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Effectiveness of twisted nematic liquid crystals as water based cutting fluid additive and tap lubricant

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1. Introduction

Cutting fluids have been used extensively in metal cutting operations for the last 200 years. In the beginning, cutting fluids consisted of simple oils applied with brushes to lubricate and cool the machine tool. Occasionally, lard, animal fat or whale oil were added to improve the oil's lubricity. As cutting operations became more severe, cutting fluid formulations became more complex. Today's cutting fluids are special blends of chemical additives, lubricants and water formulated to meet the performance demands of the metalworking industry.

The primary functions of cutting fluids in machining are [1, 2]:

♦ lubricating the tool-workpiece contact zone and reduce frictional heating;

♦ to divert the generated heat from the workpiece and tool by an adequate flow of coolant;

♦ to remove the chips produced in the process initially from the cutting tool.

Secondary functions include [1, 2]:

♦ corrosion protection of the machined surface;

♦ enabling part handling by cooling the hot surface.

In most applications process effects of using cutting fluids in machining include [1-3]:

♦ longer tool life;

♦ reduced thermal deformation of workpiece;

♦ better surface finish;

♦ ease of chip and swarf handling.

It is considered that lubricating the interface between the tool's cutting edge and the workpiece is the most important function of the cutting fluid [1]. By preventing friction at this interface, not only wear is decreased, but also some of the heat generation is prevented. This lubrication also helps prevent the chip from being welded onto the tool, which interferes with subsequent cutting.

Friction between the tool and workpiece depends on a multitude of factors such as process parameters, cutting tool geometry and tool material, acting forces, heat generation during the process, temperature of contact zone and the cutting fluid applied [1]. Cutting processes are primarily governed by extremely complex and interdependent physical-chemical-mechanical, in other word tribological, phenomena in the contact zone of the cutting tool and material causing the tool to wear, the material to be removed from the surface of the blank part, thus generating the required surface geometrical configuration, accuracy and surface quality [2].

The lubricating properties of cutting fluids can be improved by adding the additives and the liquid crystals seem very attractive additives for at least three main reasons. At first, it is proven [4-7] that liquid crystals additives to the various lubricants can significantly reduce the friction coefficient of lubricated friction pairs (in isolated cases, when twisted nematic liquid crystals are used as additives, maximum reduction of the friction coefficient of friction pairs is reached 5 times [4, 6], wear of contacting surfaces – 20 times [4] and friction zone temperature – 2 times [4, 7] in comparison with additive-free lubricants). Next, many of liquid crystals (especially twisted nematic liquid crystals – esters of cholesterol) are surface-active substances which can strengthen the P. A. Rehbinder's effect [8] and reduce the deformation resistance of the surface layer of the workpiece. Finally, it is known, that the most widely used cutting fluids in metalworking operations are straight mineral oils and mineral oil emulsions in water. Analysis of scientific papers [4, 5] dealing with the research of the tribological properties of lubricants with liquid crystal additives shows a higher efficiency of liquid crystals and mineral lubricants mixtures as compared with the mixtures of liquid crystals and synthetic lubricants.

Unfortunately, little information appears about properties of cutting fluids with liquid crystals additives. Coolants consisted of industrial mineral oil and liquid crystals have demonstrated their excellent properties in reaming machining operations. The maximum reduction of the surface roughness of reamed surface reached 1.3 times as compared with cooling with pure mineral oil [9]. Liquid crystalline additive also increased the tool life of the reamer 2 times [4]. Nevertheless, technological properties of water based cutting fluids with liquid crystalline additives are not determined still.

This paper investigates the effect of presence of the twisted nematic liquid crystal in the emulsion of mineral oil on uncoated carbide lathe tool performance when turning C45 steel at conventional cooling conditions.

2. Experimental procedure

2.1. Surface roughness

The mineral oil based emulsion with and without twisted nematic liquid crystal (cholesteryl stearate or stearin acid cholesteryl ester) additive was approved as an object of the investigation. This liquid crystal was chosen from homologous series of fatty acid (saturated) esters of cholesterol, it demonstrated the best antifriction properties as mineral motor oil and industrial oil additive [4, 6]. Molecular formula of the tested liquid crystal is presented in Fig. 1, the main properties can be described as follows: molecular weight 653.1, melting point 79-83°C.

