AISI 304 stainless steel milling process state diagnosing

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Abstract. The article presents the results of works on the analysis of using cutting forces and torque to determine AISI 304 stainless steel milling process state. The research and analyzes were carried out for the determine tool state and the process state itself. The tests were performed using Sandvik milling head, equipped with 345R-1305M-PM 4230 inserts . This study presents and discusses the obtained results determining the resultant value of the minimum and maximum cutting forces and the tool life. The results of observations of the tool's condition were presented.

1 Introduction

Milling of high-alloy steels with high chromium or nickel content is common in the industry associated with the production of various types of processing tools. Due to the need to achieve high productivity during machining, machining parameters that result in a significant load on the cutting tool should be used. Carrying out machining with high volumetric machining efficiency is associated with a relatively short tool life, which in many cases is defined as few minutes.

The available literature includes many publications on determining machining forces, determining and modeling the state of the cutting process of high-alloy steels in terms of selecting process conditions, determining its state or analyzing load, tool wear [8, 13, 14, 25] or tool damage [5]. Machining of alloy steels, due to its alloy components that are difficult to cut, is generally problematic and requires the use of wear-resistant tools; attempts are also made to carry out machining in conditions different from standard ones, for example dry or using MQL [7,12,17,18,20,23]. At the same time, work is being carried out on modifying the cutting edge geometry [1, 11] or process modeling [21, 24].

Due to the significant machining costs, also resulting from tool costs, it seems reasonable to diagnose [15,16] or monitor the cutting edge condition, enabling tool optimal use and preventing tool damage and/or the workpiece surface [2,3,6,10 ,19]
Many works describe the use of force measurement or acoustic emission to determine the state of the process, mainly due to the cutting edges condition [4, 9, 13, 22].

2 Characteristics and diagnosing AISI 304 stainless steel milling processes state

An attempt was made to determine the suitability of the cutting force generated in the tool-holder-workpiece system during milling AISI 304 stainless steel process as state determine signal. Original results were compared to cutting edge state.

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2.1 General set-up, methodology and technique of experiment

The article presents the results of original studies using the Kistler 9257B dynamometer with the 5017 signal amplifier. Measuring stand; its setup and settings are presented in detail in [16].

AISI 304 stainless steel milling conditions were:

- dimensions : 40x40x140mm, 18mm removed (18 passes of 1mm each),
- tool: Sandvik milling head, 345R-1305M-PM 4230 inserts; sintered carbides with a TiCN+Al2O3+TiN coating applied using the CVD technique,
- cutting speed $v_c = 176$ m/min, feed rate $v_f = 460$ mm/min, cutting depth $a_p = 1$ mm, cutting width $a_e = 20$ mm,
- dry machining,
- down-cut and up-cut milling (milling in both directions).

The tests were carried out on a DMG DMU50 5-axis machining center, the workpiece was clamped in a vice attached to a force gauge. Orientation axis force gauge was consistent with the orientation axis machine tools.

Optical analysis of the drills was performed using a Keyence VHX-7000 digital stereoscopic microscope. The photos were captured at x100 magnification. Dimensions markers were placed in the drawings

2.2 Measurements results

Cutting force measurement results; F_x, F_y, F_z and torque M_z were depicted in the form of selected graphs of forces and torque values changes during dry AISI 304 stainless steel milling. A hardware low-pass filter of the amplifier 10 Hz and sample rate 100 Hz was used and post process filtration was used with low-pass filtration; edge frequencies – lower (-3dB) 1Hz and upper (-3dB) 100Hz. The results of the changes in the values of forces and torque were also presented on two summary charts (Fig.1,2). The machining conditions were selected on the basis of the analysis of the available literature and previous own work so as to obtain high process efficiency and standard tool wear. Fig. 1 shows force F_x, F_y, F_z and Fig.2 - torque M_z values changes during whole milling process [15,16].

