Wood Cutting with a Pendulum Dynamometer [III]

Effect of Specimen Shape and Cutting Direction*

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野口昌巳・杉原彦一：振子式木材切削試験器による木材切削（第3報）
試験片の形状および切削方向の影響

Introduction

The present investigation described in this paper forms a link in the chain of the program which has been intended to obtain basic informations on a pendulum dynamometer and to pursue mechanism of wood cutting. Two studies had been already reported about the effects of the tool angle[1)] and the clearance angle[2)] in 1962. The present test was made to know the effects of specimen shape, cutting direction and knife material on the consumed energy in wood cutting. Besides such factors some experimental variables were considered to establish more reproducibility of the results. The principle and the procedure of this experimental method were closely discussed in a previously published paper[1)].

Design of Experiment

Specimen Shape (λ) : Four types of specimens were used in the present work and these specimen shapes are shown in Fig. 1. Each cut area ($b\times l$, where b is

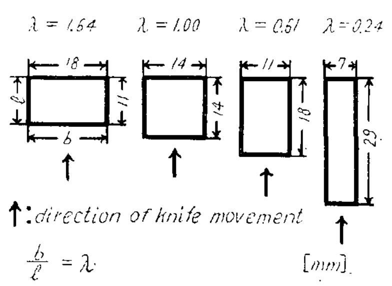

Fig. 1. Cross-section of specimens.

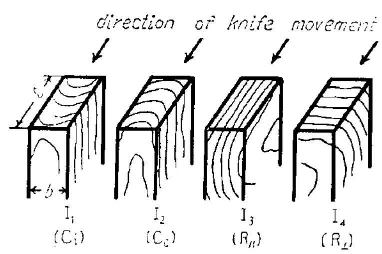

Fig. 2. Four cutting directions.

width of cut and l is length of cut) was constant at 200 mm², so the ratio of width

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of cut b to length of cut l, λ $(=b/l)$ varied to include 0.24, 0.61, 1.00 and 1.64.

Cutting Direction (I) : It has been empirically said that with cross-sectional cutting, the cutting force in the case of cutting from the inner surface (I_1 in Fig. 2) is different from that in the case of cutting from the outer one (I_2 in Fig. 2). It is a quite interesting problem to find out the difference of the cutting force, if any, in these two contrary directions to each other by means of a pendulum dynamometer, so cutting was carried out in four directions as shown in Fig. 2, comparing with radial-sectional cutting.

Sub-factors: Besides the main variables above mentioned, four factors on Table 1 were further taken up. Since it is one of the great purposes in the present work to estimate the effect of knife material, factors **A**~**D** were allotted in the table of orthogonal array $L_{27}(3^{13})$ so that the present authors might find the two-factor interactions between knife material **A** and the other three **B**, **C** and **D**. After the test, such a plan was found to be not so good, because interactions of the knife material by one of the other three factors were little. The designer of the present experiment should have rather made the plan able to know the two-factor interactions between **B**, **C** and **D**. A kind of three way layout was made with the orthogonal array and factors λ and **I**. The number of replications was three under the same experimental condition.

Table 1. Factors and levels.

Factor \ Level	1	2	3
Knife Material (A)	carbon tool steel (No. 4)	galvanized with chromium	tipped with tungsten carbide
Depth of Cut (B)	0.1 mm	0.3 mm	0.5 mm
Wood Species (C)	beech, *Fagus crenata* BLUME (density : 0.58 g/cm³)	Japanese cypress, *Chamaecyparis obtusa* ENDL (density : 0.42 g/cm³)	red lauan, *Shorea* (density : 0.41 g/cm³)
Moisture Condition (D)	wet : beech 154%, Japanese cypress 211%, red lauan 228%	dry : beech 15.9%, Japanese cypress 16.7%, red lauan 17.1%	dry : beech 15.9%, Japanese cypress 16.7%, red lauan 17.1%

Three knives were used : the first of them was made of carbon tool steel (No. 4), the second galvanized hard with chromium and the last tipped with tungsten carbide as shown in Table 1. The three knives had the same shape and size, and the clearance angle α was 20 degrees, the tool angle β 40

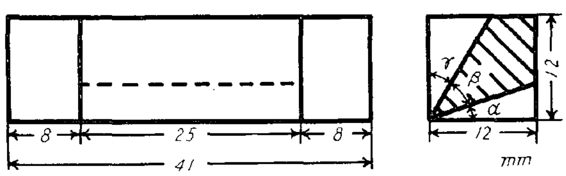

Fig. 3. Size and shape of kinfe.

