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Influence of Using Cutting Fluid under the Effect of Static Magnetic Field on Chip Formation in Metal Cutting with HSS Tools (Turning Operation)

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This paper presents a novel methodology of using cutting fluids to improve the material removal process in metal cutting. To this end, a set of orthogonal cutting experiments are conducted using various cutting fluids to calculate the chip shrinkage coefficient in the material removal process. Chip shrinkage coefficient has been focused on as an important factor that affects chip formation in the material removal process. Using cutting fluids under the influence of a static magnetic field in the metal cutting process is proposed as an innovative method to decrease the deformation that is emerged in the chip formation process while cutting cylindrical parts in lathes. Experiments showed that the application of cutting fluids under the influence of a static magnetic field decreased the shrinkage of the chip by up to 20 % in comparison to the conventional use of cutting fluids in turning cylindrical parts with HSS tools. Moreover, a mathematical model of the effect of boiling point and density of cutting fluids on tool flank wear has been developed in this paper. The obtained results present that the magnetized cutting fluids have an improved cooling capacity and they can be used as a modern cutting fluid in manufacturing.

Keywords: Cutting fluid, Chip shrinkage, Metal cutting, Magnetic field, Turning

1 Introduction

Today, increasing the strength, corrosion resistance, and heat resistance of metal cutting tools while maintaining their plasticity is one of the urgent problems of manufacture. The efficiency of mechanical processing largely depends on the cutting speed, the depth of the cut layer (depth of cut), the wear resistance of the cutting tool, etc. The wear resistance of the cutting tool is the most important indicator among these parameters. The wear resistance of the cutting tool is the main factor that determines its operational characteristics.

One of the promising directions is the issue of increasing the wear resistance of the cutting tool as a result of creating special technological environments based on the use of lubricating-cooling liquids and changing their properties. Changing the physical-mechanical properties of the metal cutting environment and increasing the wear resistance of the cutting tool based on the creation of a lubricating-cooling technological environment under the influence of a magnetic field is one of the novel issues. Application of special lubricating-cooling technological conditions in the metal cutting process gives an opportunity to increase the stability of the cutting tool, reduce the cutting forces, improve the quality of the machined surface, increase the fatigue strength of the product, increase the labour productivity and other opportunities [1, 2, 3]. This, in turn, strengthens product competitiveness. Therefore, most of the mechanical processing is carried out using lubricating and cooling technological environments. Cutting fluids 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 power and, as a result, to increase the wear resistance of the cutting tool and the quality of the machined surface [4, 5, 6, 7]. Russian scientists A.G. Kisel, D.S. Rechenko, et al. have determined the effect of coolant, in 1.5% aqueous solution of soda ash, for wear and durability of hard-alloy turning tool in various processing modes of cutting steel 45, as well as the development of recommendations for the use of this coolant. As a result, they increased the cutting time by applying a particular cutting fluid [8].

Currently, the mechanism of influence of cutting fluids on the cutting process is explained on the basis of physical-chemical theory and hypotheses (founded by P.A. Rubinder, S.Ya. Weiler, and others). It is investigated that a lubricating film is formed between the surfaces that rub against each other during the cutting process. Due to the high molecular similarity of the film material with the workpiece or cutting material, it cannot squeeze out of the cutting zone with high pressure. From this, it can be said that special environments reduce the speed of friction in all cases and reduce corrosion [9].

One of the most important properties of lubricating-cooling liquids is their cooling effect [10]. The cooling ability of cutting fluids is determined by their thermos-physical parameters, such as heat transfer ability, heat capacity, kinematic viscosity, and spatial variation of heat. These properties affect the temperature, which is the main factor of the cutting process, the nature of chip formation, tool wear and resistance, working accuracy, surface roughness, and residual stress in the surface layer of the detail.

