Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 149 (2016) 297 – 304
Procedia Engineering
www.elsevier.com/locate/procedia

International Conference on Manufacturing Engineering and Materials, ICMEM 2016,
6-10 June 2016, Nový Smokovec, Slovakia

Chip formation zone analysis during the turning of austenitic stainless steel 316L under MQCL cooling condition

R.W. Maruda[a], G.M. Krolczyk[b,*], P. Niesłony[b], J.B. Krolczyk[c], S. Legutko[d]

[a]*Faculty of Mechanical Engineering, University of Zielona Gora, 4 Prof. Z. Szafrana Street, 65-516 Zielona Gora, Poland*
[b]*Department of Manufacturing Engineering and Production Automation, Opole University of Technology, 76 Proszkowska street, 45-758 Opole, Poland*
[b]*Department of Agricultural and Forest Technology, Opole University of Technology, 5 Mikolajczyka Street, 45-271 Opole, Poland*
[d]*Faculty of Mechanical Engineering and Management, Poznan University of Technology, 3 Piotrowo street, 60-965 Poznan, Poland*

Abstract

The paper presents the influence of the cutting zone cooling method on selected indices of the chip formation zone and on the chip shape. In the process of turning 316L austenitic steel three cooling methods have been considered: dry machining, MQCL method and MQCL + EP/AW. The tests have been performed in accordance with the method of Parameter Space Investigation. It has been found that, when cooling by the MQCL method with the addition of EP/AW, the friction coefficient on the rake face, the coefficient of chip thickening is reduced and the angle of sliding increases as compared to dry machining and the MQCL method. The reduction of the friction coefficient value in the MQCL +EP/AW method is due to nano-particles based on phosphate ester added to the water. Considering the chip shape, the MQCL method has appeared more advantageous in cutting the 316L austenitic steel. When cooling by the MQCL method, useful chip shape in the form of short spirals or quite loose, which results in easier removal of it from the cutting zone.

Peer-review under responsibility of the organizing committee of ICMEM 2016

Keywords: MQCL, dry cutting, EP/AW addition, chip shape, friction coefficient

---

1. Indruction

Vast studies on metalworking fluids (MWFs) have been concentrated on extensive investigations, because they play a significant role in the process of manufacturing machine elements. One of their major advantages is reduction of friction between the tool and the material being machined, which influences the quantity of heat in the cutting zone [1, 2]. Furthermore, they have the ability of dissipating and removing the generated heat [2, 3]. Combination of the above features results in reduction of temperature in the cutting zone, which leads directly to reduction of thermal damage of the material under machining [4] and reduction of the tool wear [4-6].

As late as a few years ago, the MWFs were supplied to the cutting zone as flood cooling. The growing awareness of the danger to human health and of environment protection have encouraged scientists to work on new methods of cooling in machining. The methods of near dry cutting, cryogenic cooling [6, 7], and methods based on very small quantity of MWFs , so called minimum quantity lubrication MQL [1, 3, 5-9] and minimum quantity cooling lubrication [8, 10, 11] have become an alternative to flood cooling.

From those cooling techniques, the MQL and MQCL methods are extremely attractive to use in the production process due to improvement of the machining processes productivity and reduction of costs purchasing MWFs and removal of the worn ones [12], as well as to the reduction of the machine tool cleaning time and energy consumption associated with cutting fluid supply systems [13]. In the MQL method, the active medium is supplied in the form of a mixture of air and oil (often defined as oil

---

* Corresponding author.
E-mail address: g.krolczyk@po.opole.pl

Peer-review under responsibility of the organizing committee of ICMEM 2016
doi:10.1016/j.proeng.2016.06.670

mist); in the MQCL method, in the form of a mixture of air, emulsion concentrate and water. Two ways of aerosol supplying are distinguished:

- external way, i.e. by means of a nozzle located in a device similar to the nozzle used in flood cooling [3, 8, 14];
- internal way (through the tool) [7, 15].

In addition to the application of the basic component of the MQL and MQCL methods, oil and water respectively, works on the addition of EP (extreme pressure) and AW (anti wear) additives to the MWFs have been started, the major task of the additives is to reduce friction and to control heat generation between surfaces in contact [1,16]. The purpose of the EP/AW additives is to form a tribofilm on the cutting edge and the material under machining, the task of which is, in general, to avoid failures in boundary lubricated contacts [17]. Nowadays, the additives most commonly used in order to protect surfaces against wear include AW (zinc dialkylthiophosphates (ZDDPs), EP (phosphorus/sulphur based), detergents (overbased calcium sulphonates), dispersants [17].

