Wood Cutting with a Pendulum Dynamometer 〔V〕
—EFFECT OF MOISTURE CONTENT*—

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野口昌巳**・杉原彦一***・松吉礼三**：振子式木材切削試験器による木材切削（第5報）
—含 水 率 の 影 響—

1. Introduction

The investigation described in the present paper forms a link in the chain of the program which has been intended to obtain basic informations on a pendulum dynamometer and to establish the international test standards for the machinability of wood. Some studies has already been reported about the effects of the tool angle[1], the clearance angle[2], the rake angle[3], the shape of specimens[4], the cutting direction[1], the depth of cut[2], the wood species[2] and the material of knives[4] on the energy consumption in wood cutting by means of a pendulum dynamometer.

The present test was made to know the effects of the moisture content and the length of a specimen along the cutting direction. Besides such factors, some experimental variables were considered to give the results of the experiment more reproducibility.

The principle and the procedure of this experimental method were closely discussed in a previously published paper[1].

2. Design of Experiment

The moisture content (A) was considered as the major factor in this work and the secondary ones were the length of a specimen along the cutting direction (B), the wood species (C) and the cutting direction (D). These factors and their levels are shown in Table 1. A 7×5×4×5 factorial experiment was constructed with these four experimental factors.

For each wood species, specimens were conditioned into seven levels of the moisture content with saturated metallic salt solutions as shown in Table 1. The energy consumption in wood cutting must be necessarily proportional to the

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Table 1. Factors and levels.

Factors	Levels						
Moisture content (%)	2.8	8.8	12.7	17.7	22.6	23.4	193
Length of a specimen along the cutting direction (mm)	8	13	18	23	28		
Wood species	beech	Japanese red pine	red lauan	Japanese cypress			
Cutting direction*	D_1	D_2	D_3	D_4	D_5		

* See Fig. 1.

length of a specimen along the cutting direction in the case of a constant width of cut, but no clear effect of the length of a specimen on the energy consumption had been obtained in the last test[3], so this factor was investigated again in the present experiment. Beech (*Fagus crenata* BLUME), Japanese red pine (*Pinus densiflora* SIEB. et ZUCC.), Japanese cypress (*Chamaecyparis obtusa* ENDL.) and red lauan (*Shorea sp.* FOXW.) were selected for test purposes as representatives for the hard, the soft and the tropical woods. The specimens were 10 mm wide and the length of a specimen along the cutting direction varied from 8 mm to 28 mm in steps of 5 mm. As it is said that the cutting force in the bark-to-pith cutting direction is not equal to that in the pith-to-bark cutting direction[5], D_1 and D_2 were taken up in the levels of the cutting direction in order to inspect the difference of the energy consumption between these two cutting directions, if any (Fig. 1).

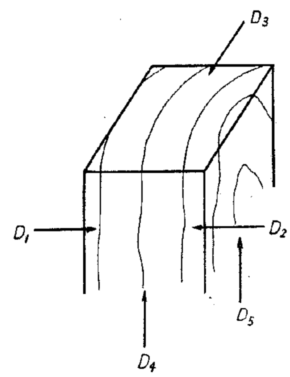

Fig. 1. Cutting direction.

Separate knives were used for different cutting directions and these knives was made of carbon tool steel (SK4) and the clearance angle of the knives was 20°, the rake angle 40°. The depth of cut was kept 0.2 mm. The number of replications was three under the same experimental conditions.

3. Experimental Results and Discussion

The various results obtained from the experiment are graphically illustrated in Figs. 2, 4, 5, 6, 7 and 8, and some discussion of the effects of the experimental factors are as follows.

3·1. Effect of Moisture Content

It is obvious from Fig. 2 that the energy consumption increases as the moisture content gradually increases from the oven-dried condition up to a moisture content of about 20% but that it begins to decrease as the moisture content ex-

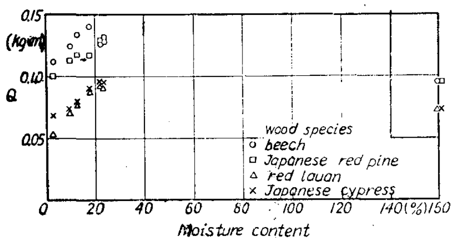

Fig. 2. Effect of moisture content on the energy consumption Q (in each wood specimen, expecting the average effect from other factors).

ceeds about 20%. Fig. 2 shows, furthermore, that the moisture contents at which the energy consumption is maximum vary with wood species and that beech requires the maximum energy consumption at a moisture content of about 18% while Japanese red pine, Japanese cypress and red lauan present the the maximum energy consumption at a moisture content of about 23%. Considering KITAHARA's paper[6] reporting that the absorbed energy in impact bending increases with the moisture content in the ranges 0% to 16% moisture content for beech and 0% and 25% for Japanese cypress, the horizontal deviation of the peaks of the energy consumption among wood species may be accepted.

