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SURFACE LAYER MICROSTRUCTURE AND MICROHARDNESS AFTER TURNING IN DIFFERENT COOLING AND LUBRICATING CONDITIONS

Tadeusz Leppert

University of Technology and Life Sciences
ul. Prof. S. Kaliskiego7, 85-789 Bydgoszcz, Poland
e-mail: tleppert@utp.edu.pl

Abstract

The cooling and lubricating liquids widely used in metal machining are more and more often considered to be harmful to the natural environment and human health. For economic and ecological reasons the industry and research institutions are searching for methods and measures to limit or eliminate them. This is naturally determined by the conditions that the quality of machined surfaces has to be the same or at least comparable to that obtained with conventional cooling methods. The article presents the results of research into the influence of cooling and lubrication on surface layer physical properties -microhardness and microstructure changes, after turning the C45 and X2CrNiMo 17-12-2 steel dry, with minimal quantity lubrication (MQL) and emulsion in a wide range of cutting parameters. Significant differences in the microhardness parameter $HV_{0,02}$ *and surface layer microstructure depending on the cutting zone cooling and lubrication conditions have been observed. The research has also shown that despite difficulty in turning X2CrNiMo 17-12-2 steel, properly selected cutting parameters help to limit or eliminate fluids used in conventional cooling and lubrication and still obtain comparable or even better surface layer quality.*

Keywords: surface layer microhardness, microstructure; dry, MQL, wet turning

1. Introduction

Eliminating or limiting the application of cutting fluids is related to changes in the interaction between the thermal and mechanical factor in the process of constituting the surface layer. As a result, the phenomena occurring in the turning process cause changes in the surface layer which, compared to the core material, can be characterized by highly differentiated microhardness and metallographic microstructure [2,3,13]. This has a considerable influence on the application-related properties of the surface produced. The significant changes in the structure of the surface layer appear in dry turning of difficult-to-machine steels e.g. titanium alloys or corrosion and temperature resistant steels [1,2,7,9]. Low thermal conductivity and high chemical reactivity of these alloys with many tool materials result in a higher temperature in the cutting zone and material increased plastic deformations. This, on the other hand, leads to an increased tool wear, greater surface roughness and strong chip-tool adhesion and surface texture deformations [1,11,13]. Additionally, the high temperature causes microstructure changes and phase transformations which can take the form of changed microhardness and metallurgical alterations in the surface layer [4]. Depending on the employed cutting parameters a white layer can be created, which causes the hardness of the surface layer to be higher or lower than that of the bulk material [2,4,5,7,8,11,12]. Surface layer properties after turning carbon and difficult to machine steels in various cooling and lubrication conditions have not been adequately investigated and remain still the subject of scientific interest.

The aim of the conducted research was to determine the influence of cooling and lubrication conditions on the surface layer microhardness and microstructure alteration in turning carbon steel C45 and austenitic stainless steel X2CrNiMo 17-12-2 dry, with MQL and emulsion in a wide range of cutting parameters.

2. Experimental procedure

Turning tests were carried out on a lathe TUD 50 for which carbon C45 and austenitic stainless steel X2CrNiMo 17-12-2 rods with 15 mm length segments for each cutting test were prepared. In advance of turning experiments, the test specimens were pre-machined with 1 mm depth of cut. The workpiece chemical composition and mechanical properties are presented in table 1.

