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Development of a mathematical model for cooling efficiency of metalworking fluids in turning

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Abstract

This study examines the sources and dissipation pathways of cutting temperature in the machining process. Energy consumption in metal cutting process and metal working fluids have taken as an object of the study. Moreover, the effect of metal working fluids in heat dissipation process and the importance of their cooling capacity is theoretically researched. As a result of the study, dependence model of temperature gradient between cutting face and metalworking fluid on fluid's density and viscosity is mathematically developed. The developed mathematical model gives an easy way to predict metalworking fluid's cooling capacity before the utilization. It can be concluded that the reduction cutting fluids' viscosity causes an increase in the cooling capacity of the fluid while high dense fluid shows a better cooling capacity.

Keywords: cutting temperature, mathematical model, heart dissipation, heat transfer, machining, metal working fluid, process digitalization

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1. Introduction

The condition of the layers of the rubbing surfaces (rake and flank surfaces of the cutting tool, front surface of the chip, machined part surface) is determined by their temperature. Therefore, it is important to have information about the temperature of the contact layers when studying the laws of friction and wear of the cutter, the main parameters of the surface quality of the machined parts [1-3].

There are also some complexities associated with machining hardened steels, such as excessive heat generation, friction and cutting forces, tool wear, and manufacturing quality for high-performance machining.

Dry machining is the ultimate goal of future processing due to its mitigation of environmental, cost, and health concerns. It is also widely accepted and sustainable method to reduce cutting problems by using fluids in the machining of commercial materials such as aluminium, steel and cast iron. Also, dry machining is a standard for measuring the effectiveness of coolants and the relationship between product quality, tool wear and temperature. At the same time, traditional cooling is often used to limit tool wear, friction and temperature, and to improve the surface quality of hardened steel products. Developing sustainable production techniques, decreasing post-purification trends, environmental and health concerns, significant contribution of cooling cost (15-17%) to total processing cost and many cooling alternatives such as cryogenic cooling (liquid nitrogen, carbon dioxide) methods, water-based oil and MQL (minimum lubrication quantity) technologies have been adopted. MQL is a "mist" cooling or near-dry machining method in the cutting zone, in which compressed air and a limited amount of pure oil (50-100 ml/h) are mixed to form a fine mist at the tool-chip interface [4]. MQL technology can be used as a solution to problems such as environmental factors, increasing productivity and improving the health of workers [5].

Moreover, today, integration of machine learning and metal cutting process is developing noticeably, and the number of researches is increasing dramatically over the last 5 years. Mate Toth et al. researched the machining

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resource-efficiency by physics-informed machine learning. Their research team focused on the optimization of the tool stability by the help of grey-box modelling method. They created a model to predict a tool life before it was used in the machining process. They summarised that physical informed machine learning is a very powerful tool for cutting tool life optimisation [6]. Anli du Preez et all. studied the machine learning application in machining process for smart manufacturing. They analysed some applications of digitalization on machining processes including milling, boring, turning and etc. They conclude that application of machine learning has a great effect on metal cutting process, such as saving cost, product quality development, and waste reduction [7]. Mohsen Soori et all. conducted research on the advantages of machine learning and Artificial intelligence on Computer Numerical Controlled (CNC) metal cutting machine tools. According to their review, application of AI in CNC machine tools has a great impact on the development of a smart manufacturing, and the field will be one of the popular future directions to study [8].

According to the researches conducted mentioned above, digitalization of metal cutting process is one of the actual problems in todays research fields. Furthermore, Integration of artificial intelligence, machine learning, internet of things in various machining processes are given as a most current topic. In this research, mathematical model of the relationship between metal working fluids (MWF) and their some properties is developed. Fluid density and viscosity considered as input parameters while MWF's temperature gradient is an output value.

