DISCUSSION

W. B. Rice

The author is to be congratulated, in general, for a significant contribution to the literature of metal cutting; and, in particular, for the emphasis he places on the fundamental task of improving the idealized picture of the cutting process.

Recently reported experimental investigations carried out at Queen's University contribute to the improvement of the idealized picture and to the author's thesis; thus they are being presented here.

Cyclic Chip Formation. Results obtained at Queen's support the author's contention that under many conditions chip formation is a cyclic phenomenon. This is illustrated in Fig. 18 of the discussion. A plausible explanation is:

1. The material is compressed ahead of the tool, bulging upward, as shown at the left of the figure, until rupture occurs.
2. Rupture occurs when the slip-line field has the appropriate configuration. That is, it occurs when (a) the direction of the maximum shearing stress, (b) the direction of the minimum area subjected to shearing stress, and (c) the direction of the minimum shearing strength are optimum. This statement will be recognized as a disguised version of the minimum energy principle. As the author has stated, metal in a cutting process is stressed in a more complicated way than the metal of a specimen in destructive testing.
3. As the segment is being displaced along the rupture surface, the formation of the next segment begins.
4. Subsequently, the newly formed segment, and the rest of the chip, consisting of previously formed segments, are forced

Fig. 18 Illustration of cyclic nature of continuous chip formation. Material, 2657 aluminum rake angle, 14°/4; cutting speed, 228 fpm; feed, 0.018 in. per rev; chip width, 0.125 in.

Fig. 19 Cyclic and noncyclic chip formation
upward by the bulging of the material of the segment being formed.

The author has pointed out that for a certain combination of cutting and speed and uncut chip thickness the cyclic chip formation does not occur. As shown in Fig. 19 of the discussion, an increase in the rake angle causes a departure from cyclic chip formation, which may be explained as follows. The upper part of Fig. 20 of the discussion illustrates the fact that the frictional force necessary to prevent a wedge from moving up an inclined surface increases as the incline decreases (that is, as $\alpha$ increases). At the same time the normal force between the wedge and the inclined surface decreases, and consequently the friction decreases, and eventually the wedge will slip. The lower part of Fig. 20 illustrates comparable conditions in chip formation. In the case of the small rake angle and limited movement up the tool face, the slip-line field, and hence the deformation, is radically different from that associated with the large rake angle and easy sliding. Thus the chips are quite different.

Chip Curl. The mechanism of chip formation just described provides an explanation of why, as the author states, the chip is "born curled." From Fig. 18 it is evident that the plastic deformation of the segment being formed rotates the previous segment counterclockwise, thus imparting curvature to the chip.

**Chip-Tool Contact.** The photograph of the plan view of the chip-tool contact area, Fig. 5(A) of the paper, indicates that maximum rubbing between the chip and the tool occurs at a considerable distance from the cutting edge. This is consistent with the experience at Queen's, and may be explained by the mechanism of chip formation illustrated in Fig. 18 of the discussion as follows:

1. Just prior to rupture there appears to be no sliding of the segment being formed relative to the tool face. The friction in the region of the tool tip is static. However, the segment which has just been completed does slide along the tool face at a considerable distance from the cutting edge.
2. At rupture sliding occurs generally.

Thus most of the sliding, and hence most of the wear, occurs at a considerable distance from the cutting edge.

When the tool face is limited to the depth of cut, or smaller, as shown in Fig. 21 of the discussion, the bulging of the segment being formed rotates the previous segment clockwise, and the chip is opposite to that encountered with the full-faced tool.

**Author's Closure**

The author wishes to thank Prof. W. B. Rice for an interesting discussion concerning the discontinuous chip formation studies made at Queen's University. Regarding cyclic events in chip formation there is more material now in preparation for further publication by the author. There are different types of cyclic events which may be observed in chip formation; one is usually termed "discontinuous chip formation" which is always cyclic in its nature because of the rupture which occurs periodically in the shear zone, yielding a segmented chip. Professor Rice illustrates and describes this type of chip formation in Fig. 18 of his discussion. Discontinuous chip formation was also studied and very well described by M. Field and M. E. Merchant in their paper "Mechanics of Formation of the Discontinuous Chip," Reference 5 of the bibliography in the paper.

Another type of chip formation, "continuous chip formation," when no periodic ruptures of the chip take place, may or may not be of a cyclic nature, depending on several conditions. This later type of chip formation was mainly the subject of the author's study. The whole classification of different types of chip formation may be conveniently summarized in the form of a table as follows:

<table>
<thead>
<tr>
<th>Types of chip formation</th>
<th>Continuous</th>
<th>Discontinuous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steady state</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuous chip formation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No ruptures occur in the shear zone;</td>
<td></td>
<td></td>
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<tr>
<td>the chip is essentially of a constant</td>
<td></td>
<td></td>
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<tr>
<td>thickness. Type 2 and 3 chip according</td>
<td></td>
<td></td>
</tr>
<tr>
<td>to Ernst and Merchant specification.</td>
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<tr>
<td>Cyclic</td>
<td></td>
<td></td>
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<tr>
<td>Cyclic chip formation</td>
<td></td>
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<tr>
<td>Continuous chip without periodic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ruptures in the shear zone. Cyclic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>variations of the chip thickness</td>
<td></td>
<td></td>
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<tr>
<td>occur due to fluctuations of shear</td>
<td></td>
<td></td>
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<tr>
<td>angle.</td>
<td></td>
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<tr>
<td>Discontinuous chip formation</td>
<td></td>
<td></td>
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<tr>
<td>Segmental chip caused by periodic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ruptures in the shear zone. Type 1</td>
<td></td>
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</tr>
<tr>
<td>chip according to Ernst and Merchant</td>
<td></td>
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<tr>
<td>specification.</td>
<td></td>
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</tbody>
</table>

In the table the commonly used terms are in italics and a brief description of the particular types of chip formation is given.