2 Methods

In the process of metal cutting, the use of lubricating-cooling fluids and their contribution to the improvement of wear resistance of cutting tools make particular importance in creating a lubricating-cooling technological environment in the machining process. Experiments and studies have shown that the lubrication, cooling, and washing properties of magnetized cutting fluids differ from those of conventional cutting fluids, and this difference is even higher when cutting fluids are magnetized in the flowing state [11, 12]. The results give a conclusion that it is possible to create a special lubricating-cooling technological environment by magnetizing cutting fluids with a high magnetic field in their flowing state in metal cutting. This poses the new problem of solving the magnetization of cutting fluids in the flowing state during the metal cutting process. In order to solve this problem, a scheme of direct magnetization in the current state of cutting fluids during the cutting process was developed (Fig. 1).

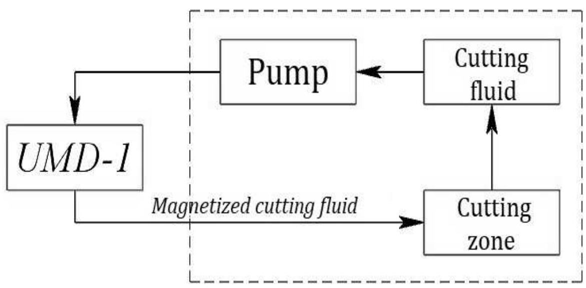

Fig. 1 *Magnetization scheme of cutting fluids in flowing condition during metal cutting*

During the metal cutting process, cutting fluid is stored in a special container of the machine where processing is carried out. The cutting fluid in the container is poured into the cutting zone using a pump through special pipes. The speed of the fluid passing through the pump is controlled by the tap. In order to magnetize the cutting fluid flowing in the pipe, it is necessary to influence the required induction of a magnetic field around the fluid passing through the pipe at a specified speed (Fig. 1). For this purpose, the pipe inside which the fluid is moving is passed through the specially developed UMD-1 universal magnetizing device [13], and under the influence of its magnetic field, cutting fluid turns into a magnetized cutting fluid.

The practical and analytical experiments conducted during the research work cannot fully answer the questions about what factors affect the reduction of the cutting temperature when using magnetized cutting fluid in metal cutting and what their contribution is to this process. Therefore, a thermal-physical analysis of the cutting process was conducted. Application of magnetized cutting fluids in the machining process causes a decrease in cutting temperature due to the following factors: a decrease in the work performed during cutting, a decrease in the degree of deformation of the cuttings, and a decrease in the cutting forces, depending on the amount of heat carried through the cutting fluid and its thermal-physical properties.

To study the temperature field in the cutting tool and the state of its temperature on the contact surfaces we made a scheme of heat sources and heat flows affecting the cutting tool, chip, and raw materials based on A.N. Reznikov theorem [14]. In the shown scheme, the chip was determined as an infinite bar with a thickness of "a" (Fig. 2). The main temperature fields in the section are the result of the combination of the temperature fields that appear under the influence of the following heat sources and currents.

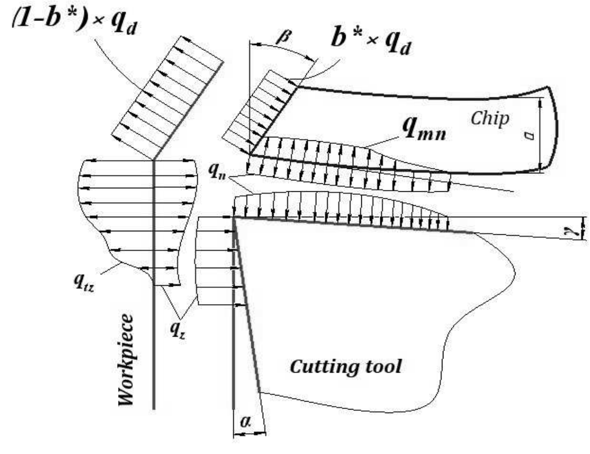

Fig. 2 *Heat flow scheme in the metal cutting process*

Where:

q_d…Heat amount generated as a result of deformation,

q_{mn}…Heat generated by the friction between the chip and the cutting edge of the cutting tool,

q_{tz}…Heat generated as a result of friction on the contact surface between the cutting tool and workpiece,

q_n…Heat exchange between the cutting tool and chip,

q_z…Heat exchange between the cutting tool and workpiece.