2. Heat Generation and Dissipation in Metal Cutting Process

In any machining operation, the main objective is to bring the material to the required dimensions and to cut it into small pieces, ensuring the quality, dimensions and shape of the part. Such processes require a lot of energy due to a large amount of plastic deformation [9]. The cutting temperature usually refers to the average temperature at the point of contact between the cutting edge and the friction surface of the tool. The level of cutting temperature depends on the amount of heat generated at that location and the speed of heat dissipation. By calculation and measurement, it is known that the average temperature is the highest in chip. The highest temperature on the rake surface of the cutting tool is located not at the cutting edge, but at a small distance from the cutting edge [10]. The cutting temperature causes the temperature of the cutting tool to rise, resulting in thermal deformation of the workpiece and the machine, affecting the machining accuracy and the surface quality of the workpiece. Cutting temperature is the main factor affecting tool life. Therefore, the study of the cutting temperature and the temperature of the cutting tool is of great practical importance [11]. All mechanical energy spent in the cutting process is converted into heat energy. Only 0.5...3% of the mechanical energy is converted into absorbed energy due to the change of crystal lattices of the processed material. In practice, the total amount of heat Q can be determined using the following expression:

$$Q = \frac{P_z v}{4190}, J/min \quad (1)$$

Where: P_z vertical component of cutting force, in [N]; v — cutting speed, m/min; 1/4190 — heat equivalent of work, in [J]. It is assumed that heat flows during cutting occur under the influence of highly concentrated sources of energy, concentrated or distributed in relatively small volumes. The process of the heat dissipation of concentrated sources acting in one or another system of solid bodies is expressed mathematically using two basic equations: heat balance equation, and thermal conductivity. The heat balance equation for the cutting process can be presented as follows.

$$Q_{def} + Q_{rake} + Q_{flank} = Q_1 + Q_2 + Q_3 + Q_4 \quad (2)$$

Where: Q_{def} —the amount of heat equivalent to the work spent on the formation of chip and the deformation and destruction of the surface layer; Q_{rake} — amount of heat equivalent to the work of friction forces when the rake face of the cutting tool of the deformed material is in contact; Q_{flank} – amount of heat equivalent to the work of friction forces on the flank surface of the cutting tool when passing through the deformed material in the surface layer of the machined part; Q_1 — the amount of heat passing to the chip; Q_2 — the amount of heat passing to the part; Q_3 — the amount of heat absorbed by the cutting tool; Q_4 — the amount of heat dissipated to the environment.

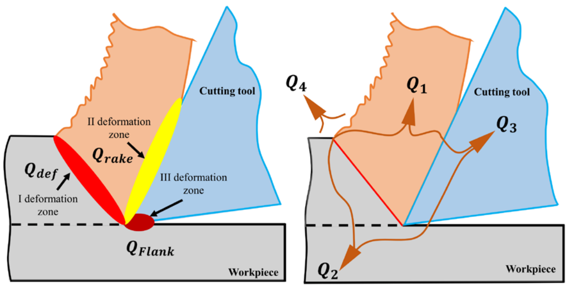

Figure 1. Sources of heat generation, and heat flow directions

The sources of heat generation during metal cutting form the left side of equation 2. The first source of heat Q_{def} is formed in the area where the largest plastic deformations occur, that is, in the chip disruption plane (Fig. 1a). The second source of heat Q_{rake} is formed on the front surface of the cutting tool - at the boundaries of the contact surface between the chip and the tool rake face. The third source of heat Q_{flank} is formed on the back surface - at the boundaries of the friction surface between the surfaces machined by the tool. The generated heat is distributed to areas that are much colder than the sources of its generation - chip, part, tool and environment (Fig. 1b). Location of heat sources are shown in Fig.1a. Undoubtedly, in the process of cutting, the directions of the movement of heat flows show complex exchanges, because the heat coming from three main sources - deformation, friction on the rake and flank surfaces of the tool - is distributed among all the bodies participating in this process. The second basic equation of heat conduction is in the form of a differential equation of heat conduction.

