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A Study of the Orthogonal Cutting Mechanism by controlled Shear Angle Experiments

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Abstract

In order to obtain new insights on the orthogonal metal cutting mechanism, cutting tests were performed under controlled shear angles, using newly developed test equipment. In the experiments, the test rig holds the upper free surface of the workpiece flat by a constraining plate up to any selected distance from the cutting edge.

Using this apparatus, it is possible to confine the chip-forming deformation to a narrow shear zone in which a single-shear plane cutting is achieved at extremely low cutting speeds where the thermal effect is negligible.

The test results indicate that minimum cutting forces are registered when the shear zone is controlled to certain shear angles, which are peculiar to various tool rake angles. Energy analysis indicates that the shear angle which gives minimum cutting forces correspond to those which minimize the sum of the energies dissipated at the shear zone and the tool-chip interface, the criterion being equal to Merchant's model.

From the study, it was understood that, insofar as the single-shear plane model is assumed, the minimum-energy principle holds only when the shear angle is controlled to the predicted value. Orthogonal cutting in conventional mode occurs at an apparent shear angle smaller than that predicted by the minimum-energy principle with a single shear plane assumption.

Introduction

In order to study the mechanism of orthogonal cutting, cutting tests are conducted using a newly developed test equipment. The test rig holds the upper free surface of the undeformed workpiece flat, up to a predetermined distance from the cutting edge by use of an upper constraining plate. Using this apparatus, it is possible to confine the chip-forming deformation in the work to a narrow shear zone in which a situation close to the single-shear plane cutting is achieved with the shear angle, namely the inclination of the shear zone to cutting direction, controlled to a programed value.

The purpose of the present study is to check, by making measurements of the cutting force in controlled shear angle experiments, whether or not the orthogonal cutting in conventional mode, namely without artificial control of shear angle

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and which will be referred to as "free cutting" hereinafter, takes place with a minimum consumption of mechanical energy.

Experimental Procedures

A hydraulic piston pushes the workpiece through the upper, lower and side constraining plates against the cutting tool edge as illustrated in Fig. 1. Shear angle ϕ is controlled by the distance CL of the edge of the upper constraining plate from the cutting edge by a relation $\phi=\tan^{-1}$ (h/CL). When the constraining plate is located at a sufficient distance from the tool, the shear angle no longer follows the above equation and free cutting is achieved. Sidewise deformation of a workpiece is controlled by the side constraining plates so that orthogonality is assured.

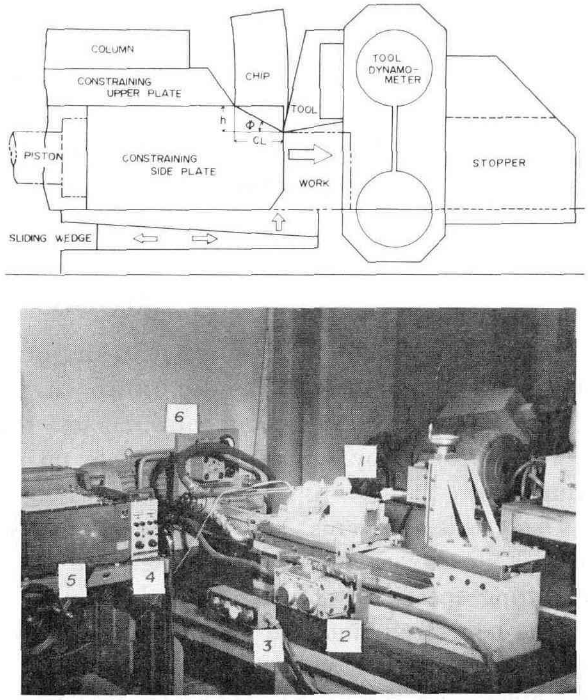

Fig. 1. Arrangement for artificially controlled shear angle cutting test.