Tab. 1. Chemical composition and mechanical properties

Steel	Chemical composition, %								
	C	Si	Mn	P	S	N	Cr	Mo	Ni
X2CrNiMo 17-12-2	<0,03	≤1,0	<2,0	≤0,045	≤0,015	≤0,011	16,5-18,5	2-2,5	10-13
C45	0,42-0,50	0,17-0,37	0,5 - 0,8	≤ 0,04	≤ 0,04	-	≤ 0,30	≤ 0,10	≤0,30
	Mechanical properties								
	R_e, MPa		R_m, MPa		A$_5$, %		HB		
X2CrNiMo 17-12-2	200		500-700		40		215		
C45	340		620		16		207		

The sintered carbide inserts SNMG 120408TF grade IC907 with a TF chip breaker covered using the PVD method with a (TiAlSi)N coating (produced by ISCAR) were used. They were fixed in a tool holder MSS 2525-12-EB (produced by Mircona AB) with cooling channels for an internal lubrication system. The tool point had the following geometry: the orthogonal rake angle γ_0=5^0, orthogonal clearance angle α_0=10^0, cutting edge angle κ_r=45^0, cutting inclination angle λ_s=0^0 and corner radius r_ε=0,8 mm. Each set of turning experiments was conducted using a new insert edge.

The cooling and lubrication methods included:

D - dry cutting,

MQL - minimum quantity lubrication, carried out by an Accu-Lube Minibooster II applicator which produced a mixture of lubricant (biodegradable vegetable oil Accu-Lube LB 8000) and air in the form of fine aerosol, targeting the rake face and principal and auxiliary flank. The oil utilization by the MQL system was 0,014 mm^3/s.

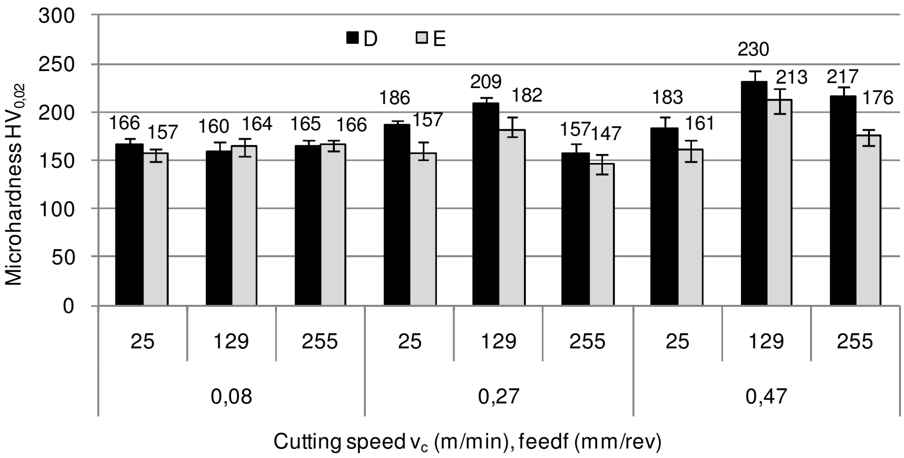
E - application of 6% emulsion with 0,07 dm^3/s flow volume.

The experiments were conducted in two steps. The preliminary tests were carried out in dry and with emulsion turning using C45 steel. For austenitic stainless steel X2CrNiMo 17-12-2 the experiments were performed in turning dry, with MQL and emulsion.

The microhardness measurements were made on metallographic specimens of the surface layer cross-sectioned perpendicularly to the machined surface. The microhardness (Vickers' method) of the external cylindrical surface as well as inside the surface layer was measured with a Hanemann-type hardness tester under a load of 0,2 N. For each set of results a mean value and standard variation were calculated. The measurement of depth of plastic deformations in the surface layer and pictures of the metallographic structure were made with an optical microscope Epityp 2 (Carl Zeiss Germany) at a 400x magnification.

