuations of cutting forces

Fig. 4 Changes of principal force

the alternating cutting resistance is analyzed. The principal force follows a saturation curve regardless of the tool rake angle as shown in Fig. 4 depending upon the increase of cutting depth, the difference being large when the cutting depth is small but small when the cutting depth is large.

The reason why the two values of the cutting resistance were repeated was clarified by the measurement of the deformed layer mentioned below. The machined surface layer was plastically severely deformed and it flowed plastically, while at the same time the cutting force increased due to the deformation hardening. When this hardened layer was cut, the power for plastic flow was small, the cutting force decreased and the stick-slip phenomena were not observed and a good finished surface was obtained. The thickness of the deformation hardened layer was slightly greater than 100μ . And when the depth of cut was less than 100μ , a work hardened layer and a soft layer underneath were cut alternately. The alternating phenomena mentioned above can be explained. For a work hardened aluminium sheet such as H-materials, the alternating phenomena were not observed. For $\frac{1}{2}$ H-materials, an intermediate tendency between O-materials and H-materials was observed. The difference in the cutting resistance and the thickness of deformed layer for non-work hardened layer and work hardened layer will be reported elsewhere⁽⁶⁾.

4. The measurement of deformed layer

X-ray diffraction, optical microscopy, etching technique, hardness method, recrystallization method etc. have been used for the measurement of the deformed layer⁽⁶⁾. Since the deformed layer is not clearly distinguished, the results differ depending on the measuring method. High precision cannot be expected except from the X-ray diffraction method which measures the lattice distortion. The authors adopted an etching pit method, which proved powerful to detect the directionality of cold rolled aluminium sheets⁽⁶⁾, in the measurement of deformed layer. And to check these results, a hardness measurement was also used. Etching pit method utilized the fact that aluminium could be etched preferentially on only (100) planes if an adequate etchant was used. The shape of etch pits was square when (100) plane of the grain was parallel to the surface, rectangular with bright spot at the center when (100) plane was parallel to the surface, and equilaterally triangular when (111) was parallel to the surface. (In this experiment, triangular pits were not observed.) From the shape of the etch pits, the axial direction of the crystal

could be determined.

A piece $12\text{ mm} \times 5\text{ mm} \times 3.9\text{ mm}$ was cut from near the center of the specimens after machining. The sample was mounted in a plastic resin so as to face the section which was perpendicular to the cutting surface and parallel to the cutting direction and to polish this surface. This surface was polished with buff and electrolytically polished with the mixture (perchloric acid 20 cc + acetic acid anhydride 60 cc + water 35 drops) and the grain boundaries were etched with a few percent hydrofluoric acid. Then the sample was dipped for 3~5 seconds in an etchant (hydrochloric acid 11 cc + hydrofluoric acid 2 cc + nitric acid 5 cc + water 4 cc); thus etching pits as shown in Fig. 5 were obtained. Figure 5 (a) and 5 (b) show the case that the cutting speed was $V=11.8\text{ m/min}$, the rake angle was $\alpha=30^\circ$ and the depth of cut was $t=25\mu$ and 50μ , respectively. The flow condition or the cutting surface layer is clear from the figure. Near the cutting surface, the crystal grains were crushed and the grain boundaries were not clear, but the grain boundaries became clear as the place was far from the cutting surface. The rotation of the direction of pits due to the plastic flow by cutting could be noticed. The direction of etching pits in underformed grains should have the same direction as the base. If the direction of a pit is different from the others within a grain, the grain is strained. (Of course, the difference due to subboundaries was sometimes observed, but this difference was less than 1° and only the distinct difference was selected.) The deformed layer can be defined from the cutting surface to the strained layer. This method is very effective and simple to determine the deformed layer compared with an elaborate X-ray diffraction method. The results obtained by this method for the thickness of the deformed layer in the annealed materials are summarized in Table 3.

Vickers hardness H_V (5 g load) was taken every 10μ from the cutting surface by a micro hardness tester. An example of the results for cutting speed

(a) $V=11.8\text{ m/min}$
 $\alpha=30^\circ$
 $t=25\mu$ (b) $V=11.8\text{ m/min}$
 $\alpha=30^\circ$
 $t=50\mu$

Fig. 5 Aspects of etching pits

of $V=11.8$ m/min, depth of cut $t=50\mu$ is shown in Fig. 6. The hardness decreased as the point was farther from the cutting surface and reached a final hardness which was the hardness of the matrix. The distance between the cutting surface and the point where the constant hardness was first obtained was taken to be the thickness of deformed layer. Since the load was small, the measuring errors do not seem to be so small. The results for undeformed matrix are shown in Table 4. Comparing with Table 3, the values obtained by this method tend to be slightly lower than the values obtained by etching pit method, but roughly speaking they are considered to be the same.

