Cutting tool wear in turning 316L stainless steel in the conditions of minimized lubrication

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Abstract

316L stainless steel has emerged as one of the most used material in design and manufacturing for automotive, aerospace, marine, civil nuclear to produce critical components (valves, seats, pipes etc.). Despite, their huge application, during the machining of 316L stainless steel numerous challenges arise in terms of tool wear that are very detrimental for the surface of machined part. To obtain an extended life of tool used for machining commonly 316L stainless steel two different methods of cooling based on minimum lubrication condition, namely Minimum Quantity Lubrication (MQL) method and Minimum Quantity Cooling Lubrication (MQCL) with the addition of extreme pressure and anti-wear (EP/AW) method, respectively were settled. The use of the MQL method resulted in a reduction of the cutting tool wear by approximately 9% compared to the MQCL + EP / AW method and by approximately 21% compared to dry machining. Further, the highest values of wear indices were achieved during dry machining and the lowest ones in the method of minimized lubrication which validate the minimum lubrication as beneficial for reducing the wear progress.

Key words: MQL, MQCL, Wedge wear, Additives EP/AW, Tribofilm, 316L stainless.

1. INTRODUCTION

In machining, the superior performances are obtained because of machining fluids which have the ability of lubrication and cooling and, consequently, leading to lower heat around cutting wedge zone – object being machined – chip. The first machining fluid worked in this process was water leading to popular process so-called wet machining [1]. We have noted that the research community tried different combination of emulsion based on an oil concentrate and on oil alone. Hence, continuous investigations focused on the machining fluids have resulted in major improvement of not only surface quality of machined part; yet, providing longer tool life and better conditions of the chip removal from the cutting zone, leading to better dimensional product accuracy. Some investigations have also proved that the application of new machining fluids becomes necessary in the case of processing hard-to-machine materials [2].

Several years ago, machining fluids were widely used in wet machining (flood method) in which the flow of the active medium was about 1200 litres per hour due to which the prices of the manufactured parts were growing [3]. Moreover, the used oils and emulsion concentrates showed negative influence on human health and environment due to the content of detrimental chemical substances [4]. Consequently, health aspects related to the hazard of lung diseases in operators and economic aspects (i.e. high cost of using machining fluids) triggered the necessity to find alternative solutions for wet machining.

As an alternative method for wet machining, the application of novel minimum quantity cooling lubrication (MQCL) and classical minimum quantity lubrication (MQL) methods were noted [5]. When is used MQCL technique, the main component of the active medium is a mixture of an oil based emulsion concentrate with water whose concentration can range between 4% to 12% [4]. Cool air is also often used to replace the water and forming the main cooling condition; the air reach the cutting zone with lower temperature around -30 ºC [6]. The use of MQL method is associated to major constituent formed from active environment which is vegetable oil [7] or mineral oil [8]. The quantity of the machining fluid used in machining by the above-mentioned methods range between 10 to 200 ml/h [6, 9].

Gupta et al. [10] have proved the advantages of using olive oil as a component of the oil mist in turning AISI 1060 hardened steel. They have compared the results in their investigations to the effects of dry machining, considering, among others, the degree of temperature formed on the cutting region and formation of cutting wedge wear. Thanks to that, they have proved that cooling generated throughout MQL method reduces the temperature in the performed process of turning by about 24% when comparing to dry machining. Here, they indicated the lack of machining fluid responsible for the occurrence of friction mechanisms, thermal cracks and for formation of accretion and the coating breaking off. The use of minimised cooling method can lead to non breaking of cutting wedge coating, prevents thermal cracks formation while the flank wear face can be much lower. Similar conclusions have been formulated by Elmunafi et al. [11] when turning hardened AISI 420 in the presence of oil mist containing ricinus oil. The later have proved that such cooling method ensures temperature reduction around cutting zone when comparing to dry machining one, which allows a longer cutting tool life. They also indicated a beneficial effect of using MQL method in terms of superior surface roughness and slightly lower cutting forces.

A different approach has been adopted by Liu et al. [12] who have checked the benefit of using MQL method to improve the wear of plates with (nc-AlTiN)/(a-Si3N4) coatings subjected to higher machining speed of titanium alloy, Ti-6Al-4V. Comparing the obtained results to those of dry machining, they have proved advantageous influence for integrating vegetable oil mist that leads longer tool life. There was highlighted as best option for the first of the mentioned coatings. They have also shown that, due to the MQL method, there was only friction wear on the (nc-AlTiN)/(a-Si3N4) coated plate and, with the lack of the cooling medium, the kinds of wear were both friction wear and oxidation. Khan et al. [13] have investigated the turning of AISI 9310 steel characteristics by using vegetable oil-based mist. When comparing MQL with the wet and dry machining it is possible to achieve positive influence on the machined surface quality and also much lower flank wear face. Indeed, the active medium can prevents the occurrence of accretion or the phenomenon of adhesion. The beneficial of using MQL method were highlighted by the investigations conducted by Chinchanikar and Choudbury [14] who have turned AISI 4340 steel in the presence of oil mist. They observed not only reduction of temperature around the cutting region, lower values of friction and diffusion wear yet they also noted lack of accretion and extension of the tool life (cc. 20-25%) when comparing to dry machining.

The current research is also focused on a better understanding of tool wear mechanism using the MQL method. Wang and Bao [15] proposed non-destructive evaluation for tool wear assessment using the MQL method after turning of samples with Inconel 182 overlays. The new measurement technique, thanks to evaluation by clustering energy Acoustic Emission (AE) allows of measuring tool wear without stopping the machine, thus saving time and avoiding errors when re-clamping the tool. When comparing tool wear in MQL cooling with dry machining, it was found that the tool flank wear can be accurately evaluated by linear fitting total energy of AE burst signals that is induced by fracture and plastic deformation. The authors explain the reduction of tool wear using the MQL method compared to dry machining by an increased lubrication effect, which was characterized by an increase in AE burst signals energy, plastic deformation and cracks, which facilitate cutting material instead of scratching material. The importance of detecting the built-up edge (BUE) development during the micro-milling of grooves in 316L stainless steel on tool wear which can affect the quality of the machined surface was presented by Wang and Kovvuri [16]. In order to determine the intensity of the

BUE influence, the authors introduced two values: BUE density and its distribution entropy. The tool wear analysis showed that when it is used the MQL method during micro-milling, the most important influence on the surface quality, apart from the chip load effect, is BUE. The authors' research shows that the formation of BUE is detrimental to the surface finish in the micromachining process. Research presented by Kaynak and Gharibi [17] confirm that the MQL method does not work well in all machining conditions. They considered three methods of cooling while cutting the difficult-to-cut material of the new generation titanium alloy Ti-5553: MQL, flood cooling and high pressure coolant (HPC). Many advantages of using HPC in terms of machining efficiency have been found. Instead, by using the MQL method, the authors obtained an unfavorable chip shape, bigger value of cutting force, and greater tool wear. Further, when using the MQL method, tool wear increased by 56% compared to HPC and about 13% compared to flood cooling. The authors explain such a large difference by the increased phenomenon of BUE formation and adhesive wear using the MQL method.

