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Original scientific paper

ON THE EFFECT OF THE SIDE FLOW OF 316L STAINLESS STEEL IN THE FINISH TURNING PROCESS UNDER DRY CONDITIONS

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Abstract. *The article presents the results of the research on the plastic flow in the finish turning of 316L (X2CrNiMo17-12-2) stainless steel under dry cutting conditions. The steel was turned at variable cutting speeds and a constant depth of cut. The investigations were based on the Parameter Space Investigation method (PSI) which allowed minimizing the number of test points. It was observed that the phenomenon of slide flow occurred in the range of cutting speeds and feed rates under examination and its intensity depended on the values of these parameters. The phenomenon was more intense in the range of medium and higher cutting speeds and lower feed rates. The side flow results in significant changes between the real and theoretical values of roughness parameter Rz, which range from 40% up to even 330%.*

Key Words: *Side Flow, Stainless Steel, Finish Turning, Dry Cutting, Surface Layer*

1. INTRODUCTION

Due to its favorable mechanical and performance properties, 316L (X2CrNiMo17-12-2) stainless steel is one of the materials most frequently used in the manufacture of medical products as described by Fazel-Rezai [1] and Ramsden et al. [2]. Ristić et al. [3] as well as Singh et al. [4] informed that in many cases it is an alternative for titanium alloys, which are widely used in the production of medical devices. Supriya et al. [5] revealed that 316L stainless steel is characterized by a high cracking strength and fatigue strength index as well as by a high corrosion resistance. According Wegener et al. [6], this material is included among materials difficult to process on account of low quality of the surface obtained, quick wear of the tool, low efficiency and high costs of machining. This is caused by a high temperature in the cutting zone as described by Mia et al. [7]. In order to reduce the temperature, Maruda et al. [8] performed machining with the use of cutting fluids, which,

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however, have a negative impact on the human health and the environment. It is for this reason, according to Bagaber et al. [9], that dry cutting should be considered an optimal solution. However, dry cutting entails threats in the form of disturbances which cause imperfections that unfavorably affect the surface integrity as described by Acayaba et al. [10]. Suresh et al. [11] found that the side flow is one of such tribological disturbances which occur in the cutting zone. It depends on numerous factors, of which the feed rate, nose radius and tool wear are of major importance [12, 13, 14].

Pekelharing, and Gieszen [15] were among the first to identify the phenomenon of side flow and described its negative impact on the machined surface quality. According to Coelho et al. [16], side flow results in deformations of a part of the undeformed chip in a direction opposite to feed f and is caused by direct compression of the material by the minor flank and the work surface, when thickness h of the undeformed chip is smaller than so-called minimum undeformed chip thickness h_{min}. On the other hand, the minimum thickness of the undeformed chip depends on the values of feed rate f and cutting speed V_c, the hardness and structure of the material being machined and the geometry of the cutting wedge. As stated in Grzesik [17], the phenomenon of side flow can also be caused by the outflow of the material plasticized under high temperatures and high pressure values generated in the cutting zone and caused by a worn out cutting wedge.

Sivaiah and Chakradhar [18] investigated the influence of cryogenic cooling on 17-4PH stainless steel turning was compared with dry, wet and MQL conditions of machining. The following parameters were applied: V_c = 78.5 m/min, f = 0.147 mm/rev and a_p = 0.20 – 1 mm. Increased depth of cut resulted in an increment of surface roughness under all cooling conditions due to a rise in temperature in the cutting zone which brings about a higher tool wear. Side flow was observed both at lower and higher depths of cut.

Fernández-Abia et al. [19] analyzed the issues related to high performance machining of austenitic stainless steels and the phenomenon of side flow. It was determined that machining a material at a higher cutting speed resulted in the formation of side flow. A complete plasticization of the material being machined was reported to be the cause of side flow. As a result of plasticization the material partly flows from the major cutting edge towards the minor one.

