DOI: 10.21062/mft.2023.020 http://www.journalmt.com

Analysis of Cutting Forces during Machining with Additive-Produced Milling Head

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Today's milling cutting tools are produced in various types and shapes for a wide variety of machining processes. Development continues and offers new technological solutions. The design of replaceable milling heads offers a significant cost reduction, as only the worn-out part is replaced instead of the entire tool. The tough connection between the tool and the shank achieves stable performance in roughing and finishing milling. Because of the possibility of using different milling inserts, the number of necessary tools will also be reduced and the flexibility of using milling tools will increase. The article examines the cutting forces when machining a milling head produced by additive technology using composite Onyx material, which is reinforced with carbon fibre. The article deals with a comparison of two machined materials using a composite milling cutter and also contains a comparison with a conventional milling cutter.

Keywords: Cutting Forces, Milling Head, Additive Production

1 Introduction

The measurement of cutting forces during machining is an important point for optimalization of the producing operation. The identification of the cutting force is necessary for the determination of suitable cutting parameters. During the machining process design and its optimization, the cutting force stands for a critical design parameter, which means that process modelling and tool optimization are often utilized for cutting forces prediction to improve the total producing performance [1,2,3].

The analysis of the components of cutting forces is irreplaceable in industries, such as medical or aircraft production, for providing of top-level quality requirements. [4,5,6]. Significant cutting forces could potentially worsen the surface finish quality [7]. The total machining force F is the action force the tool exerts on the workpiece and at which it is pressed into the machined material. The machined material generates an equally large and inversely oriented resistive reaction force on the tool. [8,9]

Carbon fibre reinforced polymer (CFRP) composites are frequently used material in aerospace and industrial applications. Their properties are strength-to-weight ratio, stiffness, corrosion resistance and optimal performance under extreme conditions. The development of the design and the optimization of these materials are still the object of the research. [10] The parts produced by additive technology often suffer from poor surface quality and dimensional accuracy though. [11,12]

Moreover, some holes and pockets are difficult to be included in the design and it is needed to produce them in an extra operation. During this post-processing, including machining, is usually achieved a higher dimensional accuracy and better surface finish. Post-process machining of polymer composites can be difficult due to the various fibrous particles' orientation [13,14]. Along with an enlargement of expanding range of applications of fibre composites, the machining of these materials has become an important area for research. [15,16,17,18,19,20]

Doubts about how the material CFRP as a tool material will perform during the machining causing the research of its properties and selection of the proper cutting conditions.

2 Instruments, machines and used material

The aim of the experiment was to produce a cutter made of Onyx material with carbon fibre reinforcement (by CFF technology). Then produced cutter was exposed to various loads, there were measured the cutting forces during machining two materials: POM-C and Duraluminium. [21] These materials were chosen because their low surface roughness after machining with higher cutting speeds.

2.1 Mark Two desktop

A 3D printer that enables additive manufacturing from carbon fibre with an accuracy of 100µm. The parameters for the printed part are max 320 mm x 132 mm x 154 mm. It contains also Eiger software, which enables to print parts with the carbon fibre. [22]

2.2 Composite carbon-fibre material Onyx

Onyx is used as plastic material and the fibre are carbon, glass, Kevlar or HSHT fiberglass (High-Strength - High-Temperature). The layer height is standard 100 µm, maximum 200 µm. This material can be suitable for its properties for producing of machining tools. [23]

Tab. 1 *Some mechanical properties of Onyx [24]*

property	value and unit
density	1180 kg.m^{-3}
heat deflection temperature	145 ˚ C
tensile strength	36 MPa
flexural strength	81 MPa

2.3 HURCO VMX 30

Experimental machining was carried out on the HURCO VMX 30 vertical machining center. The parameters for the machining center are 1020x510 mm working surface, maximum machine load is 1000 kg, power 13.5 kW, 10.000-12.000 rpm^{-1} with a torque of 214 Nm.

2.4 POM-C material

Polyoxymethylene is a plastic with high strength and good mechanical and thermal properties similar to polyamides. Polyoxymethylene (Polyacetal, Polyformaldehyde, Acetal) is produced in two forms: homopolymer POM-H and copolymer POM-C. [25] It is a high-quality construction material with good strength and stiffness. It is suitable for production of precise and shape-complex engineering parts due to its good machinability.