Numerous scientific investigations have been devoted also to use modification of the machining fluids by introducing additional substances increasing their lubricating and cooling properties, in the form of extreme pressure, EP, additives, anti-wear ones (AW) [18], nanoparticles [19] and to modification of the method of supplying the active medium [20]. Advantageous influence of those compounds has been determined not only in machining but also in other scientific disciplines [21]. Nowadays, the machining fluids are continuously modified aiming at obtaining improved cooling and lubricating properties. Xu et al. [20] have proposed that the supplied oil mist should be combined with electrostatic spraying which they have labelled EMQL method (electrostatic minimum quantity lubrication). In this method, negatively charged electrostatic field is responsible for the supply of a small quantity of oil to the contact region between the material subjected to machining and the cutting wedge due to which high wettability and penetration of cutting region is obtained. While milling 304 stainless steels, the authors have managed to reduce roughness of surface machined, the cutting wear wedge and the cutting force when comparing to wet machining, MQL machining and/or dry machining. Some scientists are of the opinion that the results obtained are due to the increase of speed at which the droplets deposit in the cutting zone. There are also many works dealing with another modification of the MQL method consisting in enrichment of the oil mist with nanoparticles which modification can be successfully used in the process of turning ensuring, among others, better tool life and/or lower surface roughness [22]. Some of the scientists have checked the potential of using of hexagonal boron nitride instead of nanoparticles. Talib and Rahim [23] have observed that the above-mentioned nanoparticles, combined with a definite preparation of modified jatropha oil at the concentration of 0.05%, have ensured tool life increase by as much as 78% as compared to synthetic ester. Investigations performed by Yildrim et al. [24] have proved that 0.5% concentration of hexagonal boron nitride in the active medium applied in machining of Inconel 625 alloy ensures tool wear reduction 43% as compared to dry machining. Singh et al. [25] have introduced graphene nanoparticles to the oil mist. The authors have obtained extension of the tool life (i.e. up to 170 - 198%) (as a function of cutting speed) when comparing to dry machining (turning) of the Ti-6Al-4V alloy. Sharma et al. [26] have proved in their experiments that enrichment of vegetable oil with TiO_2 and SiO_2 nanoparticles advantageously influences the effects of machining AISI 1040 steel. Introduction of the nanoparticles to the active medium has resulted in tool wear reduction up to 58% when comparing with dry machining. Slightly lower value (35%) was obtained when subjected to machining using cooling with conventional oil mist.

The literature survey highlights the progress of using several options of MQL and/or MQCL methods which enable optimization of machining process that potentially leads to longer tool life. The main focus was to analyse the wedge wear process when was applied the above-mentioned methods, by comparing them to wet machining, dry machining and cryogenic method, respectively. However, there, is no evidence which focus on the evaluation of emulsion mist when is applied MQL and/or MQCL methods. Therefore, the main goal of this work was to investigate the benefits of the application of the MQL and MQCL methods in order to reduce the wear on the cutting tool coated with AlTiN when turning X2CrNiMo17-12-2 steel. The present work is therefore based on systematic comparison of the method in which MQL lubrication dominates (properties of oil) and MQCL+EP/AW method having the purpose to optimize the cooling process. Due to the TiAlN coating used on the cutting edge, the difference is mainly shown on the rake surface. It is because the main aim of this coating is to reduce the adhesive wear on this surface. In addition, the formation of tribofilm in the cutting zone on the tool flank surface using the MQCL + EP / AW method were shown, which increases the lubricating properties of the active medium as a result of adding EP / AW additive based on phosphate ester. The zones of tribofilm formation are presented and their influence on reducing the wear of the cutting edge is described. To summarize, in the MQL method, the active medium is a vegetable oil, which increases the lubricating properties of the cutting fluid, while in the MQCL method, the active medium is a mixture of water with an emulsion concentrate based on mineral oil. Due to the fact that the main substance is water in the MQCL method (92%), the cutting fluid is then characterized by increased cooling properties.

Throughout it was possible to highlights the main wear patterns (material sticking, crater wear, material cracking) occurring during this machining of this challenging material which are very detrimental during machining process. The results provide a machining map for tool wedge which can be used within industrial sector to control the machining surface and inform when needs to be replaced to tool tips. Besides, the results can be used to build superior numerical models leading to better predictability of machining process.

2. METHODOLOGY OF EXPERIMENTAL INVESTIGATIONS

The tests on the present work were conducted on a conventional lathe, trademark CU-502. During the experiment, a tool with CSRNR2525 holder and SNUN120408-PF plate has been used. Cutting tool geometry was presented in Fig. 1. The cutting tool wedge material was a sintered carbide, P25 containing a resistant coating TiAlN with a homogeneous thickness of 3 μm deposited by the PVD method.

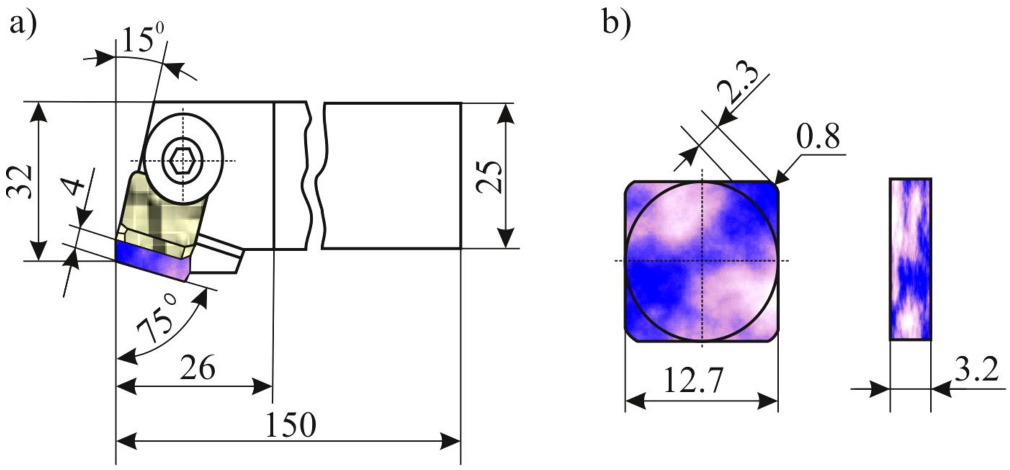


Fig. 1. Cutting tool geometry: a) top view; b) cutting insert

Three different methods of cooling were investigated, namely: dry machining, MQL method and MQCL +EP/AW method, respectively. The MQL method was employed using an active medium (i.e. commercial fluid) commercially known as ECOCUT MIKKRO 20 E, which is widely used in turning and milling. The MQCL method was employed an active medium formed as a mixture of concentrate emulsion obtained from high refined mineral oil. This later has a ratio of 8:92 in relation to water. The emulsion prepared in this way was provided with an addition of 5% EP/AW additive based on phosphate ester as per producer’s recommendation. Here, the active medium was prepared by means of an electromechanical mixer. The active medium containing EP/AW additive were homogenised with an ultrasonic homogeniser that helps to prevent formation of the additive suspensions.

The workpiece material subjected to machining was 316L austenitic steel whose chemical composition and structure can be found in table 1. For each of the cooling methods, a sample in the form of a shaft with a diameter of 80 mm was prepared and processed by the longitudinal turning operation. The cutting parameters and details of process parameters for active medium transfer to interface of machining parts (tool/workpiece) were introduced in table 2. Cutting parameters were selected in accordance with the recommendations of the tool manufacturer for finishing 316L stainless steel. Further, the parameters of the formation of the active medium in the MQL and MQCL + EP / AW method were selected by conducting a preliminary test trail considering the formation of a stream, the number of droplets delivered to the cutting zone, surface wettability which depends on the volumetric flow rate of the active medium, and the distance of the nozzle from the cutting zone in the method of minimized cooling and lubrication [27].

