HEAT CONDUCTION VS. HEAR ADECTION IN METAL CUTTING

YALLA ABUSHAWASHI, XINRAN XIAO AND VIKTOR P. ASTAKHOV

ABSTRACT: Heat format in metal cutting may flow into the workpiece, the forming chip and the tool. Heat partition plays an important role as it may affect the mechanical properties of the work material reportedly reducing its resistance to cutting, tool life due to thermal-enhanced tool failure, and chip breakability. The paper resolves the well-known discrepancy between the theoretical results obtained using the common model of chip formation and the experimentally-obtained heat partitions. It is argues that hear advection rather thermoconductivity play the most important role in heat partition in metal cutting. A new equation for heat partition in metal cutting is suggested and verified experimentally. The experimental results fully support heat partition analysis. It fully supports statement of Zorev[1] and definition of the cutting process by Astakhov[2] that the metal cutting process is a cold-working process because the temperature of the layer being removed just ahead of the tool hardly exceed 200oC.

Keywords: metal cutting process, heat partition, system approach, conduction and advection

1. INTRODUCTION

Although it is pointed out in almost any book on metal cutting that temperature, and particularly, its distribution has a great influence in machining [3], no one study known to the authors quantifies this influence. Instead, it is stated in very general and qualitative terms that temperatures in metal cutting affect “the shear properties” of the work material and, therefore, they affect the chip-forming process itself, and through their effect on the tool, they determine the limits of the process and mode of tool wear. To address each of these points, a great number of works on temperatures in metal cutting have been published. Apart from many contradictive results that can be readily found in the published works and can be logically explained by the difference in the experimental methodologies and accuracy of calibration, numerical and analytical models and the assumptions adopted in both the models, the major concern with these works is their practical significance. In other words, there is no answer to a simple question: “What should one do with the found temperature and its distribution?” The same question arises in any FEM of metal cutting as a common result of such a modeling is colorful field of temperature distribution in the tool, workpiece and chip. A question: “Is the obtained result is good or not?” Cannot be answered. In other words, there is no gage to judge ‘goodness’ or ‘optimality’ of the obtained temperature results.

Trent and Wright concluded [4] that the major objective of heat consideration in metal cutting is to explain the role of heat in limiting the rate of metal removal when cutting the
higher melting point metals. They concluded that there is no direct relationship between cutting forces or power consumptions and the temperature near the cutting edge.

Zorev[1] did not consider temperature as an important factor itself. Considering the energy balance in metal cutting, he calculated that the maximum temperature at the end of the chip formation zone does not exceed 270°C for plain and alloyed steels while a considerable reduction in the mechanical properties of these materials starts only at temperatures over 300°C. Therefore, he concluded that metal cutting is a cold-working process where temperature does not affect mechanical properties of the work material in the defacement zone although the chip leaving the cutting tool can be of cherry-red color.

According to Childs et al. [5], the two goals of temperature measurements in machining are: (a) the quantitative measurements of the temperature distribution over the cutting region is more ambitious, but very difficult to achieve, and (b) is less ambitious to measure the average temperature at the tool-chip contact. In the author’s opinion, the less ambitious goal makes sense if one know how to measure this average temperature and, that is more important, how to use the obtained result.

To understand the formation of the temperature fields in the tool, workpiece and the chip, the known publications consider the energy balance (in modern terminology - energy partition) in metal cutting. As the conservation law states and many specialists in metal cutting surprisingly agree with this law (not always the case in metal cutting studies where some fundamental physical laws can be easily declared as inapplicable, for example the principle of minimum energy as discussed by Astakhov[2, 6], the almost all the energy required by the cutting system for its existence (referred in the literature as the energy supplied to the cutting system) converts into the thermal energy or simply heat. Small portions of energy stored in the deformed chip and in the cold-worked machined surface hardly exceed 2-3% of the total energy. Therefore, the power that converts into heat in the cutting system can be calculated rather accurately as $F_c v$, where $F_c$ is the power components of the cutting force and $v$ is the cutting speed.