Table 2. Analysis of variance.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	F	ρ (%)
A (knife material)	2	2756	1378		0.4
B (depht of cut)	2	111745	55873	30.72**	16.6
C (wood species)	2	51879	25940	14.26**	7.7
D (moisture condition)	1	19301	19301	10.61**	2.9
A×B	4	827	207		—
A×C	4	733	183		—
A×D	2	441	221		—
e_1	9	16367	1819		
T″	26	204049			
λ (specimen shape)	3	2629	876	3.71*	0.4
λ×A	6	1094	182		—
λ×B	6	2207	368	1.56	0.3
λ×C	6	2876	479	2.03	0.4
λ×D	3	667	222		—
e_2	57	13438	236		
T″	107	226960			
I (cutting direction)	3	277327	92442	646.45**	41.4
I×A	6	2023	337	2.36*	0.2
I×B	6	78976	13163	92.05**	11.7
I×C	6	19507	3251	22.73**	2.8
I×D	3	10642	3547	24.80**	1.5
I×λ	9	3968	441	3.08**	0.5
e_3	291	41588	143		
T′	431	660991			
e_4	864	12494			13.5
T	1295	673485			100.0

Note** : significant at 1% level
* : significant at 5% level

F : F-ratio
ρ : contribution rate to total variation S_T

degrees and the rake angle γ 30 degrees.

In order to observe the state on the knife edges the pictures of the cutting edges were taken before and after the cutting test.

Results and Analysis

All the results were statistically analyzed and the summary of analysis of variance is shown in Table 2, where ρ denotes in the range of the present work that factor **I** (cutting direction) may introduce the most variability into the measurements and that factor **B** (depth of cut) comes next. The letter ρ is called contribution rate[3] and indicates how much effect a factor gives to the total variation of meaurements. Since it is impossible to take off much dispersion from measurements even if experimental conditions were more strictly controlled in an experiment with wood, contribution rate ρ may be quite important for estimating the effects of experimental factors.

Notation : Prior to considering the experimental results, it is necessary to define some notations that will be used in the present chapter.

λ : the ratio of width of specimen b to length of specimen l, b/l

Q : the average consumed energy in wood cutting

$Q_{\lambda 1.64}$: the consumed energy in the case of $\lambda=1.64$

$Q_{\lambda 0.24}$: the consumed energy in the case of $\lambda=0.24$

$Q_{\lambda 0.61}$: the consumed energy in the case of $\lambda=0.61$

$Q_{\lambda 1.00}$: the consumed energy in the case of $\lambda=1.00$

$\lambda \times$**I** : the two-factor interaction between specimen shape (λ) and cutting direction (**I**)

$\lambda \times$**C** : the two-factor interaction between specimen shape (λ) and wood species (**C**)

$\lambda \times$**I**$\times$**C** : the three-factor interaction among specimen shape (λ), cutting direction (**I**) and wood species (**C**)

$\lambda \times$**B** : the two-factor interaction between specimen shape (λ) and depth of cut (**B**)

Q_{Co} : the consumed energy in cross-sectional cutting from the outer surface

Q_{Ci} : the consumed energy in cross-sectional cutting from the inner surface

$Q_{R//}$: the consumed energy in radial-sectional cutting parallel to the fiber direction

$Q_{R\perp}$: the consumed energy in radial-sectional cutting perpendicular to the fiber direction

I×B : the two-factor interaction between cutting direction (**I**) and depth of cut (**B**)

Specimen Shape (**λ**) : It is obvious from Fig. 4 that the consumed energy $Q_{\lambda 1.64}$ in the case of $\lambda=1.64$ is greater than those in other three cases of $\lambda=0.24$, 0.61 and 1.00, and Table 2 indicates that the F-ratio for specimen shape λ is significant at the 5% level of probability. In order to clarify the cause of increase in the consumed energy, Figs. 5 and 6 are drawn, which show the graphs of the two-factor interactions between specimen shape and cutting direction (λ×I) and between specimen shape and wood species (λ×C), respectively. It can be assumed from these figures that in the cross-sectional cutting, especially in beech, $Q_{\lambda 1.64}$ is remarkably higher than $Q_{\lambda 0.24}$, $Q_{\lambda 0.61}$ and $Q_{\lambda 1.00}$. To prove the

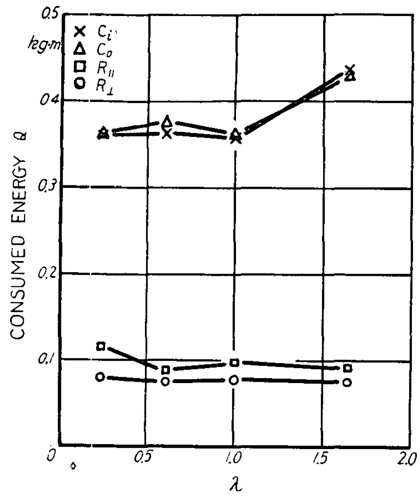

Fig. 5. Effect of λ on consumed energy (λ×I).