Table 1. 316L steel chemical composition and microstructure morphology

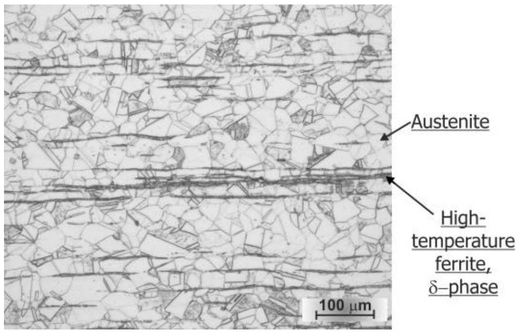
Chemical composition [%]						***Structure***
C_{max}	Si_{max}	S_{max}	P_{max}	Mn_{max}	N_{max}	
0.03	0.1	0.015	0.045	2	0.11	
Fe	*Cr*	*Mo*	*Ni*			
63.7-69.2	16.5-18.5	2-2.5	10-13			
Mechanical properties						
R_e (MPa)	R_m (MPa)	A_5 (%)	*HB*			
305	580	16	250			

Table 2. Details of cutting and parameters used to apply the active medium lubrication

Cutting parameters			***Parameters for active medium lubrication***		
Cutting speed v_c [m/min]	Feed f [mm/rev]	Depth of cut a_p [mm]	Volume air flow [l/min]	Mass flow of active medium [g/min]	Distance between the nozzle and the cutting zone [m]
210	0.1	0.5	5.8	0.44	0.3

During this investigation, two indices of the cutting wedge wear have been monitored: the wear band width which forms on the flank face (zone B), indicated as VB_B and the width of the *KB* crater. The experiment was carried on till the VB_B value reached 0.3 mm as per standard ISO 3685:1993 recommendation which indicate it as damaged. During the initial tests, different periods of the cutting wedge work have been determined for which the adopted wear indices were evaluated using a Dino Lite universal microscope. Notch wear depth associated to chipping has been determined for the individual cutting wedges after 60 minutes on a microscope, Infinite Focus G4. Measurements were made in accordance with ISO 3685:1993 (Fig. 2). In the scanning examinations, JSM-5600LV scanning microscope trademark JEOL Company has been used, which has integrated an x-ray microanalyzer, EDS 2000 made by IXRF. The qualitative and quantitative evaluation of tools investigated are based on the data gathered with a detector of secondary electrons (SEI). The analysis conducted here enable to elucidate the mechanism of deposition of oil mist with the EP/AW additive which directly can influence the creation of a lubrication film on the cutting wedge surfaces under consideration.

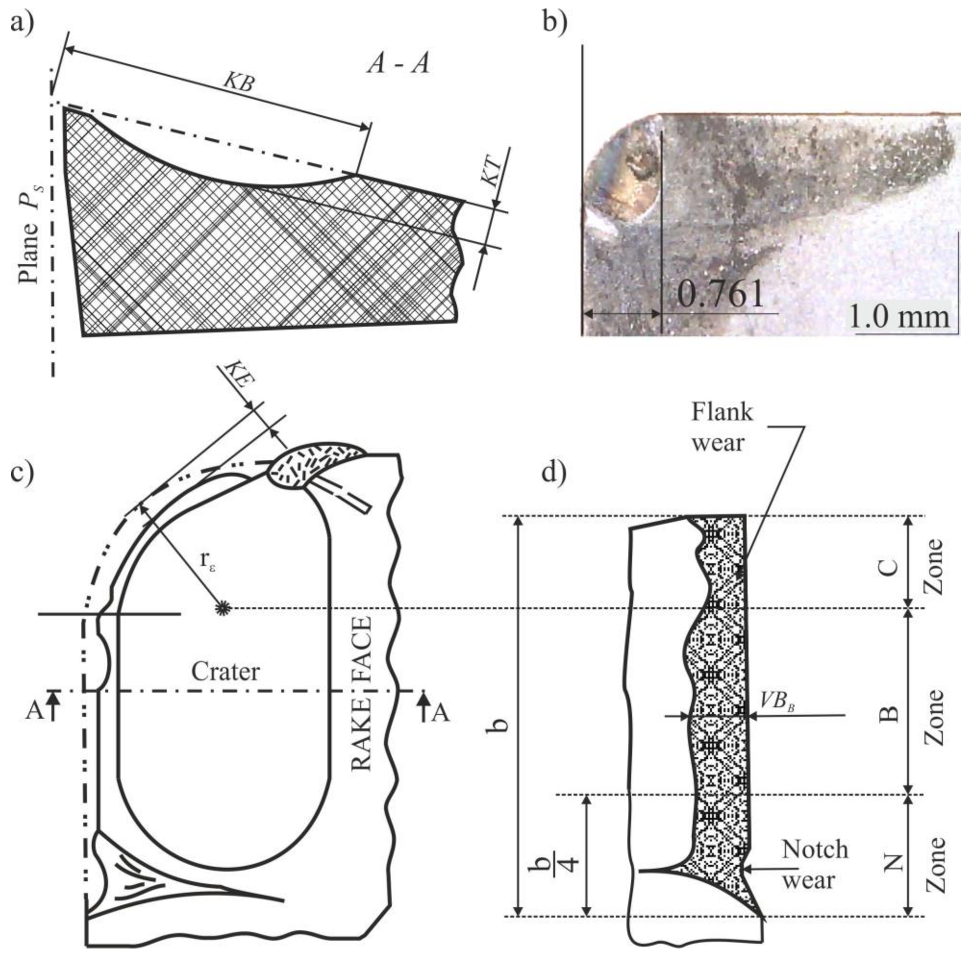


Fig. 2. Selected tool wear indicators according to ISO 3685:1993: a) crater width on the rake face *KB*; b) general view of the KB measurement on the microscope; c) rake face with *KE* wear measurement; d) major flank wear VB_B and notch wear

The tool work period and time intervals at which the cutting wear wedge required evaluation were established by conducting some preliminary examinations.

3. INVESTIGATION RESULTS

3.1. CHARACTERISTICS OF THE CUTTING WEDGE WEAR

During the turning process assume that the flank face of the cutting wedge is getting in continuous contact with workpiece surface subjected to machining. As result of continuous contact, the surface is exposed to the heat generated by friction, which results in gradual wear of the cutting wedge [14]. Fig 3 shows the values of the wear band obtained from flank face, VB_B, as a function of cooling method employed on the cutting zone during turning of 316L stainless steel.