The next issue is the distribution (partition) of this power (converted in the form of heat) in the cutting system. The heat distribution in the cutting system is originated from study by Schmidt and Roubik [7], who, according to Komanduri [8], carried out calorimetric study in cutting and their measurements, thus obtained, permit computation of work, power, forces, average temperature of the chip, etc. They also showed a good agreement between the calorimetric measurements and the power data obtained from torque and thrust measurements.

Example of Schmidt and Roubik results [9] used in the literature is shown in Figure 1. This example and its derivatives have been using in the literature since then (for example, [10, 11]) up to modern book on the subject (for example, [12, 13]). In some modern books, however, this distribution simplified up to that shown in Figure 2 [14], i.e. became of more qualitative than quantitative nature. Our critical analysis of the published data on heat partition in the cutting system revealed an obvious drawback. The partition of heat is always shown as a function of the cutting speed. In other words, the cutting feed, thermal properties of the work and tool materials, influence of MWF and many other 'thermal' particularities of a given machining operation are not accounted for. For example, it is obvious that if a tool material of high thermoconductivity, for example PCD, is used than more heat flows into the tool compare to the case when a tool material of extremely low thermoconductivity, for example
ceramics, is used. Therefore, it may be stated that heat partition in metal cutting is application specific and the ratio of the amounts of heat that go into the components of the cutting system is not fixed as shown in Figure 2 but may vary significantly depending upon particularities of a given machining operation.

Figure 1: Typical Distribution of Heat in the Workpiece, the Tool, and the Chips with Cutting Speed, After Schmidt and Roubik [9]

Figure 2: Heat Distribution between the Chip, Workpiece and Tool
The common analysis of heat distribution and temperatures in the cutting system is based on the analysis of heat sources. Because practically all of the mechanical energy associated with chip formation ends up as thermal energy [1, 2, 15], the heat balance equation is of prime concern in metal cutting studies. This equation can be written as [2].

\[ F_c v = Q_v = Q_c + Q_w + Q_t \]  

where \( Q_v \) is the total thermal energy (heat) generated in the cutting process, \( Q_c \) is the thermal energy transported by the chip, \( Q_w \) is the thermal energy conducted into the workpiece, \( Q_t \) is the thermal energy conducted into the tool. As shown in Figure 1 and Figure 2, under ‘normal’ cutting conditions, most of the thermal energy generated in the cutting process is conducted into the chip [1, 2, 15].

Example of energy balance shown in Table 1 [16] reveals two essential features:

- Most of the thermal energy generated in the cutting process is carried away by the moving chip (80-85%).
- The higher the cutting speed, the greater portion of the total heat is carried out by the chip.

<table>
<thead>
<tr>
<th>( v ) (m/s)</th>
<th>( Q_v ) (J/s)</th>
<th>( Q_v/Q_v ) (%)</th>
<th>( Q_c ) (J/s)</th>
<th>( Q_c/Q_v ) (%)</th>
<th>( Q_w ) (J/s)</th>
<th>( Q_w/Q_v ) (%)</th>
<th>( Q_t ) (J/s)</th>
<th>( Q_t/Q_v ) (%)</th>
<th>( Q_v ) (%)</th>
</tr>
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<tbody>
<tr>
<td>0.10</td>
<td>47.9</td>
<td>50.2</td>
<td>38.4</td>
<td>40.2</td>
<td>9.2</td>
<td>9.6</td>
<td>95.5</td>
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<tr>
<td>0.20</td>
<td>93.7</td>
<td>55.7</td>
<td>63.7</td>
<td>37.8</td>
<td>11.0</td>
<td>66.6</td>
<td>168.4</td>
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<tr>
<td>0.5</td>
<td>272.3</td>
<td>70.3</td>
<td>100.3</td>
<td>25.9</td>
<td>14.7</td>
<td>3.8</td>
<td>287.3</td>
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<tr>
<td>1.00</td>
<td>501.6</td>
<td>76.2</td>
<td>136.9</td>
<td>20.8</td>
<td>19.7</td>
<td>3.0</td>
<td>658.3</td>
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<td>2.00</td>
<td>1177.1</td>
<td>82.8</td>
<td>217.5</td>
<td>15.3</td>
<td>27.0</td>
<td>1.0</td>
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<tr>
<td>4.00</td>
<td>2306.2</td>
<td>86.3</td>
<td>336.7</td>
<td>12.6</td>
<td>29.4</td>
<td>1.1</td>
<td>2572.3</td>
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These facts, however, do not follow from the traditional model of metal cutting. The model shown in Figure 3 [16] illustrates the heat sources on each component of the cutting system, namely, on the tool, workpiece and chip. In this figure, \( t_c \) is the uncut chip thickness, \( \phi \) is the shear angle, \( AB \) is the length of the shear plane, \( AC \) is the tool-chip contact length, \( l_p \), \( AM \) is the length of the plastic part, \( l_p \) of the tool-chip contact length, \( l_c, A_d \) is the tool-workpiece contact length, \( \Delta \).