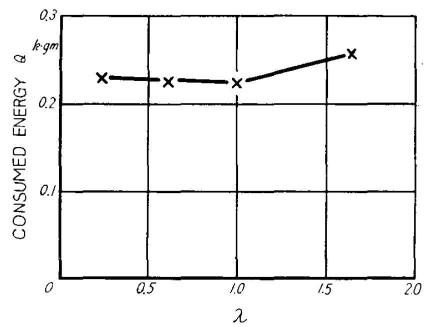

Fig. 4. Effect of λ on consumed energy.

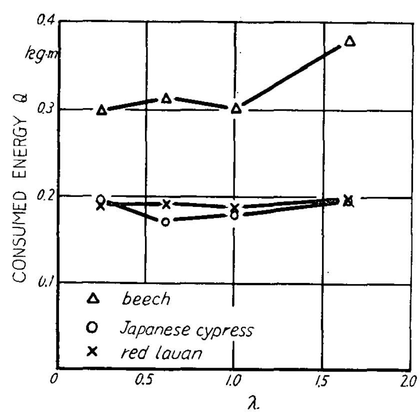

Fig. 6. Effect of λ on consumed energy (λ×C).

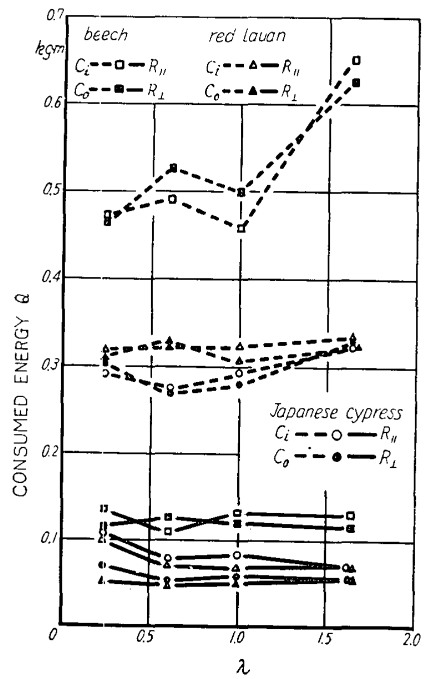

Fig. 7. Effect of λ on consumed energy (λ×I×C).

assumption, the three-factor interaction ($\lambda \times I \times C$) among specimen shape, cutting direction and wood species is graphically illustrated in Fig. 7. In addition, it may not be difficult to presume from Fig. 8 ($\lambda \times B$) that the consumed energy is remarkably great only in the case when a beech specimen of $\lambda=1.64$ is cross-sectionally cut at 0.5 mm depth of cut. The t-test for the group of the measurements marked "square" in Fig. 7 indicates that the measurements to $\lambda=0.24$, 0.61 and 1.00 belong to the same population without failure and those to $\lambda=1.64$ belong to another one.

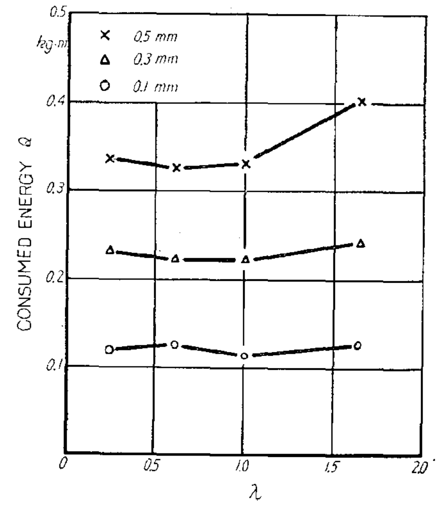

Fig. 8. Effect of λ on consumed energy ($\lambda \times B$).

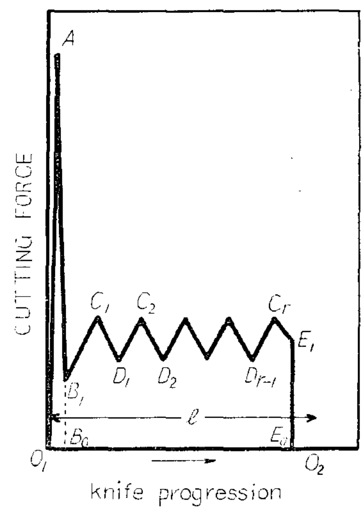

Fig. 9. Cutting force-Knife progression diagram.

It is necessary to consider the cause why only for the cross-sectional cutting at 0.5 mm depth of cut in a beech specimen the consumed energy to $\lambda=1.64$ is remarkably higher than those to other three λ. Analyzing a cutting process done with the present apparatus, a cutting force — knife progression diagram may be presumed as shown in Fig. 9: (1) the cutting force is, in a moment, remarkably large (O_1A) when the cutting edge impacts a specimen and goes into it, and then rapidly decreases (AB_1), (2) hereafter the cutting force repeats the change of the magnitude as presented in a usual static cutting (B_1C_1, C_1D_1, D_1C_2,..., C_rE_1) and (3) finally at the point of E_1 cutting goes with cleavage and so the force promptly decreases (E_1E_0), thus the cutting process ends at the point of O_2.