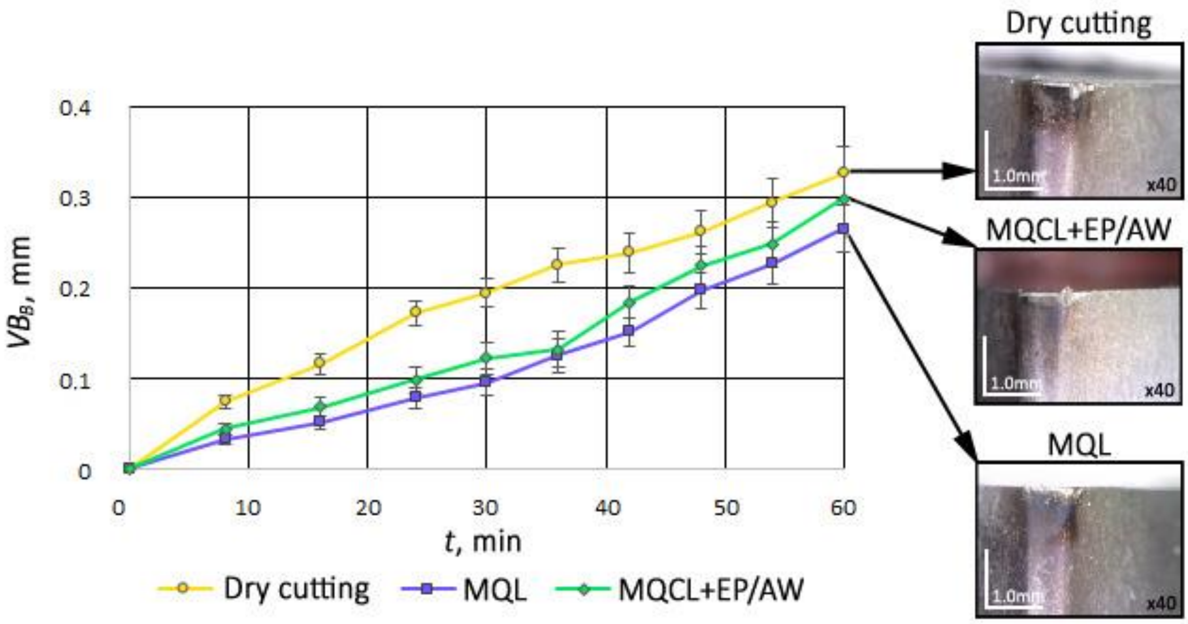


Fig. 3. Cooling method effect on the wear band of VB_B flank face during turning 316L steel

The maximum wear index, VB_B, from the turning trials of austenitic 316L steel have been recorded under the conditions of dry machining (see details in fig. 3). In contrast, the use of minimized lubrication method enabled the smallest the cutting wear wedge. The MQL method allowed a reduction of the VB_B value between 3% to 18% when was compared to application of dry machining and between 2% to 11% when was compared to the MQCL + EP/AW method. By supplying the active medium by means of a nozzle and compressed enabled an effective amount of chips removal from the cutting region and an effective spraying of oil mist droplets. Their presence at the interface of tool workpiece machined results in formation of a layer of machining liquid whose main task is to reduce friction between the cutting wedge. This is confirmed by studies conducted in [28], where, as a result of the use of the EP / AW additive in the MQCL method, when turning 316L stainless steel, a reduction in the friction coefficient on the rake face μ using the MQCL + EP / AW method was found in a range btewwen 28% - 36% compared to dry machining. Further, the workpiece subjected to machining can receive an effective lubrication of the contact zone and, consequently, which in extend prolong the tool life [28, 29]. More important, the oil mist droplets enable a more effective lubrication for cutting wedge region subjected to machining when comparing with "lubrication" medium used in the MQCL + EP/AW method [30]. The lower cutting wear wedge achieved by applying the active medium containing EP/AW additive when comparing to dry machining can be due supplying water droplets that promote a better lubrication on the cutting zone region as result of the use of phosphate ester. Phosphor based additives, as widely used ones, can promote creation of a tribofilm layer, both on the workpiece surface and on the cutting wedge [28]. This kind of layer allows to prevent damages which could occur on the contact surface as proved by many investigations performed in respect of the effectiveness of anti-wear additives [21]. As a result, the reduction of friction causes reduction of temperature which plays a very important role and has great influence on the carbide cutting wedges' properties related to their wear [30].

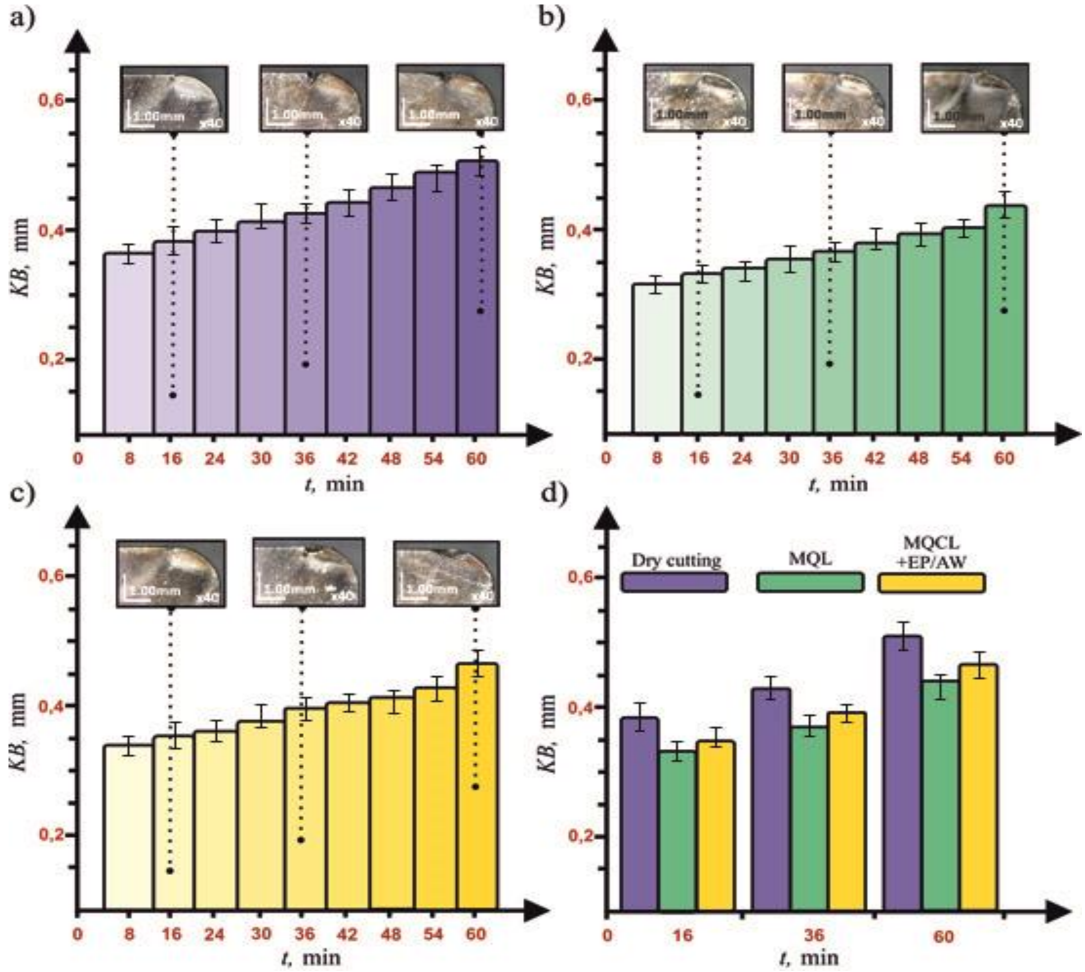


Fig. 4. Details of *KB* groove width and its rake face variation after machining (turning) of 316L steel with various conditions: a) dry machining; b) MQL method and c) MCQL +EP/AW method; d) assembly progress for selected time periods

Fig. 4 indicated that the change of the *KB* groove width is driven by the cooling method. The rake wear face occurs at the hard contact between the cutting wedge contact and the chips. One important reason of formation of the groove (crater) is high temperature released during turning of stainless steels. The analysis of *KB* groove width (fig.4a, b, c) reveals that it is characterised by even growth of the value in the whole time period for all cooling methods. The smallest *KB* values have been observed when were used the MQL method (fig. 4d). Cooling with oil mist results in *KB* reduction up to 16% when comparing to classical dry machining; slightly lower improvement was noted (6%) when comparing to the MQCL + EP/AW method. Moreover, the best advantages related to the minimized lubrication method is the ability to reduce the machining temperature. This property of oil mist enables a reduced tool wear by protection against formation of accretion, which, in turn, is a reason of reduced adhesion wear related to the formation of crater [14]. Dry machining shows a tendency to generate more heat as compared to the other methods, which results in an increased groove dimensions [31]. The MQCL + EP/AW method does not reduce friction to the same extent as the MQL method because its active medium composition contains fewer lubricating compounds (about 88% is water). The water allows a better heat circulation on the cutting region [32], in turn it causes a massive reduction of the *KB* value when comparing to dry machining.