The thermal energy in the cutting system generates:

1. Due to plastic deformation of the work material on the shear plane, \( Q_{pd} \). This energy partitions into portion that goes to the workpiece \( Q_{pd-w} = \int_{A}^{B} q_{w1}(y) \cos \phi dy \) and that goes to the chip \( Q_{pd-ch} = \int_{A}^{B} q_{ch1}(y) dy \).
2. Due to friction on the tool-chip interface, $Q_{fr}$, its portion $Q_{fr\rightarrow ch} = \int_{A}^{C} q_{ch2}(x) \, dx$ goes to the chip and $Q_{fr\rightarrow t} = \int_{A}^{D} q_{t1}(y) \, dy$ goes to the tool.

3. Due to friction on the tool-workpiece interface, $Q_{ff}$. Its portion $Q_{ff\rightarrow t} = \int_{A}^{D} q_{t2}(x) \, dx$ goes to the tool and $Q_{ff\rightarrow w} = \int_{A}^{D} q_{w2}(x) \, dx$ goes to the workpiece.

Figure 3: Areas of Heat Generation on the Tool, Workpiece and Chip

The next question is about the intensity of the heat sources. As discussed in the literature (for example [12, 15, 17], the greatest portion of energy spent in the cutting system is due to plastic deformation of the work material. Figure 4 shows an example [18]. In this figure $P_{pd}$ is the energy spent on the plastic deformation of the layer being removed, $P_{fr}$ is the energy spent due to friction at the tool-chip interface, $P_{ff}$ is the energy spent due to friction at the tool-workpiece interface, $P_{ch}$ is the cohesive energy spent on the formation of new surfaces (which can be thought of as spent on the shear plane). As follows, the energy spent on the shear plane...
is $P_{pd} + P_{ch} = 73\%$. Therefore, 73\% of the total thermal energy generated in cutting is due to plastic deformation of the work material.

As mentioned above, this total energy due to plastic deformation ($P_{pd} + P_{ch}$) is then partitioned between the workpiece (portion $Q_{pd-w}$) and the chip ($Q_{pd-ch}$). Such a partition, however, does not apparently obey the second law of thermodynamics. The problem is explained as follows.

![Figure 4: Energies Spent in the Cutting System. Work Material: AISI Steel E52100, Cutting Speed $v = 1$ m/s, Depth of Cut $d_w = 3$ mm, Cutting Feed $f = 0.4$ mm/rev; Tool – Standard Inserts SNMG 432-MF2 TP2500 Materials Group 4 (SECO) Installed into a Tool Holder 453-120141 R1-1 (Sandvik). In this Figure, $P_{pd}$ is the Energy Associated with Plastic Deformation of the Layer Being Removed, $P_{fr}$ is the Energy Spent on Friction on the Tool Rake Face, $P_{ff}$ is the Energy Spent on Friction on the Tool Rake Face, and $P_{ch}$ is the Energy Associated with the Formation of New Surfaces [19]](image)