When the cutting speed increases, the percentage of heat remaining in the part decreases as a result of the change in the ratio between the speed of heat spreading from the deformation zone and the cutting speed. In the slag separation plane, the heat flux Q_2 spreads from the heat source to the part. The speed of heat propagation depends on the temperature gradient in the plane of chip separation and in the part, and the thermal conductivity of the material being processed. If the cutting speed, that is, the speed at which the cutting edge of the tool cuts the heat flow, is small, then the heat will pass from the plane of chip separation to the part without any obstacles. As the cutting speed increases, the tool blade cuts through the heat flow faster, so that a small amount of heat is transferred to the part, and a large amount of heat remains in the chip. When the cutting speed increases, the decrease in the share of heat transferred to the tool is due to the decrease in the width of the contact surface on the rake face of the cutting edge, the heat passes from the chip to the tool through this surface. In the following figure, distribution of heat generated due to metal cutting is showed. The results is obtained by turning cylindrical part in a lathe 16K10. The workpiece material is AISI 5135 while the tool is made of T15K6 (according to ISO 513-91) with an analogue was DIN HS123. The tool materials parameters given in the table 1.

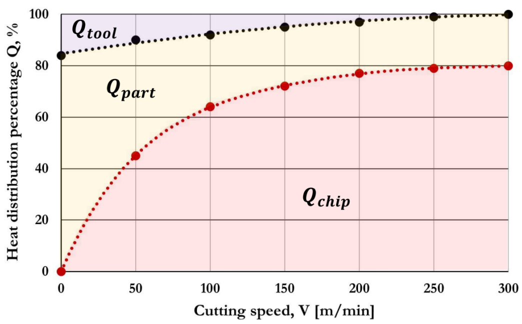

Figure 2. Distribution of Q between chip, tool and workpiece during machining of a part made of AISI 5140 steel with a tool made of T15K6 (cutting depth, t = 1.5 mm, feed, s = 0.12 mm/rev) hard alloy

Table 1. Tool material properties according to ISO 513-91

Material	Physical mechanical properties		
	Ultimate Strenth, N/mm^2	Density, x10^3 kg/m^3	Hardness, HRA
T15K6	1176	11.0-11.6	90
	Chemical Composition, in %		
	WC	TC	K
	79	15	6

It can be seen from the fig. 2 that the amount of heat transferred to the tool is very small (about 10 percent), and this heat energy is the same when cutting any materials in any mode. The reason for the low heat transfer to the tool is the low thermal conductivity of the tooling material and the narrow surfaces that the heat energy can transfer through two solid materials. Heat energy consumed by the chip generated in machining is the greatest in the process. It can be seen that about 70 percent of the overall heat energy is transferred to the chip in high cutting speeds. Because of the main heat source (1st deformation zone) located in chip generated in metal cutting, great amount of heat is consumed by chip. Despite the small percentage of heat transferred to the tool, the average temperature on the rake face of the cutting tool is several times higher than the average temperature of the chip (Fig. 3).

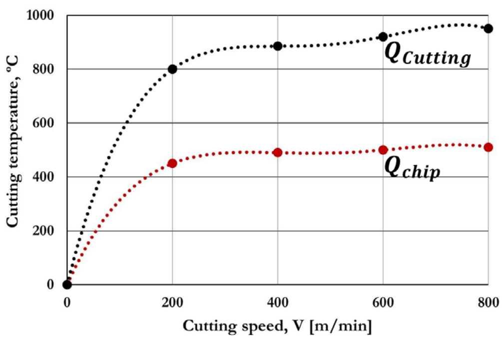

Figure 3. Effect of cutting speed V on cutting temperature and average chip heat Q when cutting a part made of 40X steel with a tool made of T15K6 (cutting depth, t = 1.15 mm; feed, s = 0.12 mm/rev) hard alloy

To study the temperature field in the metal cutting tool and the temperature state of its contact surfaces, on the basis of A.N. Reznikov's theorem [12], a scheme of heat sources and heat flows affecting the cutting tool, chip and raw materials is made. In the shown scheme, the chip was considered as an infinite beam with a thickness of a (Fig. 4). The main temperature fields in the metal cutting are the result of the combination of the temperature fields that appear under the influence of the following heat sources and currents.