A survey of investigation works concerning the application of the “near dry cutting” method has shown that, at the initial stage of using the MQL and MQCL methods, most works have rather analysed general issues, that is tool wear and durability, surface quality, economics and productivity of manufacturing, cutting forcers and power etc. [3, 7,12]. Recently, the process details are more and more frequently analysed: chip formation and changes of physical and chemical phenomena under MQL and MQCL conditions [1, 8, 9].

In the present work, an attempt has been made to determine the influence of finish machining in the process of turning 316L austenitic steel on the chip generation zone, for three methods of cooling. Due to the large number of variables, such as cutting speed, feed, mass flow of emulsion, volumetric air flow, the results concerning the chip generation zone indices have been shown with the use of correlation between the parameters by multiple linear regressions.

Nomenclature

MQCL	minimum quantity cooling lubrication
MQL	minimum quantity lubrication
PSI	parameter space investigation
v_c	cutting speed, m/min
f	feed rate, mm/rev
a_p	depth of cut, mm
P	volume air flow, l/min
E	mass flow of active medium, g/h
l	distance between the nozzle and the cutting zone, m
r_ε	corner radius, mm
h_{ch}	chip thickness, mm
h_D	average thickness of the removed layer, mm
K_h	chip thickening coefficient
Φ	sliding angle
μ	friction coefficient on the rake face
λ	angle of the main cutting edge inclination, °
K_r	main tool cutting edge angle, °
γ	rake angle, °

2. Experimental approach

2.1. Workpiece material and method

Proces badano wykorzystując tokarkę kłową i nóż tokarski z oprawką DWLNR 12 3C i płytką wymienną WNMG060408 PF 4325. Materiał płytki – węglik spiekany P25 powlekany warstwą TiAlN. Zastosowano następujące kąty ostrza: kąt przystawienia głównej krawędzi skrawającej $\kappa_r = 95°$, kąt natarcia $\gamma = -5°$, kąt pochylenia $\alpha = 15°$, promień naroża $r_\varepsilon = 0.794$ mm.

The process has been tested with the use of a centre lathe and a lathe tool with holder, DWLNR 12C and exchangeable plate, WNMG60604O8 PF 4325. Plate material – sintered carbide P25, coated with a layer of TiAlN. The following angles have been applied: main tool cutting edge angle $K_r = 95^o$, angle of the main cutting edge inclination $\lambda = 15^o$, corner radius $r_\varepsilon = 0.794$ mm.

Machinability tests have been performed on austenitic steel 316L. It characteristic feature is the ability to resist corrosion in aggressive environment at high temperatures. The corrosion resistance of the austenitic steel chemical composition (C $\leq$0.03%, Cr $\approx$ 17.5%, Ni $\approx$ 11.5%, Mn $\leq$2%, Mo $\approx$ 2.3%, N $\leq$0.11%) is ensured by the structure of stable austenite in a wide temperature range [18].

Micronizer LENOX 1LN is the device which has been applied in generation of the emulsion mist used under the conditions of cooling by the MQCL and MQCL +EP/AW method. The device is provided with the possibility of adjusting the flow of emulsion and air. The compressed air pressure was 0.48 MPa. In the test, emulsion concentrate EMULGOL, based on highly refined mineral oil, has been used. It contains, among others, additions of ionic and non-ionic emulsifiers, enriching substances and corrosion inhibitors.

The EP/AW additive was phosphorate ester named CRODAFOS EHA-LQ-(MN). CRODAFOS EHA-LQ-(MN) is compatible with synthetic oils based on petroleum distillation. Its major task is formation of a microscopic layer of tribofilm by chemical connection to the components of metal. The active medium used in the MQCL method has been made with the use of a magnetic mixer ES21H. 5% of EMULGOL concentrate has been added to water. In the MQCL +EP/AW method, the active medium has been heated up to the temperature of 60^{o} and then 5% of the additive based on the phosphorate ester has been introduced.

The chip thickness has been measured ten times by means of a ball micrometer, IP40 0–25 mm with the measurement error of ±0.004 mm.

2.2. Investigation method

During the tests, four variable parameters have been applied: two ones related to the cutting parameters, i.e. cutting speed v_c, and feed f, and two ones related to the formation of the active medium, i.e. mass flow of emulsion E, and volumetric air flow P. The cutting parameters have been selected in accordance with the catalogue of tools for the process turning austenitic steels; the range of the emulsion mist parameters has been selected after calibration of the Micronizer device [19]:

- cutting speed $v_c = 70 – 420$ m/min;
- feed $f = 0.05 – 0.3$ mm/rev;
- mass emulsion flow $E = 0.09 – 0.45$ g/min;
- volumetric air flow $P = 1.2 – 5.9$ l/min.