The machining tests involved external longitudinal turning of steel bars divided into the sections (Fig. 2). Material of the bars was C45 steel (containing 0.45% carbon). Turning experiments were carried out on conventional lathe under wet cutting at various cutting speeds, while feed rate (0.1 mm/rev) and depth of cut (0.5 mm) were kept constant. The concentration of the liquid crystal in the cutting fluid was also varied from 0.1 to 0.5% by volume. Conventional (low pressure) cutting fluid was applied by flooding the cutting zone. Uncoated titanium and tungsten carbide (5%TiC + 85%WC + 10%Co) lathe tool was used in turning operation. This carbide matches ISO P30 grade. The geometry of the tool during machining are side cutting-edge angle 45º; end cutting-edge angle 45º; side rake angle 0º; side relief angle 12º; back rake angle 0º; end relief angle 12º; nose radius 0.8 mm.

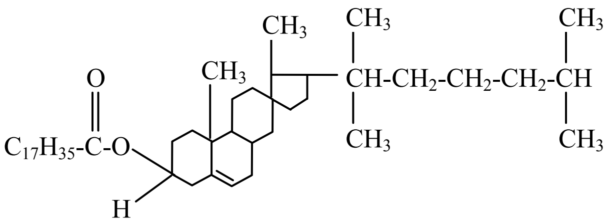

Fig. 1 Molecular formula of cholesteryl stearate

Fig. 2 Steel bar divided into the sections

The mixtures of cutting fluid and liquid crystal were prepared as follows: prepared emulsion and liquid crystal were simultaneously heated up to the melting point of the liquid crystal, mixed and cooled down to the room temperature. After those mixtures were poured out into capacities and left for 3 days on purpose to check the solubility of liquid crystal, then tested as a cutting fluid in the machining tests.

Experimental investigations of technological properties of cutting fluid with twisted nematic liquid crystalline additive was carried out by means of a two-factor second-order full factorial orthogonal design [10]. The following parameters were accepted as independent variables (factors): concentration of liquid crystal in coolant (by volume of coolant) and cutting speed. The levels and values of these variables are presented in Table 1. The average roughness *Ra* of the turned surface was served as response variable.

It was tried to obtain the model of the following type

$$Ra = b_0 + b_1 c + b_2 v + b_{12} cv + b_{11} c^2 + b_{22} v^2 \qquad (1)$$

where *Ra* is average roughness of turned surface, µm; $b_0, b_1, b_2, b_{12}, b_{11}, b_{22}$ are regression coefficients; *c* is concentration of cholesteryl stearate in the coolant, % and *v* is cutting speed, m/min.

The matrix of experiments is presented in Table 2. In accordance with it 9 experiments were carried out with cutting fluid containing liquid crystalline additive. Each experiment was repeated four times in randomized order. The average roughness *Ra* of turned surfaces was measured by roughness indicator Talysurf 4 (Taylor&Hobson), and then average value was calculated for each experiment.

In order to compare results and estimate efficiency of liquid crystalline additive experiments with pure cutting fluid (without additive) were carried out. In this instance only the value of cutting speed was varied, other conditions were kept constant.

Table 1

Variable factors and their variation ranges

Levels and variation range	Coded values of the factors		Real values of the factors	
	$X_1(c)$	$X_2(v)$	*c*, %	*v*, m/min
Basic level	0	0	0.3	176
Upper level	+1	+1	0.5	267
Lower level	–1	–1	0.1	85
Variation range	±1	±1	0.2	91

Table 2

Design of experiment (coolant with additive)

Nr. of experiment	Coded values of the factors			Real values of the factors	
	X_0	$X_1(c)$	$X_2(v)$	*c*, %	*v*, m/min
1	+1	–1	–1	0.1	85
2	+1	+1	–1	0.5	85
3	+1	–1	+1	0.1	267
4	+1	+1	+1	0.5	267
5	+1	–1	0	0.1	176
6	+1	+1	0	0.5	176
7	+1	0	–1	0.3	85
8	+1	0	+1	0.3	267
9	+1	0	0	0.3	176

2.2. Tool wear

The machining tests were carried out on conventional lathe equipped with conventional (low pressure flood) coolant system. External longitudinal turning passes were performed under wet cutting at constant cutting speed v = 160 m/min, calculated from expanded Taylor's equation (with accepted tool life value 40 min). Feed rate (0.1 mm/rev) and depth of cut (1 mm) also were kept constant. Two types of the cutting fluid were tested: mineral oil based emulsion with and without twisted nematic liquid crystal (cholesteryl stearate or stearin acid cholesteryl ester (Fig. 1)). The concentration of the liquid crystals in the cutting fluid (emulsion) was 0.1% by volume. Ø38×400 C45 steel bars were used for machining tests. Geometry of the lathe tools and material of their cutting part are described in previous subsection.