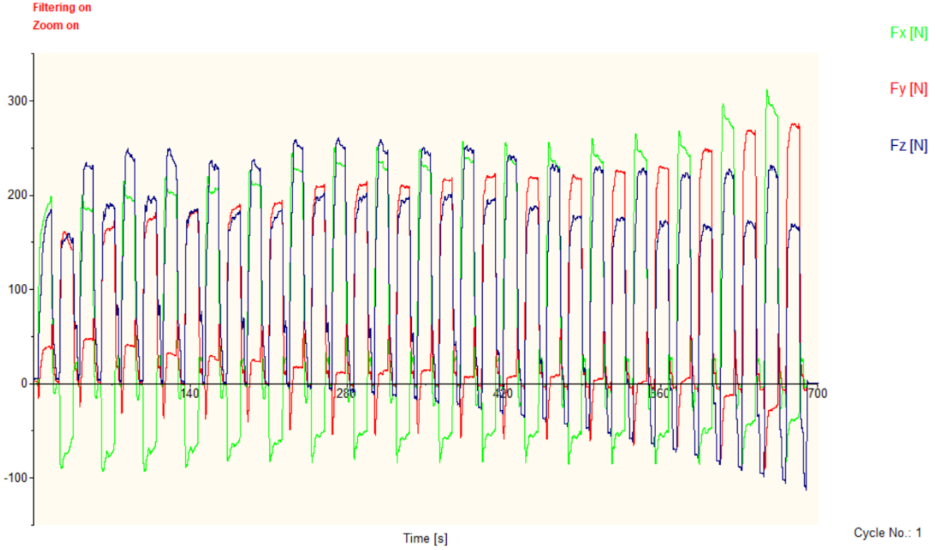

Fig. 1. F_x, F_y, F_z force values changes.

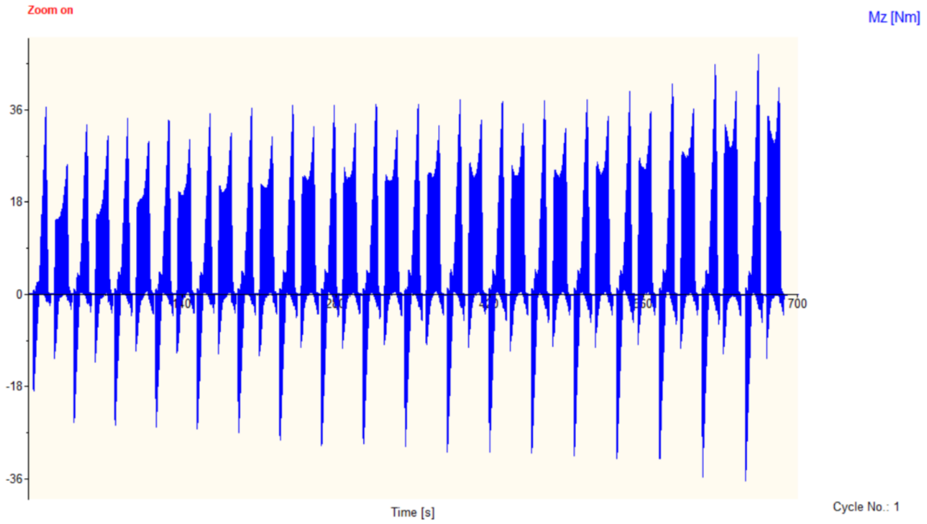

Fig. 2. M_z torque values changes.

The values of the total cutting force were determined from the relationship:

$$F_{tot} = \sqrt{F_x^2 + F_y^2 + F_z^2}, \text{N} \tag{1}$$

When determining the value of the total cutting force, the time drift of the force gauge was taken into account and eliminated. The obtained results of the total cutting force determined on the basis of measurements and transformations are presented graphically in Fig. 3.

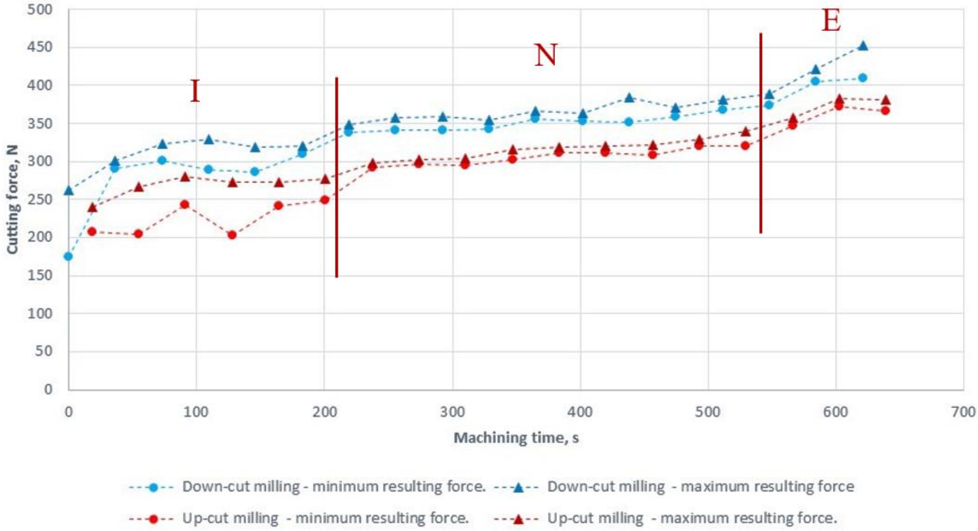

Fig. 3. Total cutting force F_{tot} values changes, I – initial wear zone, N – normal operation zone, E- excessive wear zone

