Studies on Wood Cutting with a Pendulum Dynamometer (I)*

Effect of Tool Angle and Clearance Angle

Wood Physics,Section 3 Hikoichi SUGIHARA and Masami NOGUCHI**

杉原彦一・野口昌巳：振子式木材切削試験器による木材切削に関する研究（第１報）
刃先角と逃げ角の影響について

1 Introduction

It has been tried these some dozen years to apply the principle of an Izod impact testing machine to measure cutting resistance of wood[1]. Thenceforth it was proposed[2] to make this method the standard measurement for workability of wood, and many devices and improvement have been made on such an equipment[3].

Getting the 1960 Scientific Research Fund of Ministry of Education, one of the present authors SUGIHARA had modified an Izod impact tester and made an apparatus to measure energy of cutting wood[4]. Measuring cutting resistance of wood by means of the apparatus, the present authors tried to find the limits of this measurement and to inspect some important problems.

In this paper the influence of tool angle and clearance angle on the cutting resistance of wood is mainly discussed about the results of the experiment on the basis of "Experimental Designs". As this measurement is yet in a way to development, it is not intended to draw final conclusions but interesting informations obtained have been presented in this paper.

2 Experimental Method

2.1 Principle

A general view of the experimental apparatus is shown in Photo 1. The machine is basically a standard Izod impact testing machine with a 5 ft-lb capacity. As well known, energy Q (kg·m) consumed in cutting process can be given by the following formula ;

$$Q = WR(\cos\theta - \cos\eta) - L_1 - L_2 - L_3, \qquad (1)$$

where η : initial angle of a pendulum, in the present case 120°
θ : maximum angle on the opposite side

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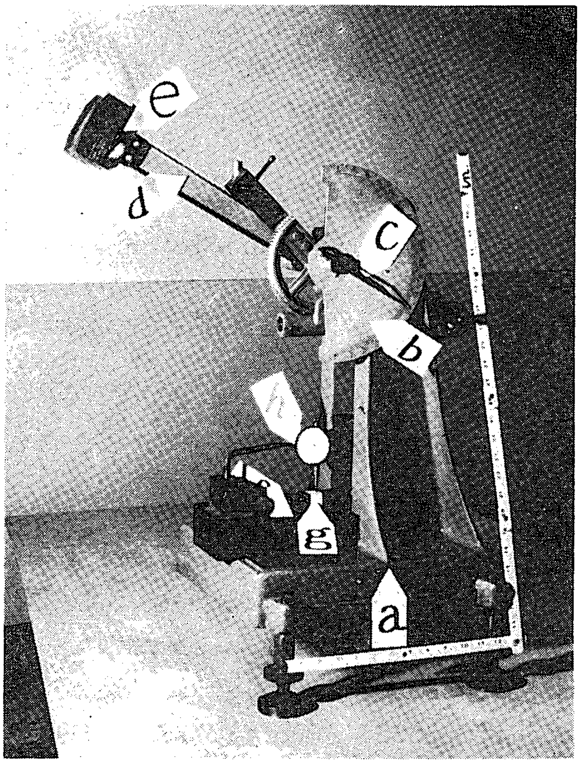

Photo 1. Experimental Apparatus.
a : Bed, b : Scale, c : Hand, d : Pendulum,
e : Knife, f : Block Holder, g : Test Block,
h : Dial Gauge.

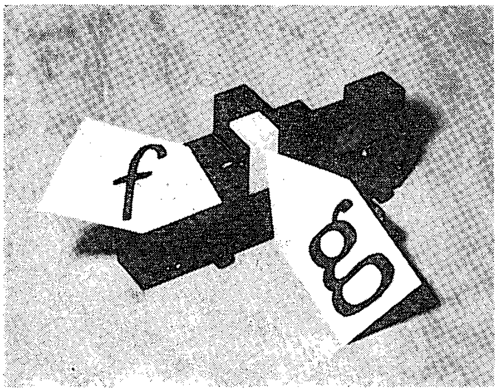

Photo 2. Block Holder.

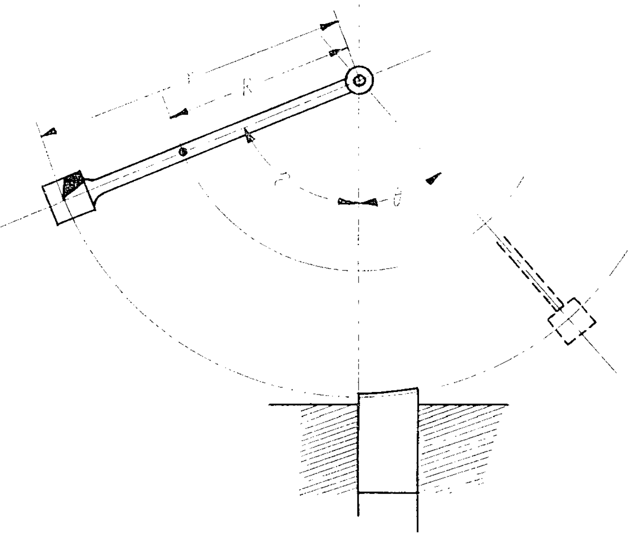

Fig. 1. Principle of Test Equipment.

W: weight of a pendulum (kg), in the present case 1.719 kg (3.789 lb)

R: distance between the centroid of a pendulum and the center of rotation (m), in the present case 0.3197 m (1.0489 ft)

L_1: energy consumption caused by air resistance of a pendulum and frictional resistance at the pendulum axis

L_2: energy consumption corresponding to motion energy given to removed chip, i.e. $\frac{1}{2}wv_2^2$ (w and v_2 represent chip weight and a knife speed at the moment of leaving a block, respectively)

L_3: all the residual energy consumption except L_1 and L_2,

this is the principle of an Izod impact tester.

2.2 Modification

Provided that L_1 is equal to L_1^0 which is energy lost in the gravitational swing, L_1 can be easily obtained. With the used apparatus the pendulum swings down freely from an initial angle of 120.9° and then rises up to the maximum angle of 120.5° on the opposite side, so L_1 can be considered to be zero. As chip weight is usually very little, it is at most 0.2 g in the present case, in addition, v_2 is at most equal to v_1 (v_2 and v_1 represent the knife speed at the moment of leaving and impacting a block, respectively) in this experiment, the following formula is obtained;

$$L_2 < \frac{1}{2g} w v_1^2 = 0.00011 \text{ (kg·m)},$$

where g represents the acceleration of gravity (9.8 m/sec^2). Being less than the sensibility of the used apparatus (0.001 kg·m), L_2 may be assumed to be zero. L_3 is energy consumption in the friction between a block and a chuck when the block is deformed by cutting force, and in other ways. Although it is quite difficult to conjecture the magnitude of L_3, it may be negligible.

The apparatus was designed so that a cutting edge might be located on the center of percussion.