Constant distance of the nozzle from the cutting zone has been established to be 0.3 m [19] and, due to the large number of variables, constant depth of cutting of 0.5 mm, which corresponds to finish machining.

In connection with the large number of variables, the PSI (Parameter Space Investigation) has been applied; the method allows for effective distribution of test points in multidimensional space [20]. The points are located in a predetermined sequence. The sequences consist in locating the individual test points in the multidimensional space in such a way that the points of their projections on axes, X_1, X_2, X_3 –X_4,..... $X_i – X_j$ are situated at equal distances from each other (Fig. 1).

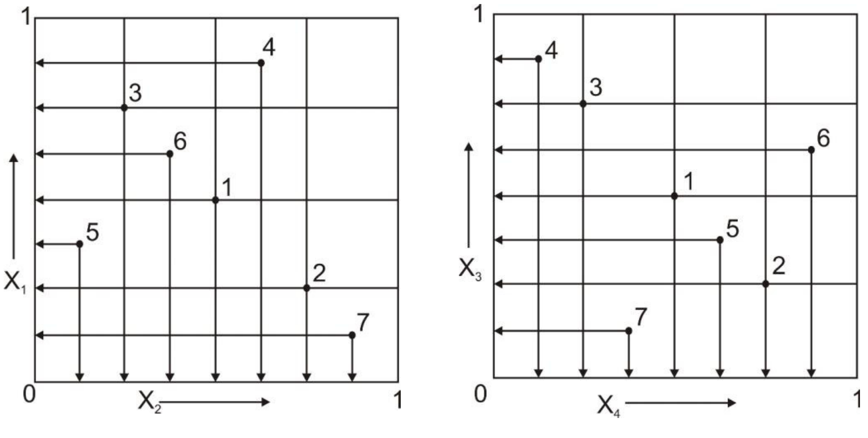

Fig. 1. Projections of experimental test points on example pairs of axes according to the PSI method.

Basing on the algorithm presented in [20], a computer program has been elaborated and the test point coordinated have been calculated for $X_{min} = 0$ and $X_{max} = 1$ (Table 1). It is easy to see that, for the analysis of the relationship, $Y = f(Xi)$, when the tests are performed in 7 points of the multidimensional space, there are 7 points on each of the X_i axes. Such a number of points is sufficient for statistical measurement calculations.

Table 1. Coordinates of the test points in the range of 0 -1.

Factors	Test Points						
	1	2	3	4	5	6	7
X_1	0,5000	0,2500	0,7500	0,8750	0,3750	0,6250	0,1250
X_2	0,5000	0,7500	0,2500	0,6250	0,1250	0,3750	0,8750
X_3	0,5000	0,2500	0,7500	0,1250	0,6250	0,3750	0,8750
X_4	0,5000	0,7500	0,2500	0,1250	0,6250	0,8750	0,3750

3. Results and discussion

3.1. Chip shape

The changes of chip shapes when turning 316L austenitic steel for the three cooling methods, depending on the cutting speed and feed can be seen in Fig. 2.

