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Survey on Estimation of Heat Generation in Metal Cutting Tools

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Abstract : Cutting tools with hard coatings have been successfully employed in the industry for almost 50 years. Nowadays, 85% of all cemented carbide tools are coated. There is an increasing demand for ever more efficient tools driven by the use of new workpiece materials as well as the demand for increased productivity of manufacturing processes. Cutting tools are an excellent example for how the development of coated products is traced methodologically by means of a holistic view over the application. The demand for innovative tooling concepts will continue to exist in the future, as will the high potential for this aim to be achieved through high-performance coatings on improved cutting materials with adjusted tool design. This paper provides a review on cutting tools and heat estimation technique in cutting tools and further finite element analysis is also performed.

Keywords: Meatal Production, Cutting Tools, Heat flux, Heat generation, Finite element

1. Introduction

The term "metal production" refers to all the processes involved in the processing of a raw material, such as a metallic mineral, in a final form in which the metal can be used for commercial or industrial purposes. In some cases, the manufacture of metal involves relatively few steps because the metal already exists in elemental form in nature. This is the case of gold, silver, platinum and other precious metals. These metals are normally naturally present in combination with other elements and can therefore be used commercially with a relatively small additional treatment. However, in most cases, metals are found in nature as compounds such as oxide or sulfide and must first be converted to the elemental state. They can therefore be processed in various ways to exploit them for specific practical applications.

The first phase of metal production always involves a form of extraction. Mining refers to the process of removing the metal in its free or combined state from the surface of the earth. The two most common forms of extraction are open mining and open mining. In the first case, the metal or its mineral can be removed from the first meters of the earth's surface. Much of the world's copper, for example, is extracted from huge open-cast mines that can be almost 1 km deep and 3.5 km wide. Underground mining is used to collect metal ores that are deeper beneath the surface of the earth.

Some metals can be extracted from seawater instead of or in addition to extraction from the earth's crust. Magnesium is an example. Each cubic mile of seawater contains about six million tons of magnesium, mainly in the form of magnesium chloride. The magnesium is first precipitated in sea water in the form of magnesium hydroxide by lime (calcium hydroxide). The magnesium hydroxide is then converted back into magnesium chloride, which is now a pure compound rather than the complex mixture that comes from the sea. Finally, the metallic magnesium is obtained from the magnesium chloride by passing an electric current through an aqueous solution of the compound.

In most cases, metals and their minerals enter the soil in complex mixtures that also contain rock, sand, clay, silt and other contaminants. The first step in the production of metal for commercial purposes is therefore to separate the mineral from the waste that constitutes it. The term mineral is used to describe a compound of a metal that contains enough of this metal to make it economically practical for extracting the metal from the compound.

An example of how a mineral can be cleaned is the foam flotation process used in copper, zinc and other metals. In this process, the impure ore extracted from the soil is first ground into powder, then mixed with water and a foaming agent, such as water. Pine oil, mixed So, a stream of air is blown through the mixture, making it puff and foam. When the foam and impurities such as sand and stone are wet from the water and sink to the bottom of the container. The mineral does not absorb water but absorbs pine oil. The oil-covered mineral floats on the top of the mixture where it can be skimmed.

The metals are always in the oxidized state in the minerals, often as metal oxide or sulphide. Therefore, to bring a mineral to its elemental state, it must be reduced. Reduction is a chemical reaction that is the opposite of oxidation. Metals can be reduced in many ways.

For iron ores, the reduction can be obtained, for example, by reaction of iron oxides with carbon and carbon monoxide. One of the most common devices used for this purpose is the blast furnace. The blast furnace is a large cylindrical vessel in which iron ore (composed of iron oxides), coke (almost pure carbon) and limestone are introduced. The temperature in the blast furnace is then raised to over 1000 ° C (1832 ° F). At this temperature, the carbon reacts with oxygen to form carbon monoxide which, in turn, reacts with the iron oxides to form pure metallic iron. The limestone from the original mixture added to the blast furnace reacts with silica (sand), a contaminant commonly found in iron ore.