Thus, from formula (1) the following formula is approximately derived in the present case,

$$Q = WR(\cos\theta - \cos\eta). \tag{1'}$$

W, R and η having previously been determined, therefore, cutting energy Q can be calculated by measuring the angle θ. In this experiment θ is measured and then Q is calculated by substituting 1.719, 0.3197 and 120° for W, R and η in formula (1'), that is

$$\begin{aligned} Q &= 1.719 \times 0.3197(\cos\theta - \cos 120^\circ) \text{ (kg·m)} \\ &= 0.275 + 0.550 \cos\theta. \text{ (kg·m)} \end{aligned} \tag{1''}$$

2.3 Analysis

Suppose a pendulum strikes a block at the speed v_1 and leaves it at the speed v_2, v_1 and v_2 are given by two formulae

$$v_1 = \frac{r}{R}\sqrt{2gh}$$

$$v_2 = \frac{r}{R}\sqrt{2gh'}$$

where r, h, h' and g represent the distance between the cutting edge and the center of rotation, the initial height of a pendulum, the maximum height on the opposite side and the acceleration of gravity. If cutting resistance is represented by $P(x)$, cutting energy Q can be written as follows;

$$Q = \int_0^l P(x)dx = \frac{W}{2g}(v_1^2 - v_2^2), \tag{2}$$

where x represents the length of the arc which the knife edge draws in a block till an arbitrary time and l that drawn by the knife edge till the end of cutting. If an average cutting resistance is P_m, the following formulae can be obtained;

$$Q = P_m \cdot l \qquad \text{or} \qquad P_m = \frac{Q}{l}. \tag{3}$$

Provided that p_m, b and δ are an average specific cutting resistance, width of a block and depth of cut, respectively, formula (4) is given;

$$p_m = \frac{Q}{l \cdot b \cdot \delta}. \tag{4}$$

Refering to cutting resistance P_m above, cutting resistance not always acts only in the holizontal direction at the edge of a knife. The resultant force P_0 and the main cutting force P_1 intersect generally with a certain angle as seen in Fig. 2. In the present experiment, strictly speaking, the cutting resistance P_m measured does not refer to the resultant force P_0 but the main cutting force P_1, and the cutting energy Q, which comes from the cutting resistance, depends only upon the main cutting force P_1 and has little connection with the thrust force P_2.

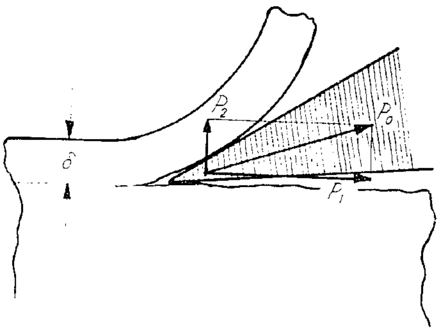

Fig. 2. Schematic diagram of force system acting in the case of orthogonal cutting.
P_0: resultant force, P_1: main cutting force, P_2: thrust force, δ: depth of cut

Keeping l constant (18 mm) in this experiment, instead of comparison with an average cutting resistance P_m in formula (3) it is permitted to discuss the cutting resistance from a comparison of the energy consumption Q. Hence the cutting energy may be regarded as the cutting resistance.

3 Design of this Experiment

In an experiment on wood, observations often show large variability (for example, the contribution rate of e_4 to total variation was 34.5 percent in Table 3) and so it is quite dangerous to draw conclusions from obtained values themselves. In such a case "Experimental Designs" teaches how to take data, how to analyze them and how to derive general conclusions from a mass of individual determinations that in themselves are meaningless. Therefore it was decided to make the experiment based on "Experimental Designs".

3.1 Factors influencing on Cutting Resistance

It is a major purpose in the present paper to know the effect of varied conditions of tools, cutting and test blocks on cutting resistance, and then to obtain basic informations about a pendulum dynamometer.

Tool conditions which influence on cutting resistance are knife angles, tool materials, shapes, sizes and so on. The cutting conditions consist of cutting speed, depth of cut, states of knife edges, etc. Conditions of test blocks are wood species, wood density, moisture condition, knots, strengths of wood, temperature and so on.

When making an experiment, it is, of course, desirable to take up all the factors described above, but an experiment is limited in number. So it must be considered whether the increased scale of an experiment can offset the increase of labor, time, cost and such like or not. Considering experience in past, some basic factors were selected from among these factors and the experiment was designed.

3.2 Selection of Factors and their Levels

Tool Condition : In the present experiment only high-carbon steel (SK 4) was taken up from various materials for tools. Knives were formed as shown in Photo 3. Fig. 3 shows the size of a knife used in the present experiment. As tool and clearance angles were the most important factors, they were treated as mentioned later.

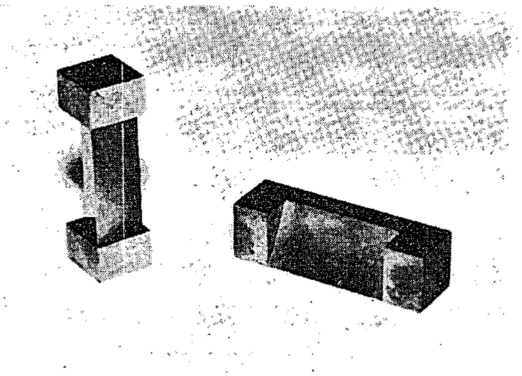

Photo 3. Shape of Knife.

Cutting Condition : It is too hard to vary the cutting speed of this apparatus (strictly speaking, the knife speed in the moment of running into a test block), so the cutting speed was kept constant (3.36 m/sec).

Depth of cut is generally in the range from 0.1 mm to 2 mm, but the levels in this experiment were decided to be 0.2 mm and 0.5 mm under the consideration of the experimental apparatus' sensibility (0.001 kg·m) and its capacity (0.690 kg·m).

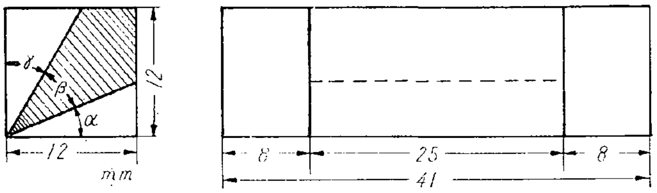

Fig. 3. Size of Knife.
α : clearance angle, β : tool angle, γ : rake angle

Fig. 4 shows six cutting directions considered in the present experiment. Though two cutting directions (from the outer surface and from the inner one) exist in a cross sectional cutting $C_\perp$, the present experiment had no difference between the two and was carried out in randomization.

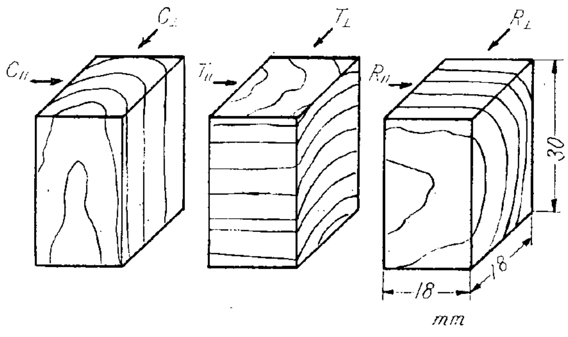

Fig. 4. Cutting Direction and Size of Test Block.

