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Effect of cooling and lubrication conditions on surface topography and turning process of C45 steel

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ABSTRACT

At present coolants and lubricants are increasingly recognized as harmful factors for environment and machine operators' health. Industry and research institutions are looking for new means of reducing or eliminating the use of cutting fluids, both for economical and ecological reasons. This can be done if quality properties of machined surfaces and process parameters in dry and wet machining are comparable. This paper presents an investigation into the influence of cutting zone cooling and lubrication on surface roughness, waviness, profile bearing ratio and topography after turning C45 steel. Dry cutting and minimum quantity lubrication (MQL) results are compared with conventional emulsion cooling. Cutting forces and their components were put under examination as well. The experimental outcomes indicate that the cooling and lubrication conditions affect significantly the investigated process and surface properties. However, the impact of the cooling and lubricating technique depends to a large extent on the applied cutting parameters, namely the cutting speed and feed rate. Turning dry or with MQL with properly selected cutting parameters makes it possible to produce better surface topography characteristics than turning with conventional emulsion cooling. Apart from improving the surface properties the MQL mode of cooling and lubrication also provides environmental friendliness.

1. Introduction

Cutting liquids in machining processes have a substantial influence on the quality of the machined surface, dimension accuracy and tool life as well as the cutting process accomplishment conditions. The results of many investigations [1–6] have shown that cutting dry or with minimal quantity cooling and lubrication (MQCL) make it possible to reduce manufacturing costs and limit environmental burdens.

Existing ecological regulations, development in cutting tool materials and coatings, increasing tool's toughness and resistance to high temperatures, together with improvements in cutting tool geometry, fixtures and machine tools constitute favorable conditions for more frequent industrial application of MQL and dry machining [4,7,8]. However, the industrial implementation of environment friendly machining processes requires successful substitution of the technological role of cutting liquids in machining operations. Investigations [5,6,9] show that the elimination of cutting fluids from turning processes is not always possible. It increases the work piece and machine tool elements' temperature, which in turn brings about deterioration of dimensional accuracy and changes in the surface layer properties [10].

Tremendous opportunities in terms of improving the overall process performance are offered by the minimum lubrication technique (MQL) [1–7,11,12]. The favorable effects of the MQL approach on the machined surface roughness have been discussed by Dhar et al. [3,9]. Comparative tests of turning AISI 1040 and AISI 4340 steel dry and with MQL have revealed smaller values of the R_a parameter for MQL turning than for dry turning. Also with the turning time, the values of this parameter increase much slower. Dry cutting and cutting with conventional cooling and lubrication of the cutting area result in an accelerated increase in the surface roughness due to a higher temperature and strain acting on the tool edge. However, the beneficial influence of MQL, compared to dry and wet turning, depends on the decrease in auxiliary flank wear and the fact that MQL creates conditions that are less conducive for build-up edge development and cutting edge micro-chipping [3,13,14].

The effect of the cutting area cooling and lubrication method largely depends on the used cutting parameters. Machado and Wallbank [5] have found that the impact of cooling and lubrication on the surface roughness after turning high and medium carbon steel is noticeable at small cutting speeds (30 mm/min) and large feeds, and that the values of the *R*a parameter are characterized by large scattering caused by build-up edge formation. An increase in the cutting speed to 200 m/min is accompanied by reduced influence of the cooling and lubrication conditions on surface roughness. The machined surface reveals better surface smoothness when

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a mixture of air with oil or water is used rather than is the case after wet or dry turning.

The elimination or minimization of the cutting liquid causes changes in the cutting process phenomena, which are connected with a change in mechanical and thermal interaction during the process of surface layer formation. One of the important symptoms of turning is the inherent cutting force whose value in particular cases can be correlated with the machined surface cooling and lubrication method and thus becomes a very important factor conditioning the possibility of eliminating or limiting cutting liquids [9,15].

An analysis of investigations conducted so far has shown that the properties of the surface layer during carbon steel turning in different cooling and lubrication conditions have not been sufficiently recognized. Assessments of the impact of a cutting environment on the surface layer state are usually made on the basis of the surface roughness parameter R_a, neglecting other features that characterize the surface texture.

The demand for increased machining shape accuracy and specific surface layer properties as well as developments in cutting tool technology require further study of cutting processes without or with minimized application of cutting fluids. Also a definition of cutting conditions is needed, which will make it possible to obtain surface layer properties that are better or comparable to those after wet cutting [4,7,16].

The study presents results of C45 steel turning dry, with minimum lubrication and a conventional emulsion supply. The paper describes the influence of these cooling and lubrication modes on the cutting force, surface roughness, waviness, profile bearing ratio as well as on the surface topography within a wide range of cutting parameters.