In the case of the cross-sectional cutting at 0.5 mm depth of cut in a beech specimen of $\lambda=1.64$, the specimen may be wholly, never locally, deformed (a specimen could be regarded as a cantilever) because of large O_1A. For Japanese cypress and red lauan chip is more easily removed before the test specimen is wholly deformed. The energy consumed in this deformation is specially greater than those at other depths of cut, therefore point B_1 is remarkably moved to the right. Area $O_1AB_1B_0$ becomes larger, so greater force resists the passage of the knife, consequently the consumed energy Q may be greater. For the specimen shape under the present cutting system, lessening l brings to deform easily a specimen (because of deflection $\delta \propto 1/l^3$) and to consume much energy for the deformation, so the amount of consumed energy does not present the pure one to remove chip. Thus, the results suggest that a specimen should be shaped under consideration about the capacity of momentum of the pendulum and the deform resistance of a whole specimen. In the present experimental condition, the critical deformation point of a specimen may be below $\lambda = 1.64$ ($b = 18$ mm, $l = 11$ mm) only in the case of cutting a beech specimen cross-sectionally at 0.5 mm depth of cut. So it may be admitted that the consumed energy is not affected by the specimen shape in usual radial- or tangential-sectional cutting.

Cutting Direction (I) : As shown in the column entitled "ρ" in Table 2 (table of analysis of variance), cutting direction (factor I) gives the greatest effect on the consumed energy Q. Q_{C0} seems to be slightly larger than Q_{Ct} in Fig. 10, but a statistical analysis denotes that no "cutting direction" difference is apparent in the two cross-sectional cuttings. Such a small difference can not be regarded as a necessary consequence due to the experimental factors.

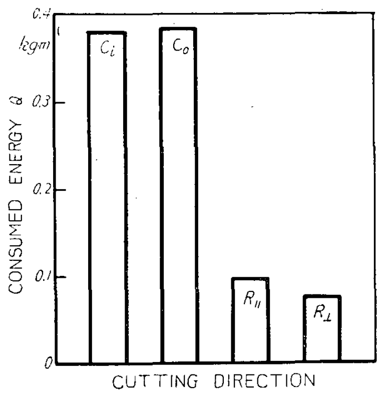

Fig. 10. Effect of cutting direction on consumed energy

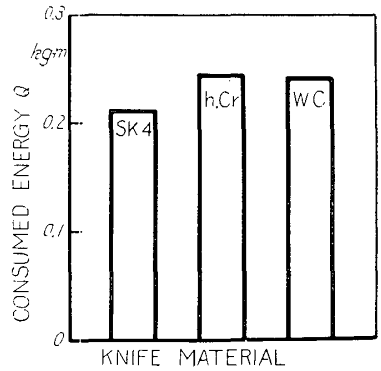

Fig. 11. Effect of knife material on consumed energy

Therefore, the present work could not judge whether there is any difference between Q_{C0} and Q_{Ct} which is empirically thought to be present.

The relationship of $Q_{R//} > Q_{R\perp}$ is always admissible in Figs. 5, 7, 10 and 13 like the results in the past[1)2)].

Knife Material (A) : The consumed energy with the knife made of carbon tool steel (No. 4) is the lowest of the three kinds of knives (carbon tool steel, galvanized hard with chromium and tipped with tungsten carbide) as shown in Fig. 11. Because of the fact that an edge of carbon tool steel can be made the sharpest, such a result could be fully expected in the present test which ended long before edge wear came into question. Furthermore, the clearance angle of the knives

Before cutting | After cutting

Carbon tool steel (No. 4)