Tab. 2 *POM-C material mechanical properties [26]*

property	value and unit
density	1140 kg.m^{-3}
melting temperature	165 ˚ C
tensile modulus of elasticity	2800 MPa
ball indentation hardness	150 MPa

2.5 Duraluminium

It is an alloy of aluminium (90-96%) with copper (3-6%) and magnesium and manganese additives. Duraluminium is five times stronger in tension and harder than pure aluminium. It is easy-to-machine. [27] The machined material was AlMg3, an aluminium alloy EN AW 5754, which has excellent corrosion resistance, especially against salt water and industrial pollution with the given properties: strength test: min. 60 MPa, tensile strength: 160-200 MPa, extension: min. 12%, Brinell hardness: 44 HB, melting temperature: 600 °C, modulus of elasticity: 68 GPa. Duralumin is quite soft, ductile and easily workable. It can be rolled, forged and extruded into various forms and products. Due to its light weight and high strength of duralumin im comparison to steel is usable for aircraft construction. [28]

Tab. 3 *Duralumin mechanical properties [29]*

property	value and unit
density	2780 kg.m^{-3}
melting temperature	570 ˚ C
ultimate tensile strength	450 MPa
Brinell hardness	120 BHN

2.6 Dynamometer KISTLER 9225A

The dynamometer collects data by means of electro analogue measurement of mechanical quantities (pressure magnification) of elastic cells. It has a high stiffness and therefore a high natural frequency. Its high resolution allows the smallest dynamic changes to be captured when measuring cutting forces. The dynamometer consists of four 3-component force transducers that are mounted under high bias between the base plate and the top plate. Each sensor contains three pairs of quartz plate crystals, one sensitive to pressure in the Z direction and the other two responding to forces in the X and Y directions. During experiment, the coordinate system of dynamometer and the coordinate system of the machine were synchronized. [30]

3 Design and production of the additive produced milling head

The presented milling cutter was designed as a simplified model of a conventional milling cutter. The created STL file is opened in the Eiger software (Fig. 1), which divides the given model into layers. This allows you to change its position, guide threads, create a support, and also includes various simulations that help prepare the model for printing. When the model was finished, the additive production starts, and its duration was 27 hours.

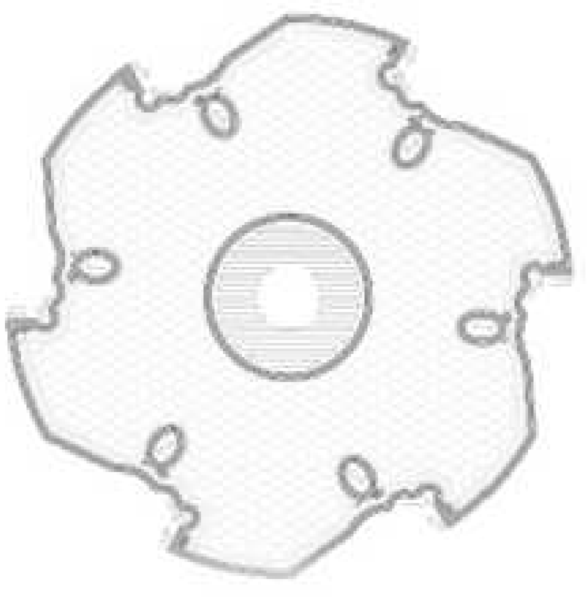

Fig. 1 *One layer of additive-produced milling cutter in Eiger software*

After removing the support structure, inserts were mounted onto milling head (Fig. 2).