Due to the decrease in the cutting force value during a single pass, the minimum and maximum force values were displayed. The direction of cuts of the cutting tool (down-cut and up-cut) was also taken into account, and thus the following output variables were determined:

- down-cut minimum resulting force,
- down-cut maximum resulting force,
- up-cut minimum resulting force,
- up-cut maximum resulting.

The analysis of the obtained results clearly indicated the occurrence of three characteristic zones, which can be attributed to different states of the cutting tool. The first zone, marked in Fig. 3 as I – initial wear zone , the second zone, marked as N is normal operation zone and the third zone, marked E to excessive wear zone. The obtained course of changes in the value of the total cutting force is consistent with the results obtained by the authors of other works [6, 24, 25].

To determine the durability period of the shortening edge, the formula (2) was used:

$$T_c = \frac{l}{v_f}, \text{min} \tag{2}$$

where:

T_c – blade durability, min,

l – cutting path in mm, determined as the product of the sample length and the number of passes to the end of zone N (fig. 3),

v_f – feed speed, mm/min.

$$T_c = \frac{30*140}{460} \approx 9min \tag{3}$$

The volumetric machining efficiency was also determined and was approximately 93 cm3/min.

A visual verification of the main cutting edge state, visible from the side of the rake plane and the flank surface of the firs insert (fig. 4) and second insert (fig. 5) cutting edge was carried out after making whole milling process. The places of the greatest tool wear (cutting edge chipping), resulting in a change in its geometry, are marked - indicated by red arrows and tool coating abrasive wear – indicated by yellow lines.

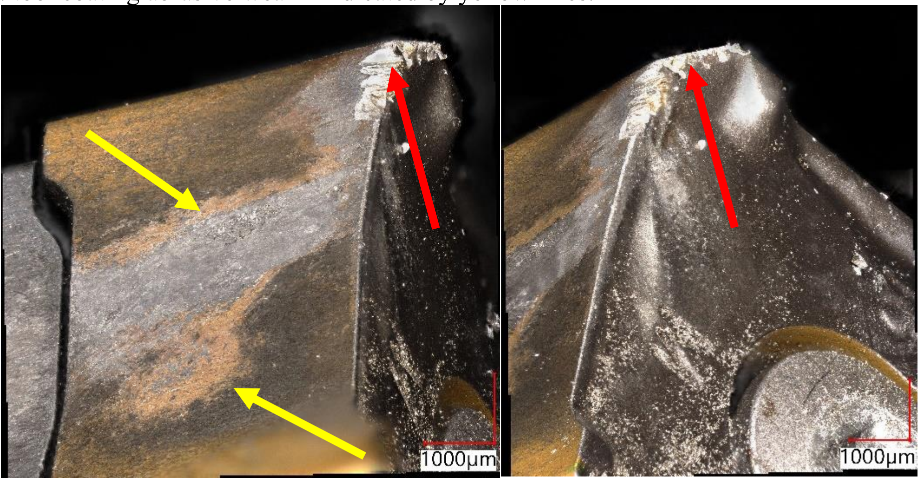

Fig. 4. Main cutting edges and surfaces view of first insert, description in text.

