Discussion

A. O. Schmidt[5] and B. F. Turkovich.[6] The determination of the temperature distribution inside a solid with prescribed boundary conditions has been, in a majority of the cases, a problem of considerable difficulty. Although the mathematical theory of heat conduction supplies the analytical methods, the experimental verification of the results seldom can be achieved in a sufficiently satisfactory manner. One of many eminently complex cases is the problem the authors proposed to solve. They are commended for their effort and ingenuity, but, as usual, there are a few questions to be raised in order to clarify certain statements and conclusions in their paper.

It is apparent from their bibliography that the authors have surveyed almost all the important analytical works on the problem of the tool-chip interface temperature. This list could be divided into two parts: One, which consists of works primarily concerned with the tool-chip interface temperature, and the other, with the problem of the temperature field in the tool itself. From the point of view of metal cutting, the tool-face temperature and its distribution are fundamentally important, and the temperature field in the tool is contingent. However, if a method is devised based on the study of the temperature field inside the tool; which would elucidate the problem of the tool-face temperature, then such an attempt is definitely welcome.

A list of cases could be made in which the temperature distribution inside a solid is known fairly accurately, but the exact conditions on the boundaries are only a matter of intelligent supposition. Although this fact could be attributed probably to the intrinsic inaccuracy of the measurements when extraneous devices are introduced within the solid, a comparison of mathematical solutions with different but congruent boundary conditions would show that, in the cases of complex transient state combined with the peculiar material properties and geometry, it is rather difficult to determine to which mathematical solution the measurements comply if the points of the instrument application are not within the very neighborhood of one of the boundaries.

Referring now particularly to the tool temperatures, it becomes clear that a method in the study primarily of the tool-temperature distribution also should permit the determination of the conditions on the boundaries more or less accurately, i.e., the average distribution of temperature and heat inputs, and provides an indication where the probable extreme may be located. This is a rather ambitious requirement but hardly less mandatory if a comparison of data with other methods of solution is desirable because almost all methods devised up to date lack more or less the generality of argument, creating an exasperating series of divergent opinions which impedes the formation of a reliable body of data upon which further research activity could be based advantageously. Every one actively interested in metal-cutting research is, however, fully aware that the problem is an extremely difficult one and it is with the spirit of hoping for the best solution yet to come that the following discussion is presented.

When the tool closely resembles a parallelepiped, the analytical approach for evaluation of temperatures based on the method of product solutions seems to be a convenient one. Although infinite series arise in the solution, making the numerical work rather tedious, it is perhaps the most straightforward method available. Since the distribution of the heat input over the chip-tool interface is still a problem which needs further research, although the investigations by Chao and Trigger (authors' reference 9) point conclusively that the assumption of a uniform plane heat source cannot be expected, the authors assumed a uniformly distributed source, probably for simplicity's sake. The boundary condition of such a state, used jointly with other conditions well justified, necessarily leads to a temperature distribution which is diametrically at variance with the findings of Chao and Trigger as well as the results known from the theory of sliding-contact heat sources. Moreover, the authors neglect to consider another source of heat, i.e., the area on the flank of tool which rubs against the workpiece. This area enlarges with time providing a constantly increasing plane heat source which, although initially of minor importance, influences considerably the temperature field inside the tool. Consequently, speaking strictly from a theoretical point of view, a truly steady state can never be arrived at. If the cutting time is short in duration, this influence can probably be neglected. However, if the flank wear approaches the magnitude of the chip thickness before deformation (feed per revolution), it is doubtful whether it can be ignored safely.

In Figs. 3 to 6 of the paper, the diagrams show the millivolts-time relationship for the thermocouples indicating a leveling off after 2-min cutting time. It would be interesting to know the behavior of these graphs after prolonged cutting, i.e., 5 to 10 min, since the tool life should not be very low at the speeds used. It is quite possible that the strong temperature fluctuations in thermocouple No. 1 in the tool M-2-2 could be attributed to the influence of this heat source rather than to the intermittent contact of the chip with the tool. The built-up edge also could play an important role.