A series of cut done with one knife was divided into three so as to know whether blunting of the knife edges during the experiment affects the results. Knife edges were used without regrinding.

Nature of Test Block: Japanese cypress (*Chamaecyparis obtusa* ENDL.), beech (*Fagus crenata* BLUME) and manggasinoro (*Shorea philippinensis* BRANDIS) were selected as representatives for soft, hard and tropical woods, respectively. The last was taken up because they say manggasinoro blunts rapidly edges of a saw.

Moisture conditions of test blocks were controlled in three levels: oven-dried, air-dried and water-saturated conditions.

3.3 Plan in the Present Experiment

The purpose of the experiment was to observe the effect of tool and clearance angles on the cutting resistance in connection with five factors shown in Table 1.

Table 1. Factors and Levels.

Factor	Levels		
A (Wood Species)	A_1 : Japanese cypress	A_2 : manggasinoro	A_3 : beech
B (Cutting Direction)	B_1 : parallel to wood fiber in radial section ($R_{/\!/}$)	B_2 : parallel to wood fiber in tangential section ($T_{/\!/}$)	B_3 : parallel to annual ring in cross section ($C_{/\!/}$)
	B_4 : perpendicular to wood fibers in radial section ($R_\perp$)	B_5 : perpendicular to wood fibers in tangential section ($T_\perp$)	B_6 : perpendicular to annual rings in cross section ($C_\perp$)
C (Depth of Cut)	C_1 : 0.2 mm	C_2 : 0.2 mm	C_3 : 0.5 mm
D (Moisture Condition)	D_1 : oven-dried	D_2 : air-dried	D_3 : water-saturated
E (Cutting Stage)	E_1 : first stage	E_2 : second stage	E_3 : third stage

Among five factors illustrated in Table 1 there are five main effects, ten 2-factor interactions (${}_5C_2$), ten 3-factor interactions (${}_5C_3$), five 4-factor interactions (${}_5C_4$) and a 5-factor interaction (${}_5C_5$). Since we can not as general rule expect to get important results from 3-factor and higher interactions in experiments with four or more factors, efforts to find such interactions very often bear no fruit.

Wood species used are a coniferous, a porous and a tropical wood, so their structures differ one after another. As the interactions between wood species and other four factors affect probably the cutting resistance, factors A~E were arranged for the orthogonal array table $L_{54}(2^1 \times 3^{25})$ so that five main effects and four kinds of 2-factor interactions ($A \times B$, $A \times C$, $A \times D$, $A \times E$) might be detected. Though six 2-factor interactions might occur among factors B, C, D and E, they were ignored because they might be less effective than interactions of wood species.

Table 2. Combination of Tool Angle and Clearance Angle (in degrees).

Clearance Angle (G)		Tool Angle (F)				
		F_1	F_2	F_3	F_4	F_5
G_1	10	25	35	45	55	65
G_2	15	25	35	45	55	65
G_3	20	25	35	45	55	65
G_4	25	25	35	45	55	65

Five varieties of tool angle seen in Table 2 were compared in connection with fifty-four different combinations of cutting conditions mentioned above, so that all the tool angles by one of factors A~E interactions could be found. Consequently a 54-plan was the primary unit and F_1, F_2, F_3, F_4 and F_5 composed the secondary one. Furthermore four levels of clearance angles G(10°, 15°, 20°, 25°) were combined with each of five tool angles, so $G_j (j=1 \sim 4)$ were the tertiary unit, and then three replications were conducted for a set of conditions. The final measures were to appear on the quartic unit and the structure of the experiment was represented with a four split-plot design. Thus the number of all the data was $3240 (=54 \times 5 \times 4 \times 3)$.

4 Experimental Procedure

Photo 1 shows the experimental apparatus. A knife is put into *e* (Photo 1) and then the pendulum *d* is lifted up to the position $\gamma = 120°$. Holding a test block *g* on the block holder *f*, the test block is fed upwards to the expected amount and then tightly held. The pendulum is released with an initial speed of zero so that it swings down and cuts a piece of chip from the face of the test block right beneath the pendulum axis. The difference between the initial angle of the pendulum and the maximum angle on the opposite side gives a measure of the energy lost in cutting process. The magnitude of this energy consumption is determined by means of the scale *b*.

5 Analysis of Data

Statistical analysis using the analysis of variance was carried out on all results and then Table 3 was obtained.

6 Discussion

In advance of discussion the signs used in the present chapter must be illustrated.

Q : average energy consumption

Table 3. Analysis of Variance Table.

Source of variation	Sum of squares (S.S.)	Degrees of freedom (d.f.)	Mean square (M.S.)	F	ρ(%)
A	134248	2	67124	5.37○	4.7
B	1049488	5	209898	16.79◎	36.7
C	308692	1	308692	24.69◎	10.8
D	55642	2	27821	2.23	
E	39660	2	19830	1.59	
A × B	36102	10	3610		
A × C	22478	2	11239		
A × D	19513	4	4878		
A × E	10085	4	2521		
e_1	262538	21	12502		
T'''	1938446	53			
F	219389	4	54847	108 ◎	7.6
A × F	14356	8	1795	3.52◎	0.4
B × F	55769	20	2788	5.47◎	1.7
C × F	23157	4	5789	11.35◎	0.8
D × F	5208	8	651	1.28	
E × F	2519	8	315		
A × B × F	6951	40	174		
A × C × F	6195	8	774	1.52	
A × D × F	4053	16	253		
A × E × F	4352	16	272		
$e_1 \times F \equiv e_2$	42862	84	510		
T''	2323255	216			

Note ◎ : significant at the 1 per cent level of probability
○ : significant at the 5 per cent level of probability
ρ : contribution rate to total variation S_T
F : variance ratio (treatment mean square/error mean square)
e_1 : error for the primary unit
e_2 : error for the secondary unit

Table 3. (continued)

Source of variation	Sum of squares (S.S.)	Degrees of freedom (d.f.)	Mean square (M.S.)	F	ρ(%)
G	40718	3	13573	86.45◎	1.4
A × G	6705	6	1118	7.12	0.2
B × G	15874	15	1058	6.74◎	0.4
C × G	6519	3	2173	13.84◎	0.2
D × G	3121	6	520	3.31◎	
E × G	2312	6	385	2.45○	
A × B × G	7021	30	234	1.49	
A × C × G	2963	6	294	3.15◎	
A × D × G	3613	12	301	1.92○	
A × E × G	2755	12	230	1.46	
e_1 × G ≡ e_3		63			
F × G	10465	12	872	5.55◎	0.2
A × F × G	4928	24	205	1.31	
B × F × G	21034	60	351	2.24◎	0.1
C × F × G	4061	12	338	2.15○	
D × F × G	5884	24	245	1.56	
E × F × G	9705	24	404	2.57◎	0.1
A × B × F × G	23538	120	196	1.25	
A × C × F × G	6642	24	277	1.76○	
A × D × F × G	8468	48	176	1.12	
A × E × F × G	7470	48	156	1	
e_2 × G ≡ e_3	49518	252	157		
T′	2566569	810			
e_4	287831	2160	133		34.5
T	2854400	3239			100.0

e_3 : error for the tertiary unit
e_4 : error for the quartic unit
T‴ : total variation of the primary unit
T″ : total variation of the secondary unit
T′ : total variation of the tertiary unit
T : total variation of all the data