1. Controlled shear angle cutting machine
2. Velocity control valve
3. Control switch
4. Instruments for measuring forces
5. Recorder
6. Hydraulic pump

Orthogonal flow pattern is first observed in partially formed chips of Pb-Sn alloy (91.5% Pb and 8.5% Sn) workpiece at a cut of 3 mm undeformed chip thickness, and 13.6 mm/sec cutting speed. In this case, square grid lines were grooved on the side of the workpiece at 0.2 mm spacing before cutting.

Force measurement is made in cutting of a 99.98% pure lead workpiece at 2 mm undeformed chip thickness, by a pair of strain gauge type hexagonal ring dynamometers. Frictional force between side constraining plates and possible side flow region is assured to be less than 18 Kg, which is less than 5% of minimum principal cutting force measured and is not subjected to compensation.

Cuts were made on 30 mm wide workpieces, at a speed of 1.68 mm/sec, where the thermal effect on chip formation is presumably negligible.

Cutting tools are made of 10% Co type high speed steel, finish ground to geometries of $\alpha=5$ deg clearance angle with $\gamma=10$, 20, 30 and 40 deg rake angles.

Experimental Results

As seen in the deformed grid patterns of Fig. 2, free cutting occurs when

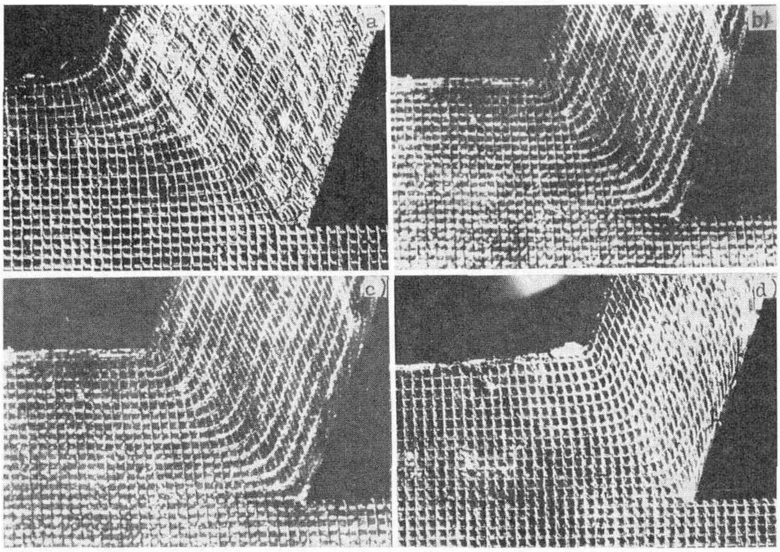

Fig. 2. Photographs of partially formed chips in free and controlled shear angle tests.

Workpiece P_b-S_n alloy. Cutting speed $v=13.6$ mm/sec.
Undeformed chip thickness $h=3$ mm.
Rake angle $\gamma=20$ deg. Cutting fluid dry.

a) Free cutting (CL=5 mm) b) $\phi=37$ deg (CL=4 mm)
c) $\phi=45$ deg (CL=3 mm) d) $\phi=57$ deg (CL=2 mm)

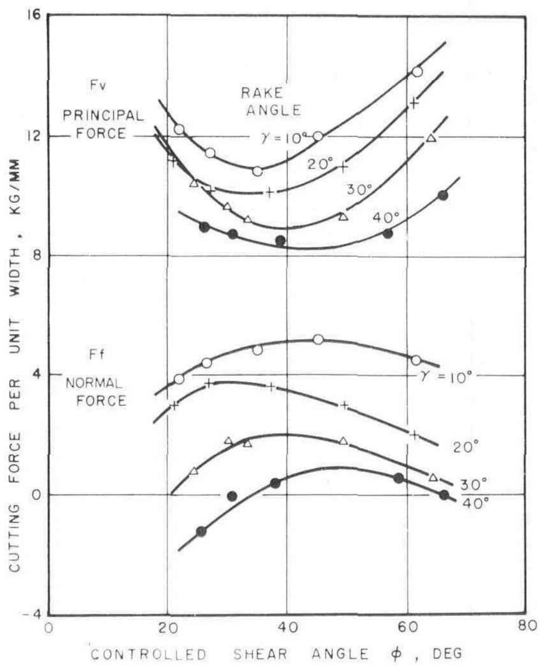

Fig. 3. Measured cutting force in controlled shear angle cutting tests.
Workpiece commercially pure lead. Cutting speed $v=1.68$ mm/sec.
Undeformed chip thickness $h=2$ mm. Cutting fluid dry.