It is unfortunate that the paper lacks additional information about cutting conditions such as chip-thickness ratio and magnitude of the contact area. Isotherms for one or two cutting conditions also would increase the informative value of the paper. Since the authors already have used rake angles of 0 and 15 deg it will be of interest to see their temperature records extended to include also rake angles in the negative range. A tool with 5-deg negative back-rake angle and a 5-deg end clearance could be made to have exactly the geometry postulated and consequently a better agreement between the calculated and measured quantities could be obtained, as is suggested by the smaller deviation in the case of the 0-deg rake tool compared to the 15-deg rake tool. However, at this point it should be mentioned that the thermocouple records shown indicate approximately the same trend in relation to time and temperature as one of the writers was able to measure with a thermocouple located underneath a thin carbide tip, when turning magnesium.[7] The depth of cut was 0.125 in., feed 0.005, 0.010, and 0.015 ipr. Thus chip formation took place on the tool face directly over the thermocouple point.

Several research workers have measured the temperature at the tool-chip interface. Most of the data were obtained employing the tool-workpiece thermocouple arrangement which basically supplies only some sort of an average temperature value on the tool-chip interface. Although this method is essentially different from the authors' approach, it is noted that almost all reports on temperatures obtained by tool-workpiece thermocouples indicate that steady temperature readings prevail after a very short cutting time, substantially shorter than that indicated by the authors. Time lag observed at thermocouple No. 1 is not due entirely to conduction, the authors state, since it took about 2 min to reach a steady state instead of the 1-min lag predicted by Equation [3]. It also appears that the temperature rise is rather rapid near the cutting edge and should reach a steady state in a very short time. However, the authors note that the transient

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[5] Research Engineer, Charge of Metal Cutting, Kearney & Trecker Corporation, Milwaukee, Wis. Mem. ASME.

[6] Kearney & Trecker Corporation, Milwaukee, Wis.

[7] "Metal Cutting Temperatures and Tool Wear," by A. O. Schmidt, *The Tool Engineer*, vol. 24, August, 1952, pp. 33–35.

period is more than twice that predicted from Equation [3] and suggest the possibility of increasing rate of heat input, as a result of the fact that the workpiece experiences a transient heating period of 2 to 3 min. When the workpiece is preheated, the steady condition is reached substantially sooner. To what temperature was the workpiece preheated?

This is a rather puzzling phenomenon. Considering that the feed at which the cutting was performed was only 0.0025 ipr, a time of 2 to 3 min seems a rather long transient period to establish the stationary state in the workpiece ahead of the shear zone. Is this the authors' implication? A substantial amount of energy can be released into the workpiece by rubbing of the flank which at fine feeds has much influence on temperature gradients. It would certainly help us to arrive at an explanation if other, coarser feeds also were considered. A twofold benefit could have been achieved: (1) The geometrical relationship would be improved (e.g., distance of the first thermocouple to the cutting edge versus chip thickness and magnitude of area of contact) and (2) the influence of feed could be clearly appreciated. Unless additional information is forwarded, the data shown in Figs. 7 and 8 of the paper should be viewed with a skepticism which not even apparent concordance with other investigators' data could mitigate.

Reluctantly we have to revert the whole problem to the conclusion that so far no successful indirect method to arrive at the tool temperature has been devised. However, anyone who has attempted to measure tool-tip temperatures can appreciate the thermocouple technique used here and the work that has gone into this investigation. Let us hope that the authors will continue to present additional experimental findings in the near future and thus will help to validate and augment the important tool-temperature data available today.

B. W. Shaffer.[8] Have the authors considered the possibility of expanding each of the infinite series found in Equation [3] with the retention of but one or two terms in each case, and then collecting the resulting expression in a compact manner? The revised expression may not only look simpler but should give results which are not too different from the more exact equation because, as the authors point out, the series converges very rapidly.

K. J. Trigger[9] and B. T. Chao.[10] The authors are to be congratulated on the interesting experimental approach to the study of the tool-chip interface temperatures. Their technique, like that employed by Axer, opens additional avenues for further investigation.