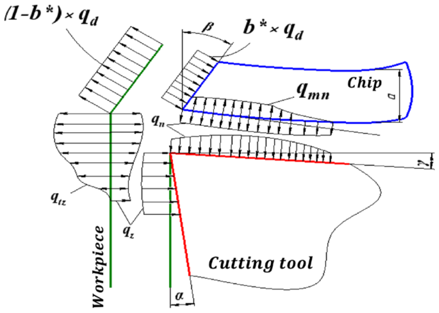

Figure 4. Heat flow diagram during cutting

q_d - heat generated as a result of deformation,
q_{mn} - heat generated by the friction between the chip and the cutting edge,
q_{tz} - heat generated as a result of friction on the contact surface between tool and workpiece,
q_n - heat exchange between chip and tool,
q_z - heat exchange between tool and raw material.

Convection can only occur in a liquid medium where heat transfer is related to the conduction of the medium itself. Convection of heat is always accompanied by heat conduction, because when a fluid or gas moves, contact inevitably occurs between individual particles with different temperatures. The combined transfer of heat by convection and conduction is called convective heat transfer.

2. Metal working fluids

The use of special lubricating-cooling technological environments (LCTE) in the cutting process allows to increase the stability of the cutter, reduce the cutting forces, improve the quality of the processed surface, increase the fatigue strength of the product, and increase the labor productivity. This, in turn, increases product market competitiveness. Therefore, most of the mechanical processing is carried out using LCTE. LCTEs actively affect the frictional plastic contact surfaces of the cutting tool.

The main purpose of using lubricating-cooling fluids is to reduce the cutting temperature, cutting forces and cutting power, and as a result, to increase the stability of the tool and the quality of the machined surface [13]. The use of LCFs in cutting high alloyed and stainless steels is of particular importance.

In the mechanical processing of details with the help of bladed cutters, when delivering lubricating coolants to the cutting zone, diverse methods are used including flooding, spraying of the liquid in the form of an air mixture (aerosol or MQL), wetting, occasionally pouring into the cutting tool before cutting (such methods as draining from a lubricator, rubbing with a brush, soaking) [14]. Among these methods, the most common one is the flooding method of LCF (injection with pressure P=0.02-0.03 MPa). The efficiency of this method depends on the consumption of lubricating-cooling fluid (5-20 liters/min) and the form and flowing trajectory. The main goal of this method is to completely cover the cutting zone with a lubricating cooling technological environment.

Lubricating and cooling properties of LCFs are the most important in their use in machining, and they are essential in reducing the cutting temperature and increasing the wear resistance of the cutting tool. Their change during machining has a high impact on the wearing level of the cutting tool. Therefore, by changing these two properties of LCFs, it is possible to significantly decrease the cutting temperature. Digitization of the above-mentioned features and control of their influence on the cutting process has got a great scientific and practical importance. The cooling ability is determined by their thermophysical parameters, such as heat transfer ability, heat capacity, kinematic viscosity and spatial variation of heat. These properties affect the temperature, which are the main indicators of the cutting process, the nature of chip formation, tool wear and life, machining accuracy, surface roughness, and residual stress in the surface layer of the part. Density and viscosity are addressed the main factors affecting the cooling ability of LCFs, and a model that can predict the cooling effect of LCF relative to its density and viscosity is developed in this research.

3. Development of a digital model

The main purpose of using lubricating-cooling (LCF) fluid in machining process is to reduce the cutting temperature, cutting forces and cutting power, and as a result, to increase the tool life and the quality of the machined surface, as well as to increase labour productivity [15, 16]. The use of LCF in cutting stainless and high-alloyed steels have particular importance.

One of the most important properties of LCFs is their cooling effect [17, 18]. The cooling ability of LCF is determined by their thermophysical parameters, such as heat transfer ability, heat capacity, kinematic viscosity and spatial variation of heat. These properties affect the temperature, which are the main indicators of the cutting process, the nature of chip formation, tool wear and life, working accuracy, surface roughness, and residual stress in the detail surface layer.