Galvanized hard with chromium

Tipped with tungsten carbide

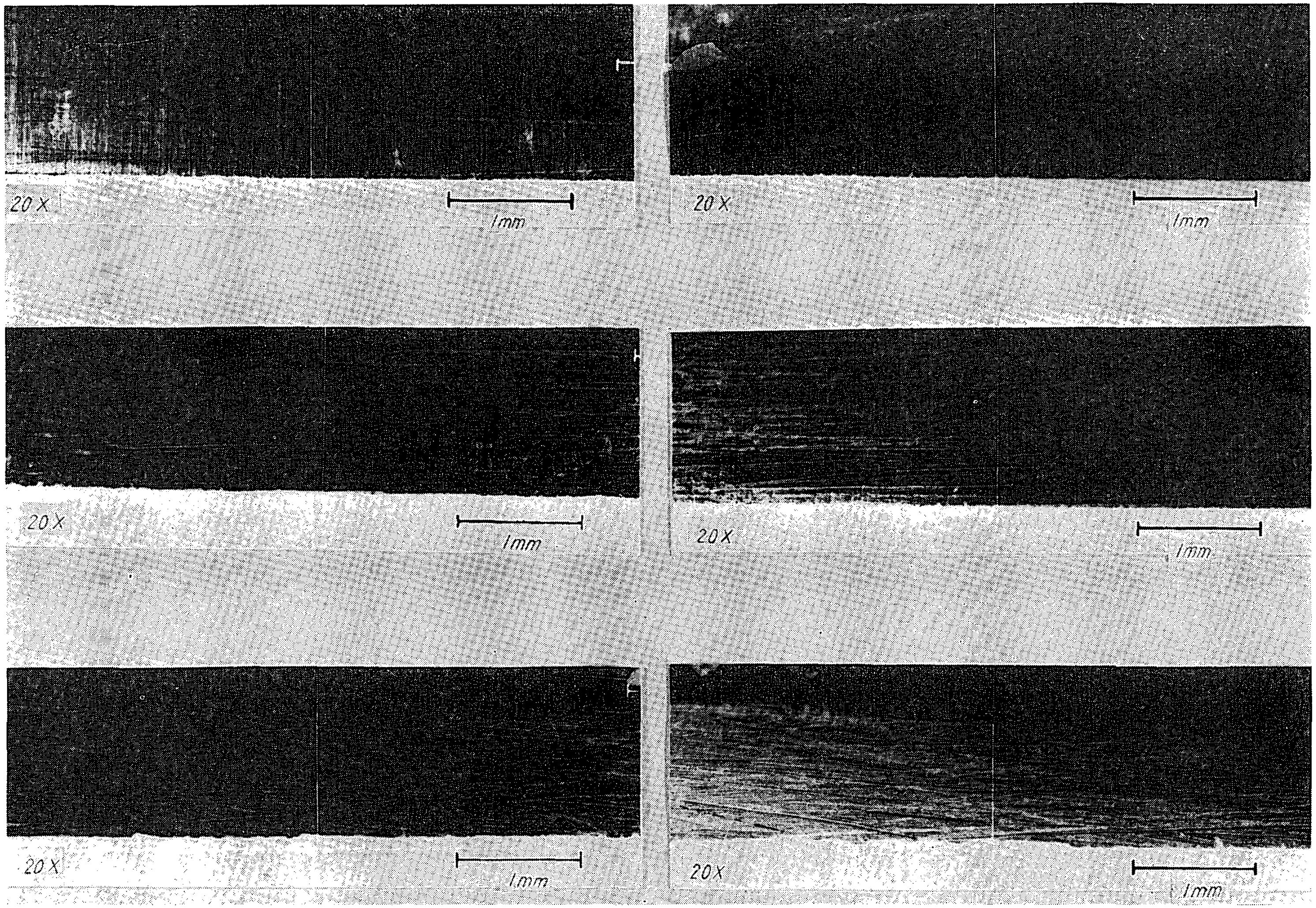

Photo. 1. Pictures of edges before and after cutting about 8 m of beech, Japanese cypress and red lauan.