3.2. SCANNING ANALYSIS OF THE CUTTING WEDGE

In order to determine the dominating wear patterns in both conditions dry machining and advanced cooling (MQL and MQCL + EP/AW method), cutting wedge optical evaluation has been performed, and the results were shown in fig. 5 – 7. Moreover, a map of distribution of selected elements has been added to the scanning analysis of the cutting wedge surface. The main elements were iron as the major element of the X2CrNiMo17-12-2 steel, titanium as dominant component of coating (Ti, Al)N, tungsten as the major component of the P25 sintered carbide and phosphor as the element present in the EP/AW additive formed from phosphate ester.

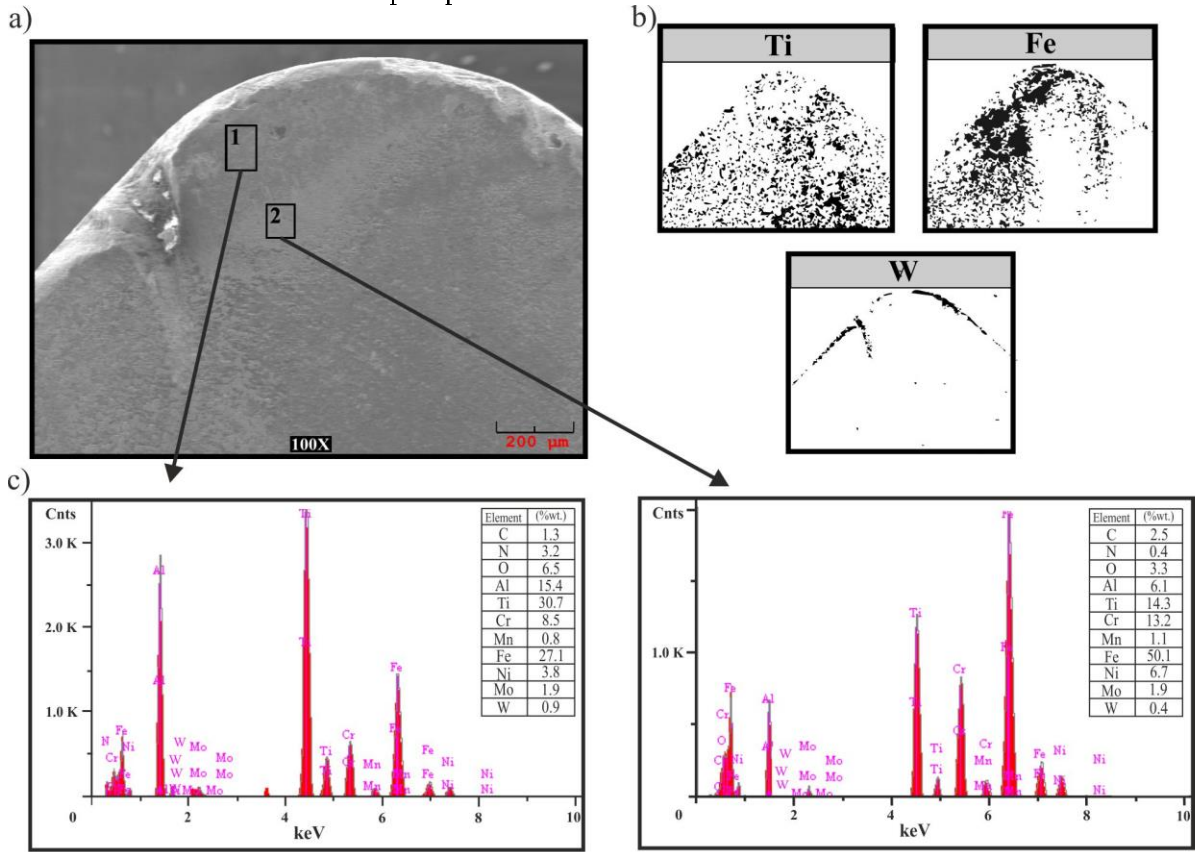


Fig.5. X- ray microanalysis from rake face for dry machining condition: a) image of the surface; b) surface map for selected elements; c) SEM analysis for micro area 1 and 2

The analysis of the element distribution and chemical composition on the investigated micro areas corresponding to rake face surface associated to cutting wedge (fig. 5, 7 and 8) indicate the formation of different type of adhesion wear for each cooling method. When is used dry machining (fig. 5a, b) it is observed that the mass of the particles of machined surface increased up to 50.1% beyond the area of the crater formation, i.e. at a longer distance of the main cutting wedge. In the vicinity of groove formation, it was found an increased content of titanium and aluminium as the basic components of the cutting wedge coating in micro area noted as 1 of contact region when comparing to micro area 2. This means that, in the contact zone further from the main cutting wedge, more intercrystalline phases forms as ferro - tungsten carbides, Fe_3C, Fe_3W_3, $(FeW)_6C$ or additional type of carbide with more complex structure. The high degree of deformation could be compared to deformations in mechanical alloying, where also coalescence and fragmentation effects are observed [33]. The high temperatures released on the contact region activate the plastic deformations mechanism while on the cutting region is promoted mutual adhesion occurrence due to the tool material sticking to the machined material, which is visualized as "smearing of workpiece surface material machined deposited as particles on the rake face (fig. 6). Moreover, some micro cracks may arise on the entire rake face due to local adhesion forces that act between the top layers of the machined material and the tool; these forces cause cracking and break-up of the cutting wedge coating. The formation of built-up edge (BUE) under dry machining conditions was also observed during the experiment. This enabled the formation of cracks and damage on the surface of the tool and ultimately led to the breaking of the cutting edge, which is confirmed by other researchers [34]. The use of MQL method enable an increase of lubrication intensity on the cutting zone (because oil is the active medium) and, consequently, the value of friction may decrease on the contact region. The content of iron beyond the wear band was only 35.6 % when were used advanced cooling (MQL method (fig.7)). This reduced amount of iron content when comparing to dry machining is a clear evidence for good activity induced by the individual percentage of each element contained in the composition of the oil concentrate (potassium, phosphor, copper); in enable a reduced adhesion wear due to deposition on the contact surfaces and, therefore, trigger lower friction at the contact between tool and chip [29].