Figure 5 and Figure 6 show the results of actual temperature measurements in the cutting system obtained by Shaw [10] and Astakhov [17]. Similar results were obtained by many specialists, for example by Smart and Trent [20], who actually measured not modeled temperature distribution using FEM with unjustifiable input parameters. The comparison of these results with the data shown in Figure 1 and Figure 2 and presented in Table 1 accounting for the common model shown in Figure 3, reveals a contradiction with the second law of thermodynamics. This law stated that heat flows naturally from a region of higher temperature to one of lower temperature. Therefore, according to the second law of thermodynamics, portion $Q_{pd-w}$ should be much higher than $Q_{pd-ch}$. Experimental results on heat partition, however, shows otherwise, i.e. a way greater part of the total heat flows into the hot small chip than that in the cold large workpiece. This is the discussed contradiction. This contradiction cannot be resolved in principle using the existing notions in metal cutting due to the fact that the traditional model shown in Figure 3 is incorrect [6].
Figure 5: Typical Temperature Field in Metal Cutting: Isoterms for Dry Orthogonal Cutting of Free Machined Steel with a Carbide Tool at Cutting Speed of 155 m/min and Cutting Feed of 0.274 mm/rev [10]

Figure 6: Typical Temperature Field in Metal Cutting: (a) Isoterms for Dry Orthogonal Cutting of ANSI 1045 Steel with a Carbide (P10) Tool (Rake Angle 12°) at Cutting Speed of 60 m/min and Uncut Chip Thickness 2 mm, (b) Temperature Distributions Over the Tool Rake and Flank Faces. Turning, a Carbide Cutting Tool Carbide M20 (92% WC, 8% Co), Depth of Cut $a = 1.5$ mm Cutting Speeds in Machining of Steel 1045-240 m/min, Titanium Alloy (Ti6Al4V) - 160 m/min, Cutting Feed - 0.25 mm/rev[17]
The objective of this study is to resolve the above-mentioned contradiction in heat partition in metal cutting. In other words, both sides of this contradiction, namely, the heat partition and the model shown in Figure 3 are analyzed in order to understand which one of these two is the source of the contradiction.

2. EXPERIMENTAL STUDY OF HEAT PARTITION

2.1 Complete Equation of Heat Balance in Metal Cutting

Using Eq.(1) and energy balance shown in Figure 4 as well as ideas of heat balance presented by Granovsky and Granovsky [21], the complete equation of heat balance in metal cutting system can be written in the following form

\[ F_{cV} = Q_{pd} + Q_{fr} + Q_{ch} + Q_{em} = Q_{c} + Q_{w} + Q_{t} + Q_{en} \] (2)

Where \( Q_{pd} \) is the heat associated with plastic deformation of the layer being removed, \( Q_{fr} \) is the heat generated due to friction on the tool rake face, \( Q_{ch} \) is the heat generated due to friction on the tool rake face, and \( Q_{em} \) is the heat due to formation of new surfaces, \( Q_{c} \) is the heat due to action of the minor cutting edge, \( Q_{w} \) is the heat that hoes into environment. Note that in Schmidt and Roubik [9] neglected this heat in their study assuming that it is negligibly small.

2.2 Experimental Apparatus and Methodologies

Dry machining tests were carried out to establish components of the heat balance Eq. (2) experimentally. The measurement of heat generation was carried according to methodology developed by Astakhov and Xiao [18], while heat partition, defined as calorimetry, was used according to the methodology presented in [17].

Machine - a special EMAG 250 DUO vertical turning center equipped with a SIMENS SINUMETRIC controller was used in the tests (Figure 7). The machine is equipped with a motor-spindle prime drive of 35kW so the power losses did not exceed 2-3%. The controller is capable to measure cutting power with not worse than 3% accuracy (Figure 8). As such, a wide range of power data sampling is available so that power variations can easily be visualized on the controller’s monitor. Moreover, the frequency of chip formation can be distinguished by adjusting the data sampling.

Work materials - standard ANSI 1045 steel was used as the work material. Its properties are as follows. Hardness, Brinell HB 170, tensile strength, ultimate 515MPa, tensile strength, yield 485MPa elongation at break 10.0 % in 50 mm, reduction of area 25.0 %, modulus of elasticity 200GPa Poisson’s ratio 0.2900, steel shear modulus 80.0GPa. Test pieces were prepared as rings having dimensions \( D \times d \times h = 180 \times 140 \times 50 \).