Some students reported the relationship between the moisture content and the cutting force in planer cutting; KIVIMAA stated that the cutting force was maximum near a moisture content of 10% for birch whatever the cutting direction may be[7], and PAHLITZSCH reported that spruce and red beech required the most energy consumption at a moisture content of about 21%[8].

The present experiment and the reports above mentioned revealed that below a certain moisture content the cutting resistance conversely decreases with decrease of the moisture content. KOLLMANN described the relationships between the moisture content and the cleavage strength of spruce, oak and beech, reporting that the cleavage strength was the greatest at a moisture content of 6% to 13%[9]. Moreover, KOLLMANN and SEKHAR inspected the relationship between the moisture content and the absorbed energy in impact bending with thinwin, sisso and axlewood and they admitted that the absorbed energy was maximum at a moisture content of 25%[10]. Cutting by means of the apparatus employed in the present experiment may be thought as a cutting action with the cleavage phenomenon, so it is of interest that the results of the present experiment resemble the tendencies of the experiments of cleavage and impact. While the resistance of wood for an external force depends on variation of bound water below the fiber saturation point and decreases with increase of bound water, but is independent of change of free water over the fiber saturation point. Such a behavior of wood is explained by the assumption that bound water soaked into the cell wall lessens cohesive force among fibers[11]. But some unstable states such an internal stress occur in the interior of wood owing to desiccation and so the resistance to the external force may decrease. This may be the reason why the strength of wood decreases with decrease of the moisture content below a certain moisture content.

Further, the strength is represented with the maximum load, while the energy consumption was measured in this study, therefore, its magnitude is determined by the area surrounded with the load-deflection curve and the axis of abscissa (Fig. 3). So it is fully possible that comparative wet specimens are more flexible than dry ones even though the former's strength of break is lower than the latter's one and that comparative wet specimens require more work load till the end of break than dry ones. TSUDA[12] and KURAMA[13] reported that the CHARPY's impulsive value was larger in wet bones of cows and horses at a 12% moisture content than in dry ones at 7%. It may be accepted from the discussion described above that the maximal value of the energy consumption is observed at somewhat higher moisture content than the moisture content at which the strength of break or the cutting force becomes maximum.

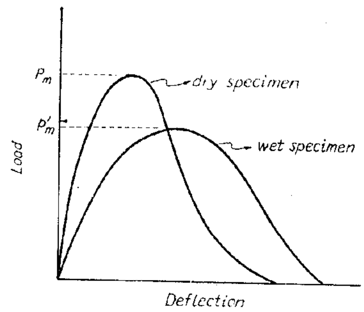

Fig. 3. Diagram of load-deflection curve.

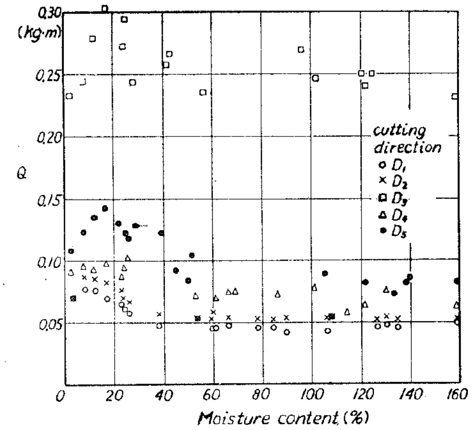

Fig. 4. Effect of moisture contet on the energy consumption Q (Beech, length of a specimen along the cutting direction of 18 mm).

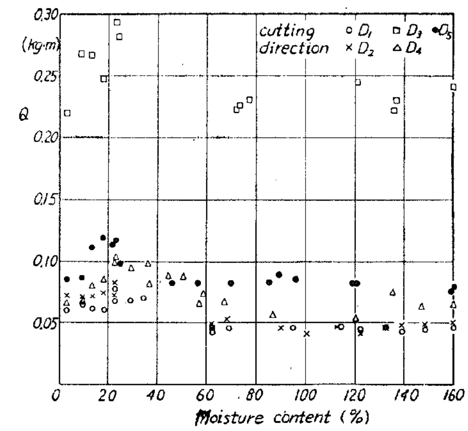

Fig. 5. Effect of moisture content on the energy consumption Q (Japanese red pine, length of a specimen along the cutting direction of 18 mm).

As obvious from Figs. 4 and 5, it may be thought that the energy consumption is almost unaffected by variation of the moisture content above about 40%, and such a tendency agrees with the strength properties of wood. It may be assumed in both figures that intersecting points with a linear section and a moun tain-shaped one lie near the fiber saturation point.