3. Results and discussion

Microhardness and metallographic structure are crucial parameters which describe physical properties of the surface layer. The results of microhardness measurements of the surface layer of C45 steel specimens presented in Fig. 1 prove that the influence of the cooling and lubrication mode in the cutting zone on the surface layer microhardness is highly diversified, without a clearly visible tendency. The existing differences in the surface layer hardness depend on the employed cutting parameters. Eliminating cooling and lubricating liquids from the process of machining of the C45 steel in the range of the used cutting speeds and feed rates causes an increase in the surface layer microhardness. At low cutting speeds (25m/min), increasing the feed rate from 0,08 to 0,47 mm/rev does not significantly influence the microhardness. When the cutting speed increases up to 129 m/min, increasing the feed rate results in a greater microhardness of the surface layer. After turning at a speed of 255 m/min, as the feed rate increases from 0,08 to 0,27 mm/rev, the surface layer microhardness becomes lower both in dry machining and in machining with emulsion. When the feed rate is increased to 0,47 mm/rev, the microhardness becomes bigger. In addition, the difference in microhardness between dry turning and turning with emulsion becomes clearer, the values for dry turning are higher by approximately 23% than those for turning with emulsion and equal to 217 and 176 $HV_{0,02}$ respectively. In many combinations of cutting speeds and feed rates, the presented results of the measurements for dry turning and turning with emulsion do not differ significantly. This may mean that a change of conditions in the chip formation zone was not significant enough to have any impact on the microhardness of the surface layer.



Rys. 1. Influence of cooling and lubricating mode on surface layer microhardness (steel C45)

The pictures of metallographic structures of the surface layer taken perpendicularly to the machined surface are presented in Fig. 2. They show plastically deformed grain of the metallographic structure created in dry turning and turning with emulsion of steel C45. The texturized grains, an effect of mechanical loads during machining, are also visible.

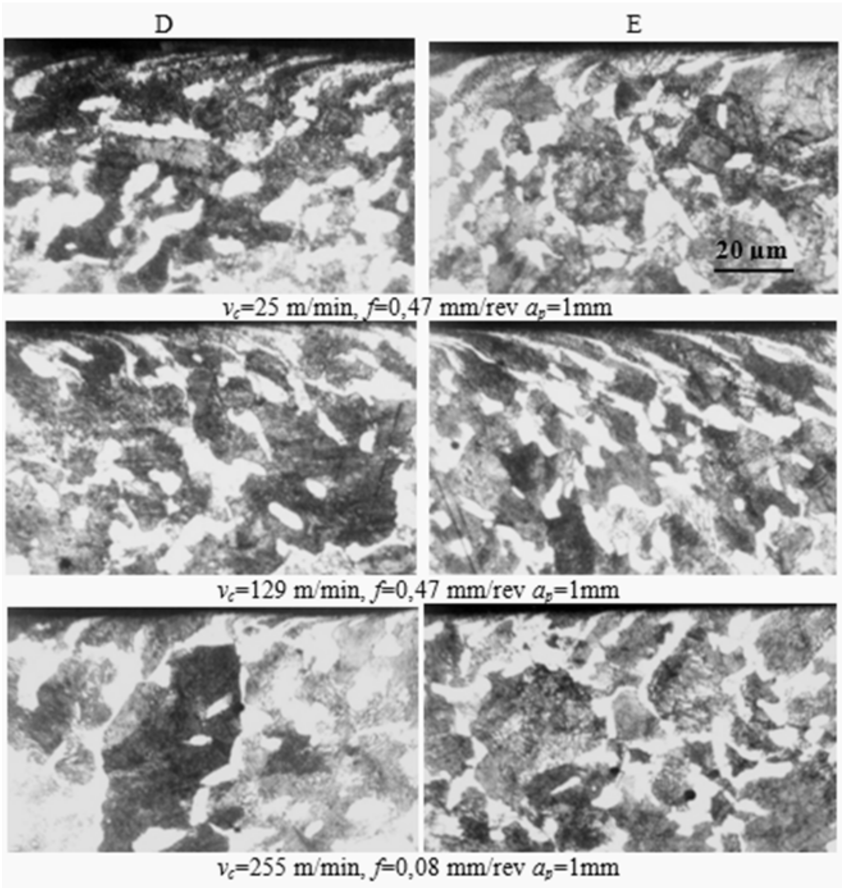


Fig. 2. Metallographic structure of the surface layer after turning dry and with emulsion, depending on the cutting speed and feed rate (steel C45)