Tool - standard inserts SNMG 432-MF2 TP2500 Materials Group 4 (SECO) installed into a tool holder 453-12014 R1-1 (Sandvik) (Figure 9). The tool-in-machine tool geometry parameters are: The tool cutting edge angle \( \kappa_{e} = 45^\circ \), tool minor cutting edge angle \( \kappa_{m} = 45^\circ \), nose radius \( r_{n} = 1 \, mm \), radius of the cutting edge \( r_{c} = 0.03 \, mm \), normal flank angle \( \alpha_{n} = 7^\circ \), the normal rake angle \( \gamma_{r} = -7^\circ \). Each insert used in the tests was examined using a digital vision system at a magnification of x25 for visual defects such as chipping and microcracks.
Figure 7: Machine Used in the Tests

Figure 8: Power Reading on the Controller’s Monitor
AL-7014 dual-purpose calorimeter was a part of the experimental setup. It is designed to function as either a standard double wall calorimeter or as an electric calorimeter. It features a 300 ml inner vessel, 900 ml outer vessel with a molded cover, rubber stopper and fiber washer to support and insulate the inner vessel, and electric heating element. A digital thermometer MC-1000 with LCD display was used to measure the temperature in the calorimeter.

2.3 Experimental Results

The terms of the heat balance Eq. (2) were estimated for three cutting speed ranges. The first range is low (for the selected work material and cutting tool) cutting speeds (less than 100 m/min), second - for recommended cutting speeds (100-200 m/min), and third - for high (higher than recommended) cutting speeds (more than 200 m/min). Experimental results for terms of Eq. (2) are shown in Figure 10 and Figure 11. As can be seen, the greatest source of heat generation in the machining system is plastic deformation of the layer being removed. As shown by experimental result, this source becomes relatively weaker with the cutting speed. The second largest source is the friction at the tool-chip interface. This source becomes stronger with the cutting speed as the chip velocity increases at this interface as the cutting speed increases. As can be seen in Figure 10, other sources are much weaker.
Analysis of the heat partition shown in Figure 11 reveals the following:

1. The relative heat that goes into the chip is in agreement with the known experimental study although its values in any of three cutting speed ranges are lower than reported.

2. Surprisingly great amount of heat goes to environment although this term was not accounted for in the known studies. Moreover, in FEM analyses of the cutting process, this term is also ignored as the model is considered to be adiabatic.
3. The relative heat partition into the tool and the workpiece is the same as reported in the literature.

The obtained experimental results show that noting is incorrect in the results reported earlier in the literature on metal cutting so that this balance is not a problem in resolving the above-mentioned contradiction.

3. PROPOSED MODEL AND ITS GOVERNING HEAT PARTITION EQUATION

3.1 System Model

Figure 12 shows the system consideration of the metal cutting model [22]. Phase 1 is the initial stage. When the tool is in contact with the workpiece, the application of the cutting force $F_c$ leads to the formation of a deformation zone ahead of the cutting edge. The tool moves forward with a cutting speed $v$. The workpiece first deforms elastically and then plastically. As a result, an elastoplastic zone forms ahead of the tool that allows the tool to advance further into the workpiece so that a part of the layer being removed comes into close contact with the tool rake face (phase 2). When full contact is achieved, the state of stress ahead of the tool becomes complex including a combination of bending and compressive stresses. The dimensions of the deformation zone and the maximum stress increase with the cutting force $F_c$. When the combined stress in this zone reaches a limit (for a given work material), a sliding surface forms in the direction of the maximum combined stress (phase 3). The partially formed chip starts to slide with a velocity $v_{ch1}$ relative to the tool rake face. This instant may be considered as the very beginning of chip formation. As soon as the sliding surface forms, all the chip-cantilever material starts to slide along this surface with a velocity $v_{ch2}$ while the whole chip slides with a velocity.