According to reports I[1] and III[3], the interaction between the tool angle and the moisture content and that between the rake angle and the moisture content were not so affected by variation of the moisture content, and it is clear from Fig. 2 that the moisture content presenting the maximum energy consumption varies with the different wood species. In addition, it was appreciated during the present experimentation that observations hardly fluctuated for wet specimens even in the cross-sectional cutting, and this fact can be worth special mentioning as a level suggesting an experimental condition under which the cutting resistance can be compared.

From these reasons described above it can be recommended to use specimens at a moisture content over the fiber saturation point in the case of comparing the difference of the cutting resistance among wood species. Though it was stated above that specimens at a higher moisture content are rather flexible and so more energy is apt to be consumed to deform the whole of the specimen, this characteristic can be avoided if specimens are used of which ratio ($\lambda = b/l$) of the width of cut b to the length of cut l is not more than 1[4].

3·2. Effect of the Length of a Specimen along the Cutting Direction

As stated in Chapter 2, it may be assumed that the energy consumption is proportional to the length of a specimen along the cutting direction l. If φ represents the central angle holding an arc drawn on a specimen by movement of a pendulum and r the distance between the center of the rotational axis of the pendulum and the cutting edge, l is given by the following formula:

$$l = r\varphi.$$

But this assumption is true only under the following condition,

$$l = l_0$$

where l_0 represents the length of an arc drawn on the specimen of which length along the cutting direction is l. The cutting form taken in the present study is, strictly speaking, different from planing because the cutting edge draws an arc due to rotation of the pendulum, but the distance between the cutting edge and the center of the rotational axis of the pendulum is 319.7 mm, while the length of a specimen along the cutting direction l is, at most, only 28 mm. In order to calculate the length of an arc drawn on the specimen of $l = 28$ mm by the cutting edge l_0, central angle φ containing the arc l_0 was computed, giving $\varphi = 0.0877$ (radians), from which l_0 was found to be 28.03 mm, so l_0 may be regarded to be equal to l. Therefore, the assumption mentioned above may be fully reasonable. But the

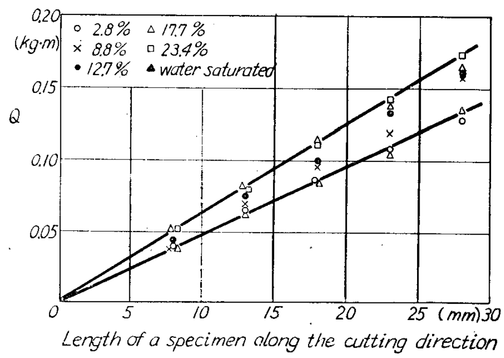

Fig. 6. Effect of length of a specimen along the cutting direction on the energy consumption Q (in each moisture content, expecting the average effect from other factors).

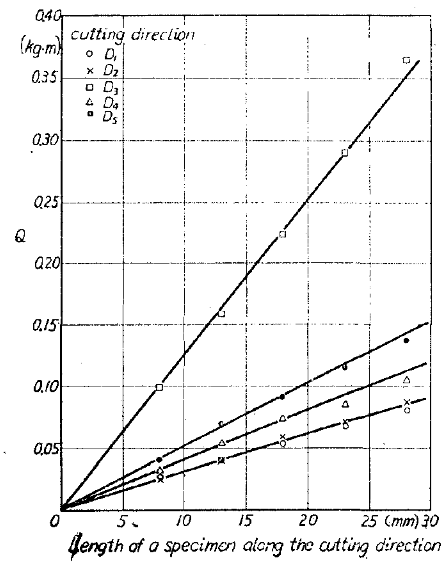

Fig. 7. Effect of length of a specimen along the cutting direction on the energy consumption Q (in each cutting direction, expecting the average effect from other factors).

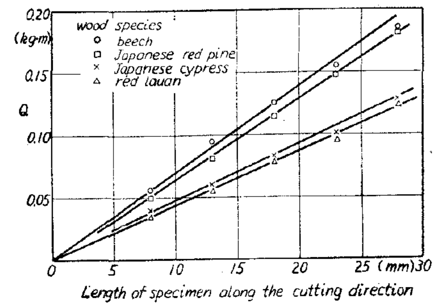

Fig. 8. Effect of length of a specimen along the cutting direction on the energy consumption Q (in each wood species, expecting the average effect from other factors).

energy consumption is not proportional to the length of a specimen l unless r is sufficiently large since not only l can be regarded as $r\varphi$ but the direction of grain at the beginning of cutting deviates from that at the end because of cutting due to rotation of the pendulum.

It is evident from Figs. 6, 7 and 8 that the energy consumption is proportional to the length of a specimen along the cutting direction regardless of the moisture content, the wood species, the cutting direction and so on.