Flank wear of the lathe tool was measured at constant 10 min cutting intervals throughout the experiments. In order to avoid measurements during initial wear stage, when width of the wear increased rapidly and unevenly first interval was chosen rather longer – 12.5 min. According to [3] gradual stage of the wear of used tools is obtained after approximately 2000 m length tool travel by cutting surface or 12.5 min at chosen cutting conditions.

Cutting tools were rejected and further machining stopped based on the following rejection criteria:

$$h_f \geq 0.8\,\text{mm} \tag{2}$$

where h_f is flank wear of the lathe tool, mm.

2.3. Antifriction properties of individual liquid crystal

Cholesteryl stearate also was tested as a dry-film lubricant to tap a thread in C45 steel workpiece. Bottoming (Nr.2) M16 hand taps (material HSS) were coated with melted liquid crystal. After solidification of the liquid crystal layer taps were used in metalworker operation. The taps were rotated by means of precision digital torque measuring wrench (Check-Line mod. DIW-75, range 0.3-75 Nm, accuracy ±0.5% FS) thus value of cutting torque was measured. In order to compare results the taps coated with calcium soap grease and without any lubricating layer also were tested. The taps weren't rejected after tapping of only hole in the workpiece, successive holes were tapped without renewal of lubricating layer. Tests were stopped only when cutting torque of the lubricated tap was similar to torque of non lubricated tap.

Cholesteryl oleate (oleic acid (unsaturated) cholesteryl ester) $C_{45}H_{78}O_2$ also was tested as dry-film lubricant. This twisted nematic liquid crystal has the similar molecular weight (651.1), but lower melting point (44-47ºC).

3. Results and discussion

3.1. Surface roughness

It should be mentioned that tested twisted nematic liquid crystal completely melted in cutting fluid. 3 days after the mixing, all the cutting fluid and liquid crystals mixtures were free from micelles of molecules of the liquid crystal, and significant changes in viscosity of mixtures were not observed.

Upon statistical processing of the experiment results in accordance with the recommendations [10] the following regression equation was obtained

$$Ra = 2.56 - 2.57X_2 + 1.76X_2^2 \tag{3}$$

where Ra is the roughness of the turned surface, µm; X_2 is coded value of cutting speed factor ($-1 \leq X_2 \leq +1$).

Eq. (3) also can be written as follows

$$Ra = 13.68 - 0.098v + 0.0002v^2 \tag{4}$$

where Ra is the roughness of the turned surface, µm; v is real cutting speed value ($85 \leq v \leq 267$ m/min).

Also the similar regression equations for pure emulsion were obtained. They can be presented as follows

$$Ra = 3.23 - 2.74X_2 + 1.79X_2^2 \tag{5}$$

$$Ra = 14.72 - 0.10v + 0.0002v^2 \tag{6}$$

All these equations give a good fit tested by Fischer's variance ratio at chosen significance level 0.05 [10].

Fig. 3 illustrates that while the cutting speed v grows from 85 up to 267 m/min, the average roughness of the turned surface Ra decreases as long as the cutting speed does not exceed 245 m/min and then increases slightly. The curves show that lower surface roughness values were generated with the cutting fluid containing liquid crystalline additive while higher values were generated with cutting fluid without additive. When the cutting speed is 85 m/min the average roughness of the turned surface Ra reduces from 7.7 to 6.8 µm or 1.1-fold as compared with cooling the cutting process with pure cutting fluid. At the mean cutting speed value 176 m/min the average roughness Ra reduces from 3.3 to 2.7 µm or 1.2-fold as compared with cooling with pure cutting fluid. When the cutting speed 267 m/min Ra reduces from 2.3 to 1.8 µm or 1.3-fold as compared with use of additive-free cutting fluid.

From Fig. 3, it was observed that both Ra-v curves were similar in trend and the behaviour of surface roughness against cutting speed was similar in nature.

Such positive effect can be explained by double action of liquid crystalline additive. First, ester of cholesterol behaves as surface-active substance. Adsorption of molecules of surface-active substances reduces the surface energy and shear strength of the material creating plasticization effect on the removal metal layer due to the high local pressure and temperature in the contact areas. Next, the reduction of the friction coefficient takes place in the tool-chip-workpiece interface zones. The contact surfaces are covered with a continuous film of the structured molecules of surface-active substances presented in the cutting fluid. These molecules orientate the molecules of the liquid crystal parallel to their longitudinal axes (liquid crystalline layer). Molecules of liquid crystals are much larger and provide better protection from direct metal contact.