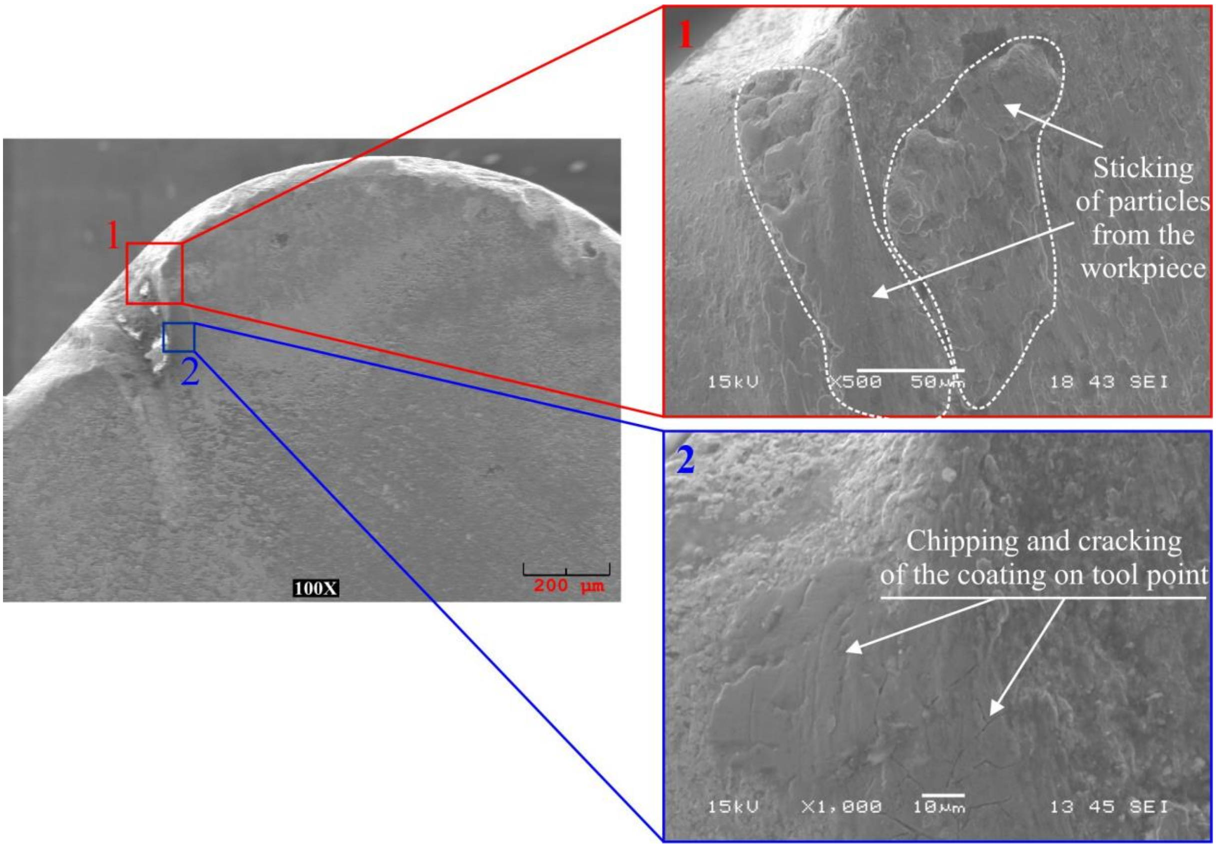


Fig. 6. Scanning analysis of the cutting wedge/ rake face under the conditions of dry machining after turning of 316L steel

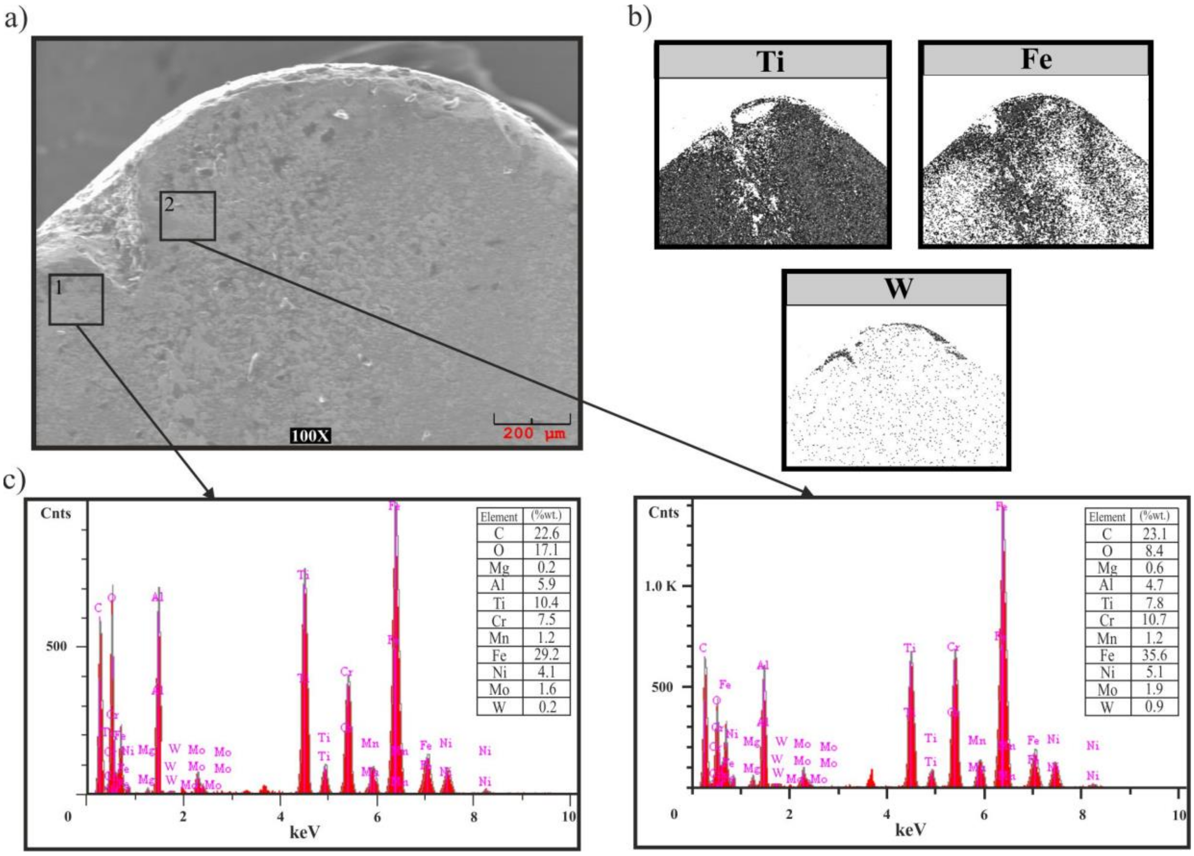


Fig. 7. The results of X-Ray micro analysis obtained from rake face using MQL cooling method: a) image of the surface; b) surface map for selected elements; c) SEM analysis for micro area 1 and 2

The above results are confirmed by the investigations of Devillez et al. [35]. They performed machining with almost the same cutting parameters (f =0.1 mm/rev and a_p = 0.5 mm) by using minimized cooling and lubrication, in which were observed only minor or very limited mechanism of sticking of machined material on tool surfaces. It is because the tool surfaces temperature is much lower in the advanced lubrication (MQL) when comparing to dry machining. Moreover, the use of MQCL method which contain EP/AW allows the generation of a phosphate ester based tribofilm on the cutting wedge surfaces. Indeed, the evaluation of rake face (fig. 8) indicated an increase of phosphor content (up to 24.3% - micro area 1) which trigger lower wear band and iron content reduced to 20.1%. In the band that is related to chip/rake face contact, phosphor content drops to as low as 0.7% (micro area 3) and the amount iron content can reach up to 36.2%. Probably, once the phosphate ester based tribofilm break, the iron may penetrate within the contact surface (adhesion wear) that act as a barrier for formation new tribofilm to protect the wear band. In the scanning analysis (fig. 5, 7, 8) it was noted an increased content of oxygen, which proves the occurrence if chemical wear as oxide. Then, sintered carbides components may trigger a chemical reaction with the oxygen.