Some metal oxides do not give chemical reduction reactions as easily as the blast furnace process described above. The reduction of aluminum in aluminum is an example. Until 1886 no economically satisfactory method had been discovered to perform this process. So Charles Martin Hall, a young chemistry student, invented an electric method to reduce alumina.

In the first step, the alumina is separated from other oxides (such as iron oxides) with which it also occurs after the Bayer process. In the Bayer process, the naturally occurring oxide mixture is added to the sodium hydroxide which liberates the alumina and leaves other oxides. The alumina is then dissolved in a mineral known as cryolite (sodium fluoride and aluminum fluoride) and placed in an electrolytic cell. When the electric current passes through the cell, the molten aluminum is formed which flows towards the bottom of the cell and can be removed from the cell.

In some cases, a mineral is worked to change its chemical state before it is reduced. The most common zinc minerals are, for example, sulfides. These compounds are first roasted in excess of air to convert zinc sulfide into zinc oxide. The zinc oxide is then reduced by reaction with coke (as in the case of iron) or by electrolysis (as in the case of aluminum).

Often pure metals are unsatisfactory for many practical applications. For example, pure gold is too soft for most applications and is combined with other metals to form harder and stronger mixtures. Mixtures containing two or more metals are known as alloys. Steel is the best known and most used of all alloys.

The term steel refers to a number of different substances containing iron as the main component with one or more other elements. For example, stainless steel contains about 18% chromium, 10% nickel and small amounts of manganese, carbon, phosphorus, sulfur and silicon with iron. When niobium is added to a steel alloy, the end product has exceptionally high strength. The addition of cobalt produces a form of high temperature resistant steel for jet engines and gas turbines, and silicon steels are used in the production of electrical equipment.

In the final stages of metal production, the final product is put into a form that can be used in other industries to produce finished products. Therefore, steel can be purchased in the form of flat sheets, rings, cables and wires, plates, cylinders and other shapes.

2. Metal Cutting

Cutting may be a collection of processes whereby material is delivered to a specific geometry by removing excess material using numerous styles of tooling to go away a finished part that meets specifications. The net results of cutting is two product, the waste or excess material, and therefore the finished part. In woodworking, the waste would be sawdust and excess wood. In cutting metals the waste is chips and excess metal.

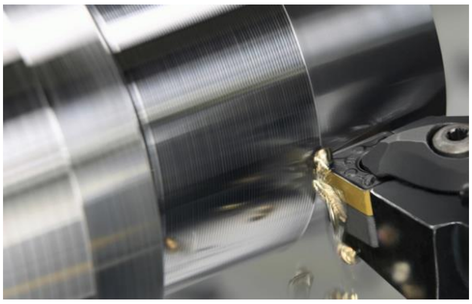
Cutting processes fall into one of three major categories:

- Machining i.e. Chip producing processes
- Burning i.e. to separate pieces of metal by the process of oxidation
- Miscellaneous specialty process

The use and application of metals depend on the specific needs of the customer, which define the shape, size, construction, thickness and favorable nature of metallic materials. Therefore, it is important to use precise metal cutting processes to ensure that the work of the metal meets the customer's specifications with versatility and flexibility. To acquire the types of metal with the required names, it is essential to apply a number of competitive devices and measures to cut metals.