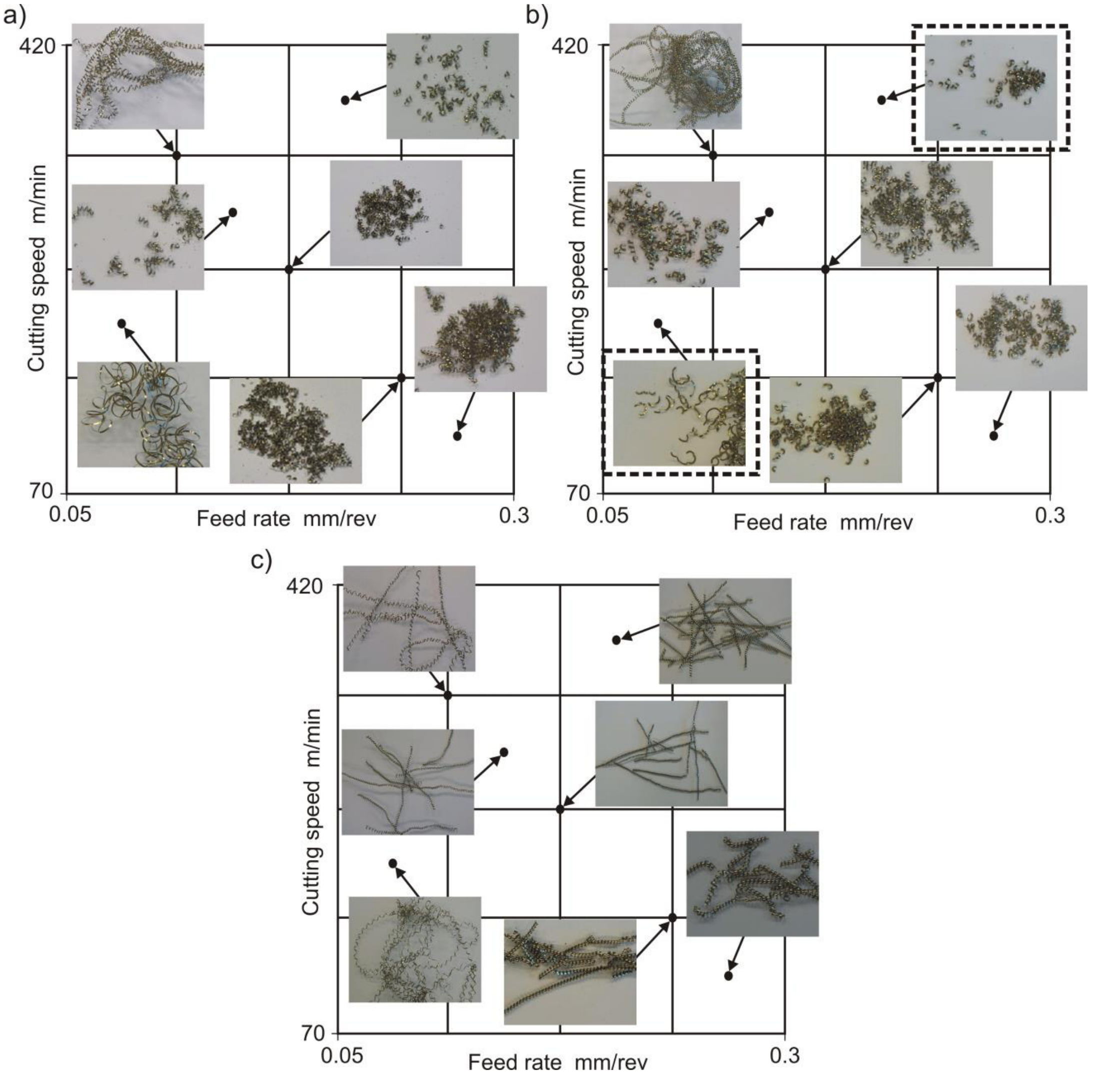

Fig. 2. Chip shapes after the process of turning 316L austenitic steel for: (a) dry machining; (b) MQCL; (C) MQCL +EP/AW.

In the analysis of the chip shape depending on the way of cooling (Fig. 2), it has been found that the most advantageous chip shape has been obtained under the conditions of MQCL cooling. For this method of cooling, the range of cutting parameters with which the chip in the form of short spiral fractions or quite loose has been obtained increases (Fig. 2b – broken line). Such chips are easy to remove from the cutting zone and they do not damage the surface of the material under machining. In Fig. 2b, one can see the areas of the chip shape changes in the MQCL method as compared to dry machining. This is due to the lower temperature in the cutting zone resulting in changes of the chip deformations [21]. The least advantageous chip shapes have been obtained for the MQCL +EP/AW method (Fig. 2c) where the chip has helical conical shape or long open one and long tubular one. Such a chip can damage the machined surface and, consequently, increase its roughness. The change of the chip shape under the conditions of MQCL +EP/AW cooling can be due to the formation of a tribofilm based on phosphorate ester on the cutting edge, which results in a change of the chip winding in the cutting plate groove. It is worth stating here, too, that the geometry of the cutting plate, WNMG060408-PF, ensures chip removal from the surface under machining.

3.2. Indices of the chip formation zone

The basic indices characterising the details of the chip formation process are the chip thickening coefficient K$_h$, the sliding angle Φ, and the coefficient of friction on the rake face μ. The chip thickening coefficient determines the speed of the chip travel along the rake face. The changes of the sliding angle indicate the deformations of the material layer when it is transformed into chips, while the friction coefficient is one of the parameters determining the temperature in the cutting zone. In the calculation of the chip thickening coefficient, first the average thickness of the removed layer has been determined. In turning with small depths, both the main cutting edge and the corner participate in the process of cutting. The average thickness of the removed layer can be calculated from the formula [22]:

$$\overline{h_D} = \frac{f}{1-\frac{r_\varepsilon}{a_p}\left[1-\sqrt{1-\left(\frac{f}{2r_\varepsilon}\right)^2}\right]} \cdot \sin arctg \cdot \frac{1-\frac{r_\varepsilon}{a_p}\left[1-\sqrt{1-\left(\frac{f}{2r_\varepsilon}\right)^2}\right]}{\left[1-\frac{r_\varepsilon}{a_p}\left(1-\cos\kappa_r\right)\right]\cdot ctg\kappa_r + \frac{r_\varepsilon}{a_p}\left(\sin\kappa_r + \frac{f}{2r_\varepsilon}\right)}, \tag{1}$$

where: f – feed; a_p – cutting depth; r_ε – corner radius; κ_r – main cutting edge angle. Then, the value of the chip thickening coefficient K_h, is equal to [23]:

$$K_h = \frac{h_{ch}}{\overline{h_D}}, \tag{2}$$

where: h_{ch} – chip thickness.