It seems to be very attractive to expand the quite narrow chosen concentration factor variation range, but there are at least two limitations for concentration of liquid crystals in cutting fluid. Primarily the cutting fluids are used in large amounts in machines and the production costs can be sufficiently increased due the high price of the liquid crystals. Finally as reported [4] the sufficient changes in viscosity of the lubricant can occur when the concentration of liquid crystals in lubricants exceeds 2%.

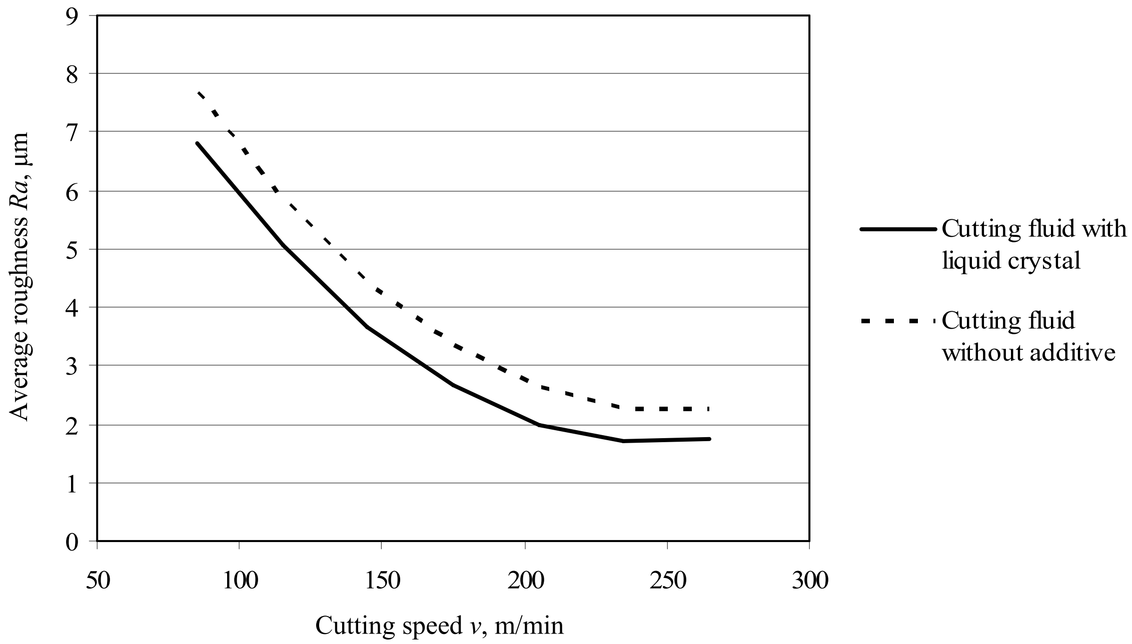

Fig. 3 Average roughness *Ra* of turned surface as the function of cutting speed *v* and composition of the cutting fluid

3.2. Tool wear

Fig. 4 shows the lathe tool flank wear plot when machining at a constant cutting data with various cutting fluids. This shows that wear of the tools used when machining in the presence of cutting fluid without liquid crystal additive was always greater than that when machining in the presence of cutting fluid with liquid crystal additive. Tool life increased about 10 min or 25%. From Fig. 4, it was observed that curves were also similar in trend.

The cause of the decrease of flank wear and improvement of toll life when machining in the presence of cutting fluid with liquid crystal additive is friction reduction in the tool-chip-workpiece interface zones. It shows that low friction liquid crystalline layer was formed on the surfaces of the tool and workpiece.