3. Metal Cutting Approaches

1. **Turning:** In turning process when a sharp point of a cutting tool is applied to the metal surface and is quickly rotated by other support devices, such as a lathe. In this process, the metal layers are removed until the favorable and predetermined size is reached.
2. **Grinding:** In this process the grinder with a grinding wheel is applied to the metal, which has a smooth surface to transport it effortlessly and accurately.
3. **Drilling:** In this process a drill is used when a perfect hole must be made on the metal surface, and this is done by a combination of force and rotation on the metal surface.
4. **Laser:** Laser cutting technology is used when extreme precision, precise shape and tight control of metal dimensions are required. A laser is an intensely focused light beam that is reduced to a miniscule point by an extremely high temperature to cut metals with exact tolerance. Often, this process is computer controlled to obtain the most accurate prefabricated model.
5. **Welding:** When the metal surfaces are heated to a certain temperature to soften and break the surfaces along a carefully modeled line, it is called welding or burning.
6. **Water jet:** When water mixed with abrasives is used with an extremely high force to erode the metal surface with precision and perfection, it is called water jet cutting. The technology has some advantages that make it a preferred type of metal cutting because it is faster and cheaper than laser cutting with a clean and dense edge quality.

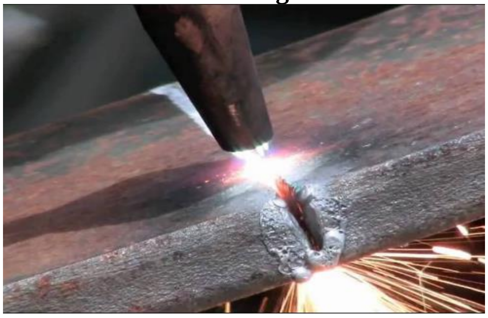


Turning

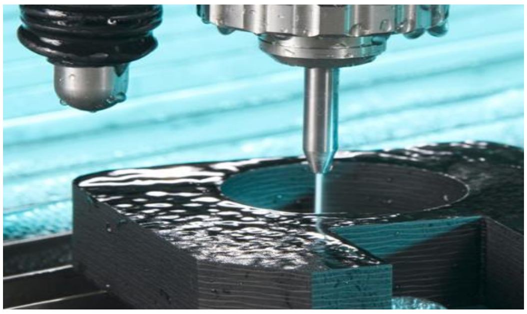
Grinding

Drilling

Laser



Welding



Water Jet

Figure 1 Different Metal Cutting Approaches

Cutting Tool Failure Mechanisms:

1. By Plastic deformation
2. By chipping due to mechanical breakage
3. Burning of the tool
4. By gradual wear

4. Heat Transfer

Thermal energy is related to the temperature of the material. For a given material and mass, the higher the temperature, the greater the thermal energy. Heat transfer is a study of the exchange of thermal energy through a body or between bodies, which occurs when a temperature difference occurs. When two bodies have different temperatures, the thermal energy passes from one to the highest temperature at the other to the lowest temperature. The heat is always transferred from hot to cold. Heat is typically given the symbol Q, and is expressed in joules (J) in SI units. The rate of heat transfer is measured in watts (W), equal to joules per second, and is denoted by q. The heat flux, or the rate of heat transfer per unit area, is measured in watts per area (W/m²), and uses $\overrightarrow{\emptyset_q}$ for the symbol.

4.1 Heat Flux

Heat flow is defined as the amount of heat transferred per unit of area per unit of time from or to a surface. In a fundamental sense, it is a derived quantity, since in principle it contains two quantities, namely: the amount of heat transfer per unit of time and the zone of / to which this heat transfer takes place.

The heat flux with temperature T(x) in a material of thermal conductivity ‘k’ is given by Fourier’s law:

$$\overrightarrow{\emptyset_q} = -k\frac{dT(x)}{dx} \quad \text{(i)}$$

The negative sign shows that heat flux moves from higher temperature regions to lower temperature regions.

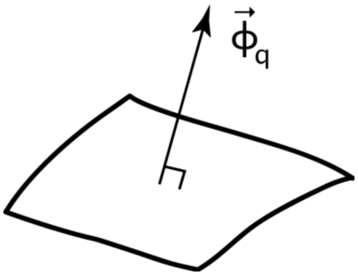


Figure 2: Heat Flux Through a Surface

In practice, the heat flow is measured by the temperature change caused by its action on a known surface sensor. The incident heat flow can create a stationary temperature range or a transient temperature range in the sensor. The applied temperature range can be perpendicular to the heat flow direction or parallel to the heat flow direction.