The depth of the deformed surface layer determined on the measurements of the plastically deformed grains of the metallographic structure in the range of the used cutting parameters varies from 5 to 24 µm (Fig. 3). Eliminating emulsion from the process of machining contributes to an increased depth of deformations in the surface layer at low cutting speeds (25 m/min). As the depth increases, so does the depth of plastically deformed layer after turning with emulsion, which can be attributed to lower material hardness at a higher temperature of machining and material's increased tendency to undergo plastic deformations [6]. Out of the technological parameters of machining, the greatest influence on the depth of plastic deformations in the surface layer is exerted by the feed rate: increasing it leads to deeper plastic deformations. The impact of the cutting speed depends on the used mode of cooling and lubrication and on the feed rate. Increasing the cutting speed from 25 to 255 m/min at a fixed feed rate of 0,08 mm/rev causes deeper plastic deformations both in dry machining and machining with emulsion. The depth of plastic deformations in the former is higher.

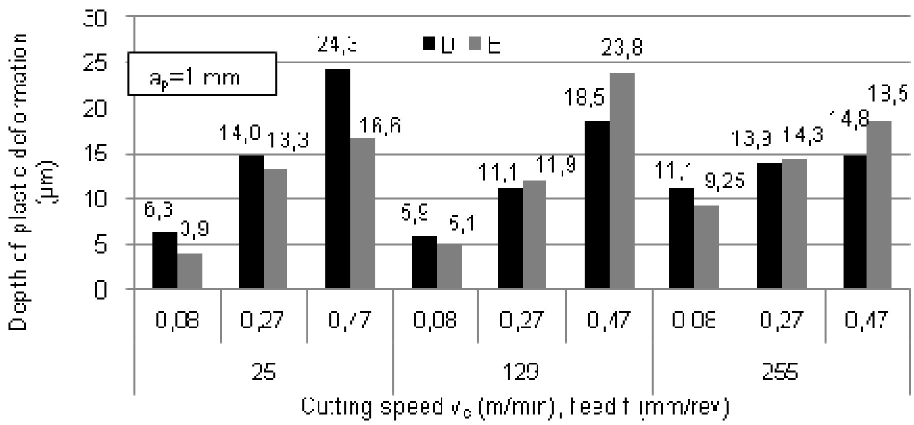
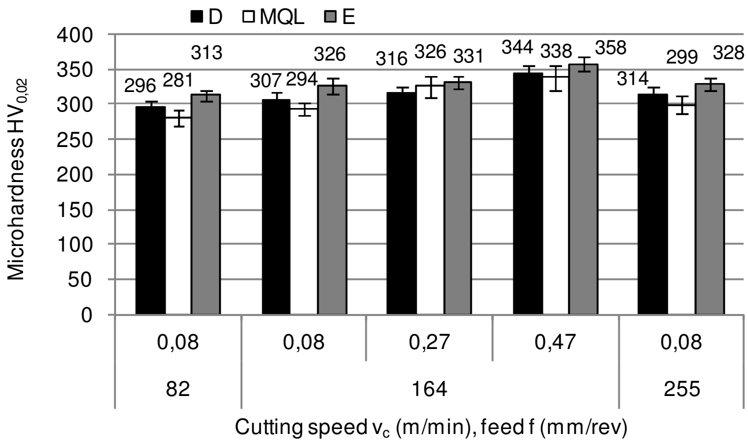


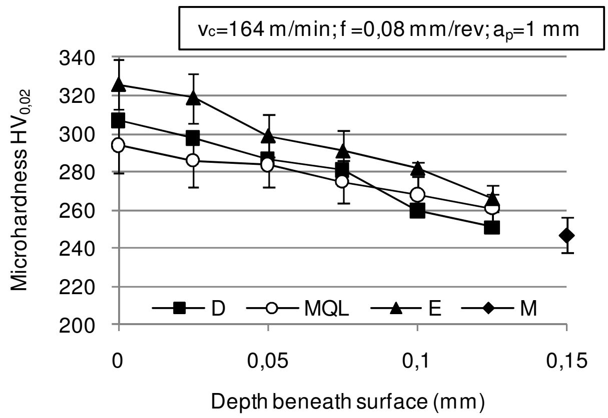
Fig. 3. Influence of cooling and lubrication mode on the depth of plastic deformations in the surface layer (steel C45)