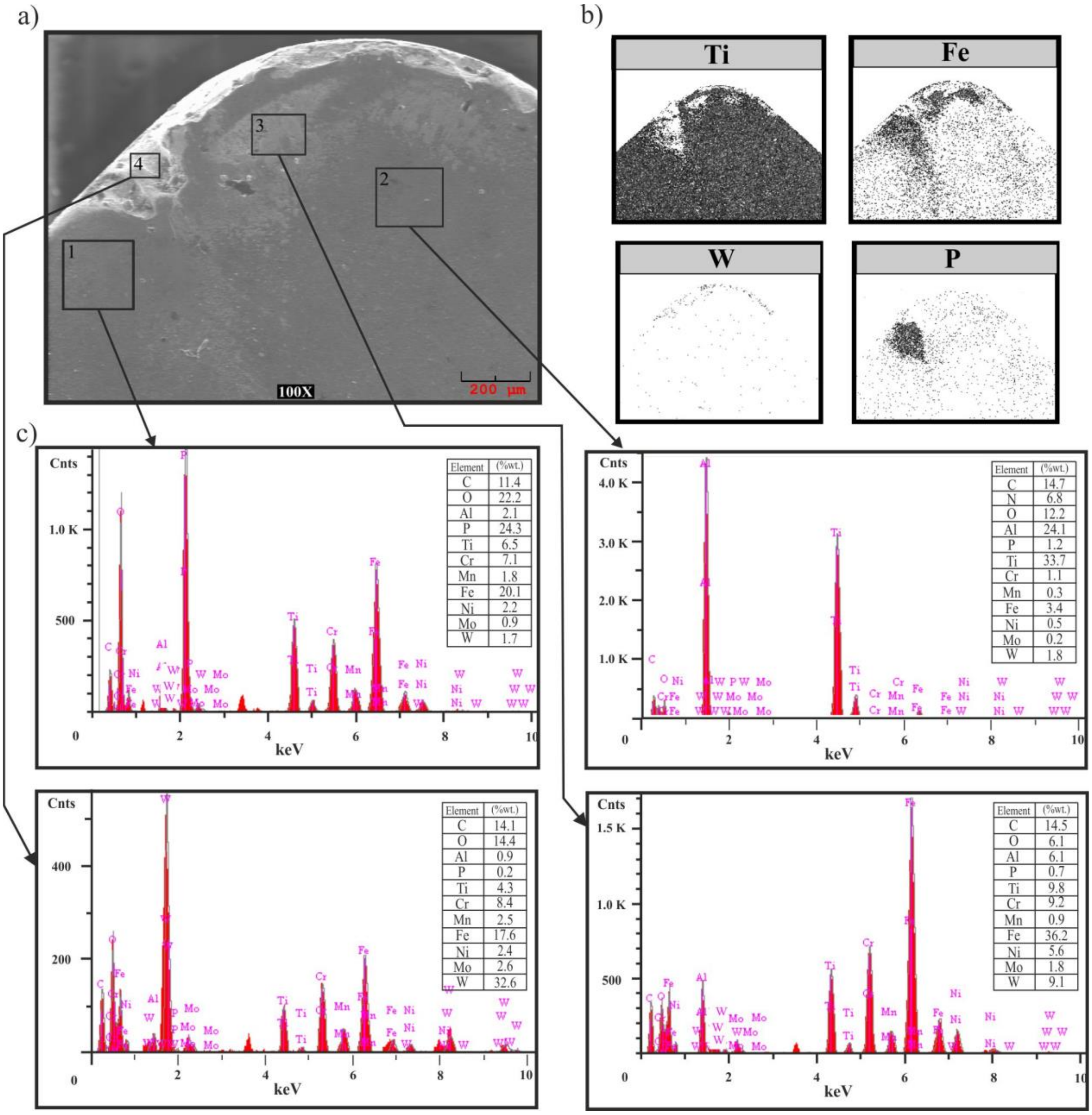
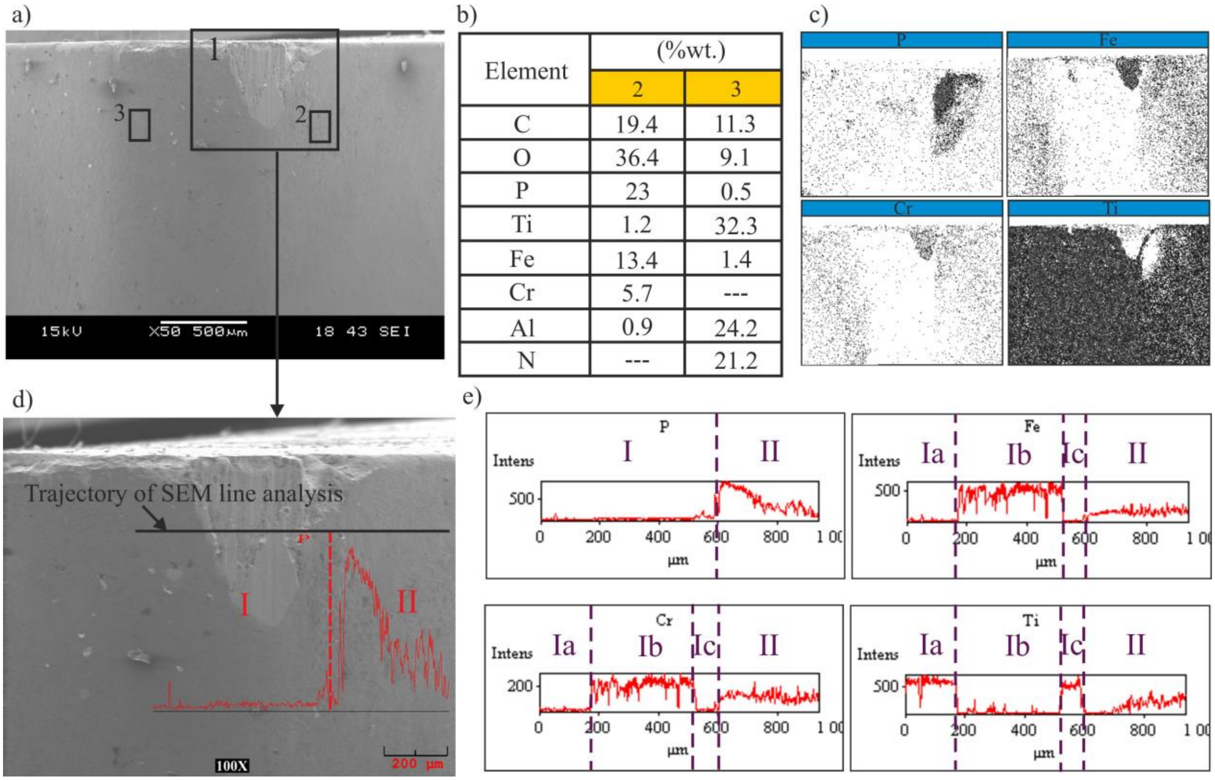


Fig. 8. The results of x-ray micro analysis acquired from rake face using cooling by the MQCL +EP/AW method: a) image of the surface; b) surface map for selected elements; c) SEM analysis for micro area 1 – 4

The lubricating film deposited on the flank face, generated under cooling with the MQCL + EP / AW method (Fig. 9), is a phosphorus-based layer distributed over the entire tool may enable a massive tool wear reduction. However, the lubricating film can break at the hard contact chip/tool. Nevertheless, the adhesion can process can have an accentuated progress in which the machined particles from the material (iron) are deposited there. Due to the continuous friction generated from the chip on the rake face, the lubricating film does not re-form (Fig. 9c). The analysis showed the highest content of phosphorus on the main flank face (up to 23%), when the phosphorus content on the auxiliary flank face is only 0.5%. This proves that the lubricating film forms only in the zones with higher temperatures, which allow evaporation of water and the interaction of chemical compounds contained in the emulsion [36].