Convection can only occur in a fluid condition where heat transfer is related to the conduction of the condition itself. Convection of heat is always accompanied by heat conduction, because when a liquid 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.

Reducing the cutting temperature by the lubricating-cooling liquid is determined by the amount of heat the lubricating-cooling liquid takes with it from the cutting zone. The process of heat exchange in the cutting fluid and cutting zone takes place due to convection. In the process of heat transfer, convection always comes with heat conduction. That is, when the cutting fluid moves along the surface of a solid body, energy exchange occurs between the particles of the liquid at 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 liquid and a body moving on the surface of a solid body is expressed by the Newton-Richman theorem.

$$Q = \alpha(T_d - T_{MSS}) \cdot F \quad (1)$$

Where:

α…Heat transfer coefficient [W/m²·K],

T_d …Temperature on the workpiece surface [°C],

T_{MSS}…Cutting fluid temperature [°C],

F…The surface that the fluid is moving [m²].

Based on the expression (1), it can be said that the temperature carried by the cutting fluid is equal to $\Delta T=T_d-T_{MSS}$, and the higher the temperature carried by the cutting fluid, 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 (heat transfer coefficient) in expression (1) and find ΔT from the Nusselt criterion, which describes the similarity of heat transfer processes between a solid body and a liquid flow, the following expression (2) is formed:

$$q = \frac{Q}{F},\ Nu = \frac{\alpha \cdot l}{\lambda},\ q = \frac{Nu \cdot \lambda}{l}\Delta T \Rightarrow \Delta T = \frac{q \cdot l}{Nu \cdot \lambda} \rightarrow \begin{cases} \Delta T \approx \frac{1}{\lambda} \\ \Delta T \approx \frac{1}{Nu} \end{cases} \quad (2)$$

The following equation can be recommended to calculate the Nusselt criterion value:

$$Nu = 0.008 \cdot Re^{0.9} \cdot Pr^{0.43} \rightarrow [Nu \approx Re] \quad (3)$$

The value of the Reynolds number (*Re*) is calculated using the following expression:

$$Re = \frac{w \cdot l \cdot p}{\mu} \rightarrow \begin{cases} Nu \approx \frac{1}{\mu} \\ Nu \approx \rho \end{cases} \quad (4)$$

As a result of combining the expressions above (1), (2), (3), and (4), the following expression of the dependence of the temperature change between the cutting surface and the cutting fluid on the viscosity and density of it is derived:

$$Re = \frac{w \cdot l \cdot p}{\mu} \rightarrow \begin{cases} Nu \approx \frac{1}{\mu} \\ Nu \approx \rho \end{cases} \quad (5)$$

It can be said from expression (5) that a decrease in the viscosity of cutting fluid and an increase in its density cause an increase in cutting fluid's cooling properties. The results of an experimental study on the viscosity and density of magnetized cutting fluid show that the use of MSS in the process of magnetic 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.

In the cutting process, there are different types of cutting tool wear, among which the wear of the tool on the back surface has the greatest effect on the surface and dimensional accuracy of the workpiece being processed. The effect of the temperature generated in the cutting zone on the back surface wear of the cutting tool is high.

We express the heat generated on the back surface of the cutting tool by the following expression:

$$Q_z = P_z v \rightarrow [\frac{J}{s}] \quad (6)$$

Where:

P_z…Friction force on the back surface.

Based on expression (6), we create the following expression for the amount of heat source that appears under the influence of frictional forces on the contact surface of the raw material with the cutting tool.

$$q_z = \frac{P_z \cdot v}{b \cdot h_z} \rightarrow [\frac{J}{mm^2 \cdot s}] \quad (7)$$

Where:

h_z…Wear of the back surface of the cutting tool, mm.