When the feed rate is increased to 0,27 mm/rev, the influence of the increased cutting speed on the depth of plastic deformations is lower, and at a feed rate of 0,47 mm/rev it can be seen that the depth of plastic deformations in the surface layer in the function of the cutting speed after dry turning is lower as well. This is a result of the cutting temperature becoming higher, which reduces cutting resistance. In machining with emulsion, the depth values are similar. The resultant changes of the thickness of the plastically deformed surface layer depend on the strength of the mechanical and thermal factor [4]. At the same time the deformation of the metallographic structure proves that the mechanical factor plays a crucial role in turning with emulsion.

The results of the measurements of the surface layer microhardness after dry turning of the X2CrNMo17-12-2 steel, turning with MQL and turning with emulsion reveal significant differences in microhardness values both on external surfaces and deeper into the workpiece (fig. 4). As the depth of the surface layer increases, the variation of microhardness disappears or becomes insignificant (Fig. 4b). The change of the surface layer microhardness value compared to the core hardness (M point) ranges from 326 to 248 $HV_{0,02}$ and appears at a depth of 0,13 mm. In the range of the used modes of cooling and lubrication as well as cutting parameters, the lowest values of microhardness were recorded after turning with MQL (281 $HV_{0,02}$), and the highest after turning with emulsion (358 $HV_{0,02}$). This can be justified by a tendency of this steel to become hardened as a result of plastic deformations when the action of a cooling medium is intensified [9]. The increase of the temperature in dry turning caused greater plasticization of the material in the chip formation zone, which negatively affected the cutting force and work piece hardening in the surface layer. The impact of MQL caused a larger decrease in microhardness in turning with emulsion than was the case in dry turning, especially at a low feed rate (0,08 mm/rev). The action of the lubricating medium in oil aerosol, despite lowered friction between the moving surfaces of the tool edge and machined workpiece, had a limited influence on the decrease of surface layer microhardness as compared to dry turning.



(a)



(b)

Fig. 4. Influence of cooling and lubrication mode on surface layer microhardness (a) and inside the surface layer (b) (steel X2CrNiMo17-12-2)

The influence of the cutting parameters on the surface layer microhardness measured on external surface of the machined sample is presented in Fig. 5. The measurement results revealed a significant impact of the cutting speed (ranging from 82 to 164 m/min) on the surface layer microhardness after turning with MQL and with emulsion (Fig. 5a). A further increase in the cutting speed up to 255 m/min influenced the surface layer microhardness to a lesser degree. In dry turning and in turning with MQL it increased by app. 2% whereas in turning with emulsion the increase equaled to 0,6%. A greater increase in the surface layer microhardness was caused by the feed rate and depth of cut. However, similarly to the cutting speed, the two parameters do not change the impact of the cooling and lubricating mode. After dry turning and turning with emulsion a greater increase of the surface layer microhardness was observed when the feed rate increased from 0,27 to 0,47 mm/rev than when it increased from 0,08 to 0,27 mm/rev and equaled to app. 28 $HV_{0,02}$ (Fig. 5b). In the case of MQL machining, the greatest increase of the surface layer microhardness (45 $HV_{0,02}$) was recorded when the feed rate ranged from 0,08 to 0,27 mm/rev. As the depth of cut increased from 0,5 to 2 mm, the values of the surface layer microhardness became higher both in dry and MQL turning as well as in turning with emulsion (Fig. 5c). The greatest increase (from 284 to 312 $HV_{0,02}$) was observed in MQL turning. The increase in value of these parameters means a larger cross-section of undeformed chip and greater machining resistance, both of them influencing the action and level of plastic deformations in the cutting zone, which cause greater hardness of the surface layer [10]. The observed differences in these values may be attributed to the influence of cooling and lubricating conditions of the cutting zone and to their impact on thermal and mechanical factors.