Zou et al. [20] analyzed the mechanism of tool wear in the process of the finish turning of stainless steels, i.e., 17-4 PH martensitic and 321 austenitic steels. For both steels the following parameters of cutting were used: f = 0.10 mm/rev and a_p = 0.30 – 0.35 mm, whereas for 17-4 PH stainless steel: V_c = 350 – 400 m/min, and for 321 stainless steel: V_c = 300 – 350 m/min. For both stainless steels the phenomenon of slide flow was observed, in particular for 321 stainless steel. Similarly, Fernández-Abia et al. [19] determined that the occurrence of side flow was related to the action of high pressure and temperature in the contact zone of the chip with the cutting wedge, which as a result cause a complete plasticization of the material. Plasticization generates a partial flow of the material from the major to the minor cutting edge and its adhesive bonding to the freshly machined surface of a workpiece. According to the authors, a partial diffusion of 321 steel to the cutting wedge material takes place simultaneously with the side flow, but this opinion has not been verified by tests.

Liew et al. [21] investigated wear of tools made of PCBN in the turning process of AISI 420 modified stainless steel at low cutting speeds. It was determined that the phenomenon of side flow occurred at cutting speeds of 44 m/min and 130 m/min. As reported by Kishawy and Elbestawi [22], the analysis of the impact of process parameters on the phenomenon of side flow of a material being hard turned revealed a strong dependence of side flow on the material being machined on the cutting wedge features. An increase in the nose radius and its wear enhances side flow of the material, whereas the feed rate only slightly affects the intensity of the phenomenon.

The aim of the investigations presented herein is to determine the impact of the cutting speed and feed rate on the intensity of side flow in the finish turning process of 316L stainless steel under dry conditions.

2. CONDITIONS

316L (EN X2CrNiMo17-12-2) stainless steel of the chemical composition as illustrated in Table 1 was machined.

Table 1 Chemical composition of EN X2CrNiMo17-12-2 (EN 10088-:2014 standard)

Element	C	Cr	Fe	Mi	Mo	Ni	P	Si	S
%	≤ 0.030	16.0 – 18.0	61.9 – 72.0	≤ 2.0	2.00 – 3.00	10.00 – 14.00	≤ 0.045	≤ 1.0	≤ 0.030

The tests were performed on the CNC lathe, type CTX 510, manufactured by DMG MORI. A cutting tool with CoroTurn SDJCR 2525M11 holder and CoroTurn DCMX 11 T3 04-WM 1115 insert made of a cemented carbide type GC1115 with $(Ti,Al)N+(Al,Cr)_2O_3$ coating deposited by the PVD method. The geometry of the cutting edge was as follows: tool cutting edge angle κ_r = 93°, tool rake angle γ = 18°, tool clearance angle α = 7°, nose radius r_ε = 0.4 mm, land width of the face $b_{\gamma n}$ = 0.1 mm.

The cutting data were as follows: cutting speed in the range of 150 − 500 m/min, the feed rate in the range of 0.05 – 0.4 mm/rev, and constant depth of cut equal to 0.5 mm. These data correspond to the finish turning conditions.

Feifei et al. [23] claim that the plastic side flow contributes to the increment of the *Rz* (maximum height of the roughness profile) roughness parameter when elasto-plastic materials are machined. It was determined that when a material is turned at a feed rate *f* with a tool which has nose radius r_ε, the real value of parameter *Rz* can be significantly higher than the Rz_t value calculated according to the well-known equation [24]:

$$Rz_t = f^2/(8r_\varepsilon) \tag{1}$$

where *f* is the feed and r_ε is the nose radius.

The tests were planned on the basis of the Parameter Space Investigation method (PSI). The method allows planning an experiment with minimizing the number of test points, which are located in determined places in a multi-dimensional space, as Statnikov and Matusov described in [25]. It means that the test points projections on the X_1, X_2 , etc. axes are located at the same distance from one another (Fig. 1). The method has been successfully used for the investigation of cutting processes by Maruda et al. [8, 26].

The texture of the machined surface was analyzed with the use of an Alicona Infinite SL optical measuring system and the results of measurements were obtained using the IF-Laboratory Measurement Module software package.

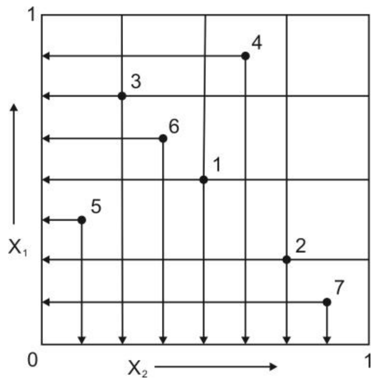

Fig. 1 Location of test points in a multi-dimensional space in accordance with the PSI method

Table 2 Coordinates of test points according to the PSI method

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

3. Results

A scheme of the side flow formation is presented in Fig. 2. When very thin chips are formed, the conditions which ensure a high or complete plasticization of the chip material are created.