![Figure 12: System Consideration of the Chip Formation Process in Metal Cutting](image-url)
v_{ch} along the rake face (phase 4). Upon sliding, the resistance to the tool penetration decreases, leading to a decrease in the dimensions of the plastic part of the deformation zone. However, the structure of the work material, which has been deformed plastically and now returns to the elastic state, is different from that of the original material. Its appearance corresponds to the structure of the cold-worked material. Experimental studies [1, 2, 23-25] showed that the hardness of this material is much higher than that of the original material. The results of an experimental study using a computer-triggered, quick-stop device proved that this material spread over the tool-chip interface by the moving chip constitutes the well-known chip contact layer (phase 5), which is now believed to be formed owing to severe friction conditions in the so-called secondary deformation zone that exists over the tool-chip interface [1].

The chip fragment continues to slide until the force acting on this fragment from the tool is reduced, when a new portion of the work material enters into the contact with the tool rake face. This new portion attracts part of the cutting force $F_c$. As a result, the stress along the sliding surface diminishes, becoming less than the limiting stress and arresting the sliding. A new fragment of the chip starts to form (phase 6).

Chip formed in this way is referred to as the continuous fragmentary chip [24] and it is the most common chip type formed in metal cutting although its appearance may vary depending on particular machining conditions. As such, the cutting speed has a major influence [17]. It has a saw-toothed free side and a non-uniform strength along its length. The shear strength of the fragments is much greater than that of fragment connections.

### 3.2 Governing Equation

Many cases considered in the literature deal with the so-called stationary systems. There are examples of materials processes in which a solid body is moving out of a hot region and it sheds heat to the environment as it moves away from that heat source. Some examples of this configuration include a long slab of steel emerging from a furnace, a polymer strand leaving an extruder, metal wire being drawn, or a metal rod undergoing continuous induction hardening. The same can be said about moving chip. In many cases, the heat transfer can be approximated as occurring in one dimension (the direction of motion, or the axial direction) and treating heat losses in perpendicular directions as heat sinks. In order for this approximation to be valid, the heat flow in the body must be oriented so that it is mainly in the axial direction. If the heat flux in the direction of the moving body is much greater than the direction normal to motion, then the one-dimensional approximation is reasonable.

If the moving body can be modeled as one-dimensional, then one can define a control volume over which he/she can perform an energy balance in order to derive a conservation equation for thermal energy in terms of temperature [26]. In this control volume (of length $\Delta x$, cross-sectional area $A_{ch}$, and perimeter $p$), thermal energy is transferred by conduction ($q_x$) and advection. Advection is the transport of energy due to the flow of the solid in the $x$ direction through the control volume. The amount of energy which is brought into the control volume at location $x$ by bulk solid motion is $(\dot{m}e_x)$, where $e_x$ is the specific enthalpy at $x$. The mass flow rate (which is constant along the length of the moving body) is $\dot{m} = \rho_{ch}A_{ch}v_{ch}$, where $\rho_{ch}$ is the density of the work material, $v_{ch}$ is the velocity of the chip relative the tool rake face. The rate at which energy is advected out of the volume can be different and is written as $(\dot{m}e_x + \Delta x)$. 


 Also, heat can be generated in the volume \( \dot{q} \) and it is also lost to the ambient by convection. For the rest of this derivation, it is assumed that the volume velocity, material properties, and geometry which do not change along the direction of motion \( x \). It is reasonable assumptions for the chip because as it forms, its velocity relative to the tool and geometry do not change.

Using these conditions, Bejan [26] derived the energy conservation equation which describes the temperature along the length of the moving body, subject to heat generation and convective heat loss in the following form

\[
\frac{d}{dx} \left( \frac{d}{dx} \left( k A_{ch} \frac{dT}{dx} \right) \right) - (\rho c_p) \frac{dT}{dx} - h c_v (T_{ch} - T_{en}) + \dot{q} A_{ch} = 0
\]  

(3)

where \( k \) is the thermoconductivity of the work material (or material of the chip), \( c_p \) is the specific heat of this material, and \( h c_v \) is the convection heat transfer coefficient of the process, \( T_{ch} \) and \( T_{en} \) are the temperatures of the chip and environment, respectively.