By equating the resulting expression (7) to Fourier's law of heat exchange, we derive the expression of the dependence of the cutting tool wear on the rear surface on the thermal conductivity of the cutting fluid.

$$\frac{P_z \cdot v}{b \cdot h_z} = -\lambda \cdot \text{grad}\theta \quad (8)$$

$$h_z = \frac{P_z \cdot v}{b \cdot \lambda \cdot \text{grad}\theta} \quad (9)$$

By equating the expression of the dependence of the thermal conductivity of the liquid on its density and boiling temperature developed by Minsar with λ in (9), we derive the expression of the dependence of the cutting tool wear on the boiling temperature and density of the cutting fluid.

$$\lambda = \frac{90 \cdot 10^{-6}}{N^{1/4}} \cdot \sqrt{T_{qay} \cdot \rho} \cdot c_p \quad (10)$$

$$h_z = \frac{P_z \cdot v \cdot N^{1/4}}{b \cdot 90 \cdot 10^{-6} \cdot \sqrt{T_{qay} \cdot \rho} \cdot c_p \cdot \text{grad}\theta} \quad (11)$$

From expression (11), it follows that the wear of the cutting tool is inversely proportional to the boiling temperature and density of the cutting fluid. According to this, it can be concluded that increasing the density and boiling temperature of cutting fluids leads to a decrease in the flank wear of the cutting tool.

From the results of experimental studies on the magnetization of cutting fluids and from the expression (11), the magnetic field causing an increase in the density of cutting fluid leads to an improvement in the thermal conductivity of magnetized cutting fluids, which leads to an increase in the wear resistance of the cutting tool.

3 Experimental condition

UMD-1 magnetizing device [12, 13, 16] was developed for the magnetization of flowing liquids with a permanent magnetic field, and 10 neodymium super magnets (N40) were used in it, the size of each magnet is 50x20x10 mm, and the maximum induction of the magnetic field is B=400 mT. All obtained sample liquids were rotated through the UMD-1 magnetizing device for 60 minutes at a speed of 1 m/s.

In order to determine the effect of different cutting fluid conditions on the chip shrinkage coefficient, all the experiments were conducted in 3 different environments (dry, conventional lubricating cooling condition fluid, and lubricating cooling condition under the influence of static magnetic field in flowing state). In addition, the process of cutting a cylindrical workpiece made of Stal 45 (carbon steel) on a lathe with the help of a full-pass lathe HSS cutting tool made of material P18 and P6M5 was used (Table 1).

***Tab. 1** Mechanical properties of HSS cutting tools and workpiece material used in the experiment*

Material type	σ_b, MPa	σ_T, MPa	δ_5, %	ψ, %	KCU, kJoul/m²	HB 10^{-1} MPa	Standard
P18	840	510	8	10	190	255	GOST 19265
P6M5	850	510	12	14	180	255	GOST 19265
Stal 45	540	-	13	40	-	241	GOST 1050-88

Where:

σ_b …Ultimate strength,

σ_T …Limit of proportionality (Yield strength for residual deformation),

δ_5 …Elongation at break,

ψ …Contraction ratio,

KCU…Impact strength.

Modern lubricating cooling fluids, which are widely used in many production enterprises operating in the Republic of Uzbekistan, were used to create the lubricating cooling technological condition. One of them is a 5 percent solution of LACTUCA LT 3000 liquid in clean water, which is widely used in cutting machine details all over the world. Table 2 lists the properties of LACTUCA LT 3000 lubricating cooling liquid.

***Tab. 2** Specifications of cutting fluid LACTUCA LT 3000*

TOTAL LACUCA LT 3000	Value	Standard
Density, kg/m³ (T= 15⁰C)	890	ISO 3675
Kinematic viscosity, mm²/s (T= 0⁰C)	34	ISO 3104
Dynamic viscosity, *10⁶ Pa*s. (T = 30⁰C)	461	-
pH(5% concentration)	8.8	NF T 60 193

The second liquid is a 2 percent concentration of potassium dichromate ($K_2Cr_2O_7$) powder in clean water. This mixture is one of the liquids widely used in enterprises in Uzbekistan for many years. One of the special properties of this liquid is that it does not have a high effect on the corrosion of metals. Table 3 shows the properties of the mixture.