The calculation of the sliding angle *Φ*, has been performed basing on the relationship [22]:

$$tg\Phi = \frac{\cos\gamma + 0.05K_h}{0.9K_h - \sin\gamma}. \tag{3}$$

The friction coefficient on the rake face μ, has been calculated with the application of the E.H. Lee and B.W. Shaffer's formula [22]:

$$\mu = tg\left(\frac{\pi}{4} - \Phi + \gamma\right). \tag{4}$$

Using the computer program and the PSI method, regression equations have been obtained; the influence of the cutting speed vc, and the feed f, on the chip thickening coefficient when turning the 316L austenitic steel has been shown in Fig. 3; the influence on the sliding angle in Fig 4; the influence on the friction coefficient on the rake face in Fig 5.

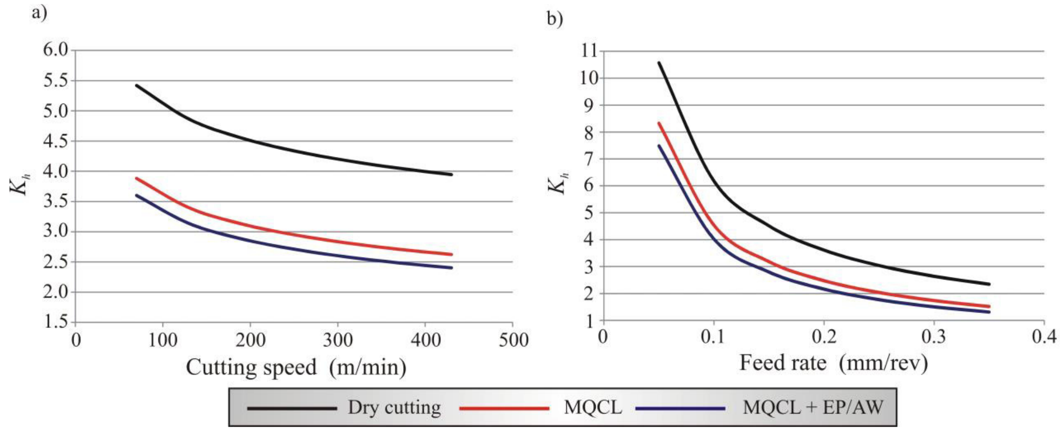

Fig. 3. The influence of the cooling method on the chip thickening coefficient, K_h, for $E = 0.29$ g/min and $P = 4$ l/min depending on: (a) variable cutting speed for $f = 0.15$ mm/rev; (b) variable feed for $v_c = 200$ m/min.

The lowest values of the chip thickening coefficient, in the whole range of the variable cutting parameters vc and f, have been obtained for cooling under the MQCL +EP/AW conditions (Fig. 3). The MQCL + EP/AW method reduces the K_h value for variable cutting speed (Fig. 3a) by about 32% to 40% as compared to dry machining and by 5% to 8% as compared the MQCL method. The value of the chip thickening coefficient decreases with the increase of the cutting speed and feed. For variable feed (Fig. 3b), smaller differences (by up to 28%) of the chip upsetting between the selected cooling methods have been found.