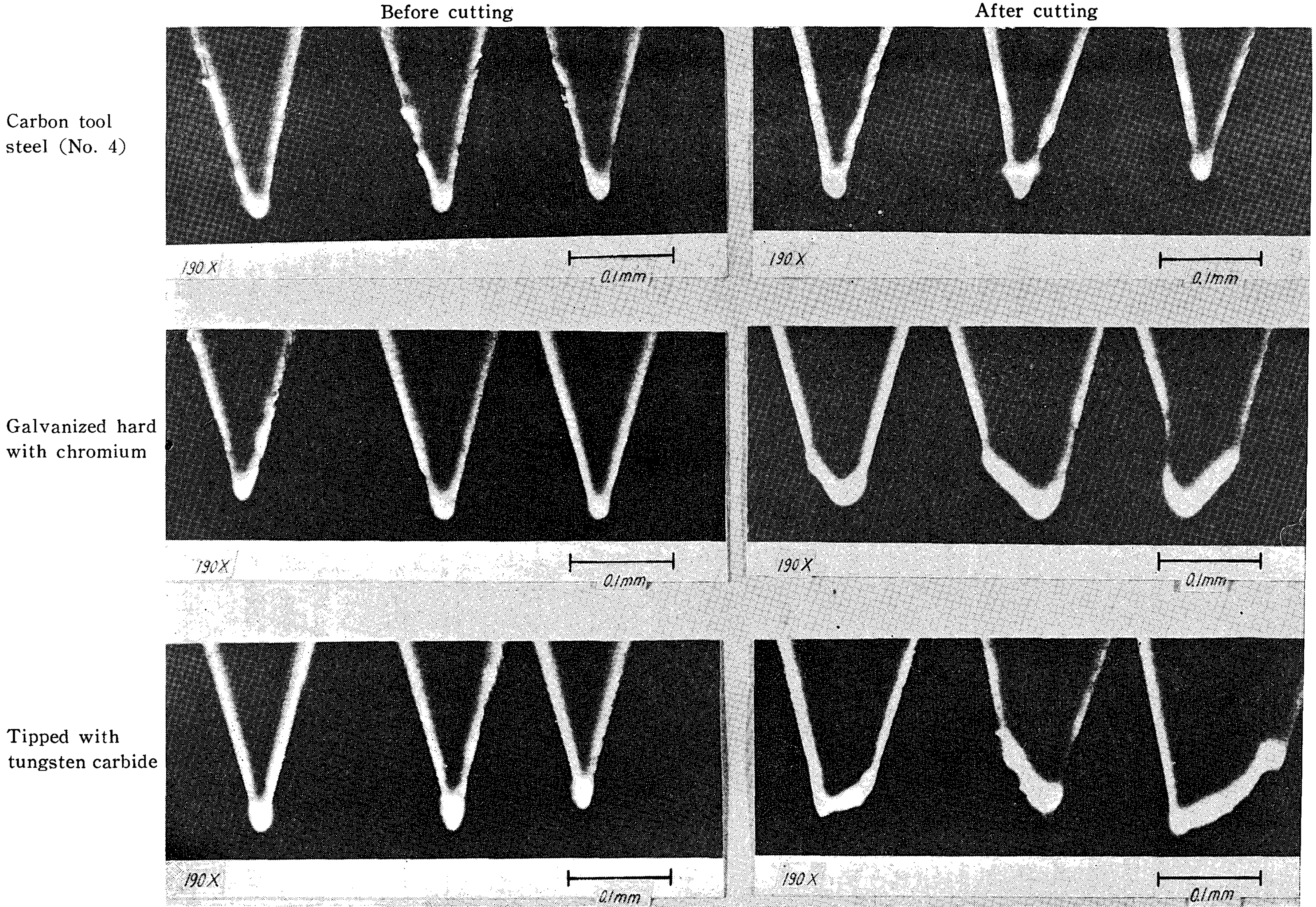

Photo. 2. Pictures of edges before and after cutting about 8 m of beech, Japanese cypress and red lauan (by means of optical slit method).

Wood Research No. 29 (1963), p. 5 eq. (7)

error $S=3W(l-l')2bh^2$

correct $S=3W(l-l')/2bh^2$

used were so large (20 degrees) and the rake angle so small (40 degrees) for knives made of harder materials such as chromium and tungsten carbide that some nicks were observed on cutting edges. It may be assumed that the result shown in Fig. 11 was obtained.

In order to know the effect of knife material on the consumed energy, a comparative experiment should be carried out under the condition where every material could fully demonstrate its characteristic.

Photos 1 and 2 seem to be a powerful proof for the consideration above mentioned and the effect of knife material will be more closely inquired in future.

Depth of Cut (B) : It is clear from Table 2 that cutting direction (factor **I**) affects most the consumed energy and the depth of cut (factor **B**) comes next. Though the main effect of depth of cut is shown in Fig. 12, Table 2 denotes that the cutting direction by depth of cut interaction (**I**×**B**) is highly significant at the 1% level of probability. So it is not sufficient to judge the effect of depth of cut from Fig. 12 only.

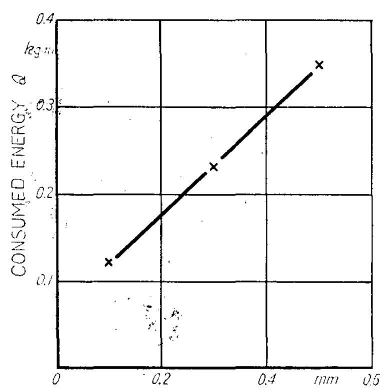

Fig. 12. Effect of depth of cut on consumed energy.

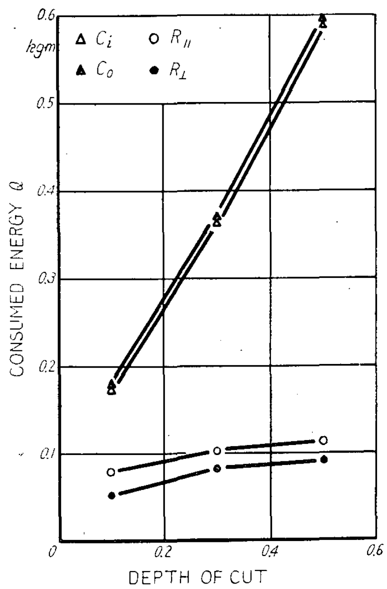

Fig. 13. Effect of depth of cut on consumed energy (B×I).

Fig. 13 is shown to illustrate this two-factor interaction, which indicates that the consumed energy increases with depth of cut in every cutting directions and that the effect of depth of cut is more noticeable in the cross-sectional cutting than in the radial-sectional one.