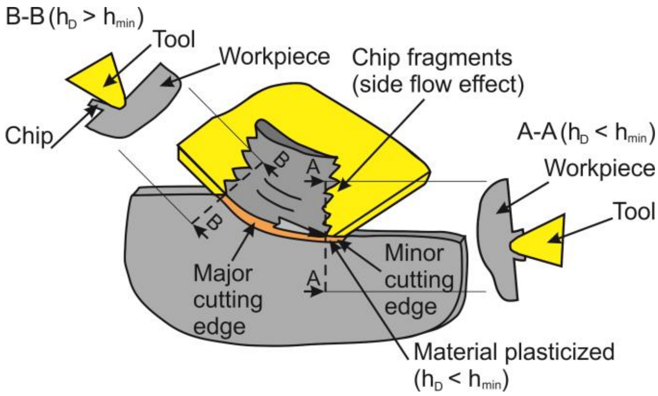

Fig. 2 The scheme of the side flow formation (based on [17])

Fig. 3 presents images of machined surfaces obtained for 7 test points in accordance with the PSI method. Side flow of the material was observed at each of the points. The intensity of the phenomenon was higher within the range of medium and higher cutting speeds and at lower feed rates (red color), whereas side flow was less intense in the whole range of cutting speeds, but at higher feed rates, which were within the range under examination (blue color).