$Q_{C\perp}$: energy consumption in cross sectional cutting perpendicular to annual rings
$Q_{C/\!/}$: energy consumption in cross sectional cutting parallel to annual rings
$Q_{R\perp}$: energy consumption in radial sectional cutting perpendicular to wood fibers
$Q_{R/\!/}$: energy consumption in radial sectional cutting parallel to wood fibers
$Q_{T\perp}$: energy consumption in tangential sectional cutting perpendicular to wood fibers
$Q_{T/\!/}$: energy consumption in tangential sectional cutting parallel to wood fibers
$Q_{0.5}$: energy consumption in cutting where the depth of cut was 0.5 mm
$Q_{0.2}$: energy consumption in cutting where the depth of cut was 0.2 mm
Q_{D0} : energy consumption in cutting test blocks at oven-dried moisture condition
Q_{Dw} : energy consumption in cutting test blocks at water-saturated moisture condition
Q_{Da} : energy consumption in cutting test blocks at air-dried moisture condition
A×F : 2-factor interaction between wood species (A) and tool angle (F)

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A×C×F : 3-factor interaction among wood species (A), depth of cut (C) and tool angle (F)

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6.1 Main Effect (A~E)

Main effects, considering only one factor under an average effect of other factors, were illustrated in Figs. 5~9.

Fig. 5 showed that beech required expectedly more energy consumption than other

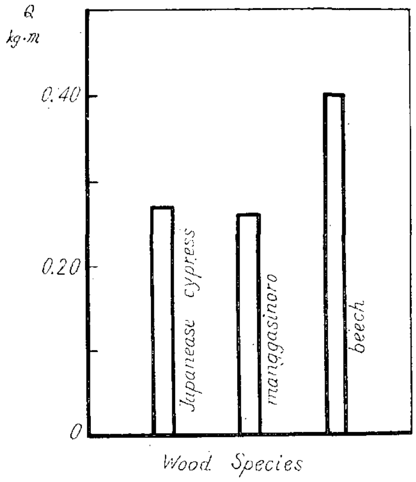

Fig. 5. Effect of Wood Species on Cutting Energy. (A)

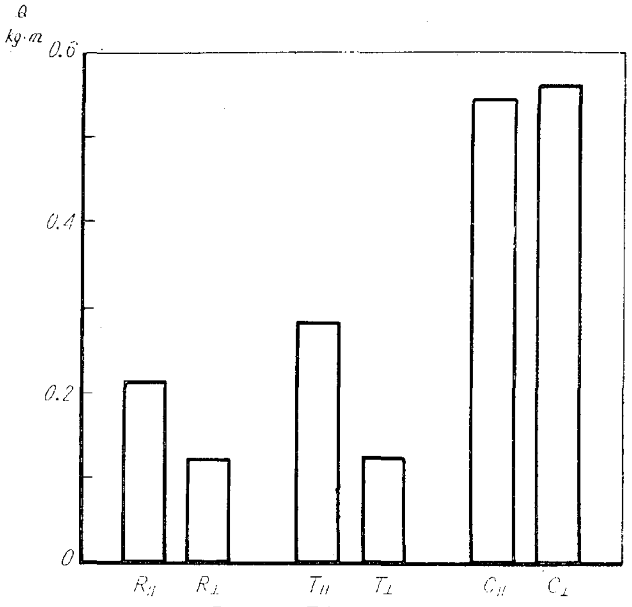

Fig. 6. Effect of Cutting Direction on Cutting Energy. (B)

two wood species and the energy consumption Q in cutting manggasinoro differed hardly from Q in cutting Japanese cypress.

The cutting energy depended highly upon the cutting directions as seen in Fig. 6. With regard to the cross sectional cutting, as had reported on many papers[5,6], the energy consumption Q was positively more than Q in other directions, while $Q_{C\perp}$ hardly differed from $Q_{C/\!/}$. In the cases of radial and tangential cutting $Q_{R\perp}$ and $Q_{T\perp}$ did not differ each other and they were the least and $Q_{T/\!/}$ was larger than $Q_{R/\!/}$.

Fig. 7 denoted that $Q_{0.5}$ was of course more than $Q_{0.2}$, and that for specific cutting resistance p_m the relationship of magnitude was reverse.

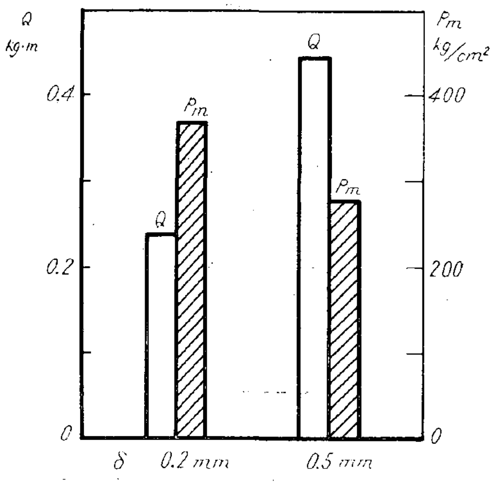

Fig. 7. Effect of Depth of Cut on Cutting Energy (Q) and Specific Cutting Resistance (p_m).

(C)

The analysis of variance, as the levels of the present experiment, did not indicate that the main effect D of the moisture condition was significant. On the other hand the considerable difference had been found in the experiments[5,7,8] with more levels of moisture condition and the tendency agreed well with the results of the present experiment. In fact, Fig. 8 showed that the energy consumption in cutting oven-dried blocks Q_{Do} was more than Q_{Dw} and less than Q_{Da}.

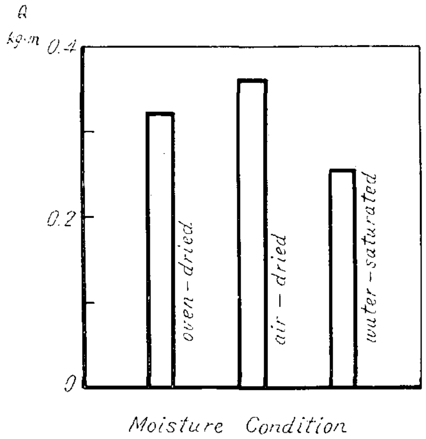

Fig. 8. Effect of Moisture Condition on Cutting Energy.