4.2 Types of Heat Transfer Modes

The heat is transmitted by solids (conduction), liquids and gases (convection) and electromagnetic waves (radiation). The heat is usually transmitted in a combination of these three types. For example, the thermal environment of a building is influenced by heat flows through the floor (pipe) and the building envelope (mainly convection and radiation).

1. **Conduction:** Conduction is transferred from solids or stationary liquids. When you touch a hot object, the heat you hear is transmitted through the heat through the skin. Two mechanisms explain how heat is transferred by conduction: the vibration of the lattice and the collision of particles. Conduction through solids occurs through a combination of both mechanisms i.e. the heat mainly passes through molecular collisions with stationary liquids.

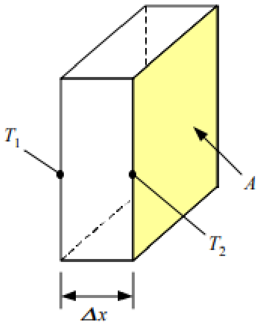


Figure 3: Heat Transfer through Conduction

Conductivity is measured in watts per meter per Kelvin (W/mK). The rate of heat transfer by conduction is given by:

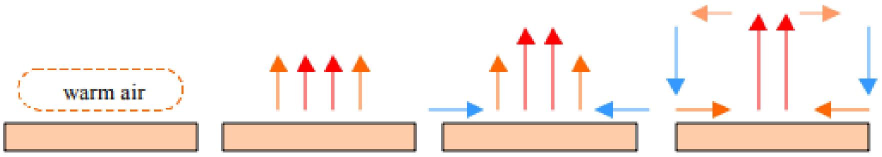
$$q_{Conduction} = -kA\frac{dT}{dx} \tag{ii}$$

where A is the cross-sectional area through which the heat is conducting, dT is the temperature difference between the two surfaces separated by a distance dx.

2. **Convection:** Convection uses the movement of liquids to transfer heat. In a typical convection heat transfer, a hot surface heats the surrounding liquid, which is then carried away by the fluid movement, such as the wind. The hot liquid is replaced by a colder liquid, which can remove more heat from the surface. As the heated liquid is constantly replaced by a colder liquid, the heat transfer rate increases. Natural convection (or free convection) refers to a case in which fluid movement is generated by the hot liquid itself. The density of the liquid decreases when it is heated; As a result, hot liquids are lighter than cold. The hot liquid surrounding a hot object rises and is replaced by a colder liquid. The convection coefficient h is the measure of the efficiency with which a fluid transfers heat by convection. It is measured in W/m²K, and is determined by factors such as the fluid density, viscosity, and velocity.

$$q_{Conduction} = -hA(T_{surface} - T_{\infty}) \tag{iii}$$

where A is the surface area of the object, $T_{surface}$ is the surface temperature, and T_{∞} is the ambient or fluid temperature.



1) hot surface heats surrounding air
2) warm air rises
3) air is replaced by cool air
4) circulation begins

Figure 4: Heat Transfer through Convection

3. **Radiation :** Radiation or radiant heat transfer does not require the passage of a fluid; Thus, it is the only form of heat transfer in the vacuum. It uses electromagnetic radiation (photons) that travels at the speed of light and is emitted from the material at a temperature above 0 ° Kelvin (-273 ° C). Heat transfer by irradiation occurs when the emitted radiation hits another body and is absorbed. We all transmit radiant heat every day; The solar radiation absorbed by our skin is the reason why we feel warmer in the sun than in the shade.
The amount of radiation emitted by an object is given by:

$$q_{emitted} = \varepsilon\sigma * AT^4 \qquad \text{(iv)}$$

where A is the surface area, T is the temperature of the body, σ is a constant called Stefan-Boltzmann constant, equal to 5.67×10-8 W/m^{2}K^4 , and ε is a material property called emissivity.