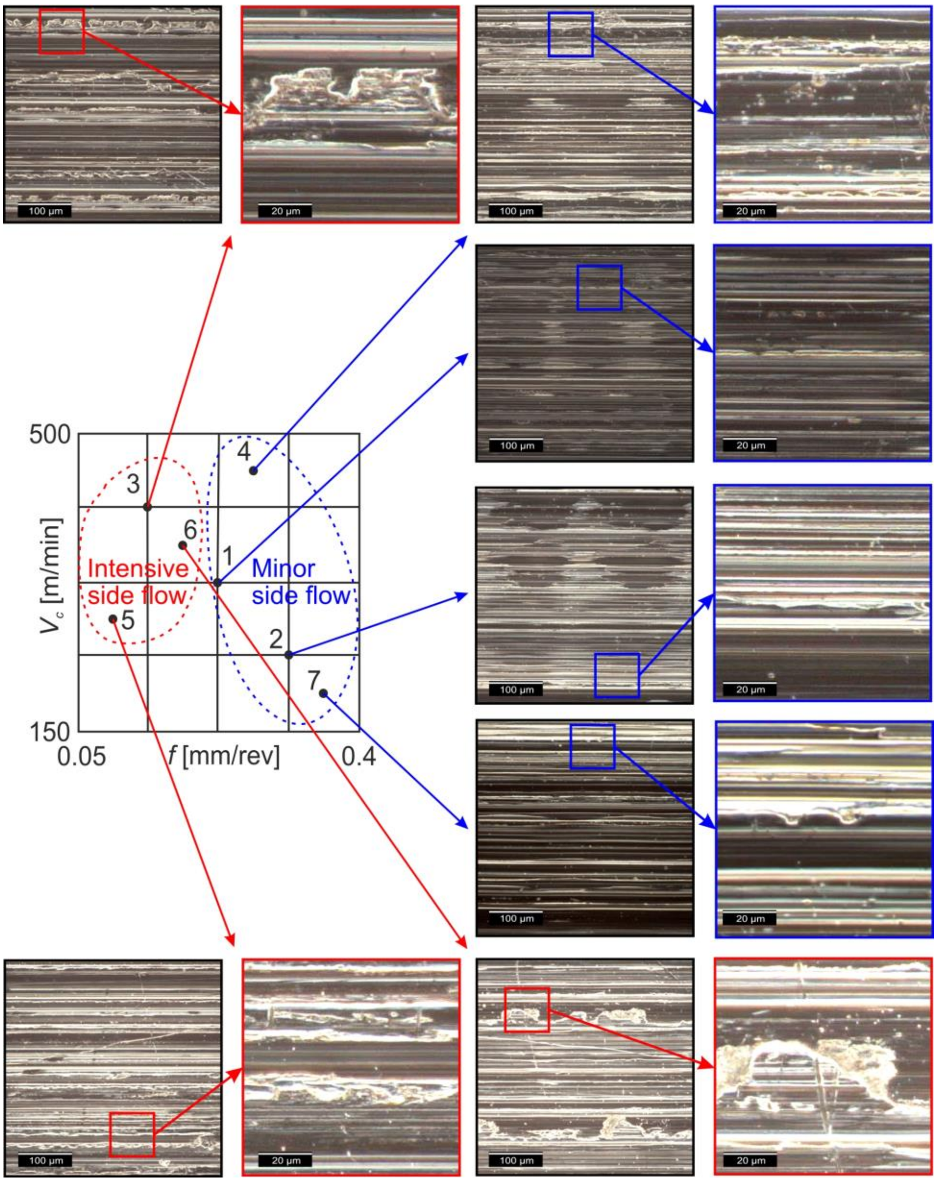

Fig. 3 2D images of 316L stainless steel machined surfaces

Fig. 4 presents 3D images of machined surfaces obtained for 7 test points in accordance with the PSI method. In the zone of an intense plastic side flow (red color) for higher cutting speeds and lower feed rates an irregular distribution of single burrs and a few clear areas of the flowing material were observed, whereas within the range of medium cutting speeds and lower feed rates side flow was regular on the whole length of the machined surface. In turn, in the zone of a slight intensity of plastic side flow (blue color) within the range of medium and higher cutting speeds and medium feed rates minimal and irregular side flow was observed, whereas within the range of lower cutting speeds and higher feed rates minimal side flow was observed on the whole length of the machined surface.