The note of Professor Rice on chip curling concerns again the discontinuous chip of a segmental nature. The author's efforts were to describe the nature of curling of a continuous chip. One
of the reasons for curling of a continuous chip has been pointed out by the author, Reference [1] of the paper’s bibliography. There, the ploughing effect was found to press additional metal into the chip surface, thus expanding one side of the chip and contributing to its curling. Another event which would contribute to chip curling has been indicated in the present paper. It has been shown that the normal stress along the shear zone from the cutting edge to the work surface (line AB in Fig. 2 of the paper) is not constant. Compressive stress normal to AB is higher in the vicinity of A than it is in the vicinity of B. This means that the metal which is in the plastic state in the shear region of A and this will cause the chip to curl in the way it does. Another effect of the stress normal to the shear zone would be the widening of the chip which was usually neglected in the past because in most cases it is small. Actually if we consider only the shear component \( \tau_s \) of the stress in the shear zone, as in the case in Merchant’s first solution, the state of stress in the shear zone will be described by the tensor \( S_{ij} \):

\[
S_{ij} = \begin{bmatrix}
0 & \tau_s & 0 \\
\tau_s & 0 & 0 \\
0 & 0 & 0 
\end{bmatrix} = \text{stress tensor of Merchant's first solution.}
\]

The tensor of stress deviation \( S'^{ij} \) in this case would be the same as stress tensor \( S_{ij} \) because all normal stresses (in the main diagonal) are zero. Because \( s_{11} = s_{22} = s_{33} = 0 \) there will be no chip widening, \( w_1 = w_2 \), and no chip curling in this solution.

In view of the fact that in a metal cutting process all six components of the symmetric stress tensor \( S_{ij} \) are generally other than zero, the author’s suggestion in this paper is to take into account at least one of the normal stress components in addition to the shear stress component considered before. In this case the stress tensor would have two components; one the shear stress \( \tau \) and the second the stress \( \sigma \) normal to the shear zone.

\[
S_{ij} = \begin{bmatrix}
\sigma & \tau & 0 \\
\tau & 0 & 0 \\
0 & 0 & 0 
\end{bmatrix} = \text{stress tensor suggested by the author in the paper.}
\]

The tensor of stress deviation \( S'^{ij} \), which indicates the nature of plastic deformation which would take place will have the form:

\[
S'^{ij} = \begin{bmatrix}
\frac{2\sigma}{3} & \tau & 0 \\
\tau & -\frac{\sigma}{3} & 0 \\
0 & 0 & -\frac{\sigma}{3}
\end{bmatrix} = \text{state of stress considered by Drucker.}
\]

The presence of the normal stresses indicates that widening of the chip would take place and the variation of \( 2\sigma/3 \) along the shear plane, in the direction from the cutting edge to the work surface, would contribute to the curling of the chip. These two additional effects are included in the state of stress suggested by the author. The main effect of the introduction of \( \sigma \), that is, its effect upon the shear angle, has been discussed in the paper.

Another variant of the state of stress in the shear zone in a metal cutting process was suggested by D. C. Drucker in his paper “An Analysis of the Mechanics of Metal Cutting” (Journal of Applied Physics, November, 1949). The state of stress suggested by Drucker is shearing plus hydrostatic pressure. The stress tensor corresponding to such a state of stress will be:

\[
S_{ij} = \begin{bmatrix}
\sigma_x & \tau & 0 \\
\tau & \sigma_y & 0 \\
0 & 0 & \sigma_z
\end{bmatrix} = \text{state of stress considered by Drucker.}
\]

The tensor of stress deviation \( S'^{ij} \) in this case will be identical with the stress deviation of Merchant’s first solution. That means that only plastic deformation due to shear will occur and no plastic deformation due to normal stresses will take place. Consequently the components \( \sigma_n \) would have no effect upon the shear angle, widening of the chip, or curling of the chip.

A general question about the number of stress components of the complete stress tensor:

\[
S_{ij} = \begin{bmatrix}
s_{11} & s_{12} & s_{13} \\
s_{21} & s_{22} & s_{23} \\
s_{31} & s_{32} & s_{33}
\end{bmatrix}; \quad s_{12} = s_{21}; \quad s_{11} = s_{33}; \quad s_{22} = s_{33};
\]

which should be considered to obtain good agreement between theory and observation depends on a number of conditions. For instance the properties of the metal cut would be one of the major factors. Just to give an example, let us compare the cross sections of chips obtained by machining two steels of different mechanical properties shown in Fig. 22 of this closure. Chip cross section (a) is of an extremely ductile steel; it shows a great variation in thickness after separation from the workpiece. In this case stress components \( s_{22} \) and \( s_{33} \) produce an appreciable plastic deformation in the chip and thus cannot be disregarded. Chip cross section (b) of the same Fig. 22 shows a chip of a different kind of steel; its thickness remains essentially constant across the width of the chip. This indicates that the same stress components \( s_{22} \) and \( s_{33} \) cause very little plastic deformation in this material and therefore can be safely neglected in describing the state of stress of this particular chip formation process.