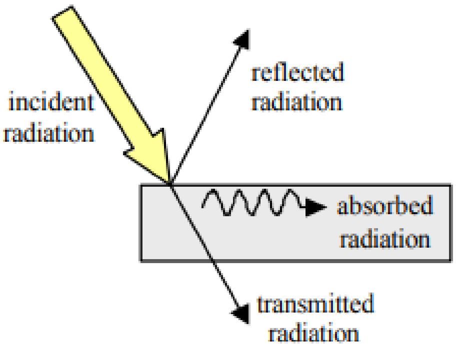


Figure 5: Heat Transfer through Radiation

5. Heat Produced during Metal Cutting

During metal cutting, a large amount of heat and high temperatures in the range of a few hundred to over one thousand degrees Celsius are generated because the energy consumed and removed by friction for plastic deformation is largely converted into heat near the cutting edge of the 'tool. As a result, these high temperatures control the wear rate and friction of the tool in the tool and tool interfaces. In quantifying the thermal behavior of the cutting area, great attention is paid to the determination of the heat and temperature quantities in the tool, in the chip and in the workpiece.

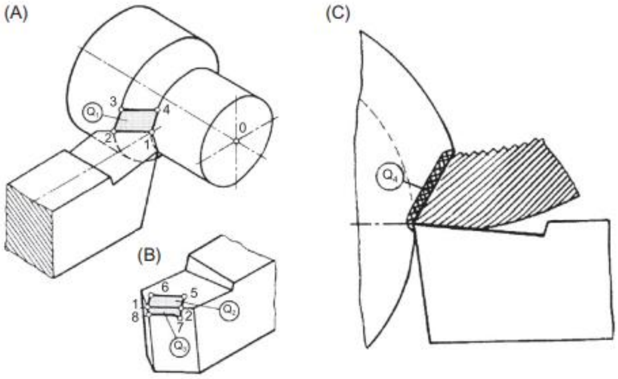


Figure 6: Sources of Heat Generation in Metal Cutting

Fig. 6 shows four basic heat sources that are present during the machining area in (ie the heat source q_1 due to the intensive-cut plastic deformation (section 1- 2-3-4), the q_2 interface of the friction chip located for friction of the tool (range 1- 2-5-6), q_3 at the contact between the workpiece and the side wall (range 1-2-7) -8), and of which a small part of the heat is transferred to the substrate layer and causes residual stresses) an additional source of t_4, The quantities of heat generated q_1 and q_2 can be roughly determined and considered as cutting or contact surface of the chip of tool. As a general rule, in the thermal analysis of the cutting process, the heat source q_3 for the surface of the worn side of the tool is large and the heat source q_4 is relatively small and neglected. Therefore, in practice, the conversion of shear energy into heat in the first deformation zone (PDZ) and the deformation zone occur secondary (SDZ).

The thermal currents flowing towards the chip (q_c), the tool (q_t) and (q_w) of the workpiece, can be schematically different in the figure as 7. (t_o). Note here that their components are generated by different heat sources, such as $q_c = q_{1c} + q_{2c}$. The three consecutive parts of the total amount of heat depend on the thermal properties of the cutting tool and the workpiece materials, on the cutting parameters, with the predominant effect of the cutting speed and an applied cooling process. The fact that the cutting speed noticeably affects not only the temperature but also the heat distribution between the chip, tool and workpiece has been put into practice.