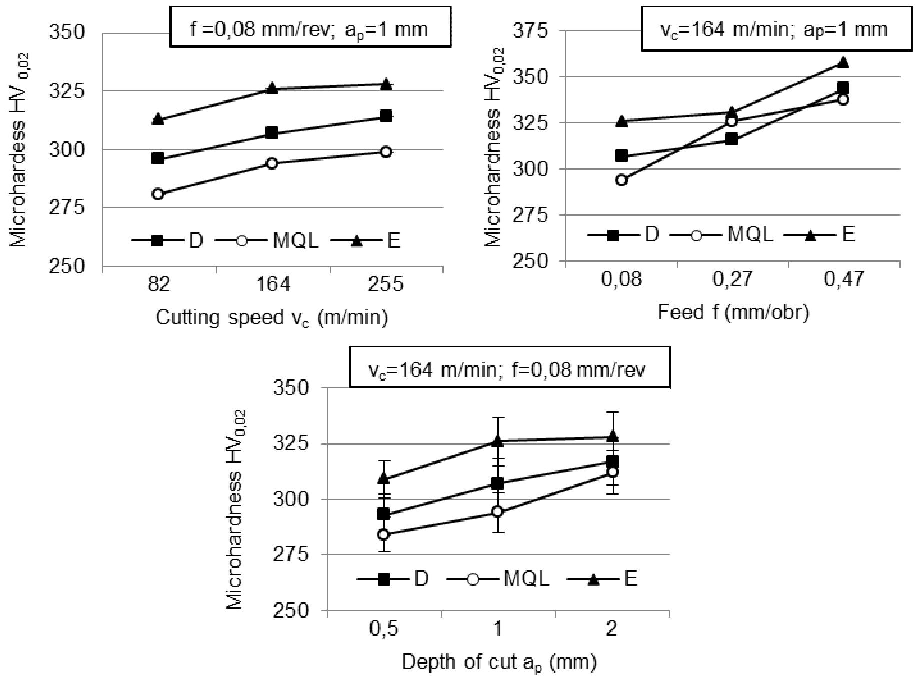


Fig. 5. Influence of cutting speed (a), feed rate (b), depth of cut (c) on surface layer microhardness in used cooling and lubrication conditions (steel X2CrNMo17-12-2)

The pictures of metallographic structures after turning X2CrNiMo17-12-2 steel at a feed rate of 0,08 mm/rev do not show any clear changes of grains, depending on the cooling and lubrication mode in the cutting zone (Fig. 6). The change of the cutting speed from 82 to 255 m/min did not cause any change in the shape of the grain in the metallographic structure of the surface layer. Increasing the feed rate to 0,47 mm/rev caused slight texturizing of the grain at a depth of app. 4 µm in turning with emulsion and in dry turning.