The graphs about the radial-sectional cutting in Fig. 13 resemble those in the present authors' last paper[2] in shape. On the contrary, for the cross-sectional cutting the larger the depth of cut is, the higher the increasing rate of the consumed energy seems to be. The cause of increase in the consumed energy may be assumed that the effect of λ is remarkable only for the cross-sectional cutting at 0.5 mm depth of cut in a beech specimen as discussed above. Fig. 14 shows graphically the specimen shape by depth of cut interaction ($\lambda \times B$) in the cross-sectional cutting.

Some recognized a linear relationship between cutting force and depth of cut in the following ranges : NAKAMURA and AOYAMA[4] (0.15 mm~0.8 mm in the radial-sectional cutting; 0.13 mm~0.5 mm in the cross-sectional), KINOSHITA[5], HAYASHI[6] (0.1mm~0.5 mm in the rotary cutting) and PAHLITZSCH and MEHRDORF[7] (0.15 mm~0.75 mm).

The present authors wanted to classify the graphs in Fig. 13 into the group of wood species, but regret to say that the attempt could not be carried out because of a defect in the experimental design (the two-factor interaction between knife material and other factors were considered, too).

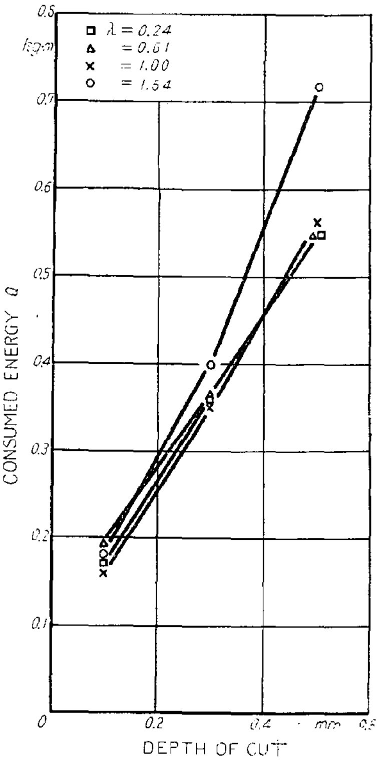

Fig. 14. Effect of depth of cut.

Wood Species (C) : It is natural that beech requires the most consumed energy of three wood species as mentioned in many papers, and the consumed energy in cutting Japanese cypress is slightly less than that in red lauan. This relationship of magnitude of the consumed energy agrees with that in the authors' paper[2]. Fig. 15 shows the wood species and cutting direction interaction.

Moisture Condition (D) : The main effect of moisture condition is graphically illustrated in Fig. 16, which shows that the ratio of the consumed energy in cutting dry specimens to that in wet ones is 146/100. This ratio was calculated to be 144/100 in the authors' test with beech, Japanese cypress and manggasinoro[1]. KINOSHITA[5] and HAYASHI[6] reported the same values in their papers on cutting force, and PAHLITZSCH and MEHRDORF[7] found the ratio to be 136/100 in beech and 142/100 in pine.

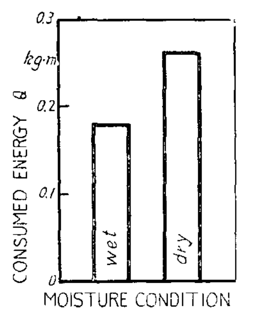

Fig. 15. Effect of wood species on consumed energy.

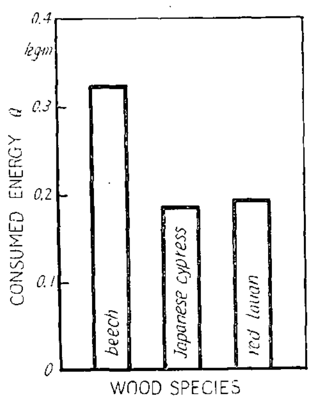

Fig. 16. Effect of water condition on consumed energy.

Moisture content and many mechanical strengths of wood have a close affinity with each other and this may not be also unusual in the present testing method. So the effect of this factor will be soon investigated in an experiment under the condition where moisture content will be treated as a major factor.

Conclusions

The following conclusions might be drawn from the experimental evidence.

Specimen Shape (λ) : Under the present experimental system no reasonable data could be obtained if specimens were easily deformed with the impact of the pendulum. So the cutting test should be carried out using specimens with a suitable ratio of width of cut to length of cut under suitable impact momentum of the pendulum. For example, in the present experiment no effect of specimen shape λ was present with the exception of the case in which a beech specimen was cross-sectionally cut at 0.5 mm depth of cut (Figs. 7 and 8).

Cutting Direction (I) : Though it is empirically said that for the cross-sectional cutting the consumed energy in cutting forward to the inner surface differs from those in the reverse cutting, the present work could not judge the existence of such a difference (Figs. 10 and 13).

Knife Material (A) : It was impossible to discuss the effect of knife material such as carbon tool steel (No. 4), chromium and tungsten carbide, because a clearance angle of 20 degrees was too large and a tool angle of 40 degrees too small for the knives made of harder material used in the present work. A comparative study should be carried out under the condition in which every material could give full play to its strong point.