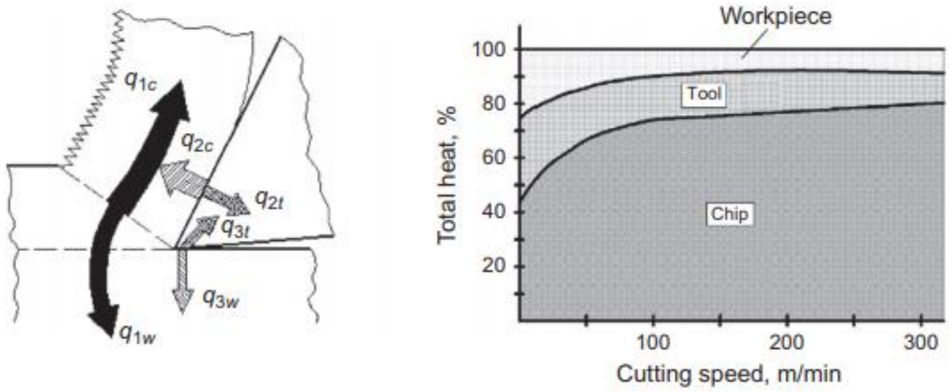


Figure 7 (a) A Scheme of Heat Flow (b) Percentage of the Heat Generated in Workpiece, Tool and Chip with Variable Speed

As Figure 7 (b) shows, as the cutting speed increases, more of the heat generated by the chip is removed and less heat is applied to the part. As the cutting speed increases, the time during which the flow of heat q_{1w} and q_{2t} flows into the workpiece flows and the tool is shortened. For example, in cutting steel at a cutting speed of 150 m / min, 75-80% of the heat is transported through the chip, 10-15% is introduced into the instrument and the remaining 5-10% are introduced in the room. On the other hand, when aluminum is processed at the same cutting speed, most of the heat flows into the piece by about 75%. As a result, at extremely high cutting speeds characteristic of high speed machining, most of the heat generated is removed from the chips and the cutting temperature decreases significantly.

In today's machining processes, complex temperature fields occur, but the maximum temperature on the cutting surface is observed near the center of the tool cutting interface. Since the temperature is not evenly distributed, the term cutoff temperature, which refers to the average temperature of the chip / chip interface, is commonly used in the theory and practice of metal cutting.

6. Estimation of Heat Generation in Metal Cutting

During the cutting process, the tool performs the cutting process overcoming the shear strength of the workpiece material. This creates a large amount of heat in the room, resulting in a highly thermo mechanically coupled deformation in the cutting area. Temperatures in the cutting zone significantly influence the stress-strain ratio, fracture and flow of the workpiece material. In general, increasing the temperature reduces the strength of the workpiece material and therefore increases its ductility. It is now assumed that almost all tool work and energy input are converted to heat during the machining process [1,3,4].