Table 3 Thickness of deformed layer in μ measured by etching pit method

α	$V=4.38$ m/min				$V=11.8$ m/min				$V=16.8$ m/min			
	25	50	100	200	25	50	100	200	25	50	100	200
0°	100	100	160	220	110	120	150	220	80	110	120	180
10°	100	120	140	160	140	90	140	160	70	70	120	150
20°	80	120	120	140	100	60	110	170	40	40	60	130
30°	70	80	90	110	70	50	90	150	40	50	70	100

Table 4 Thickness of deformed layer in μ measured by hardness method

α	$V=4.38$ m/min				$V=11.8$ m/min				$V=16.8$ m/min			
	25	50	100	200	25	50	100	200	25	50	100	200
0°	125	140	200	180	110	100	110	100	70	100	120	130
10°	120	120	100	120	80	100	100	100	100	100	80	100
20°	70	100	110	150	90	70	110	60	120	40	150	100
30°	110	80	100	100	80	80	100	150	80	50	60	100

Table 5 Classification number of specimen

t	$V=4.38$ m/min				$V=11.8$ m/min				$V=16.8$ m/min			
	0°	10°	20°	30°	0°	10°	20°	30°	0°	10°	20°	30°
25 μ	1	5	9	13	17	21	25	29	33	37	41	45
50 μ	2	6	10	14	18	22	26	30	34	38	42	46
100 μ	3	7	11	15	19	23	27	31	35	39	43	47
200 μ	4	8	12	16	20	24	28	32	36	40	44	48

V : Cutting speed α : Rake angle t : Depth of cut

Fig. 6 Changes of micro hardness in neighbourhood of cut surface

As the rake angle was increased and the cutting speed was increased, it was found, the thickness of deformed layer decreased. This is consistent with the previous results⁽⁷⁾ in which the depth of cut was much larger, $t=0.1\sim0.5$ mm for aluminium alloys.

5. Regions of deformed layer

To distinguish the change of the rotation of the axis by cutting, the layers are divided into three regions as shown in Fig. 7; in Region I, the grain boundaries are not clear; in Region II, the grain boundaries can be distinguished but deformed; and in Region III, they are not deformed. To obtain the crystalline axis which controls each region, this was divided into three directions: Direction 1, $30\sim60^\circ$ between the pit axis and the cutting direction, Direction 2, $15\sim30^\circ$ and $60\sim75^\circ$ and Direction 3, $0\sim15^\circ$ and $75\sim90^\circ$ as shown in Fig. 8. The grain area was measured when the grain boundaries could be recognized, in the part where the grain boundaries were not recognizable, the area was measured by dividing it mechanically. In the region where the pits were rotated, each part was divided and the area percentage for each direction was obtained. In this way the crystal

Fig. 7 Division into regions

Fig. 8 Classification of directions of etching pit

orientation was determined.

Specimens were numbered as shown in Table 5 under each experimental condition. In each region, the percentage belonging to each direction was obtained and given in Fig. 9. As shown in the figure, in Region III which is the farthest from the cutting surface the ratios of the crystal axis are (Direction 1) : (Direction 2) : (Direction 3) = 1 : 1 : 1, which shows that this region has the same direction as the matrix. In Region I, Direction 3 is much increased and in Region II, Direction 3 is intermediate. Therefore in Region I the directionality appears in the crystal structure and shows some kind of deformation texture in which the crystal axis has the same orientation as the cutting direction, hence the finished surface condition after machining can be studied by etching pit method.

6. Conclusions

Aluminium (2S) sheets were orthogonally cut, and the cutting of pure aluminium was studied with respect to the cutting resistance, the formation of chips, and the deformed layer. The results are summarized as follows:

(1) When O-material of aluminium sheet is cut, the cutting resistance in different depending on whether the deformation layer is cut or not while

the depth of cut is small.

(2) When the cutting resistance shows fluctuation, the formation of the chips also shows stick-slip phenomenon and the finished surface conditions vary accordingly. When the cutting resistance is small and the compression coefficient of the chips is low, a good finished surface is obtained. When the cutting resistance is high and the compression coefficient of chips is high, the finished surface is poor.

(3) When H-material is cut, the alternate variation in the cutting resistance, the chip formation and the finished surface conditions was not observed. $\frac{1}{2}$ H-material showed an intermediate situation.

(4) The etching pit method used in the report is effective to measure the deformed layer which is connected with the lattice strain.

(5) Near the cutting surface, a texture, a kind of machine deformed texture and the directionality were found.

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Fig. 9 Summarizations of axial direction