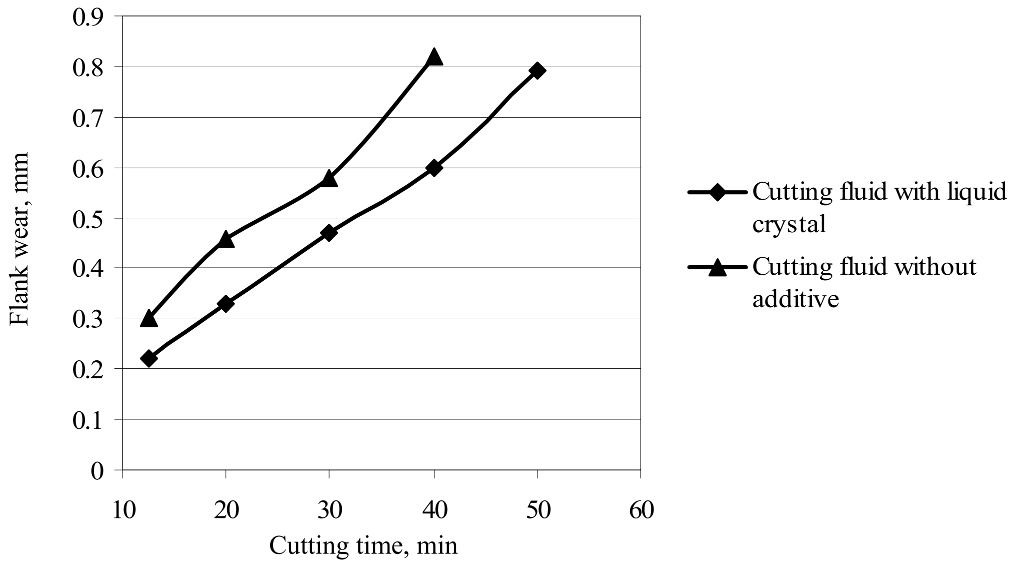

Fig. 4 Lathe tool flank wear curves when turning steel at constant cutting conditions with cutting fluid with and without liquid crystalline additive

3.3. Tapping torque

Results as graphs of the dependence of cutting torque of the tap on lubricant type and number of tapped holes are presented in Fig. 5. From Fig. 5 it is observed that in case when the taps coated with cholesteryl stearate liquid crystal were used in tapping operation value of torque decreases 2.2-fold as compared with the value of the taps coated with calcium soap grease. Lubricating effect of soap grease was disappeared after tapping of two holes. In case when cholesteryl stearate was used as lubricant the lubricating effect remained at the least for three holes. When cholesteryl oleate was used as lubricant five holes were tapped without renewal of the lubricant layer. Up to 4-fold reduction of torque was achieved with this liquid crystal as compared with torque values of the taps coated with calcium soap grease.

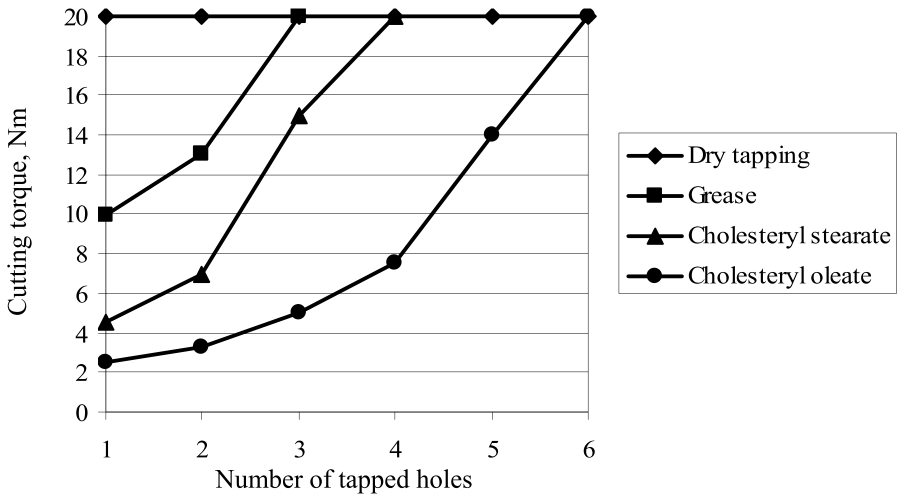

Fig. 5 Changes of cutting torque of bottoming tap (Nr.2) depending on the number of tapped holes and lubricant (average values of three series of experiments are presented)

The results obtained can be explained by phase change of liquid crystal due to heat energy emission during friction and metal plastic deformation processes. Local increases of temperature in the contact zone allow the liquid crystal to melt into liquid crystalline phase. Molecules of liquid crystals are high-ordered in this phase and have a layered structure characterized by low shear resistance and friction force respectively [4]. When the temperature is on the decrease during the motion of the tap, liquid crystal solidifies again and adheres to the tap teeth, lubricating effect remains for the following holes. Cholesteryl oleate is in the semiliquid state at room temperature, it adheres better to the surface of the teeth, and this explains the longer lubrication effect. This crystal contains unsaturated acid which characterized high chemical activity which explains better anti-friction properties.