Reducing the cutting temperature of the lubricating coolant is determined by the amount of heat it takes with it from the cutting zone. The process of heat exchange in the LCF and cutting zone takes place due to convection. In the process of heat transfer, convection always comes with heat conduction. That is, when the LCF moves along the surface of a solid body, energy exchange occurs between the particles of the fluid with different temperatures. As we know, the transfer of heat energy through convection and heat conduction is called convective heat transfer. Based on this, the process of heat exchange between a fluid and a body moving on the surface of a solid body is expressed by the Newton-Richman theorem.

$$Q = \propto (T_d - T_{LCF}) \cdot F, \quad (3)$$

Where, α – heat transfer coefficient [$Vt/m^2 \cdot K$], T_d – temperature on the part surface [°C], T_{LCF} – The temperature of the LCF [°C], F – the surface that the fluid is flowing [m^2].

Based on the expression (1), it can be said that the temperature carried by the LCF is equal to $\Delta T = T_d - T_{LCF}$, and the higher the temperature carried by the LCF, the smaller the value of ΔT from this. It follows that the decrease in the value of ΔT depends on the decrease in the cutting temperature.

If we put α in expression (3) and find ΔT from the Nusselt criterion, which describes the similarity of heat transfer processes between a solid body and a fluid flow, the following expression (4) is formed:

$$q = \frac{Q}{F}$$

$$Nu = \frac{\alpha \cdot l}{\lambda}$$

$$q = \frac{Nu \cdot \lambda}{l} \Delta T \Rightarrow \Delta T = \frac{q \cdot l}{Nu \cdot \lambda} \longrightarrow \begin{cases} \Delta T \sim \frac{1}{\lambda}, \\ \Delta T \sim \frac{1}{Nu}, \end{cases} \quad (4)$$

The following equation can be recommended for calculating the Nusselt criterion number according to [19]:

$$Nu = 0.008 \cdot Re^{0.9} \cdot Pr^{0.43} \longrightarrow [Nu \sim Re], \quad (5)$$

The value of the Reynolds number is calculated using the following expression [19]:

$$Re = \frac{w \cdot l \cdot \rho}{\mu} \longrightarrow \begin{cases} Nu \sim \frac{1}{\mu}, \\ Nu \sim \rho \end{cases}, \quad (6)$$

As a result of combining the above expressions (3), (4), (5) and (6), the following expression of the dependence of the temperature change between the cutting surface and the LCF on the viscosity and density of the LCF is derived:

$$\Delta T = \frac{q \cdot l}{0.008 \cdot Re^{0.9} \cdot Pr^{0.43} \cdot \lambda} \longrightarrow \begin{cases} \Delta T \sim \mu, \\ \Delta T \sim \frac{1}{\rho}, \end{cases} \quad (7)$$

It follows from the expression (7) that the decrease in the viscosity of LCF and the increase in its density cause an increase in its cooling properties. The results of an experimental study on the viscosity and density of magnetized LCF show that the use of LCF in the process of metal cutting in the flow state directly leads to a decrease in the cutting temperature and, in turn, to an increase in the wear resistance of the cutting tool.

Developed model has a good potential to use optimization of technological processes, it is possible to choose the optimal option depending on the viscosity and density of various lubricating and cooling fluids, which increases the efficiency of the cutting process. Moreover, the model helps to determine the heat distribution in the cutting zone, improving the surface quality and extending the service life of the tools. In addition, the model can be used in the development of new types of LCFs, where the optimal density and viscosity parameters are calculated in advance.

Conclusions

The greater the work required to cut metals, the higher the cutting temperature when other parameters being equal. As the hardness and strength of the processed material increases, the cutting temperature increases. The thermal conductivity and heat capacity of the processed material also have a great effect. The higher the thermal conductivity of the material being processed, the higher the speed of heat transfer to the chip and workpiece, which means that the cutting tool heats up less. The amount of heat received by tool and workpiece depends on the heat capacity of the material being processed.

Moreover, mathematical model of the effectiveness of LCF in machining is developed and the model can predict the temperature gradient of the LCF depending on its density and viscosity. Developed model can be used in digitalization of the metal cutting process, sensor assisted machining and other automation processed that applied in metal cutting.

The developed mathematical model for determining the cooling properties of lubricating-cooling fluids depending on viscosity and density can also be used for Machine Learning (ML) algorithms. In particular, using ML algorithms, it is possible to predict the cooling properties of liquids with different densities and viscosities, analyse the effectiveness of various liquids through it, and choose the best option.

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