(D)

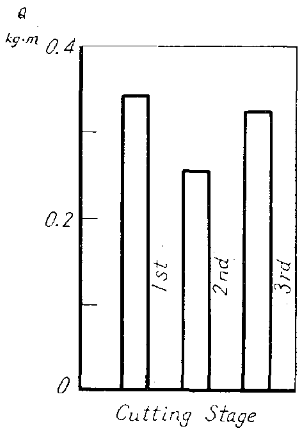

Fig. 9. Effect of Cutting Stage on Cutting Energy.

(E)

Fig. 9 showed that Q in the third stage was larger than Q in the second one but was less than Q in the first. With the present experiment where the total cutting length was too short, not so valuable was the effect E of the cutting amount or the state of wearing in cutting edges, and the analysis of variance did not indicate that the effect E was significant.

The main effects of tool and clearance angles (F and G) will be stated in more detail.

6.2 Tool Angle F

The main effect of tool angle was shown in Fig. 10, which indicated that Q decreased as a tool angle (β) was smaller, but from $\beta=35°$ to $\beta=25°$ Q reversely increased.

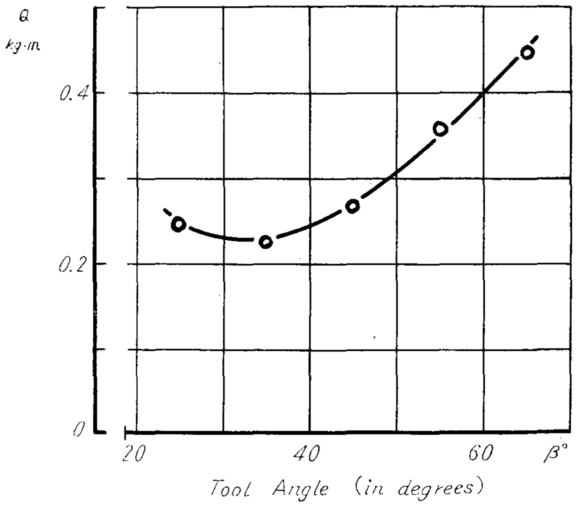

Fig. 10. Relation of Tool Angle to Cutting Energy.
(F)

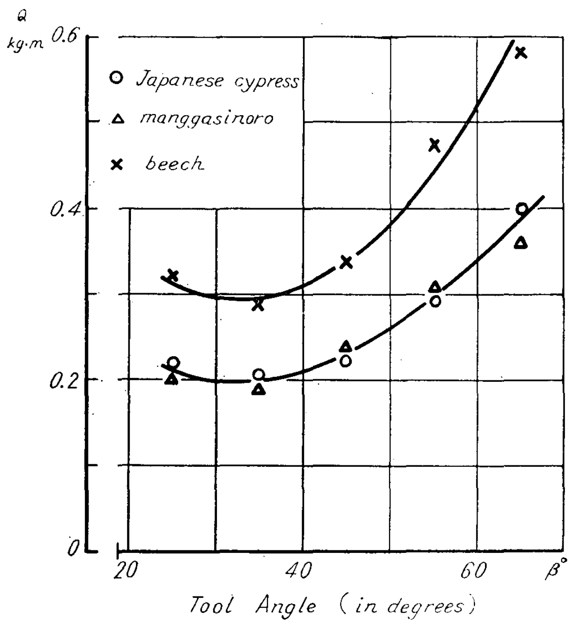

Fig. 11. Relation of Tool Angle to Cutting Energy.
(A×F)

As Table 3 denoted that the 2-factor interactions such as A×F, B×F and C×F were significant, the curve on Fig. 10 was divided into each wood species, cutting direction and depth of cut, and then Figs. 11~13 were drawn, of which curves were all concave upwards. When cutting beech, the energy consumption especially increased with tool angle. The relationship between the energy consumption and tool angle depended highly upon the cutting direction (in Fig. 12). In radial and tangential sections $Q_{R\parallel}$ and $Q_{T\parallel}$ showed the highest rate of increase in energy consumption with tool angle, while $Q_{R\perp}$ hardly differed from $Q_{T\perp}$. It was stated above that the cutting energy increased below the tool angle $\beta=35°$, and now Fig. 12 clarified this increase resulted mainly from the cutting in cross section and the same figure is in agreement with the papers[5][9] reported in past.

Fig. 13 showed that $Q_{0.5}$ increased remarkably in larger tool angles and that specific cutting resistance p_m in 0.2 mm thick cut was larger than that in 0.5 mm thick one.

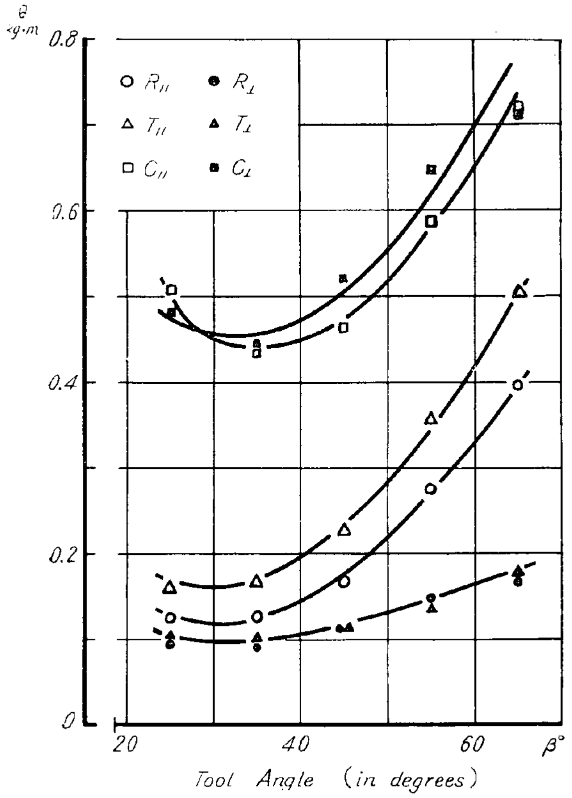

Fig. 12. Relation of Tool Angle to Cutting Energy.
(B×F)

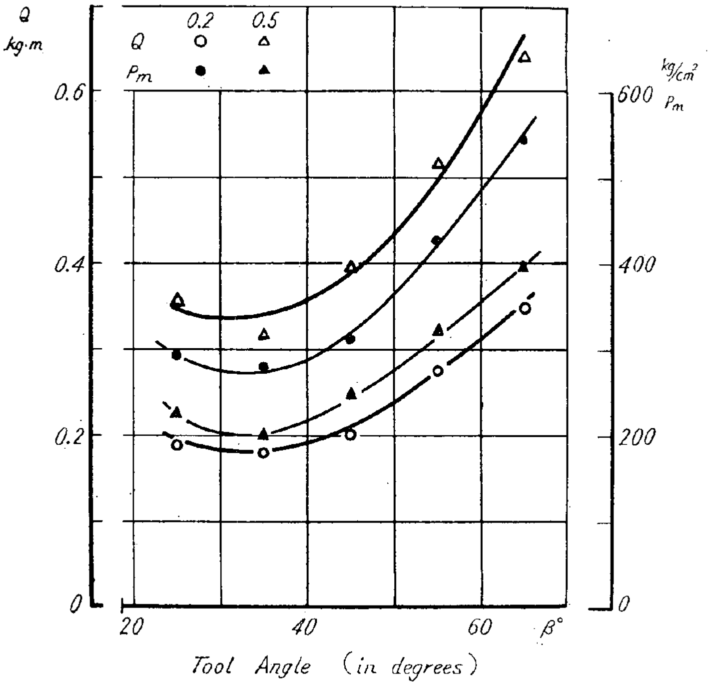

Fig. 13. Relation of Tool Angle to Cutting Energy.
(C×F)