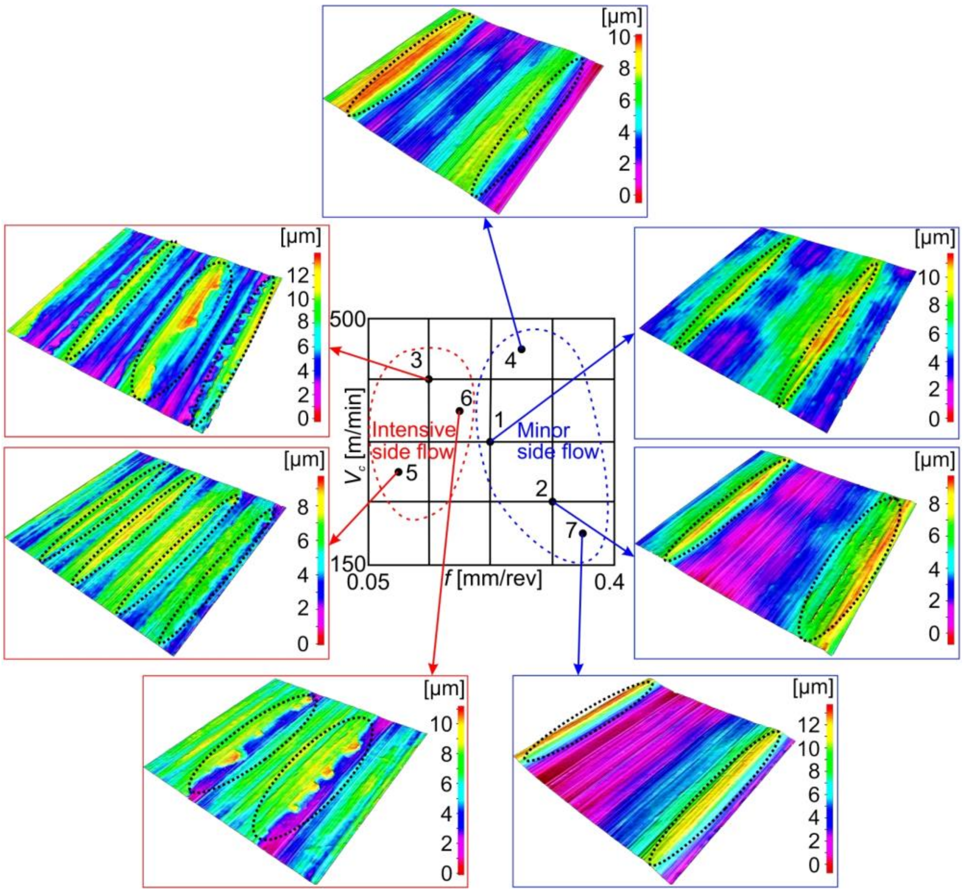

Fig. 4 3D images of 316L stainless steel machined surfaces

Fig. 5 illustrates surface roughness profiles and values of surface roughness parameter *Rz* obtained at individual test points in accordance with the PSI method. Lower values of surface roughness parameter *Rz*, from 3.58 μm to 4.42 μm were obtained at points 3,5,6 (blue color), medium, from 6.38 μm to 6.69 μm, at points 1 and 4 (green color), and maximum values, from 9.20 μm to 12.2 μm, were obtained at points 2 and 7 (red color). Thus, it follows that higher and medium cutting speeds from the range under examination and lower feed rates ensure a decrease of surface roughness parameter *Rz*, whereas higher feed rates cause its increase.

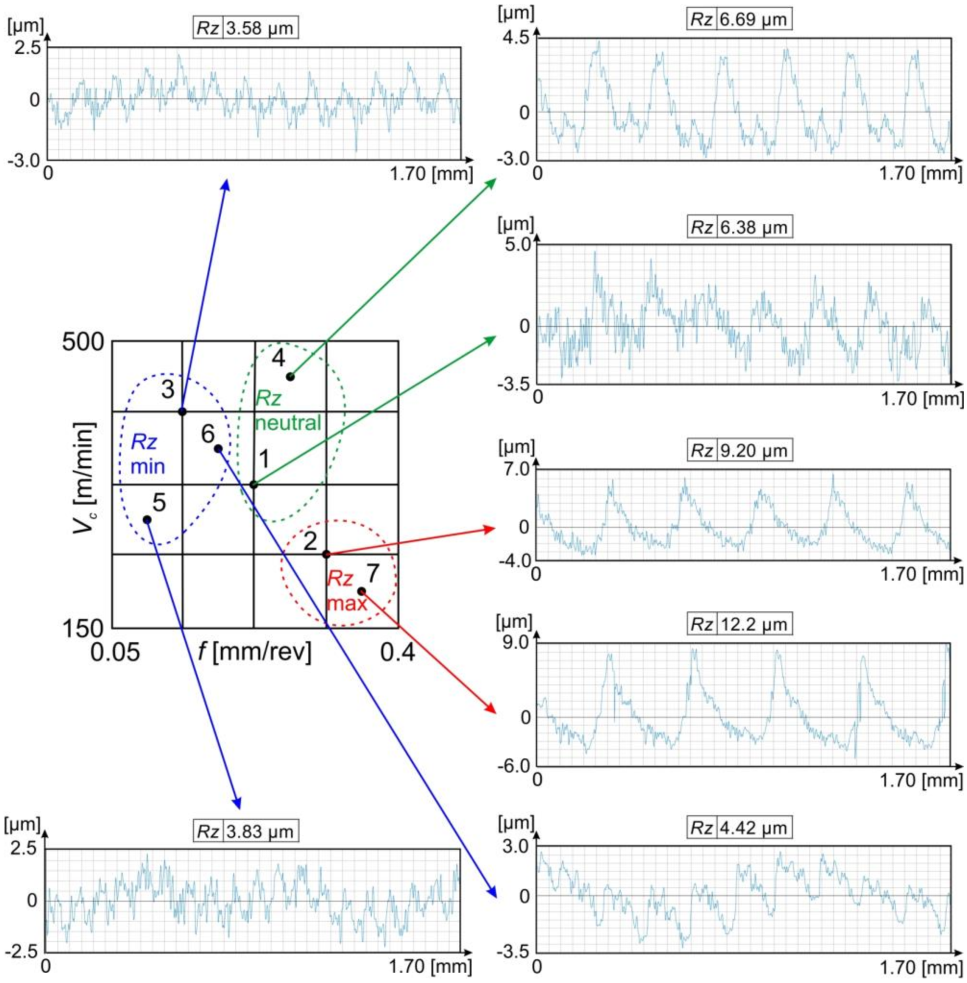

Fig. 5 Surface roughness profiles of 316L stainless steel

The real and theoretical values of surface roughness parameter *Rz* were also analyzed. Fig. 6 illustrates the percentage differences between them.