It is useful to look carefully at this energy equation to remind ourselves of the physical phenomena which govern it. One must never view such an equation in a purely mathematical light, but must keep in mind the physics represented by it. The first term represents the diffusion of thermal energy along the length of the body due to a temperature gradient within it. This diffusion of heat happens regardless of the magnitude of the motion and is independent of it. The second term is the change in the thermal energy of a mass as it moves through space. It is the difference between the energy advected into and out of a control volume of length \( dx \). The third term is the heat lost through convection to the environment and the final term is heat generated in the body. In metal cutting, the chip move very fast so that the convection term can be neglected [17].

The heat transfer by conduction and convention are normally considered in the literature on metal cutting while that by advection does not prevent so much attention. Thermal (or heat) advection is the transport of sensible or latent heat by a moving body, such as the chip in the considered case. Therefore, the role of heat advection, known also as mass transportation, as applicable to metal cutting should be examined in order to fulfill the objection of this study.

### 3.3 Péclet Number

To do exin the rople of advection in metal cutting, Eq. (3) is considered together with a simplified model of chip formation shown in Figure 13. In this model, the deformation of the layer being removed into the chip takes place ‘instantly’ on passing the shear plane so that the whole amount of heat due to the plastic deformation is generated along this plane. Being generated, the heat due to plastic deformation may go to the chip due to advection and to the layer being removed due to thermoconductivity. Note that the structure of Eq.(3) clearly shows that the generated heat cannot go into the chip by thermoconductivity as per the second law of thermodynamics, i.e. because the temperature of the chip is higher than that of the shear plane and heat goes from a region of higher temperature to that of lower temperature. Therefore,
there are two competing mechanisms of heat conduction: thermoconductivity that attempts to bring a portion of the generated heat into the layer being removed and advection that attempts to bring a portion of this heat into the chip due to its motion.

The next question to be answered is about the ratio of the portions of the heat generated on the shear plane due to thermoconductivity and that due to advection. It is well-known in heat transfer studies that such a ratio is determined by the Péclet number \([26]\). This number is a dimensionless number relevant in the study of transport phenomena in fluid flows. It is named after the French physicist Jean Claude Eugène Péclet. It is defined to be the ratio of the rate of advection of a physical quantity by the flow to the rate of diffusion of the same quantity driven by an appropriate gradient, i.e.

\[
Pe \equiv \frac{\text{[advection of heat]}}{\text{[conduction of heat]}} = \frac{VL}{\alpha}
\]

where \(V\) is the velocity scale, \(L\) is the length scale, and \(\alpha\) is the thermal diffusivity.

To comprehend the significance of this number, let’s consider an example. Figure 14 shows a flow of a fluid in a tube where a heater is installed. When the fluid is motionless, \(v_f = 0\), then the Péclet number is also zero according to its definition given by Eq. (4). As such, there is no advection. The heat from the heater flows in both sides at the same rate. When, however, the fluid velocity becomes \(v_f > 0\), then heat advection takes place so that, according to Eq. (3), the temperature on the right side of the heater becomes great than that on its left side. When the fluid velocity becomes great enough that the Péclet number is equal to 10, then only 1/10 of the heat supplied by the heater flows into the fluid in the left side of the heater while 9/10 of this heat flows to the fluid on its right side. No matter how powerful is the heater, this proportion is still the same.
In metal cutting, the Péclet criterion is represented in terms of machining process parameters as follows [17]

\[ Pe = \frac{v_{ch}}{w_w} \]  

(5)

where \( v_{ch} \) is the velocity of a moving heat source, \( i.e. \) the velocity of chip relative the tool rake face (m/s), \( w_w \) is the thermal diffusivity of the work material (m²/s)

\[ w_w = \frac{k_w}{(c_p \rho)_w} \]  

(6)

where \( k_w \) is the thermoconductivity of the work material, \((J/(m\cdot s\cdot °C)))\), \((c_p \cdot \rho)_w \) is the volume specific heat of work material, \((J/(m^3 \cdot °C)))\).