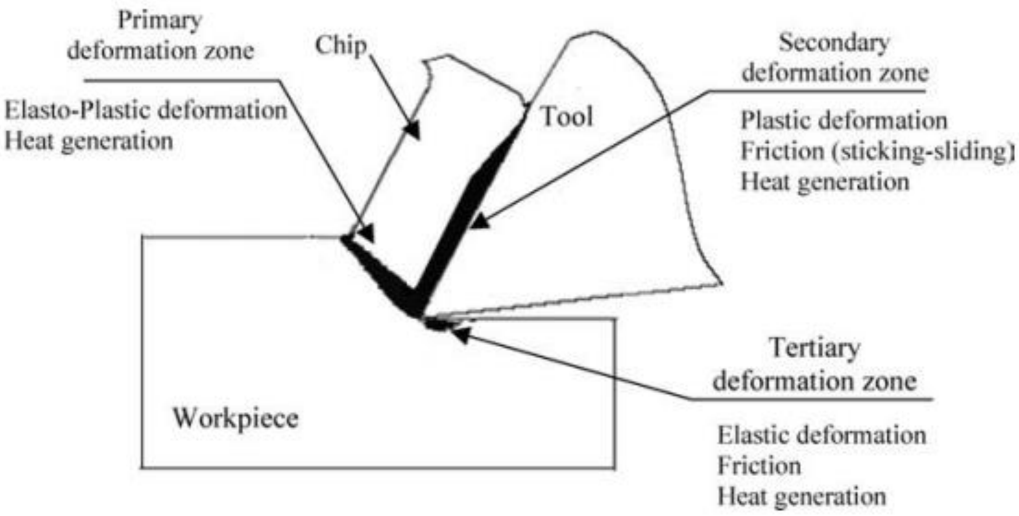


Figure 8 Sources of Heat Generation in the Orthogonal Cutting Process

The main regions where heat is generated during the orthogonal cutting process are shown in Figure 8. First of all, the heat is generated in the primary deformation zone due to the work of the plastic in the cutting plane. Local heating in this area leads to very high temperatures, which soften the material and allow greater deformation. Secondly, the heat is generated in the secondary deformation zone due to the work done to deform the chip and overcome the sliding friction in the chip-chip interface. Finally, the heat generated in the tertiary deformation zone at the workpiece-tool interface is due to the work of overcoming the friction that occurs in the friction contact between the surface of the tool flank and the newly formed surface. Heat generation and temperatures in primary and secondary areas are heavily dependent on cutting conditions, while heat generation in the tertiary area is strongly influenced by wear on the tool flank wear.

In conclusion, energy consumption and heat generation in machining processes depend on the combination of physical and chemical properties of the workpiece material and cutting tool material, cutting conditions and cutting tool geometry.

The heat generated during processing can be determined by calorimetry or by measuring the cutting forces. Knowledge of cutting forces, the consumption of energy during metal cutting is specified as:

$$W_c = F_v * V \tag{v}$$

where F_V is the cutting force in N and V is the cutting speed in m/s. Assuming that all the mechanical work done in the machining process is converted into heat, then heat generation, Q_S in J/s in the primary deformation zone may be calculated from the work done as:

$$Q_s = W_c = F_v * V \tag{vi}$$

where, F_V is the tangential cutting force or the force in the velocity direction and V is the cutting velocity. The amount of heat generated due to the work done in the secondary deformation zone along the tool rake face is calculated from the friction energy given by the following equation:

$$Q_r = \frac{F_{fr} * V}{\lambda_h} \tag{vii}$$

where F_{fr} is the total shear force in N acting on the rake face, and λ_h is the chip thickness ratio. The force F_{fr} can be calculated by using the following equation:

$$F_{fr} = F_V \sin\alpha + F_s \cos\alpha \tag{viii}$$

where F_S is the feed force and a is the rake angle. Heat is removed from the primary, secondary and tertiary zones by the chip, the tool and the workpiece.

Figure 9 shows schematically this heat dissipation. The temperature rise in the cutting tool is mainly due to the secondary heat source, but the primary heat source also contributes to the temperature rise of the cutting tool and indirectly affects the temperature distribution on the surface cutting the tool. During the process, some of the heat generated in the shear plane flows convectively through the chip and through the interface into the cutter. Therefore, the heat generated in the shear zone affects the tool's temperature distributions and the tool chip faces, and the temperature increase on the cutting surface is due to the combined effect of the shear zone. heat produced in secondary areas.