It may be considered on the basis of the length of a specimen along the cutting direction if l and r can satisfy the following inequality:

$$r > 10\, l,$$

or φ can satisfy the following one:

$$\varphi < 0.1 \quad \text{(radian)}$$

$$\fallingdotseq 6 \quad \text{(degrees)}$$

where l represents the length of a specimen along the cutting direction, r the distance between the center of the rotational axis of the pendulum and the cutting edge and φ the central angle holding an arc drawn on the specimen by the cutting edge.

3·3. Effect of Cutting Direction

It was stated in Chapter 2 that the objective of interest consisted in the relationship between the energy consumption in the bark-to-pith cutting (D_1) and that in the pith-to-bark cutting (D_2) in the case of the radial-sectional cutting perpendicular to the axis of wood.

It is obvious from Figs. 4, 5 and 7 that the energy consumption is larger in the cross-sectional cutting than in any other cutting directions, and this tendency agrees with the results obtained in the experiments which were already carried out. In the case of the radial-sectional cutting perpendicular to the axis of wood, the energy consumption in the pith-to-bark cutting is slight higher than that in the reverse at every level of the moisture content except the water saturated condition, but the t-test does not indicate that such a small difference between these two energy consumptions is a necessary consequence coming from the difference of the level in an experimental factor. The tendency in the magnitude of the energy consumption is as the same as the results of the experiments previously carried out[1~4].

4. Conclusions

In the present study the factors affecting the cutting resistance of wood were investigated with a pendulum dynamometer and the following conclusions are drawn from the experimental evidences and discussion.

Moisture Content

The energy consumption increases as the moisture content gradually increases from the oven-dried condition but begins to decrease when the moisture content reaches a certain value, and further over the fiber saturation point it is scarcely affected by variation of the moisture content (Figs. 4 and 5). The energy consumption is maximum at a moisture content of about 18% for beech and of about 23% for Japanese red pine, Japanese cypress and red lauan (Fig. 2). It is convenient for comparison with the cutting resistance of wood species to cut specimens with a moisture content above the fiber saturation point.

Length of a Specimen along the Cutting Direction

In the case of a constant width of cut the energy consumption is proportional to the length of a specimen along the cutting direction l (Figs. 6, 7 and 8), but the limit of l where the proportional relationship comes into existence depends on the length of the arm of the pendulum r used in cutting. It might be considered that the energy consumption is proportional to the length of a specimen along the cutting direction l, if r is, at least, as follows:

$$r>10\,l.$$

Cutting Direction

The energy consumption is the largest in the cross-sectional cutting and that in the tangential-sectional cutting comes next. In the radial-sectional cutting perpendicular to the axis of wood, the energy consumption seems to be slightly lower in the bark-to-pith cutting than in the reverse, but such a small difference is not statistically admitted.

5. Summary

The effects of some experimental factors on the energy consumption was investigated in wood cutting with a pendulum dynamometer. The moisture content was the major factor and had seven levels of 2.8, 8.8, 12.7, 17.7, 22.6, 23.4 and 193%. For secondary factors the length of a specimen along the cutting direction, the wood species and the cutting direction were considered.

The experimental results obtained are summarized as follows.

(1) Though the energy consumption increases as the moisture content increases from the oven-dried condition, it begins to decrease above a certain moisture content. The moisture content at which the energy consumption is maximum varies with wood species.

(2) The energy consumption is proportional to the length of a specimen along the cutting direction.

(3) There is no evident difference of the energy consumption between the bark-to-pith cutting and the reverse in the radial-sectional cutting perpendicular to the axis of wood.

摘　　要

数個の因子について，木材の切削所要エネルギーにおよぼす影響を振子式木材切削試験器を用いて検討した。

試験片の含水率を主要因子とし，2.8, 8.8, 12.7, 17.7, 22.6, 23.4, 193%の7段階に変化させた。副次的因子として，試験片の切削方向の長さ，樹種，切削方向の3因子をとりあげた。

切削に用いたナイフの掬い角は 30°，逃げ角は 20°，刃先角は 40° であり，材質は SK4 であつた。切削試験片の幅は 10mm，切り込み深さは 0.2mm とした。

実験結果を次に要約する。

(1) 試験片の含水率が絶乾状態から増加するにつれて，切削所要エネルギーは増大するが，含水率がある点まで増加すると切削所要エネルギーは減少し始める。切削所要エネルギーが最大に達する場合の含水率は樹種によつて異なる。

(2) 切削所要エネルギーは試験片の切削方向の長さに比例する。

(3) 柾目面において，木材の繊維方向に垂直に木表から木裏に向かつて切削しても木裏から木表に向つて切削しても，切削所要エネルギーには顕著な差は見られない。

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