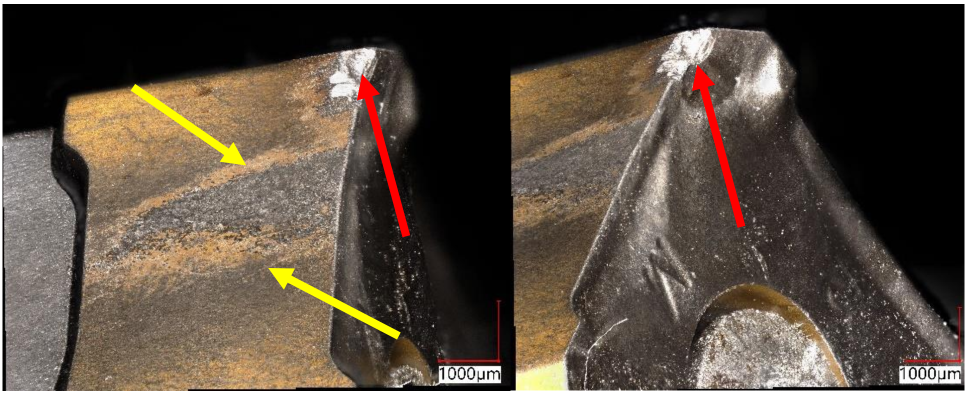

Fig. 5. Main cutting edges and surfaces view of second insert, description in text.

3 Discussion and conclusions

The tests of AISI 304 stainless steel milling resulted in tool wear and changes in the values of the measured quantities, i.e. cutting forces and torque, which were diagnostic signals of the state of the process. It was shown, similarly to previous works [15,16], that measurements of changes in the values of forces or torque can be a good diagnostic signal of the state of the cutting process. The experiment was stopped when increased force values were obtained in order to avoid catastrophic wear of the tool. The edge durability period obtained during the tests, approximately 9 minutes, was lower than expected, however, probably if the force values had not been measured, the processing would not have been interrupted; the increase in power demand observed at the same time (on the machine controller screen) was small and it is unlikely that in production conditions the operator would interrupt the processing due to such a small increase in power demand. Very intensive wear of the anti-wear multi-coat TiCN+Al2O3+TiN coating of inserts was observed. This indicates the abrasive nature of wear of the coating itself and the cutting edge. This form of wear was undoubtedly influenced by the processing conditions used; significant cutting speed, feed and dry machining. Cutting forces and torque online measurements enabled the critical condition in the form of accelerated wear of the cutting edge detection and prevented damage.

Based on the literature review and the results of own work, the following conclusions were formulated:

- online measurements of forces during the milling process of AISI 304 steel enabled supervision of the process and prevented damage,
- the durability period of the cutting edge under the conditions of the experiment was approximately 9 minutes and was shorter than the assumed durability period of the blade,
- force measurement systems require intervention in the processing zone and are cost-intensive, which translates into limited applicability of such solutions in industrial conditions.

References

1. K., A. Abou-El-Hossein, Z. Yahya, *High-speed end-milling of AISI 304 stainless steels using new geometrically developed carbide inserts*, Journal of Materials Processing Technology, 162–163, 596–602 (2005)
2. D. Bartona, J. Federhena, J. Fleischera, *Retrofittable vibration-based monitoring of milling processes using wavelet packet transform*, CIRPe 2020 – 8th CIRP Global Web Conference – Flexible Mass Customisation, Procedia CIRP 96, 353–358 (2021)