2. Experimental procedure

Cylindrical turning tests were carried out on bars of carbon structural steel C45 (AISI 1045) of 60 mm diameter with separated 15 mm long segments for each cutting test. Before machining, the bars were pre-machined with a 1 mm cut to remove any possible surface irregularities and ensure similar surface properties for all the specimens. The chemical composition of C45 steel as well as of the cutting tool material, its geometry and cutting conditions are presented in Table 1.

In order to minimize the influence of cutting tool wear on the investigated quantities, each set of turning experiments was conducted using a new insert edge.

The following cooling and lubrication techniques and their designations were used in the experiments:

D—dry cutting, without cooling or lubrication,

MQL—minimal quantity lubrication, executed by a Minibooster II applicator (produced by Accu-Lube Manufacturing GmbH) for coolant fed tools. The applicator produced a mixture of lubricant and air in the form of a fine aerosol, which was supplied to the cutting edge by the coolant feed holes of 4 mm diameters built inside the tool holder, targeting the rake face as well as the principal and auxiliary flanks. An Accu-Lube LB 8000 biodegradable vegetable oil with kinematic viscosity of 37 mm^2/s at 40 °C was used as the lubrication medium. The oil consumption by the MQL system was adjusted at a level of 50 ml/h.

E—overhead flood supply of 6% emulsion oil with 4 l/min flow volume, made on the basis of the emulsifying oil ARTEsol Super EP (produced by W.O.P. ARTEFAKT). The oil, which comprised up to 35% of mineral oil and additives increasing lubricity in quantities of 15%, was designed for multi machining operations of steel, cast iron and non-ferrous metals.

The cutting force was measured using a Kistler 9247B dynamometer connected to an amplifier and a computer equipped with the manufacturer's DynoWare software.

Measurements of the surface roughness parameter R_a (arithmetic average deviation of the profile) and waviness W_a (profile arithmetic mean deviation) as well as the surface profile bearing ratio were performed on a Hommel-Tester T2000 profilometer equipped with a Tk300 sensor with the following parameters: an evaluation length of 4.8 mm and a sampling length of 0.8 mm. The tests were repeated 5 times and the mean values with a standard deviation were determined.

The pictures of the machined surfaces were taken using a JOEL 5600 laser scanning microscope and an Olympus LEXT OLS3100 laser scanning confocal microscope.

3. Results and discussion

3.1. Cutting force

One of the inherent phenomena of the cutting process is the cutting force. The measurement results presented in Fig. 1 show that the cutting area cooling and lubrication method has a limited influence on the cutting force and its impact depends on the used cutting parameters. A comparison of the resultant force F values (Fig. 1a) revealed the most similar values in dry and emulsion turning at a feed rate of 0.08 and 0.27 mm/rev, with the exception of a feed rate of 0.08 mm/rev and a cutting speed of 76 m/min. The resultant force in dry turning was 18.8% larger than in turning with emulsion. At low cutting speeds and feeds the access of the emulsion to the cutting area was easier; therefore the cooling and lubricating effect of the emulsion exceeded the softening effect of increased temperature and friction in the chip tool interface in dry turning and allowed for reduction of the resultant force. With an increase in the cutting speed the differences between the resultant forces in dry and wet turning diminish as a consequence of reduced penetration of emulsion into the cutting area [15,17].

Large differences in the resultant force F in the range of the used cutting speeds appeared between dry and wet turning at a feed rate of 0.47 mm/rev. In such conditions the resultant force in dry turning was lower, from 3.5% at a cutting speed of 76 m/min to 8.3% at 237 m/min. The lower values of the resultant force in dry turning were the effect of decreased work piece material resistance due to an increase in cutting temperature and heat concentration near the cutting edge. The cooling and lubrication effect of the emulsion did not cause any significant change in friction conditions

Table 1
Experimental conditions.

Work piece	Material—C45 (carbon structural steel), diameter—60 mm, length of cut 15 mm
	Composition—C 0.42–0.50%, Si 0.17–0.37%, Mn 0.5–0.8%, $P \leq 0.04\%$, S ≤ 0.04%, Cr ≤ 0.30%, Mo ≤ 0.10%, Ni ≤ 0.30%
Tool	Tool holder MSS 2525–12-EB (Mircona AB)
	Carbide insert SNMG 120408-TF, grade IC 907, PVD coating composition TiAlN (Iscar LTD)
Tool geometry	Rake angle $\gamma_0=5°$, clearance angle $\alpha_0=10°$, cutting edge angle $\chi_r=45°$, cutting inclination angle $\lambda_s=0°$, corner radius $r_\varepsilon=0.8$ mm
Cutting parameters	Cutting speed—76, 190, 237 m/min, cutting feed rate—0.08, 0.27, 0.47 mm/rev, depth of cut 1 mm
Cutting environment	D—dry, MQL—minimum lubrication, E—emulsion