Tab. 3 *Specifications of cutting fluid Potassium dichromate ($K_2Cr_2O_7$) in 2% concentration of water*

$K_2Cr_2O_7$(2% concentration in water)	Value	Standard
Density, kg/m^3 (T= 15^{0}C)	1008	ISO 3675
Kinematic viscosity, mm^2/s (T= 0^{0}C)	3.7	ISO 3104
Dynamic viscosity, *10^6 Pa*s. (T = 30^{0}C)	427	-
pH(5% concentration)	7	NF T 60 193

In order to increase the accuracy of the obtained results, all experiments were carried out under the same conditions. In this case, the same values were chosen for the angles of the cutting tool, and all the experiments were performed at the selected values of the angles of the cutting tool. Table 4 shows the laboratory conditions in which the experiments were conducted.

Tab. 4 *Specifications of cutting fluid Potassium dichromate ($K_2Cr_2O_7$) in 2% concentration of water*

1	Atmospheric pressure		755 mmHg
2	Humidity		16%
3	Pipe diameter		10
4	Height above sea level		440 m
5	Duration of magnetization		60 min
6	HSS cutting tool materials		P18
			P6M5
7	Workpiece material		Stal 45
8	Model of the cutting machine		1M63MF101
9	Geometrical parameters of the cutting tools	Main rear angle - $\alpha=\alpha_1$	6^0-8^0
		Front angle - γ	0^0
		The main angle in the plan - φ	45^0
		An auxiliary angle in the plan - φ_1	45^0

During the experiments, three different cutting conditions were created. First, the cylindrical workpiece was machined in a dry environment at 4 different cutting speeds (25 m/min, 40 m/min, 50 m/min, and 60 m/min). In the second case, the cylindrical workpiece was subjected to mechanical processing with 4 different cutting speeds, using 2 different cutting fluids of we were chosen before, creating a lubricating cooling condition. In the third case, it was mechanically processed at 4 different cutting speeds with a lubricating cooling liquid under the effect of the static magnetic field. In this case, the liquid flowing through a plastic pipe with a diameter of 10 mm was magnetized using the UMD-1 magnetizing device, and then it was poured into the cutting point.

4 Results and discussions

In the cutting process, it undergoes plastic deformation during the chip formation, and as a result, heat is generated. In Fig. 3, the main sources of heat generated in the cutting zone are divided into four categories, and here zone II is the deformation zone of the chip. It is known that much of the heat generated during the metal-cutting process is because of the deformation in zone II shown in Fig. 3 [15].

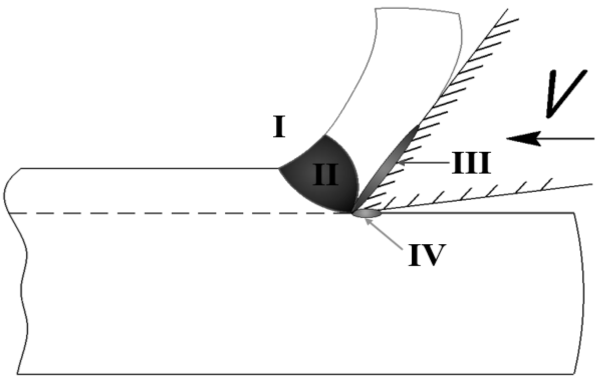

Fig. 3 *Chip formation process in metal cutting. I – the outside of the chip, II – deformation zone, III – cutting tool-chip contact zone, IV – cutting tool-workpiece contact zone*

Deformation during the metal cutting process was expressed by the chip shrinkage coefficient, and the small value of the chip shrinkage coefficient indicates the smallness of the plastic deformation. Cutting fluid is directly in contact with the part being processed through the deformation zone over a large surface. This makes it possible for the cutting fluid to take away more heat with itself as a result of convection. As a result, the reduced temperature in the cutting zone reduces the deformation of the chip and leads to a decrease in the amount of heat generated in zone II (Fig. 3). In order to study the effect of magnetized cutting fluid on the deformation of a chip, two types of cutting fluids were used in metal cutting in the conventional and magnetized state, and the resulting chip shrinkage coefficients were experimentally studied. We used the mass method to determine the shrinkage coefficient of the chip and calculated it using the following expression (12).

$$\xi = \frac{m \cdot 1000}{l \cdot \rho \cdot s \cdot t} \quad (12)$$

Where:
m…Weight of the chip [gr],
l…Length of the chip [mm],
ρ…density of the material of the chip [g/sm^3],
s…Feed [mm/rev],
t…Cutting depth [mm].