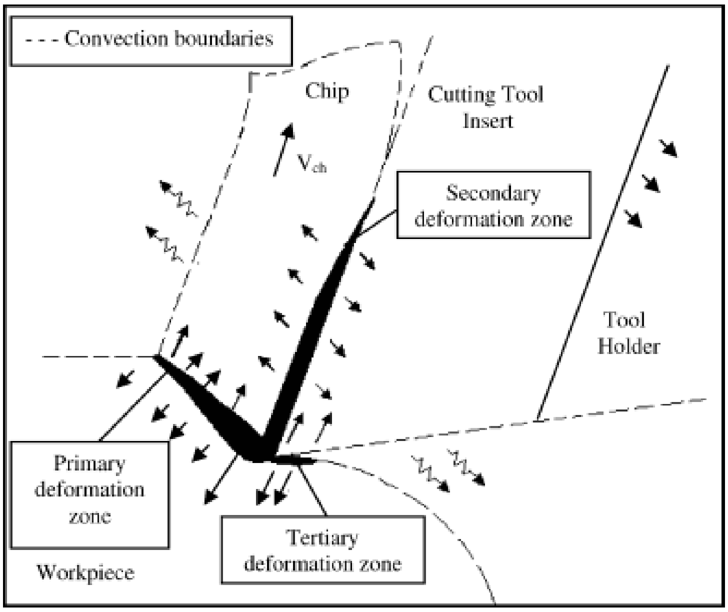


Figure 9: Schematic Representation of a Heat Transfer Model in Orthogonal Metal Cutting Considering the Combined Effect of the Three Heat Sources

According to [7] and [8], the total heat generation due to plastic deformation and sliding in the secondary deformation zone for continuous chips made from a non-abrasive medium cutting speed material is between and 35% of the heat. This means that taking into account the temperatures on the cutting tool, in addition to the direct effect of heat generation on the cutting surface and on the heat source in the primary zone, it is necessary to take into account. Vernaza et al. reports that 17% of the primary thermal area flows into the room [2]. However, at very low metal removal rates, it is generally assumed that this amount of heat is 50% . In [3], it is assumed that half of the heat generated by the friction between the tool and the work piece is supplied to the workpiece and the other half to the tool in the form of heat flow. He also said that 10-30% of total heat production enters the tool.

7. Properties of Cutting Tool Materials

Cutting tools must be able to meet the growing demands in terms of productivity and profitability, as well as to deal with exotic materials that are rapidly advancing science and technology. The material of the cutting tool of the day and of the future essentially requires the following properties to support or delay the phenomena that lead to an accidental or early error of the tools as:

i. High mechanical strength
ii. High tensile strength
iii. Toughness
iv. High hardness for abrasion resistance
v. High resistance to plastic deformation
vi. Reduced wear rate
vii. Chemical stability
viii. Resistance to adhesion and diffusion
ix. Thermal conductivity
x. High heat resistance and stiffness
xi. Manufacturability, availability at low cost

8. Finite Element Simulation of the Metal Cutting Processes

The finite element method (FEM) has been the most widely used numerical tool in metal cutting simulation since 1973. The use of the FEM in machining analysis allows to integrate the actual constitutive relationship of the metal to accurately model the interaction between the two chips and the cutting tool and to account for the effects of the free chip surface. More importantly, the complete technique of the FEM field allows the determination of stress, strain and temperature distribution to predict optimal cutting conditions.

8.1 Finite Element Simulation Requirements

i. Reproduction of the macro/ micro geometry of the tools and kinematic of the cutting process.
ii. Modelling of the thermo mechanical material behavior for the entire temperature and strain rate range.
iii. Implementation of damage approaches, texture microstructure and phase transformation.
iv. Simulation of chip form (remeshing, material separation, etc.)
v. Consideration of friction, wear and coating.
vi. Modelling of heat generation and transfer (conduction, convection, radiation)
vii. Consideration of the influence of cooling lubricant
viii. Utilization of the Lagrangian solving method
ix. Generation of a finely structured FE mesh and adaptive remeshing
x. Appropriate computation time

9. Conclusion

During the cutting process, the tool performs the cutting process overcoming the shear strength of the workpiece material. This creates a large amount of heat in the room, resulting in a highly thermo mechanically coupled deformation in the cutting area. Temperatures in the cutting zone significantly influence the stress-strain ratio, fracture and flow of the workpiece material. In general, increasing the temperature reduces the strength of the workpiece material and therefore increases its ductility. It is now assumed that almost all tool work and energy input are converted to heat during the machining process. This paper illustrates the use of the FEM in machining analysis allows to integrate the actual constitutive relationship of the metal to accurately model the interaction between the two chips and the cutting tool and to account for the effects of the free chip surface. More importantly, the complete technique of the FEM field allows the determination of stress, strain and temperature distribution to predict optimal cutting conditions.

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