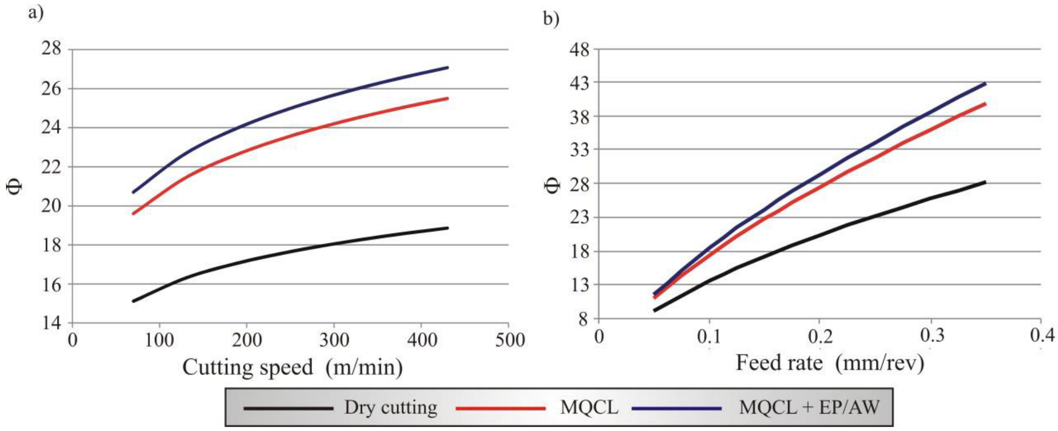

Fig. 4. The influence of the cooling method on the sliding angle Φ, for $E = 0.29$ g/min and $P = 4$ l/min depending on: (a) variable cutting speed for $f = 0.15$ mm/rev; (b) variable feed for $v_c = 200$ m/min.

With the increase of the cutting parameters (Fig. 4), the value of the sliding angle increases. In the whole range of the variable cutting speed, the highest values of the sliding angle have been obtained for the MQCL + EP/AW method; the lowest ones for dry machining.

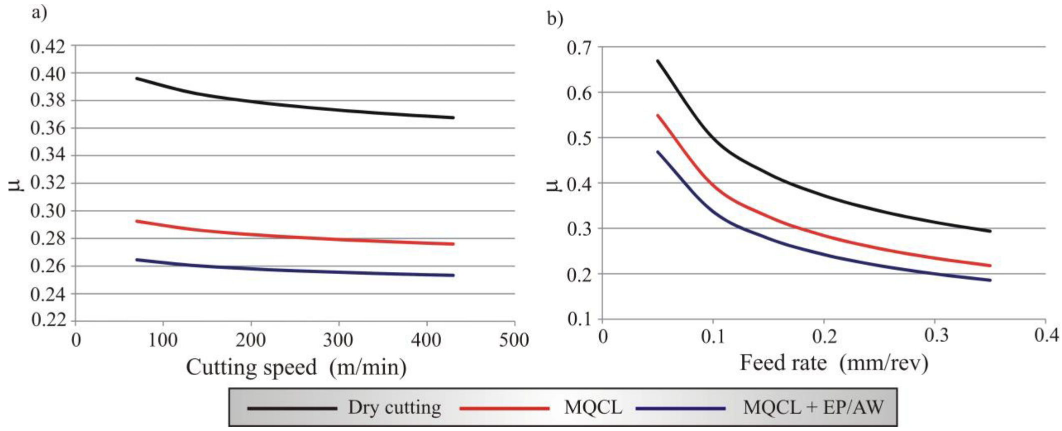

Fig. 5. The influence of the cooling method on the friction coefficient, μ, on the rake face for $E = 0.29$ g/min and $P = 4$ l/min depending on: (a) variable cutting speed for $f = 0.15$ mm/rev; (b) variable feed for $v_c = 200$ m/min.

In an analysis of the values of the friction coefficient on the rake face (Fig. 5), it has been found that the lowest values have been obtained for cooling under the MQCL +EP/AW in the whole range of the variable cutting speed and feed. The MQCL +EP/AW method reduces the μ value by 28% to 36% as compared to dry machining and by 9% to 12% as compared to the MQCL method. Friction reduction on the chip-edge interface is due to the formation of a tribofilm on the cutting edge surface [1]. When the MQCL method is applied, it is possible to select such parameters of emulsion mist formation that all the droplet supplied to the cutting zone evaporate in 1 second [19, 24] and all the chemical compounds contained in the emulsion mist remain on the surface of the material under machining [19], the cutting edge and the chip thus reducing friction between the mating surfaces [1].

Figure 6 presents the percentage changes of μ parameter after turning 316L steel for various cooling methods depending on variable emulsion mass flow *E* and volumetric flow of air *P*.