As an example, consider machining of AISI 1040 steel under the typical machining conditions: operation – turning; Tool – MTJNR-1616H-09 (ISO 5608: 1995) with a carbide insert; cutting speed \( v = 3 \text{m/s} \) (180 m/min); cutting feed \( f = 0.25 \text{mm/rev} \), chip compression ratio \( \zeta = 2 \), and thus the velocity of the chip with respect to the tool rake face is calculated as \( v_{ch} = v/\zeta = 3/2 = 1.5 \text{ m/s} \). Thermal diffusivity of the work material is \( 6.67 \cdot 10^{-6} \text{ m}^2/\text{s} \). For the J-style tool holder, the tool cutting edge angle is \( \kappa = 93° \), thus the uncut chip thickness calculates as \[ t_1 = f \cdot \cos(\kappa - 90°) = 0.25 \cdot \cos(93° - 90°) = 0.24965 \text{ mm} \]. Thus, the Péclet criterion is calculated as \[ Pe = \frac{1.5 \cdot 0.25 \cdot 10^{-3}}{6.67 \cdot 10^{-6}} = 66 \]. Therefore, 98.5% of the heat generated on the shear plane due to plastic deformation of the layer being removed flows into the chip while only 1.5% of this heat flows into the workpiece.

4. CONCLUSIONS

The obtained result has the following significance:

1. It explains the experimentally obtained low temperatures in the workpiece below the shear plane, for example those shown in Figure 1 and Figure 2. It explains why at low cutting speed the distribution of heat becomes more even. For example, referring to Table 1, when \( v = 0.1 \text{ m/s} \), then the amount of heat that goes into the chip is 47.9% while 38.4% goes into the workspace.

2. It explains the above-stated contradiction between the experimentally obtained heat balance in metal cutting (Figure 1, Figure 2 and Table 1) and the model shown in

![Figure 14: Example of Use of the Péclet Number](image)
Heat Conduction vs. Heat Advection in Metal Cutting

Figure 3. Moreover, it signifies the necessity of the system consideration of the chip formation process in the manner shown in Figure 12 instead of its static analogue exclusively used in the literature.

3. It fully supports statement of Zorev [1] and definition of the cutting process by Astakhov [2] that the metal cutting process is a cold-working process because the temperature of the layer being removed just ahead of the tool hardly exceed 200°C. In other words, the heat due to plastic deformation of the layer being removed does not affect the mechanical properties of the work material as this heat goes mostly into the chip due to mass transportation, i.e., advection.

One may argue, however, that the shear plane is not a plane in reality by as suggested by some researches, e.g., Spaans and Oxley [28, 29], in a narrow zone. To discuss the influence of temperature in this case, Rosenberg and Rosenberg [31] proposed to estimate the period of time necessary for a microvolume of work material to pass through the deformation zone. It follows from the above discussion that a microvolume of the layer being cut, passing through the shear zone, changes its velocity from the cutting speed \( v \) to the chip velocity \( v_{ch} = v/\zeta \) where \( \zeta \) is the chip compression ratio [17]. Thus, the average velocity of the micro volume is \( 0.5 \, v \) (1 – \( \zeta \)). Therefore, the time \( T_p \) necessary to pass the shear zone having the width of \( h_{sz} \) would

\[
T_p = \frac{h_{sz}}{0.5 \, v \left(1 + \frac{1}{\zeta}\right)}
\]  

(7)

Following a suggestion by Spaans, the width of the shear zone is \( h = 0.5t_1 \) [28], one can estimate the time which is necessary for a microvolume to pass the deformation zone for a typical cutting regime using Eq.(7). When the workpiece is made of a plain carbon steel, a typical cutting regime is as follows: \( v = 120 \, \text{m/min} = 2 \, \text{m/s}; \zeta = 2.5; \) uncut chip thickness \( t_1 = 0.2 \, \text{mm} \). Thus, the estimated time is \( T = 0.000071 \, \text{s} \). When the workpiece is made of a high-strength, low-alloy steel, the typical cutting regime may be as: \( v = 120 \, \text{m/min} = 2 \, \text{m/s}; \zeta = 1.3; t_1 = 0.05 \, \text{mm} \). As such, \( T = 0.000014 \, \text{s} \). As seen, the time necessary for a microvolume to pass the deformation zone is extremely short. As a result, heat generated in this zone due to plastic deformation of the layer being removed can be considered as occurring instantly, i.e., over the shear plane.

References


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