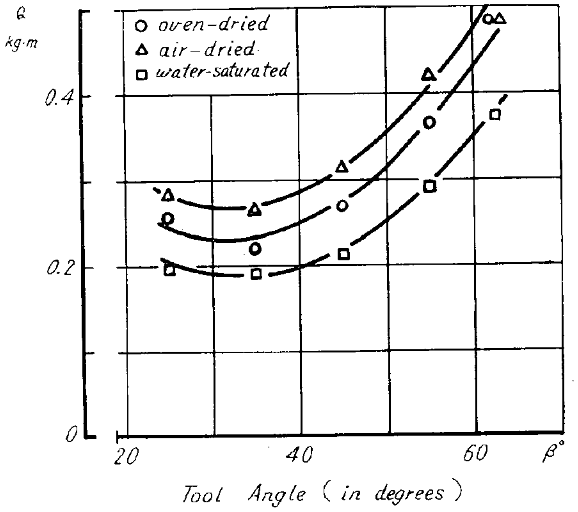

Fig. 14. Relation of Tool Angle to Cutting Energy.
(D×F)

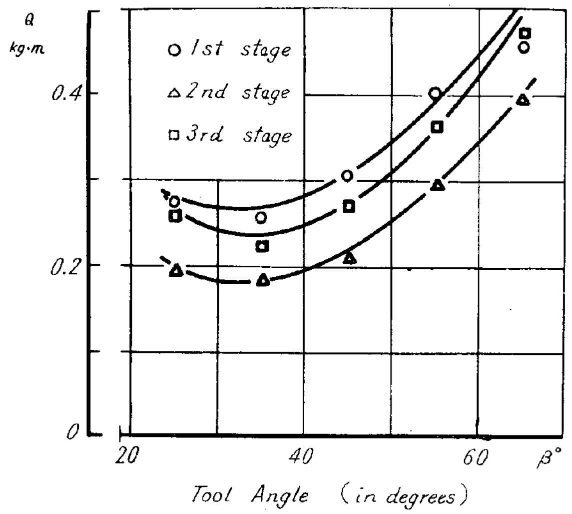

Fig. 15. Relation of Tool Angle to Cutting Energy.
(E×F)

As Table 3 did not indicate that the interactions D×F and E×F were significant, it may be stated that the effect of tool angle on the cutting energy did not so much vary its tendency with the change of moisture condition or cutting stage (in Figs. 14 and 15).

Further the analysis of variance denoted that 3-factor interactions, A×B×F, A×C×F, A×D×F and A×E×F were not significant even at the 5 per cent of level, namely, though the 2-factor interaction A×F was divided into the 3-factor interaction, these did not show a different tendency compared with their average effect.

6.3 Clearance Angle G

The effect of clearance angle α on the cutting energy was plotted on Fig. 16, in which the cutting energy decreased with decrease of clearance angle α ($10° \leqq \alpha \leqq 25°$), while a paper had reported cutting energy had promptly increased as a clearance angle had approached to zero.

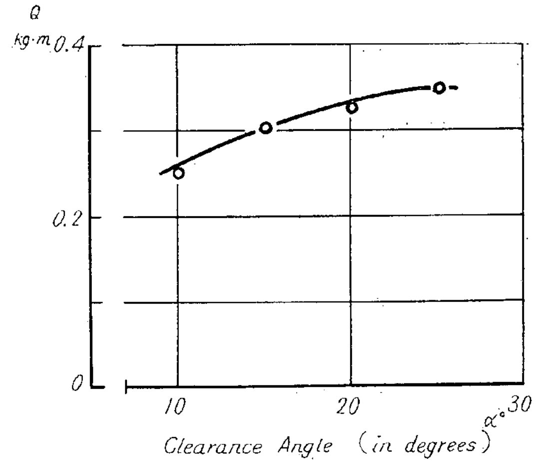

Fig. 16. Relation of Clearance Angle to Cutting Energy.
(G)

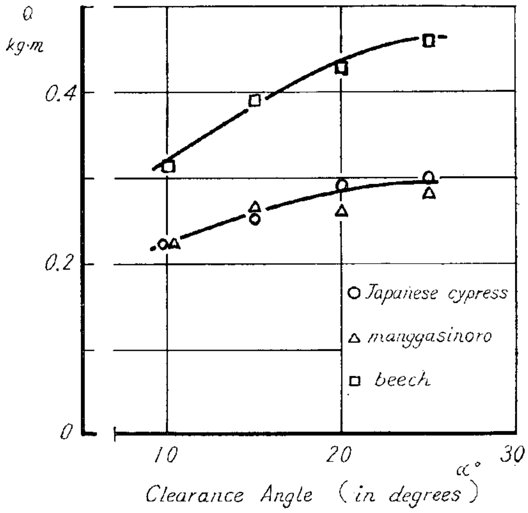

Fig. 17. Relation of Clearance to Cutting Energy.
(A×G)

Table 3 indicated the interaction A×G, B×G, C×G and E×G were significant. These interactions were plotted on Figs. 17~21, of which abscissa represented clearance angle. As seen in these figures, like the case of tool angle, the cutting energy drew increasing curves with clearance angle, but all the curves were convex upwards.

With 3-factor interactions, the analysis of variance denoted that the interactions A×B×G and A×E×G were not significant and that A×C×G was significant at the 1 per cent level and A×D×G at the 5 per cent level. The 3-factor interaction A×C×G was illustrated, divided into each wood species and depth of cut, in Fig. 22, of

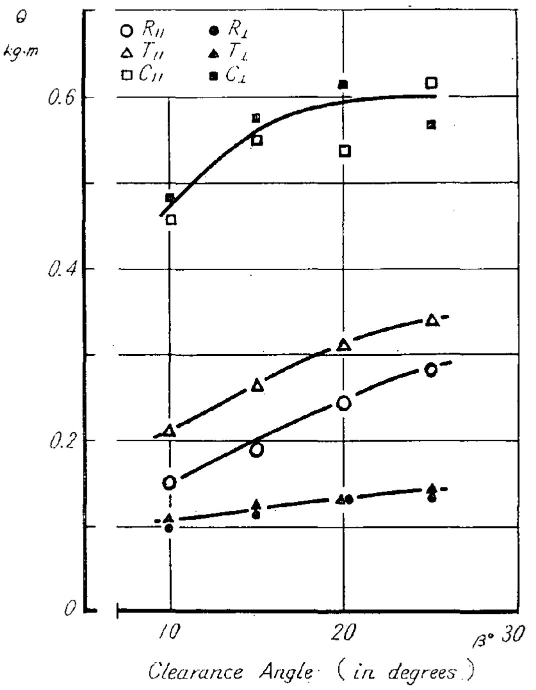

Fig. 18. Relation of Clearance Angle to Cutting Energy.
(B×G)