the edge of the constraining plate is located at a distance of 5 mm. In this case, shear angle ϕ is obtained from the measurement of chip thickness by using a micrometer. When the distance is 4 mm or less, however, shear angles are controlled to scheduled values, pre-flow curves of the upper free surface are smaller, and the chip-forming flow is limited to a narrower zone.

Results of cutting force measurement are plotted in Fig. 3, where data at free cutting appear at the left end among plots for each tool rake angle. As seen in the figure, the principal component F_v and normal component F_f have their minimum and maximum respectively when shear angle ϕ is controlled to certain values.

Since mechanical work done by cutting tool is dependent only on the principal component F_v, the above indicates that the free cutting does not correspond to the conditions of minimum energy. It seems from the figure that the shear angle which results in minimum energy tends to be greater in cutting by a tool with a greater rake angle.

Analysis of Experimental Results

From above experimental data, it is possible to estimate the average force or stress values in the tool rake face as well as in the shear zone, based on the

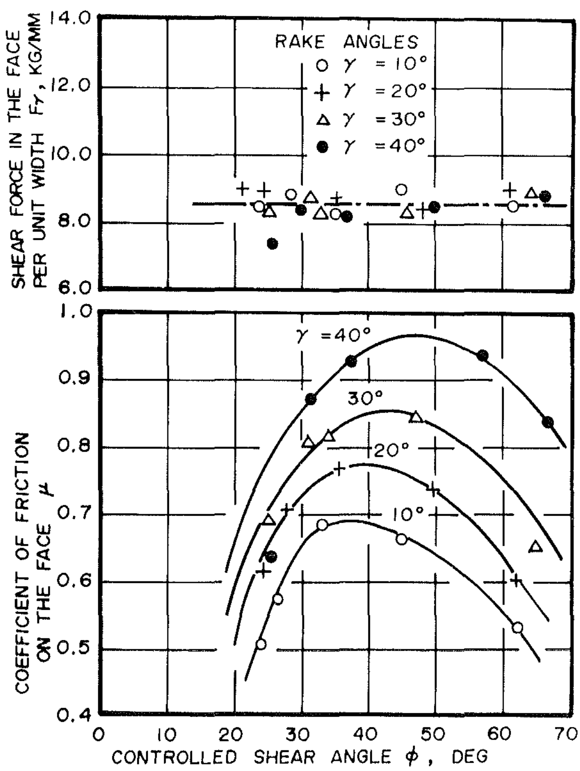

Fig. 4. Shear force in the face and apparent coefficient of friction in controlled shear angle cutting tests.

equilibrium of force together with an assumption of a single-shear plane. This will lead to detailed knowledge on the nature of flow stress present in the sets of tests performed, and will also make it possible to compute the amount of energy shared by the friction in the rake face, and the shear deformation in the shear zone.

In the top graph of Fig. 4, are shown shear force in the rake face per unit width of cut, F_γ, computed from measured F_v and F_f force components, versus the controlled shear angle ϕ. It may be understood from the figure that a newly constant shear force of $F_\gamma=8.5$ kg/mm was present in the rake face irrespective of shear angle ϕ. On the contrary, the apparent coefficient of friction μ on the rake face is not constant and varies with the shear angle ϕ and tool rake angle γ as shown in the lower graph of Fig. 4.

When the computed shear force in the shear plane F_{shi} was plotted versus the area of the shear plane A_{shi}, it was found that F_{shi} was a linear function of A_{shi}, which was not reduced to zero but held a value $F_{shi0}=0.55$ kg/mm if extrapolated to $A_{shi}=0$. This F_{shi0} is attributed to the force acting on the edge of the cutting tool, and therefore, should be off-set when computed for shear stress in the shear plane τ_{shi}. Thus, τ_{shi} is computed by $\tau_{shi}=(F_{shi}\text{-}F_{shi0})/A_{shi}$, and the result is plotted against the computed normal stress σ_{shi} on the shear plane as shown in Fig. 5.