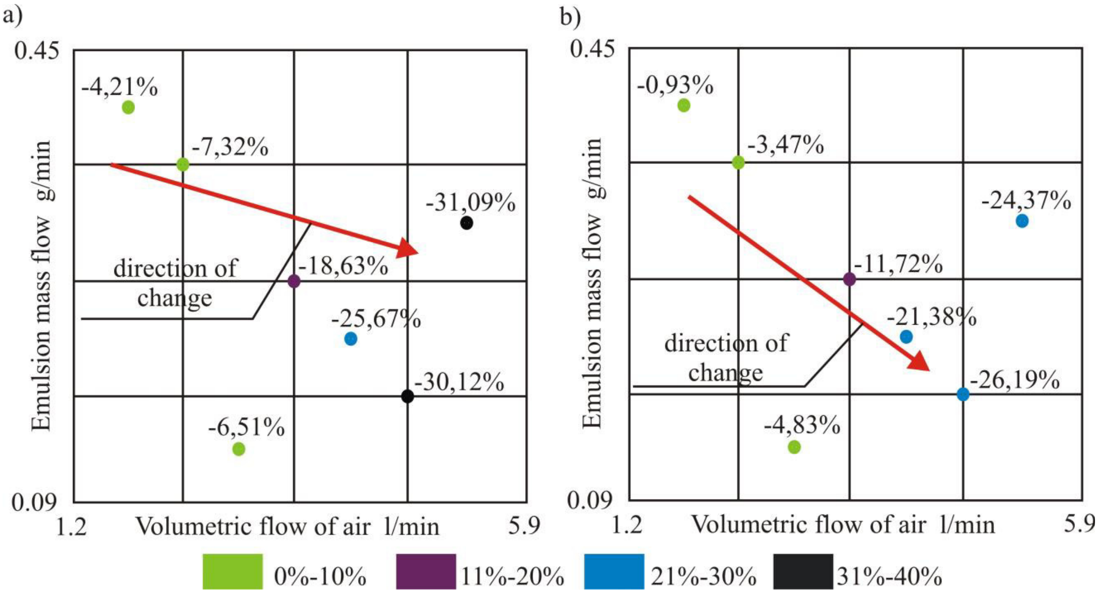

Fig. 6. Changes of the friction coefficient parameter on the rake face μ, after the process of turning 316L steel in dry machining as compared to cooling by: (a) MQCL; (b) MQCL + EP/AW.

Analysis of the percentage changes of the friction coefficient on the rake face (Fig. 6) has shown that reduction of the μ value, when the MQCL and MQCL + EP/AW methods are applied, is mostly influenced by the volumetric flow of air. The larger is the volumetric air flow, the larger are the percentage differences between dry machining and the MQCL and MQCL +EP/AW cooling methods. The mass flow emulsion does not significantly influence the change of friction in the zone of the edge contact with the chip. This is due to the fact that when the air flow is increased, the diameter of the droplets decreases [9, 19], which results in better penetration of the cutting zone. Droplets of smaller diameter are more advantageous, particularly for micro-machining applications where the cutting surface is relatively small [25].

4. Conclusions

Based on the experimental observations, the authors formulated the following conclusions:

- The most advantageous chip shape, for its easy removal from the cutting zone, has been obtained under the conditions of cooling by the MQCL method. With the application of the MQCL method, the range of cutting parameters for which chip in the form of short spirals or quite loose has been obtained has increased.
- The least values of the chip thickening coefficient K_h, the friction coefficient on the rake face μ, and the highest values of the sliding angle Φ, have been obtained for cooling by emulsion mist with the addition of EP/AW, which proves better conditions of the process of machining.
- Increase of the volumetric air flow results in decreasing of the friction coefficient with the application of the MQCL and MQCL +EP/AW methods as compared to dry machining, however, for low values of *P* = 1.2 – 2.0 l/min, the difference between the cooling conditions under consideration does not exceed 8%.
- The mass flow of emulsion does not a definite influence the value of the friction coefficient on the rake face.

References

[1] D. Setti, M.K. Sinha, S. Ghosh, P.V. Rao, Performance evaluation of Ti-6A1-4V grinding using chip formation, and coefficient of friction under the influence of nanofluids, Int. J. Mach. Tool. Manuf. 88 (2015) 237–248.
[2] J.M. Vieira, A.R. Machado, E.O. Ezugwu, Performance of cutting fluids during face milling of steels, J. Mater. Process. Tech. 116 (2001) 244–251.
[3] M.J. Hadad, T. Tawakoli, M.H. Sadeghi, B. Sadeghi, Temperature and energy partition in minimum quantity lubrication-MQL grinding process, Int. J. Mach. Tool. Manuf. 54–55 (2012) 10–17.
[4] E. Brinksmeier, J.W. Huntemann, Wirkmechanismen von Kuhlschmierstoffadditiven im Zerspanprozess, FVA Forschungsvorhaben nr. 4761, Heft 886, FVA, Frankfurt, 2009.
[5] M. Okada, A. Hosokawa, N. Asakawa, T. Ueda, End milling of stainless steel and titanium alloy in an oil mist environment, Int. J. Adv. Manuf. Technol. 74 (2014) 1255–1266.