Significant differences between the real and theoretical values of roughness parameter *Rz* were observed. Within the range of higher cutting speeds and lower feed rates a decrease of the order of 40% in the real value of roughness parameter *Rz* was obtained. In the other ranges of machining parameters an increase from 40% up to 330% was achieved.

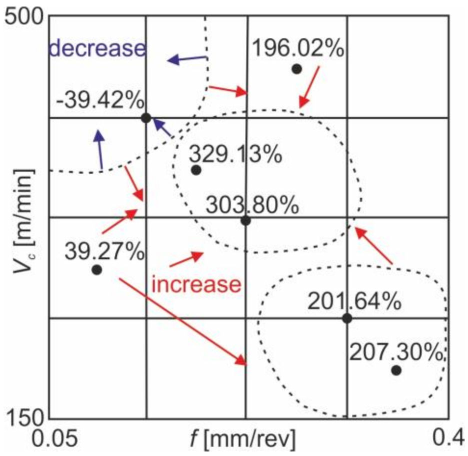

Fig. 6 Percentage differences between real values of surface roughness parameter *Rz* obtained after finish turning of 316L stainless steel compared to theoretical (t) values Rz_t

4. CONCLUSIONS

The paper presents the results of research on plastic side flow of 316L stainless steel (EN X2CrNiMo17-12-2) in the finish turning process under dry cutting conditions. The effect of the cutting speed and feed rate on the intensity of side flow was analyzed. The following conclusions are made:

- Plastic side flow of the material occurs within the whole range of cutting speeds and feed rates under examination.
- In the cutting speed ranges from 280-420 m/min and feed rates 0.1-0.2 mm/rev a higher intensity of plastic side flow was observed, whereas lower was obtained in the range of feed rates 0.1-0.2 mm/rev at cutting speeds 190-460 m/min.
- Surface roughness parameter *Rz* depends on the values of cutting speed and feed rate. Surface roughness parameter *Rz* decreased within the range of cutting speeds 280-420 m/min and feed rates 0.1-0.2 mm/rev, whereas it increased within the range of cutting speeds 190-460 m/min and feed rates 0.2-0.35 mm/rev.
- A significant difference, ranging from 40% up to even 330%, was noted between the real and theoretical values of surface roughness parameter *Rz.*

REFERENCES

1. Fazel-Rezai, R., 2011, *Biomedical engineering – from theory to applications*, In Tech, Rijeka.
2. Ramsden, J.J., Allen, D.M., Stephenson, D.J., Alcock, J.R., Peggs, G.N., Fuller, G., Goch, G., 2007, *The design and manufacture of biomedical surfaces*, Annals of the CIRP, 56, pp. 687–711.
3. Ristić, M., Manić, M., Mišić, D., Kosanović, M., Mitković M., 2017, *Implant material selection using expert system*, Facta Universitatis-Series Mechanical Engineering, 15(1), pp. 133–144.
4. Singh, D., Singh, R., Boparai, K.S., 2018, *Development and surface improvement of FDM pattern based investment casting of biomedical implants: A state of art review*, Journal of Manufacturing Processes, 31, pp. 80–95.