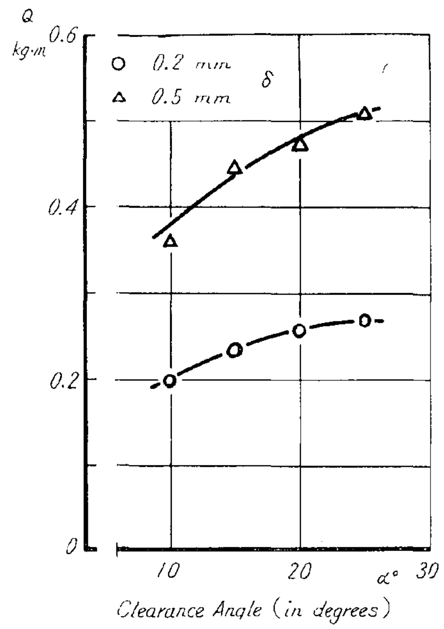

Fig. 19. Relation of Clearance Angle to Cutting Energy.
(C×G)

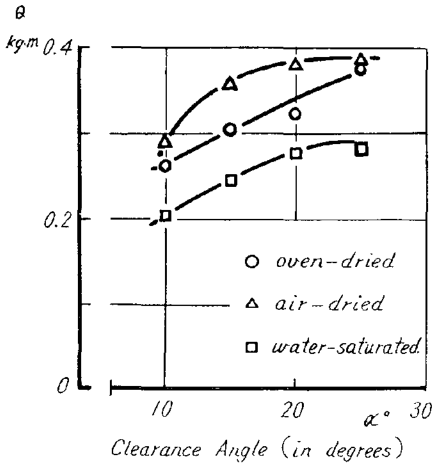

Fig. 20. Relation of Clearance Angle to Cutting Energy.
(D×G)

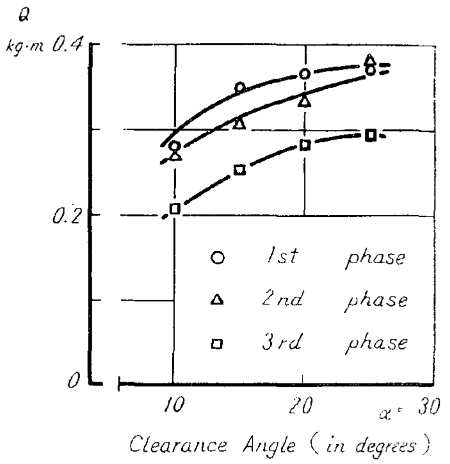

Fig. 21. Relation of Clearance Angle to Cutting Energy.
(E×G)

which abscissa represented clearance angle. This figure showed that Q in cutting beech amounted to a great quantity.

6.4 Tool and Clearance Angle F×G

Table 3 indicated that the interaction F×G was highly significant at the 1 per

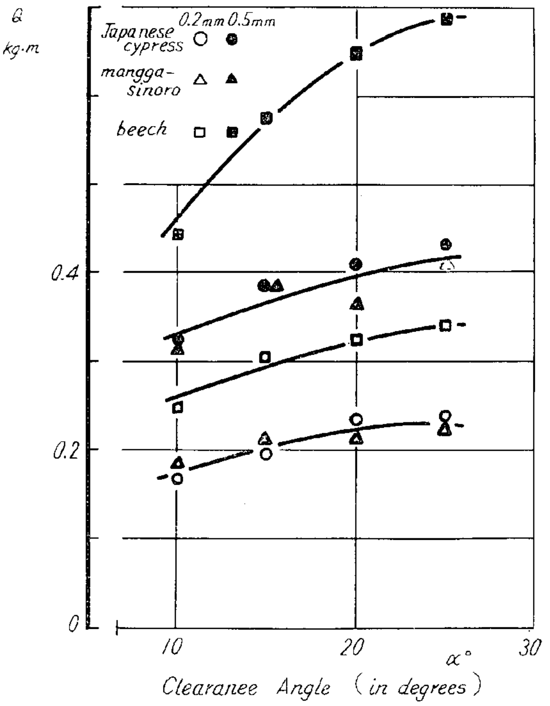

Fig. 22. Relation of Clearance Angle to Cutting Energy.
(A×C×G)

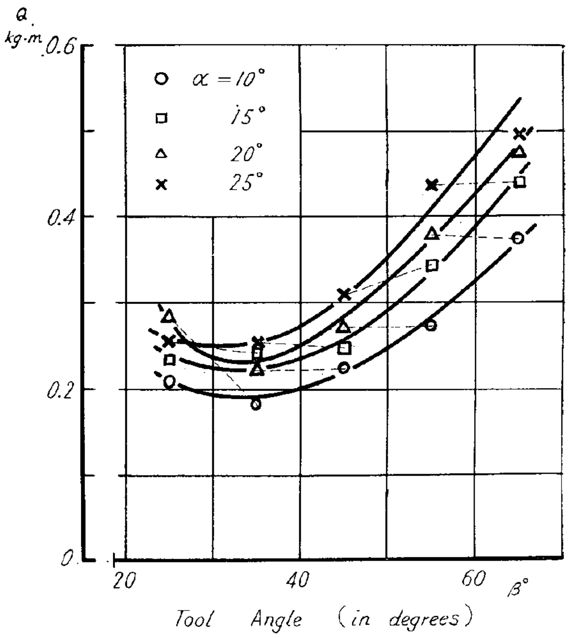

Fig. 23. Relation of Tool Angle to Cutting Energy.
(F×G)

cent level of probability, that is, the effect of tool angle (or clearance angle) F (or G) on the cutting energy varied its tendency with clearance angle (or tool angle). Such a relationship was showed in Fig. 23, in which clearance angle was a parameter and the abscissa represented tool angle, on the other hand the same relationship was also showed in Fig. 24, of which abscissa indicated clearance angle and tool angle was used as a parameter. According to Fig. 24 it was obvious that the cutting energy increased with clearance angle α whatever tool angle β and in the cases of $\beta=55°$ and $\beta=65°$ the cutting energy clearly increased with clearance angle, but the energy did not increase so much in the range of $25° \leqq \beta \leqq 45°$.