3. C. Bisua, L. Olteanua, R. Laheurteb, Ph. Darnisb, O. Cahucb, *Experimental approach on torsor dynamic analysis for milling process monitoring and diagnosis*, 8th CIRP Conference on Intelligent Computation in Manufacturing Engineering, Procedia CIRP **12**, 73 – 78 (2013)
4. C. Cooper, J. Zhang, R., X. Gao, P. Wang, I. Ragai, *Anomaly detection in milling tools using acoustic signals and generative adversarial networks*, Procedia Manufacturing, **48**, 372-378, (2020)
5. O. Gopkaloa, G. Bezlyudkob, V. Nekhotiashchiyc, O. Gopkaloa, Y. Kurasha, *Damage evaluation for AISI 304 steel under cyclic loading based on coercive force measurements*, International Journal of Fatigue, **139**, 105752 (2020)
6. J. He, Y. Sun, H. Gao, L. Guo, A. Cao, T. Chen, *On-line milling tool wear monitoring under practical machining conditions*, Measurement **222**, 113621 (2023)
7. V. Kharka, S. Mujumdar, S. Shukla, *Study on Helical Milling of SS 304 with Small Diameter Tools under the Influence of Minimum Quantity Lubrication (MQL)*, 51st SME North American Manufacturing Research Conference (NAMRC 51, 2023), Manufacturing Letters **35**, 1312–1317 (2023)
8. J. Liang, H. Gao, D. Li, Y. Lei, S. Li, L. Guo, L. Chen, Z. Leng, Y. Sun, C. Li, *Study on milling tool wear morphology and mechanism during machining superalloy GH4169 with PVD-TiAlN coated carbide tool*, Tribology International, **182**, 108298 (2023)
9. C., K. Madhusudana, H. Kumar, S. Narendranath, *Condition monitoring of face milling tool using K-star algorithm and histogram features of vibration signal*, Engineering Science and Technology, an International Journal, **19**, 1543–1551 (2016)
10. T. Mohanraj, S. Shankarb, R. Rajasekarc, N., R. Sakthivela, A. Pramanikd, *Tool condition monitoring techniques in milling process — a review*, Journal of Materials Research and Technology, **9**, Issue 1, 1032-1042 (2020)
11. P. Muthuswamy, *Investigation on sustainable machining characteristics of tools with serrated cutting edges in face milling of AISI 304 Stainless Steel*, Procedia CIRP, **105**, 865–871 (2022)
12. M. Naresh Babu, V. Anandan, N. Muthukrishnan, M. Santhanakumar, *End milling of AISI 304 steel using Minimum Quantity Lubrication*, Measurement, **138**, 681–689 (2019)
13. V., A. Pechenin, A., I. Khaimovich, A., I. Kondratiev, M., A. Bolotov, *Method of controlling cutting tool wear based on signal analysis of acoustic emission for milling*, Dynamics and Vibroacoustics of Machines (DVM2016), Procedia Engineering, **176**, 246 – 252 (2017)
14. G., M. Pittalàa, S. Rizzutia, *An investigation of the effect of tool wear on cutting force coefficients for solid end mills*, 19th CIRP Conference on Modeling of Machining Operations, Procedia CIRP, **117**, 444–449 (2023)
15. R. Polasik, J. Musiał, J. Jasik, I. Kovtun, A. Povareho, *Selected aspects of diagnosing material removal machining processes state*, MATEC Web Conf., **332**, 01014 (2021)
16. R. Polasik, A. Troszyński, B. Nowinka, S. Matiukh, *Diagnosing of the Glass Fiber Reinforced Polymer Material High Performance Drilling Process State*, MATEC Web Conf., **375**, 01003 (2023)
17. G. Pradeep Krishnan, D. Samuel Raj, *Machinability and tribological analysis of used cooking oil for MQL applications in drilling AISI 304 using a low-cost pneumatic operated MQL system*, Journal of Manufacturing Processes, **104**, 348–371 (2023)
18. A. Sakib, S. Saiful Islam, A. Naheen Ibn, M. Md Mirajul, M. Md Golam, *The influence of a newly developed refrigeration cycle based workpiece cooling method in milling AISI 304 stainless steel*, Results in Engineering, **20**, 101616 (2023)
19. A. Schustera, H. Rentzscha, S. Ihlenfeldta, *Energy self-sufficient, multi-sensory tool holder for sensitive monitoring of milling processes*, 19th CIRP Conference on Modeling of Machining Operations, Procedia CIRP, **117**, 80–85 (2023)

20. M. Stanford, P., M. Lister, K., A. Kibble, *Investigation into the effect of cutting environment on tool life during the milling of a BS970-080A15 (En32b) low carbon steel*, Wear, **262**, 1496–1503 (2007)
21. A. Uysal, I., S. Jawahir, *Analysis of slip-line model for serrated chip formation in orthogonal machining of AISI 304 stainless steel under various cooling/lubricating conditions*, Journal of Manufacturing Processes, **67**, 447–460 (2021)
22. K., A. Vikrama, Ch. Ratnamb, K., S. Narayanaa, *Vibration diagnosis and prognostics of Turn-milling operations using HSS and carbide end mill cutters*, 3rd International Conference on Innovations in Automation and Mechatronics Engineering, ICIAME 2016, Procedia Technology, **23**, 217 – 224 (2016)
23. K., K. Wika, P. Litwa, C. Hitchens, *Impact of supercritical carbon dioxide cooling with Minimum Quantity Lubrication on tool wear and surface integrity in the milling of AISI 304L stainless steel*, Wear, 426–427, 1691–1701 (2019)
24. H. Zhou, S. Gao, Y. Xie, C. Zhang, J. Liu, *Multi-condition wear prediction and assessment of milling cutters based on linear discriminant analysis and ensemble methods*, Measurement, **216**, 112900 (2023)
25. Y. Zou, K. Ding, K. Shi, X. Lai, K. Zhang, G. Ding, G. Qin, *Wear identification of end mills based on a feature-weighted convolutional neural network under unbalanced samples*, Journal of Manufacturing Processes, **89**, 64–76 (2023)