Setting the selected cutting modes and parameters given in the table 4, the experiment has been conducted to calculate and manage the chip shrinkage coefficient in different lubricating-cooling technological condition. After every experiment, specific parameters (chip length, weight) of the chip have been measured and calculated using equation [15]. Using the results obtained in different lubricating-cooling technological condition, the dependence line graphs of shrinkage coefficient [mm] and cutting speed [m/min] have been generated.

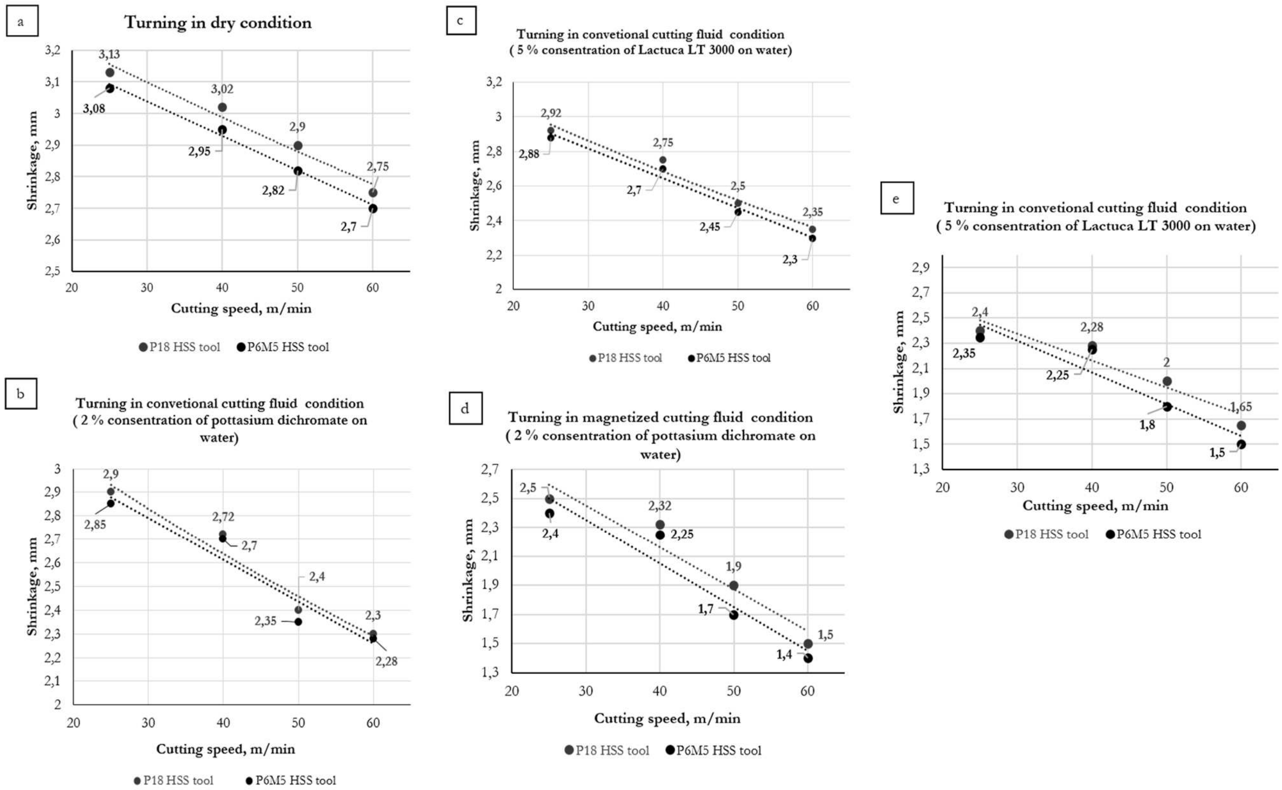

Fig. 4 *The influence of magnetized cutting fluid on the chip shrinkage. Where, HSS cutting tool materials are P18 and P6M5, workpiece material is Stal 45, feed is s=0.45 mm/rotate, cutting depth is t=1 mm. flowing speed of cutting fluid is v_s=1 m/s*