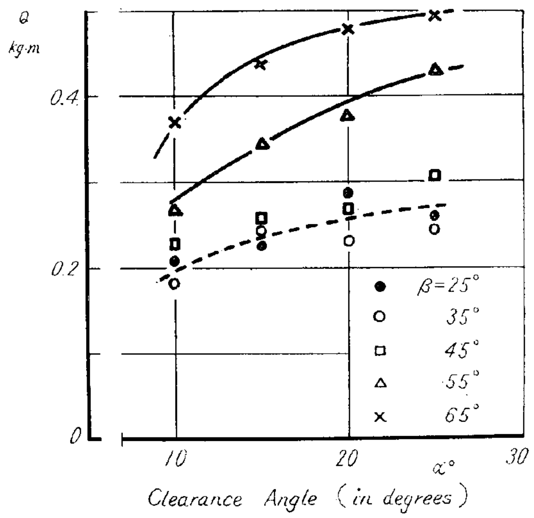

Fig. 24. Relation of Clearance Angle to Cutting Energy.
(G×F)

Considering the condition of $\alpha+\beta+\gamma=90°$ the cutting energy could be plotted on Fig. 25 of which abscissa represented rake angle γ. This figure showed that the cutting energy decreased with rake angle γ and over $\gamma=30°$ the rate of the decrease was smaller. In the range of 10°≦γ≦45° the present experiment had eight pair of tool angles (or clearance angles), which differed each other by 10°, corresponding to one rake angle, and the pair of measures hardly differed each other in the range of 10°≦γ≦40°, while at the point γ=45° a pair of cutting energy considerably differed each other. It may be assumed with regard to this variation, hesitating to say for lack of observations in the cases of rake angles 50° and 55°, that the effect of a too small tool angle appeared. The fine broken lines in Fig. 23 represented these relationships.

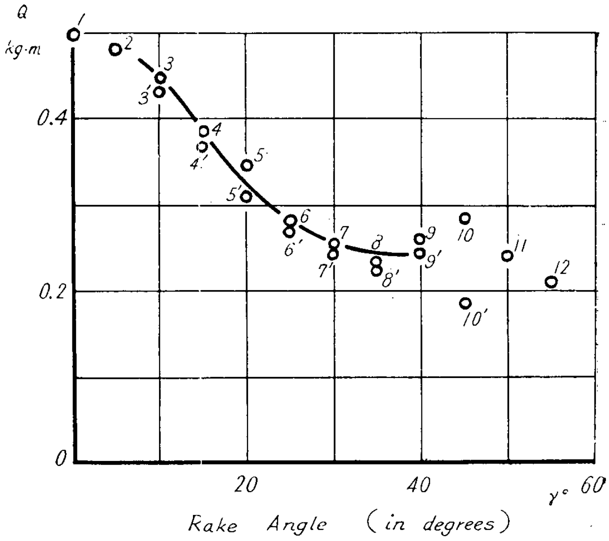

Fig. 25. Relation of Rake Angle to Cutting Energy.

No.	1	2	3	4	5	6	7	8	9	10	11	12
β°	65	65	65	55	55	45	45	45	25	25	25	25
β°			55	65	45	55	35	35	35	35		
No.			3′	4′	5′	6′	7′	8′	9′	10′		

Table 3 told that three 3-factor interactions and a 4-factor interaction were significant among 3-factor interactions combined F×G with one of other five factors; wood species, cutting direction, depth of cut, moisture condition and cutting stage, and 4-factor interactions combined A×F×G with one of cutting direction, depth of cut, moisture condition and cutting stage. A set of F and G makes the shape of a knife because F and G represent tool angle and clearance angle, respectively. Therefore the significant 3 or 4-factor interactions mentioned above show that the effect of the shape of a knife on the cutting energy varied with cutting direction, depth of cut, moisture condition and cutting stage.

7 Summary of Conclusions

The conclusions from the experiment might be summarized as follows.

Under almost all conditions of cut the energy consumption was minimum near tool angle (β) of 35°, and over 35° the energy increased as tool angle was larger.

The cutting energy increased with clearance angle (10°≦α≦25°) in most sets of cutting conditions.

The average cutting energy decreased with rake angle (γ) in the range of 0°≦γ≦35°, but the present experiment had two observations corresponding to a certain rake angle 10° to 45° and the two values hardly differed each other in spite of deviation of 10° in tool angle β (or clearance angle) except γ=45°.

Although it is said manggasinoro is apt to blunt cutting edges of a saw, this wood species did not show the significant difference of the cutting energy compared with Japanese cypress which is easily sawn.

In the case of the cross sectional cutting it was hard to state the energy consumption in cutting parallel to annual rings differed from that in cutting perpendicular to them. Of the six cutting directions the tangential and the radial cut perpendicular to wood fibers showed the least energy consumption, but the two hardly differed each other.

8 Complementary Remarks

Many faults to be improved were found about the mechanism of the pendulum dynamometer tested in the present experiment.

Reliability of Feed: As test blocks were fed by means of a screw, it was quite difficult to feed up the test block strictly vertically. Furthermore the amount of feed were measured with a dial gauge (*h* in Photo 1) to the nearest 0.01 mm, we could not pass over danger to read a wrong height owing to local roughness on the cut surface. So we consider to use a reading microscope in an attempt to avoid such a danger.

Cutting Speed: Cutting speed differed from these in practice but could not be controlled. It is quite desirable to change cutting speed with a certain device.

Moving Picture: As moving picture might be a helpful method in such a research, we are going to try this attempt.

Cutting Direction: It has been considered, this paper did not refer, that there is the difference of energy consumption between cutting from the outer surface of specimens and from the inner one. Can such a difference be inspected by means of a pendulum dynamometer?

Knife Angle: It seemed apparently that each effect of tool angle, clearance angle, and rake angle were obtained. But, to speak the truth, there exists the condition of $\alpha+\beta+\gamma=90°$. Even if, keeping clearance angle α constant, cutting energy corresponding to various tool angles β could be plotted on a graph, it may be wonder whether the change appeared on the figure results purely from the increase of tool angle or the decrease of rake angle. We hope to find a method to answer this question.

Break of Test Block: With the tangential cut perpendicular to wood fibers ($T_\perp$) it was observed that chip was not horizontally removed from a workpiece but along annual rings at the end of cutting work. To lessen the effect of this fault longer length of cut is required, so a longer arc drawn by the knife of a pendulum can not be approximated by a segment. Here are also some problems.

Plan of Experiment in this Work : Before the experimentation the interaction of wood species was thought to be highly significant, but the analysis of variance denoted this interaction was not significant even at the 5 per cent level of probability. Such a wrong plan let us not know the interaction which might occur among the cutting direction, the cutting stage and so on. Hence the design of an experiment in future will be more effectively planed in the light of this failure.

The authors wish to express our gratitude to Mr. NISHIKAWA who made the experiment with us and to thank Mr. YOSHIDA for making many test blocks.

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要　　旨

先に試作したアイゾット形衝撃試験器の原理を用いた振子式木材切削試験器によつて，刃先角を 25°，35°，45°，55°，65°；逃げ角を 10°，15°，20°，25° と変化させてその各組み合わせの刃20個を用いて切削抵抗を測定した。

この20個の刃に樹種（ヒノキ，ブナ，マンガシノロ），切削方向（木口面，板目面，柾目面），切り込み量（0.5 mm，0.2 mm），含水率（絶乾，気乾，飽水），切削距離をからませて，実験計画法に基いて実験を行ない，結果を解析した。