It is indicated in Fig. 5, that a higher normal stress is present on the shear

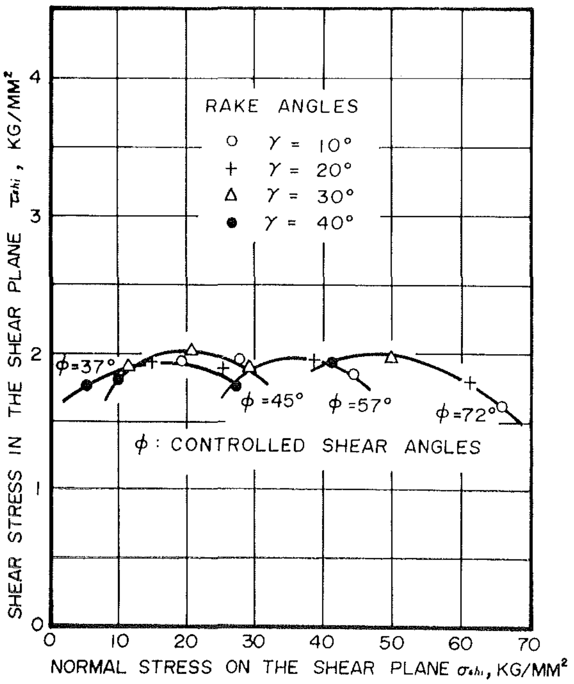

Fig. 5. Shear stress in the shear plane τ_{shi} versus normal stress on the shear plane σ_{shi} in controlled shear angle cutting tests.

plane, when the shear angle ϕ is controlled at a higher value. It is also indicated, however, that τ_{shi} is independent of σ_{shi} and holds an average value of $\tau_{shi}=1.8\,kg/mm^2$. Therefore, it is understood further that the internal friction principle as considered by Merchant[1] in his modified shear angle equation did not show its effect in the sets of cutting test performed in the present study.

Assuming that the average shear stress obtained in the above is representative of the shear stress in the shear zone, the rate of mechanical energy dissipated by the shear in the shear zone Ws is computed by the following equation.

$$Ws = v \cdot h \cdot b \cdot \gamma_{shi} \cdot \tau_{shi}$$

In the equation, the notations are as follows

v : cutting speed

h : undeformed chip thickness

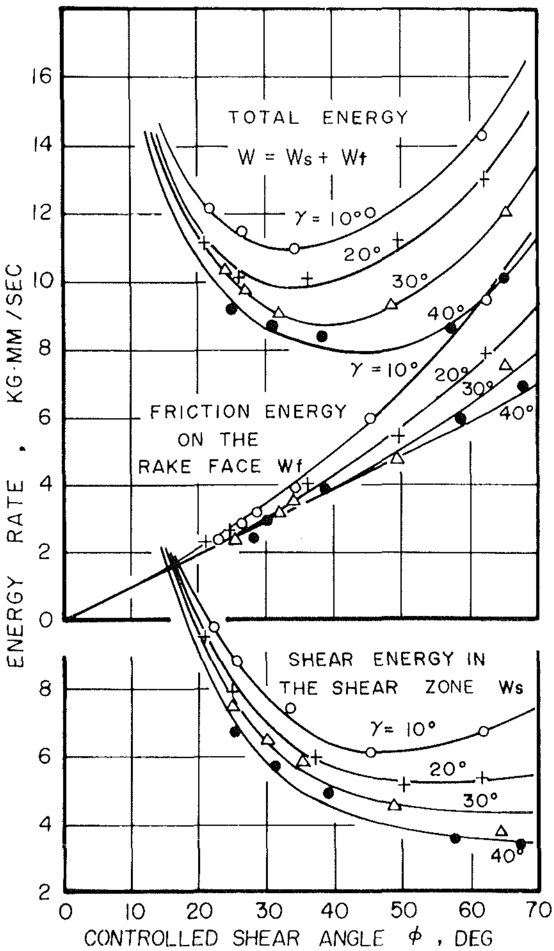

Fig. 6. Shear deformation energy rate in the shear zone W_s, friction energy rate on the rake face W_f, and total energy rate $W=W_s+W_f$ in controlled shear angle cutting tests.