The lubrication properties of liquid crystals persist also in isotropic liquid phase as shows the difference between melting points of the tested liquid crystals.

4. Conclusions

1. Cholesteryl stearate has a positive influence on technological properties of water based cutting fluid within cutting speed variation range. When using it as emulsion additive average 1.2-fold reduction in the surface roughness *Ra* of the turned surface was reached as compared with an additive-free cutting fluid. Tool life was improved 25% respectively.

2. The effect of use the cholesteryl stearate as cutting fluid additive marginally depends on cutting speed. The maximum reduction (1.2 - 1.3 times as compared with additive-free cutting fluid) of average roughness *Ra* of turned surface is obtained at the medium and higher cutting speeds (i. e. 176-267 m/min). The improvement of the effect with cutting speed increase can be explained by increase of chemical activity of the molecules of additive due to the temperature growth in the cutting zone.

3. The concentration of cholesteryl stearate in cutting fluid does not impact the roughness of turned surface within the concentration variation range. It is advisable to use the liquid crystal at the lowest concentration 0.1% and reduce the machining costs.

4. Individual liquid crystals have excellent lubricating properties. Up to 4-fold reduction was achieved when hand tap was lubricated with cholesteryl oleate liquid crystal. Anti-friction properties of liquid crystals also remain in isotropic liquid state.

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CHOLESTEROLINIŲ SKYSTŲJŲ KRISTALŲ KAIP TEPIMO IR AUŠINIMO EMULSIJOS PRIEDO BEI SRIEGIKLIO TEPALO EFEKTYVUMAS

R e z i u m ė

Buvo tiriamos mineralinio tepalo vandeninės emulsijos su cholesterolinių skystųjų kristalų (stearino rūgšties cholesterolio esterio) priedu technologinės savybės tekinant plieną tradicinio (be dangų) kietlydinio peiliu. Patobulintos sudėties tepimo ir aušinimo skystis buvo naudojamas tekinimo staklių mažo slėgio aušinimo sistemoje. Buvo matuojamas tekinto paviršiaus šiurkštumas ir peilio dilimas. Eksperimentams atlikti buvo taikomas dviejų veiksnių antros eilės ortogonalusis planas. Kaip valdomi veiksniai buvo pasirinkti skystųjų kristalų koncentracija tepimo ir aušinimo skystyje (kitimo intervalas 0.1–0.5% pagal tepimo ir aušinimo skysčio tūrį) ir pjovimo greitis (kitimo intervalas 85-267 m/min). Tekinto paviršiaus šiurkštumo parametras *Ra* buvo pasirinktas kaip tyrimo parametras. Apdorojus eksperimento rezultatus buvo nustatyta, kad paviršiaus šiurkštumas sumažėjo 1.2 karto, palyginti su tuo atveju, kai aušinimui naudojama emulsija be priedų. Peilio patvarumas atitinkamai padidėjo 25%.

Cholesteroliniai skystieji kristalai taip pat buvo naudojami kaip tepimo medžiaga sriegikliams tepti sriegiant. Nustatyta, kad juos naudojant pjovimo jėgų momentas būna 4 kartus mažesnis nei tada, kai tepama plastiškuoju tepalu.

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EFFECTIVENESS OF TWISTED NEMATIC LIQUID CRYSTALS AS WATER BASED CUTTING FLUID ADDITIVE AND TAP LUBRICANT

S u m m a r y

An experimental investigation on the performance of an emulsion of mineral oil with twisted nematic liquid crystal (cholesteryl stearate) additive when turning steel with uncoated carbide lathe tool was carried out. Cutting fluid was applied by flooding the cutting zone from low pressure coolant system of conventional lathe. Machined surface roughness and flank wear of the tool were monitored during machining tests. Experimental investigation was carried out by means of a two-factor second-order full factorial orthogonal design. The concentration of liquid crystal in cutting fluid (0.1-0.5% by volume) and cutting speed (85-267 m/min) were chosen as independent variables and surface roughness *Ra* was chosen as response variable. It was found that surface roughness with the cutting fluid containing liquid crystalline additive was better (decreased 1.2-fold) that with the additive-free coolant. Tool life increased 25% as compared with additive-free coolant.

Twisted nematic liquid crystals were also used as a dry-film lubricant of hand taps. It is established that liquid crystals reduce cutting torque up to 4 times as compared with grease.

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