5. Supriya, S.B., Srinivas, S., 2018, *Machinability Studies on Stainless steel by abrasive water jet – Review*, Materials Today: Proceedings, ICAMA 2016, 5, pp. 2871–2876.
6. Wegener, K., Kuster, F., Weikert, S., Weiss, L., Stirnimann, J., 2016, *Success story cutting*, Procedia CIRP, 46, pp. 512–524.
7. Mia, M., Rifat, A., Tanvir, Md.F., Gupta, M.K., Hossain, Md.J., Goswami, A., 2018, *Multi-objective optimization of chip-tool interaction parameters using Grey-Taguchi method in MQL-assisted turning*, Measurement, 129, pp. 156–166.
8. Maruda, R.W., Krolczyk, G.M., Niesłony, P., Krolczyk, J.B., Legutko, S., 2016, *Chip formation zone analysis during the turning of austenitic stainless steel 316L under MQCL cooling condition,* Procedia Engineering, 149, pp. 297–304.
9. Bagaber, S. A., Yusoff, A.R., 2017, *Multi-objective optimization of cutting parameters to Minimize power consumption in dry turning of stainless steel 316,* Journal of Cleaner Production, 157, pp. 30–46.
10. Acayaba, G.M.A., Munoz de Escalona, P., 2015, *Prediction of surface roughness in low speed turning of AISI316 austenitic stainless steel*, CIRP Journal of Manufacturing Science and Technology, 11, 62–67.
11. Suresh, R., Basavarajappa, S., Gaitonde, V.N., Samuel, G.L., Davim, J.P., 2013, *State-of-the-art research in machinabilty of hardened steels. Journal of Engineering Manufacture*, 227(2), pp. 191–209.
12. El-Wardany, T.I., Elbestawi, M.A., 1998, *Phenomenological analysis of material side flow in hard turning: causes, modeling and elimination*, Machining Science and Technology, 2(2), pp. 239-251.
13. Weber, M., Hochrainer, T., Gumbsch, P., Autenrieth, H., Delonnoy, L., Schulze, V., Löhe, D., Kotschenreuther, J., Fleischer, J., 2007, *Investigation of size-effects in machining with geometrically defined cutting edges*, Machining Science and Technology, 11(4), pp. 447-473.
14. Weber, M., Autenrieth, H., Kotschenreuther, J., Gumbsch, P., Schulze, V., Löhe, D., Fleischer, J., 2008, *Influence of friction and process parameters on the specific cutting force and surface characteristics in micro cutting*, Machining Science and Technology, 12(4), pp. 474-497.
15. Pekelharing, A.J., Gieszen, C.A., 1971, *Material Side Flow in Finishing Turning*, Annals of the CIRP, 20(1), pp. 21–22.
16. Coelho, R.T., Diniz, A.E., de Silva, T.M., 2017, *An experimental method to determine the minimum uncut chip thickness (hmin) in orthogonal cutting,* Procedia Manufacturing, 10, 194–207.
17. Grzesik, W., 2011, *Mechanics of cutting and chip formation*, Machining of Hard Materials, Springer, pp. 87–114.
18. Sivaiah, P., Chakradhar, D., 2018, *Effect of cryogenic coolant on turning performance characteristics during machining of 17-4 PH stainless steel: A comparison with MQL, wet, dry machining*, CIRP Journal of Manufacturing Science and Technology, 21, pp. 86–96.
19. Fernández-Abia, A.I., García, J.B., López de Lacalle, L.N., 2013, *High-performance machining of austenitic stainless steels*, Machining and machine-tools: Research and development, pp. 29–90.
20. Zou, B., Zhou, H., Huang, C., Xu, K., Wang, J., 2015, *Tool damage and machined-surface quality using hot-pressed sintering Ti(C7N3)/WC/TaC cermet cutting inserts for high-speed turning stainless steels*. International Journal of Machine Tools and Manufacture, 79, pp. 197–210.
21. Liew, W.Y.H., Ngoi, B.K.A., Lu, Y.G., 2003, *Wear characteristics of PCBN tools in the ultra-precision machining of stainless steel at low speeds*, Wear, 254, pp. 265–277.
22. Kishawy, H., Elbestawi, M., 1999, *Effects of process parameters on material side flow during hard turning*, International Journal of Machine Tools and Manufacture, 39(7), pp. 1017–1030.
23. Feifei, X., Fengzhou, F., Xiaodong, Z., 2018, *Effects of recovery and side flow on surface generation in nano-cutting of single crystal silicon*. Computational Materials Science, 143, pp. 133–142.
24. Shaw, M., 2005, *Metal Cutting Principles-Oxford Series on Advanced Manufacturing*, Publ. Oxford University Press, New York, USA.
25. Statnikov, R.B., Matusov, J.B., 2002, *Multicriteria Analysis in Engineering*, Springer.
26. Maruda, R.W., Legutko, S., Krolczyk, G.M., Hloch, S., Michalski, M., 2015, *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*, International Journal of Surface Science and Engineering, 9, pp. 452–465.