b : width of cut

γ_{shi} : shear strain taken by the chip
$[=\cot\phi+\tan(\phi-\gamma)]$

Also, rate of energy dissipated by the friction in the rake face W_f is computed by

$$W_f = v\cdot Ch\cdot b\cdot F_r$$

In this equation, Ch stands for the chip thickness ratio, and can be obtained by $Ch=h/hc$, where hc is the chip thickness.

Values of Ws and W_f as computed by the above equations are shown in Fig. 6, together with the total energy rate $W=Ws+W_f$. In the figure, curves show computed results based on average force and shear stress values, whereas plots represent results computed from individual data of each test set.

Essentially, ϕ values which give a minimum total energy rate W correspond to the shear angles predicted by Merchant's equation with an absence of internal friction effect. In a comparison run against Merchant's equation this is clearly seen when test points are plotted in ϕ and $(\beta-\gamma)$ coordinates as illustrated in Fig. 7. When this is conducted, the apparent friction angle on the tool rake face β is available from apparent coefficient of friction μ shown in Fig. 4, by $\beta=\tan^{-1}\mu$.

Fig. 6 and Fig. 7 indicate that, the cutting as predicted by Merchant's line is feasible, and actually gives minimun consumption of energy. However, this

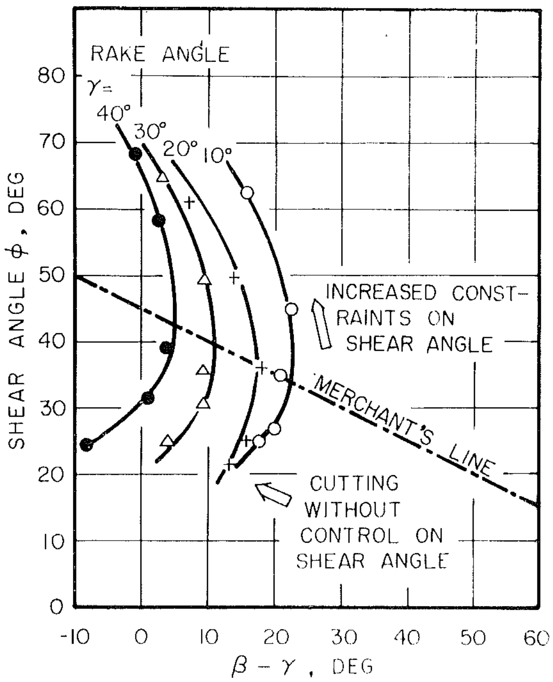

Fig. 7. Correlation between shear angle ϕ and $(\beta-\gamma)$ in controlled shear angle cutting tests.

holds true only when constraint is made on the shear angle, and in this case, it might be necessary to consider a third energy in the system, which is the work done by the edge of the upper constraining plate.

Conclusion Remarks

By use of the new test equipment, orthogonal cutting was performed under conditions where the shear angle is controlled to scheduled values, and compared to condition of free cutting (no control on shear angle).

From the cutting force measurements under various test conditions and also from associated calculations, it is concluded that the free cutting is not the condition where work done by the cutting tool is minimum.

The cutting geometry as predicted by the Merchant's equation, and which dictates the condition for the work done by the tool to be minimum, is achieved only when a constraint is in effect in such a way that the shear angle is controlled. In such a case, however, extra work might be introduced to the system by the friction between the undeformed workpiece and the edge of the upper constraining plate. It is probable that a continued study might prove the free cutting still to be the condition of minimum energy dissipation if this third energy would be included in the theory.

Acknowledgment

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Reference

1) M. E. Merchant, Mechanism of the Metal Cutting Process, Journal of Applied Physics, Vol. 16, 1945, 318 to 324.