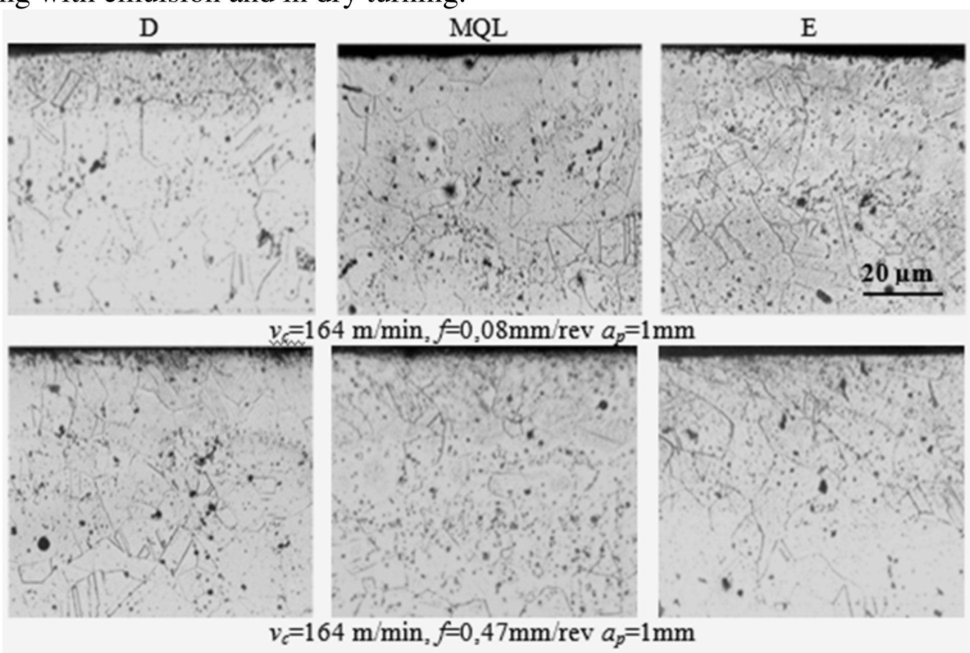


Fig. 6. Metallographic structure of the surface layer after turning dry, with MQL and with emulsion (steel X2CrNiMo17-12-2)

The application of oil fog, depending on the cutting parameters, limits plastic deformations. This is a result of lower friction and cutting force which, on the other hand, is caused by the presence of a lubricant between the moving surfaces of the tool edge and machined work piece with lower material strength in higher temperatures in dry turning, as compared to turning with emulsion.

4. Conclusions

The research has shown that the diversified influence of the cooling and lubricating mode of the cutting zone on the surface layer microhardness depends on the type of machined materials and cutting parameters.

Eliminating emulsion from the process of turning steel C45 causes increased the microhardness of the surface layer. In the range of the used cutting parameters, the values of the microhardness ranged from 157 to 230 $HV_{0,02}$, and it was the feed rate that influenced it to the largest extent..

The microhardness after turning austenitic stainless steel X2CrNMo17-12-2 is lower after dry turning and turning with MQL than that after machining with emulsion. The differences in the surface layer microhardness depending on the cooling and lubricating mode disappear as the distance from the external surfaces increases. The greatest variation in the surface layer microhardness compared to the core hardness was observed after turning with emulsion. It ranged from 326 to 248 $HV_{0,02}$.

When the cutting speed, feed rate and depth of cut increase, so does the microhardness of the surface layer. The greatest influence on the increase in microhardness is exerted by the feed rate and depth of cut.

The cooling and lubrication mode in the cutting zone has a considerable influence on the depth of a plastically deformed surface layer of the C45 steel, whose value was app. 0,13 mm. Eliminating emulsion from the cutting process leads to higher values of the depth of plastic deformations in the surface layer at a low cutting speed (25 m/min). As its value increased, a higher value of the thickness of the plastically deformed layer was recorded after turning with emulsion. .

The conditions of cooling and lubricating of the cutting zone and cutting speed in turning steel X2CrNiMo17-12-2 did not reveal any significant variation of the grain shape in the metallographic structure when the feed rate equaled to 0,08 mm/rev. Increasing the value of this parameter to 0,47 mm/rev caused a slight texturizing of the surface layer grain at a depth of up to 4 µm, in dry turning and turning with emulsion.

In the conditions of properly selected cutting parameters, the values of the analyzed indicators of surface texture after dry and MQL turning proved comparable to those achieved in emulsion turning. This means that an effort to eliminate or limit the application of cutting fluids in turning of the C45 and X2CrNiMo17-12-2 steel without quality deterioration is fully justified.

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