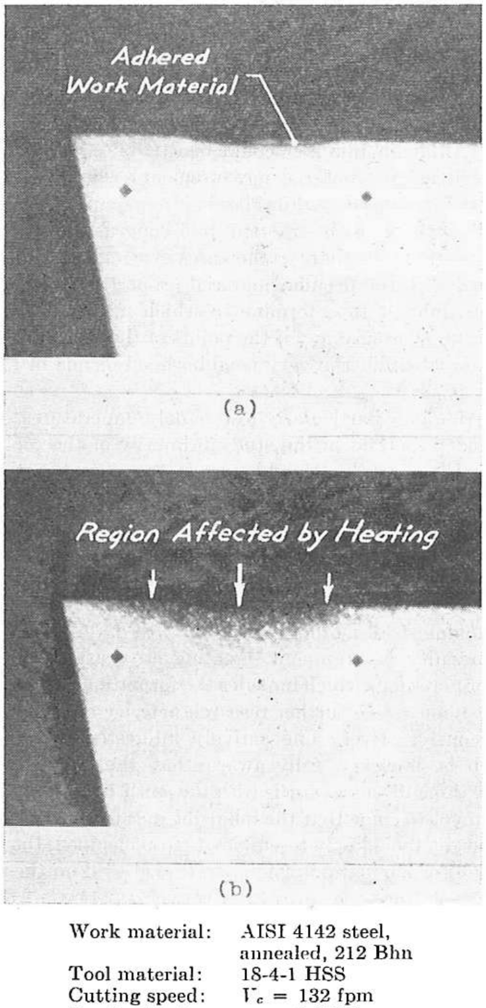
There are, however, some aspects of the paper which need further discussion. The writers submit the following comments as constructive criticism in the hope of contributing to the value of the paper.

The assumption of a uniform heat-flux distribution at the tool-chip interface leads to the anomalous situation of an incompatible temperature distribution at the tool-chip interface when calculated from the point of view of the moving chip and that determined from the point of view of the tool. The authors' reference (9) contains a procedure for the quantitative evaluation of both the heat-flux distribution and the corresponding compatible tool-chip interface temperature distribution.

Metallurgical evidence of the interface temperature distribution can be seen in Fig. 12 of this discussion which shows a sectioned HSS tool after cutting under the conditions shown. The indicated (average) interface temperature was about 1060 deg F. Fig. 12 (*a*) shows the crater with some adhered work material. Fig. 12 (*b*) shows the same section after additional etching in a somewhat stronger solution. The darkening in the crater region is caused by a more rapid etching rate which is due to the additional tempering of the high-speed steel as a consequence of heating by the sliding chip. The nonuniformity of the temperature distribution along the path of contact is indicated by the varying depth of the heat-affected zone. The temperature distribution appears to be nearly symmetrical with respect to the center of the crater and the temperature at the cutting edge is clearly less than that at other points of contact. Indeed, the temperature there appears to be considerably lower than that at the point of departure of the chip from the tool. The geometrical shape of the crater conforms to the temperature distribution at the interface.

In view of these findings the writers cannot agree with the statement: "Results indicated a nearly uniform temperature across the interface, being a maximum at the cutting edge and decreasing only a few degrees in the region of chip separation."

The authors have acknowledged that the difference between



Work material: AISI 4142 steel, annealed, 212 Bhn
Tool material: 18-4-1 HSS
Cutting speed: $V_c = 132$ fpm
Depth of cut: $w_1 = 0.100$ in.
Feed: $t_1 = 0.00979$ ipr
Cutting time: 1.20 min

Fig. 12 Section of Crater Surface of a High-Speed-Steel Tool Showing (*a*) Adhered Work Material, and (*b*) Region of Structural Change Due to Heating by Sliding Chip

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[8] Associate Professor of Mechanical Engineering, New York University, New York, N. Y. Assoc. Mem. ASME.

[9] Professor of Mechanical Engineering, University of Illinois, Urbana, Ill., Mem. ASME.

[10] Professor of Mechanical Engineering, University of Illinois, Urbana, Ill.

their temperature distribution and that presented by the writers (reference 9 of the paper) is due to the assumption of a uniform heat-flux distribution. The writers have found that both the heat flux and temperature distribution across the interface are invariably nonuniform.

It would appear for the 0-deg back-rake angle, Fig. 8 of the paper, that extrapolation to the center of the tool-chip contact area leads to excessive temperatures there.

Research by the writers, using the tool-work thermocouple technique, has revealed that high-speed steel tools become temperature sensitive at indicated (average) interface temperatures around 1050 F and that the indicated value is some 1250 F at failure.

If as shown in Fig. 8 the temperatures were to rise to 1400 F under the cutting conditions shown, tool failure would ensue quickly. This has not been the experience in machining 1020 steel (100 Bhn) at 100 fpm with the light feed and at the rake angle indicated.