[6] R.B. Da Silva, J.M. Vieira, R.N. Cardoso, H.C. Carvalho, E.S. Costa, A.R. Machado, R.F. De Avila, Tool wear analysis in milling of medium carbon steel with coated cemented carbide inserts using different machining lubrication/cooling systems, Wear. 271 (2011) 2459–2465.
[7] F. Klocke, L. Settineri, D. Lung, P.C. Priarone, M. Arft, High performance cutting of gamma titanium aluminides: Influence of lubricoolant strategy on tool wear and surface integrity, Wear. 302 (2013) 1136–1144.
[8] R.W. Maruda, S. Legutko, G.M. Krolczyk, P. Raos, Influence of cooling conditions on the machining process under MQCL and MQL conditions, Teh. Vjesn. 22 (2015) 965–970.
[9] K.H. Park, J. Olortegui-Yume, M.C. Yoon, P.Kwon, A study on droplets and their distribution for minimum quantity lubrication (MQL), Int. J. Mach. Tool. Manuf. 50 (2010) 824–833.
[10] F. Klocke, G. Eisenblätter, Dry Cutting, CIRP Ann. - Manuf. Technol. 46 (1997) 519–526.
[11] R.W. Maruda, S. Legutko, G.M. Krolczyk, S. Hloch, M. Michalski, An influence of active additives on the formation of selected indicators of the condition of the X10CrNi18-8 stainless steel surface layer in MQCL conditions, Int. J. Surf. Sci. Eng. 9 (2015) 452–465.
[12] F. Pusavec, D. Kramar, P. Krajnik, J. Kopac, Transitioning to sustainable production – part II: evaluation of sustainable machining technologies, J. Clean. Prod. 18 (2010) 1211–1221.
[13] T. Obikawa, Y. Asano, Y. Kamata, Computer fluid dynamics analysis for efficient spraying of oil mist in finish-turning of Inconel 718, Int. J. Mach. Tool. Manuf. 49 (2009) 971–978.
[14] T. Tawakoli, M.J. Hadad, M.H. Sadeghi, Influence of oil mist parameters on minimum quantity lubrication–MQL grinding proces, Int. J. Mach. Tool. Manuf. 50 (2010) 521–531.
[15] P. Hänle, D. Gsänger, MMS – gerechte Gestaltung des Bohrenschaftes. Werkstatt und Betrieb. 136 (2003) 54–56.
[16] U.M.R. Paturi, S.K.R. Narala, Experimental investigation to study the effect of electrostatic microsolid lubricant-coated carbide tools on machinability parameters in turning, Proc. I. .Mech. E., Part B: J Eng. Manuf. 229 (2015) 693–702.
[17] B. Vengudusamy, A. Grafl, F. Novotny-Farkas, T. Schimmel, K. Adam, Tribological behaviour of anti wea radditives used in hydraulic applications: Synergistic or antagonistic with other surface-active additives? Tribol. Int. l67 (2013) 199–210.
[18] L. Dobrzański, Metal Science and Heat Treatment, School and Pedagogical Publishers, Warsaw, 1997.
[19] R.W. Maruda, G.M. Krolczyk, E. Feldshtein, F. Pusavec, M. Szydlowski, S. Legutko, A. Sobczak-Kupiec, A study on droplets sizes, their distribution and heat exchange for minimum quantity cooling lubrication (MQCL), Int. J. Mach. Tool. Manuf. 100 (2016) 81–92.
[20] R.B. Statnikov, J.B. Matusov, Multicriteria Analysis in Engineering, Springer, 2002.
[21] F. Ducobu, E. Rivière-Lorphèvre ,E. Filippi, Materiał constitutive model and chip separation criterion influence on the modeling of Ti6A14V machining with experimental validation, in strictly orthogonal cutting condition, Int. J. Mech. Sci. 107 (2016) 136–149.
[22] V.P. Astakhov, J.C. Outeiro, Metal Cutting Mechanics, Finite Element Modelling, in: Machining. Fundamentals and Recent Advances. J. Paulo Davim (Eds.), Springer-Verlag, London, Limited, 2008.
[23] E.M. Trent, P.K. Wright, Metal Cutting. fourth ed, Butterworth-Heinemann, Woburn, 2000.
[24] R.W. Maruda, E. Feldshtein, S. Legutko, G.M. Krolczyk, Research on emulsion mist generation in the conditions of Minimum Quantity Cooling Lubrication (MQCL), Teh. Vjesn. 22 (2015) 1213–1218.
[25] M.B.G. Jun, S.S. Joshi, R.E. DeVor, S.G. Kapoor, An experimental evaluation of an atomization-based cutting fluid application system for micromachining, Trans. ASME, J. Manuf. Sci. Eng. 130 (2008) 031118-031118-8.