It can be seen from the results of the experimental study presented in Figure 4 that the chip shrinkage coefficient changes inversely with the cutting speed, that is, with the increase of the cutting speed, the shrinkage coefficient of the chip decreases. However, changing the cutting environment made this process even better. To be more specific, when cutting in a lubricating-cooling technological environment, the coefficient of shrinkage is lower than it was in a dry environment (Fig. 4a). When cutting using a 2% concentration of potassium dichromate in water as a cutting fluid (Fig. 4b), it was observed that the chip shrinkage coefficient was reduced by 12% on average. When we cut using a 5 percent solution of Lactuca LT 3000 in water as the second lubricating-cooling liquid (Fig. 4c), the coefficient of shrinkage decreased by an average of 8 percent. After that, the results obtained when these cutting fluids (magnetized in a flowing state) were used under the effect of the static magnetic field with a strength of B=300mT in the metal cutting process became even more surprising. When using a 2% concentration of potassium dichromate in water under the influence of the magnetic field in turning (Fig. 4d), the chip shrinkage coefficient decreased by an average of 20% compared to the conventional method of using this cutting fluid (Fig. 4b), and by an average of 32% compared to the dry cutting method (Fig. 4a). Then, when the 5 % concentration of Lactuca LT 3000 on the water under the influence of B=300mT static magnetic field in flowing condition was used as a cutting fluid in turning cylindrical workpiece (Stal 45) (Fig. 4e), the coefficient of shrinkage is decreased at average 20 percent compared to the process it was used as conventional method (Fig. 4c). Furthermore, in this condition, the shrinkage coefficient was average 29 percent lower than the cutting in dry condition (Fig. 4a).

It is known that the chip shrinkage coefficient is related to the plastic deformation in the cutting zone and the deformation is one of the main causes of heat emerging while cutting metals. Cutting temperature can be decreased by declining the deformation in the cutting process. The shrinkage coefficient is also related to the deformation in the cutting zone or more accurately when the deformation is decreased the chip formation process gets better and the shrinkage coefficient is reduced. Based on those observations, we measured the chip shrinkage coefficient to analyze the deformation changes in turning.

The results obtained from experimental research show that using cutting fluid under the influence of a particular static magnetic field in flowing conditions has a noticeable effect on the deformation in the metal cutting process. According to the experiments conducted using two various cutting fluids, it is investigated that the shrinkage coefficient is reduced when cutting fluids are used under the effect of a static magnetic field in their flowing state and this causes to increase in the wear resistance of the cutting tool.

5 Conclusions

Based on the experimental research results, it is proposed to use cutting fluids under the effect of a static magnetic field and magnetizing the cutting fluids in their flowing condition. The application of magnetized cutting fluids in turning cylindrical parts decreased the chip shrinkage coefficient by 20% in comparison to use the cutting fluids in the conventional method. As a result of this, the deformation in the shear zone is decreased and it causes a reduction in the cutting temperature.

The influence of a static magnetic field on flowing cutting fluids affects the boiling point and density of cutting fluids. Paying attention to this, a mathematical model of the effect of boiling point and density of cutting fluids on tool flank wear has been developed. The model is beneficial to predict the tool flank wear in selected conditions.

It can be concluded that using magnetized cutting fluids has an advantage in reducing the cutting temperature generated in the shear zone and it is beneficial to the chip formation process. Decreasing the cutting temperature and increasing the chip formation process escalates the tool wear resistance. The proposed method of using cutting fluids in workshops can decline the expenditures for cutting tools by increasing the tool wear resistance. Moreover, an improved chip formation process has a positive effect on the machined surface.

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