Element	(%wt.)	
	2	3
C	19.4	11.3
O	36.4	9.1
P	23	0.5
Ti	1.2	32.3
Fe	13.4	1.4
Cr	5.7	---
Al	0.9	24.2
N	---	21.2

Fig. 9. SEM images showing the flank face generated with MQCL+ EP/AW after turning steel X2CrNiMo17-12-2: a) Surface morphology; b) elemental details from micro-areas 2 and 3; c) Surface mapping; d) linear analysis for SEM diagram; e) rate of distribution of chemical elements in linear analysis.

On the flank face (fig. 9 d) two main zones of occurrence of selected elements were distinguished (fig. 9 e):

- zone I, which covers part of the relief flank face and the wear line is characterized by a very low phosphorus intensity. Outside the wear range, there is a high percentage of titanium which is the main component of the coating (Ti, Al) N, and in the wear zone, iron and chromium are the main components of X2CrNiMo17-12-2 steel;

- zone II – covers the main flank face, where the higher amount of phosphorus content is indicated, which reduces the adhesion on the tool point (lower iron content was acquired).

3.3. TOPOGRAPHY OF THE CUTTING WEDGE

Fig. 10 presents details of different wear patterns identified on the worn areas of cutting wedge part generated due to various method of cooling.

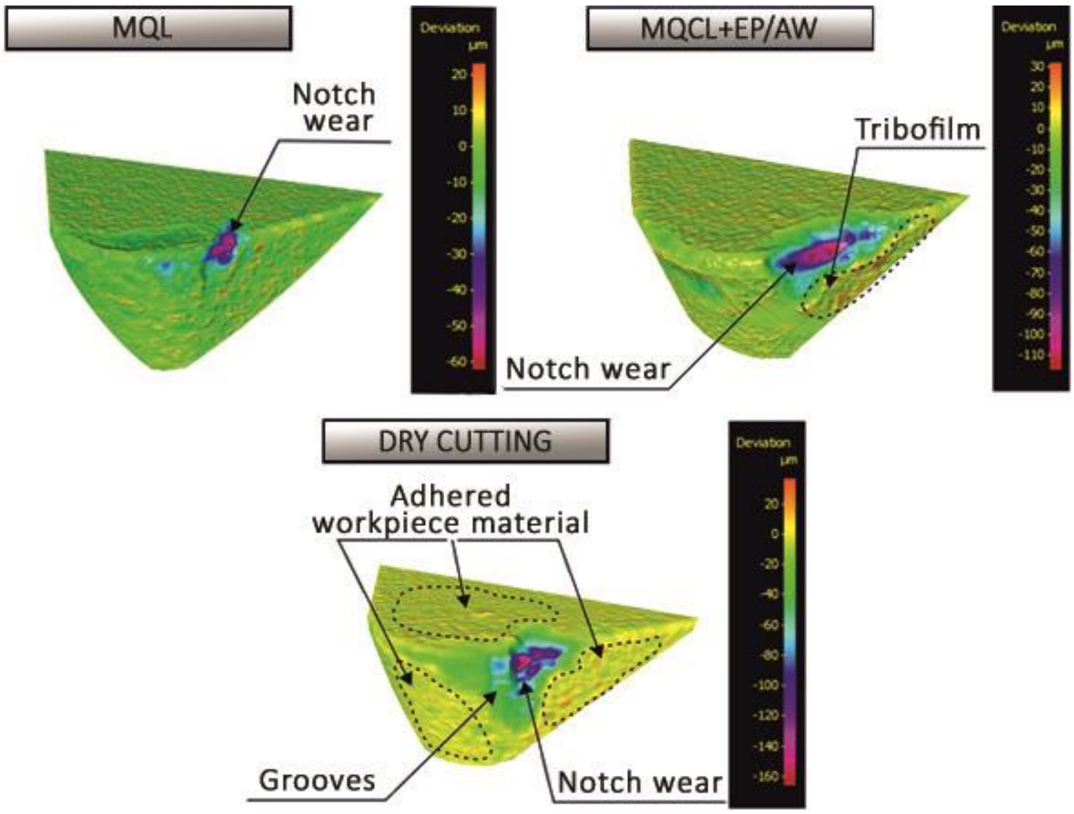


Fig. 10. Cutting wedge wear patterns depending on the conditions of cooling

The analysis conducted on the topographic images associated to the cutting wedges (fig. 10) reveals that the main wear on the cutting wedge is located near the corner, in all wedges, as a notch wear. Also, we have found patterns of adhesion wear which can be sign of most prominent wear mechanisms, particularly on the main cutting edge [37]. It is recognized that the loss of a tool's ability to work usually occur due to breaking of a corner; and the flank face or plastic deformations takes place due to intense action of temperature, pressures or dynamic loads which influence the wear of the cutting wedges particularly when are considered the tool materials with low resistance to cracking and small strength [13]. By comparing dry machining, MQL and/or MQCL + EP/AW method generally a gradual increase of wear is observed. This effect is more visible for dry machining condition endorsed by the notch wear depth value. The least notch wear as chipping associated on the main cutting edge was achieved by using the method based on minimized lubrication, MQL (about 60 µm) while chipping value generated using dry machining was found about 160 µm. We speculated the reason of very low value of this parameter for the ability of MQL to reduce the cutting zone temperature that in turn drives the intensity of diffusion and wear adhesion. Consequently, the wear progress is produced into very limited extent [11]. Furthermore, the use of the MQL and MQCL + EP/AW method allows to reduce the intensity of sticking / adhesion of the machined material when comparing to dry machining. Nevertheless, the MQCL + EP/AW method, can enable the formation of specific bands of phosphate ester based tribofilm [14].

4. CONCLUSIONS

The present work was focused to systematically evaluate three different method in which MQL lubrication dominates were used during machining of 316 stainless steel. By analysing the data achieved in the present work, it was possible to formulate the following conclusions:

– dry machining cannot ensure a satisfactory productivity due to the wear of the cutting wedge formed during turning of 316L steel. For all the monitored wear indices, the highest value has been obtained in dry machining while a minimum one were achieved applying minimized lubrication. The use of MQL method enabled a reduction of wear band identified on the flank face by as much as 18% and a decrease of groove width by as much as 16% when comparing to dry machining;

– the oil mist used in the MQL method enabled the formation of a machining liquid layer on the entire workpiece surface and on the tool, which further allowed a reduced friction activity in the cutting region. Besides, it promotes a reduction of wear on the cutting wedge, for both part of rake face and flank face, when comparting to emulsion mist used in the MQCL method that contain EP/AW;

– the EP/AW additive introduced into the active medium of MQCL method, forms a phosphate ester based tribofilm on the cutting wedge of rake faces promoting a reduced cutting wedge wear when comparing to dry machining. Its breaking, however, causes adhesion wear and prevents the mechanism which enable the tribofilm layer formation;

– the cutting wedge morphology obtained after dry machining indicated areas of the machined material sticking and large zone presenting patterns of abrasive wear. The application of the MQL method ensured better lubrication which in turn promoted a reduction of adhesion wear and, consequently, the hazard of formation of sticking on the cutting wedge surface was diminished. The MQCL + EP/AW method prove to be an effective solution for preventing the formation of sticking progress. The effectiveness is due to tribofilm layer which forms on the surfaces of the cutting wedge as a protection barrier.

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