Summary

Four types of specimens as shown in Fig. 1 were tested in order to know the effect of specimen shape on the consumed energy in wood cutting with a pendulum dynamometer. As it has been empirically said that for the cross-sectional cutting the cutting resistance in cutting from the inner surface (I_1 in Fig. 2) is different from that in the opposite direction (I_2 in Fig. 2), a factor of cutting direction was considered as shown in Fig. 2 so as to detect such a difference in two contrary directions of cutting. The experimental results and discussion are summarized as follows :

The consumed energy in the case of λ (the ratio of width of cut, b to length of cut l) $=1.64$ was larger than those for the other three $\lambda=0.24$, 0.61 and 1.00 (Fig. 4), and especially this tendency was remarkable in cutting cross-sectionally a beech specimen at 0.5 mm depth of cut (Figs. 7 and 8). For the specimen shape in this cutting system, a specimen may be more easily deformed by means of lessening l (deflection of a specimen $\delta \propto 1/l^3$, where l is length of cut) and then much energy is consumed to deform a specimen. So reasonable data would not have been obtained unless the value of λ was under 1 or so.

It is observed in Figs. 10 and 13 that the consumed energy in cutting from the outer surface seemed to be slightly greater than that in the contrary direction. This work could not conclud the difference of the consumed energy between the two opposite directions in cross-sectional cutting.

In the present work a clearance angle was too large (20 degrees) and a tool angle too small (40 degrees) for harder material such as chromium and tungsten carbide to estimate reasonably the effect of knife material.

Fig. 13 showed that the consumed energy increased with depth of cut in every cutting direction and that the effect of depth of cut was significantly less in the radial-sectional cutting than in the cross-sectional one.

As reported in the previous paper[2], the consumed energy in cutting beech was largest and Japanese cypress required less consumed cutting energy was reguired in Japanese cypress than in red lauan (Fig. 15).

The ratio of the consumed energy in cutting dry specimens to those in cutting wet ones was calculated to be 1.46 (Fig. 16), which agreed with the values reported by many papers[5)6)7)].

The authors want to express their gratitude to Mr. YOSHIDA for making many test specimens and the present experiment could not have been carried out without the help of Mr. KAMIJO who graduated from the Department of Forestry, Kyoto University, in 1963.

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摘　　要

振子式木材切削試験器における切削試験片の形状効果を検討するために，試験片の切削表面積を 200 mm^2 に保ち，その縦横比 λ を 4 段階に変化させ (Fig. 1)，λ が切削所要エネルギ

ーに及ぼす影響を調べた。同時に，木口面を木表側から切削した場合と木裏側から切削した場合とでは，切削抵抗に差があると従来言われてきたので，本試験器を用いてその差の有無を検出しようとして，Fig. 2 のような因子をとりあげた。以上の主要因子の他に，切削用ナイフの材質，切り込み深さ，樹種，含水率なども考え (Table 1)，実験結果に再現性を与えるように配慮した。

試験片の形状：「ブナの気乾材を切り込み深さ 0.5 mm で木口面切削」という実験条件においてのみ，λ の効果が見られた (Fig. 7, 8, 14, 16 から)。本実験のような切削システムにあつては，試験片の切削長さ l を減ずると試験片全体（片持ちハリと考えて）が変形しやすくなり（試験片のタワミは l^3 に反比例する)，その変形のために多くのエネルギーが消費されるので，上述のような結果が得られたと思われる。従つて本実験のような場合には，振子の運動量と試験片全体の変形抵抗とを考えあわせて，切削試験片の形状を決定しなければならない。本実験では λ が 1 以下に保たれれば試験片の形状効果は抑えられると推察される。

切削方向：Fig. 10, 13 では木口面切削において木表から切削した方が木裏から切削するよりも，切削所要エネルギーは多い。しかし t 検定によれば，この程度の差は実験因子による必然的な差とは認められない。従来言われていたような切削方向による切削所要エネルギーの差の有無について，本実験では断定するには至らなかつた。

ナイフの材質：各材質の長所が十分発揮されてはじめて，ナイフの材質の影響を云々できる。本実験で用いた硬質材料（ハードクローム鍍金やタングステンカーバイド・チップ）にとつては，逃げ角は過大 (20°) であり，刃先角は過小 (40°) であつたため，妥当な判断を下すに足る資料は得られなかつた (Fig. 11, Photo. 1, 2)。

切り込み深さ：切り込み深さが増すに従つて切削所要エネルギーも大になるのは勿論であるが，その程度は木口面切削において特に著しかつた (Fig. 13)。

樹種：機械的諸強度が大であるブナが最も多くの切削エネルギーを要し，ヒノキはラワンよりやや少なかつた (Fig. 15)。

水分状態：Fig. 16 に示したように，湿潤材と気乾材の切削所要エネルギーの比は100対146であつた。これとほぼ等しい値が内外の報告にも見られる。