It is hoped that the authors will pursue their study and perhaps compare their results with those determined directly from the measured temperature distribution using Axer's successive grinding technique.

Authors' Closure

The authors sincerely appreciate the interesting and constructive discussions of this paper. The observations and comments offered are well founded, pointing up definite need for additional study of this problem. The following information is submitted in answer to the several questions raised.

The suggestion that the temperature fluctuations noted in the experimental measurement of Figs. 3 to 6 might be attributable to the heat input on the flank of the tool does not seem likely, since, as already pointed out, these fluctuations disappear when a change from a discontinuous to a continuous chip takes place (see Fig. 5).

The reason for the difference between the findings of other investigators and the results presented in this paper regarding the duration of the transient heating period is due to the difference in workpiece geometry. For the tests described herein, orthogonal cutting of a hollow tubular specimen was used, as compared to a large solid cylindrical workpiece employed by others. A solid workpiece will act as a heat sink immediately behind the plane of cutting, and any heat which is conducted into the workpiece as a result of the cutting process can easily be absorbed by the large thermal capacity of the specimen. Thus the temperature of the specimen remains substantially constant, and the duration of the transient period is of the order of seconds. However, with orthogonal cutting of a tubular specimen, there is only a thin walled section through which the heat can be conducted away from the cutting plane and the thermal capacity is relatively low. Hence the energy entering the workpiece causes a gradual rise in temperature of the workpiece. Since this transient heating of the workpiece is, however, much slower than the simple heating of the tool, a much longer transient period is indicated by the tool temperature records.

The details of the simple experiment conducted to verify the foregoing explanation were as follows: First, after cutting of an initially unheated workpiece for two minutes, the distance from the cutting edge which could be safely touched by hand was determined (about 9 inches from the cutting edge). Next, a similar workpiece was preheated by playing an acetylene flame on its end while rotating it until the temperature at a distance of about 9 inches from the end began to rise. Cutting was then initiated and the tool temperature recorded. The results of these two tests are presented in Fig. 11.

The possibility of developing a compact closed expression for the temperature based on a limited number of terms from Equation [3], as suggested by Professor Shaffer, has been given some attention. This effort has not as yet, however, yielded a result that can be recommended in place of Equation [3].

The value of 1250 F obtained by Professors Trigger and Chao for the average interface temperature at which high-speed steel tools would fail was of considerable interest. The peak value estimated for the average interface temperature by the authors was 1300 F (see Fig. 7) for the zero-degree back-rake angle tool. It was at this temperature that failure of the tool actually occurred. In view of the close agreement between these two temperatures, it would appear that the upper curve in Fig. 8 should be drawn through the two points shown and should level off to a maximum around 1300 F.

To investigate further the heat-rate distribution along the tool-chip contact area (0.110 inch × 0.050 inch), a linear variation was considered, i.e., $Q = A + Bz'$ was assumed in Equation [3] where A and B are constants. A solution for this case is possible and evaluation of the constants A and B can be accomplished if the temperature at two points is known. The calculations for one of the tests using this assumed distribution were carried out. The results indicated that the heat rate increased from the cutting edge to the point of chip separation. The heat flow at the cutting edge was positive; that is, into the tool, and the increase over the chip contact length was about 15 per cent of the value at the cutting edge. The average value agreed very closely with that previously determined for an assumed uniform heat rate.

In contrast to this, Chao and Trigger (9) found a negative heat flow at the cutting edge and a much larger gradient in the direction of chip travel. It is recognized, however, that the heat-rate distribution found by Chao and Trigger differs significantly from linearity near the cutting edge and chip separation point. In addition, cutting speeds were quite different so that a comparison may not be proper. It was also noted that in our tests, rubbing of the tool flank against the workpiece occurred over an area of one third to one half of the tool-chip contact area. Possible heat flow in through this area would tend to indicate a higher heat rate near the cutting edge of the tool-chip contact area.

It is felt that the observation of Dr. Schmidt and Mr. Turkovitch, that a truly steady state never occurs, merits emphasis in connection with the heat rate and temperature distributions along the tool-chip contact area. In reviewing the results of this investigation, it appears quite likely that tool wear, particularly in the case of the zero-degree back-rake angle tool, during the course of the tests influenced the results. Unfortunately, the temperature measurements were neither close enough to th ecutting edge nor sufficiently close to point values to resolve this question. Although very small thermocouples were used further refinement is necessary.