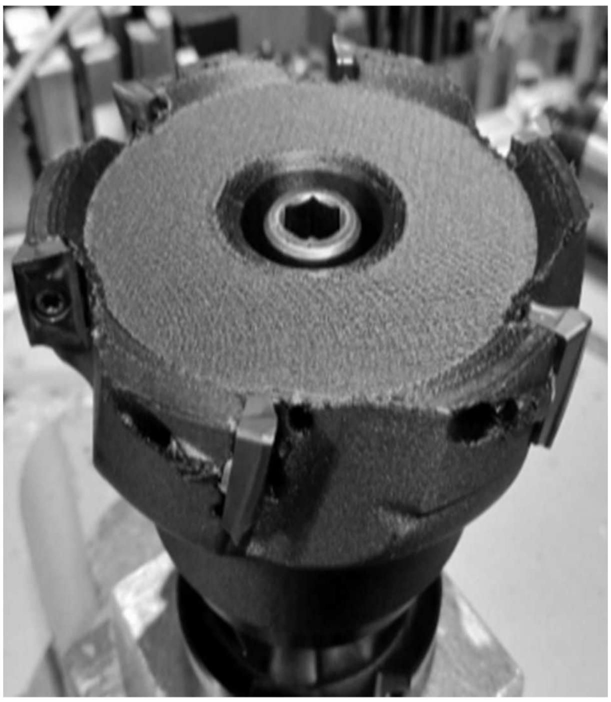

Fig. 2 *Additive produced milling cutter after mounting of inserts*

4 Experimental conditions

The milling cutter was mounted with the cutter fixture. Experiments were carried out on the HURCO.

VMX-30-t machining center. The cutting parameters were chosen due to some mechanical properties (high ductility and softness) and missing practical machining experience. The following cutting conditions were used for machining of material POM-C.

Tab. 4 *Cutting parameters for POM-C material machining*

experiment nr.	v_c (m.min^{-1})	f_z (mm)	a_p (mm)
1	200	0.025	2
2	400	0.01	2
3	400	0.025	2
4	400	0.025	1
5	400	0.025	3
6	400	0.04	2
7	600	0.025	2

Table 4 Cutting parameters for POM-C material machining - continue

For the machining of duraluminium were used the cutting conditions (Tab.5):

Tab. 5 *Cutting parameters for duraluminium material machining*

experiment nr.	v_c (m.min^{-1})	f_z (mm)	a_p (mm)
1	200	0.025	2
2	400	0.01	2
3	400	0.025	2
4	400	0.025	1

5 Evaluation of the experiments

The first experiment, material POM-C was machined. In the following picture (Fig.3) are showed cutting forces.

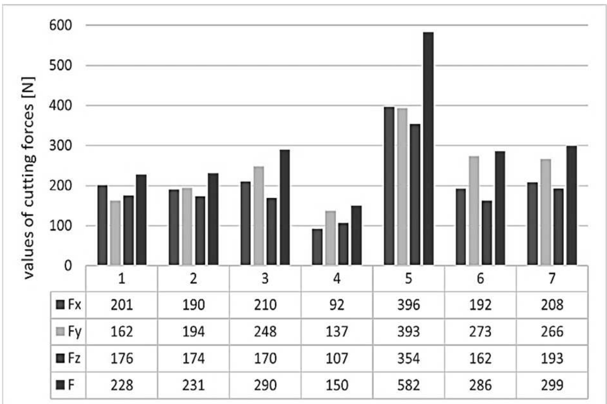

Fig. 3 *Cutting forces during machining of POM-C*

The highest value of Fx component was recorded in the experiment nr. 5 with cutting parameters v_c = 400 m.min^{-1}, f_z = 0.25 mm, and a_p = 3 mm. The highest value of Fy component was reached also in the experiment nr. 5 with the cutting parameters. At last, the component Fz, just as total cutting force F, had the highest value in the experiment nr. 5.

In the Fig. 4 are depicted cutting forces during the machining od Duraluminium.

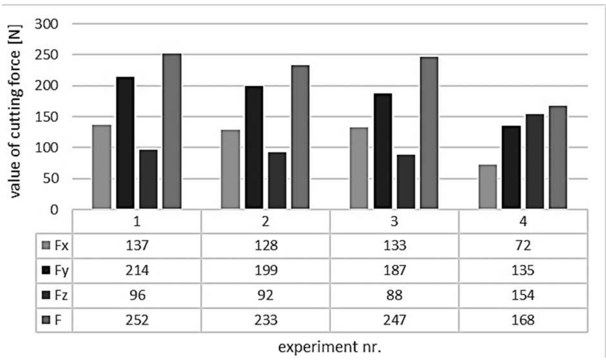

Fig. 4 *Cutting forces during machining of Duraluminium*

As the graph shows, Fx component's values are quite the same size. The highest value of this cutting-force-component was measured during the experiment nr. 1, with cutting parameters v_c = 200 m.min^{-1}, f_z = 0.25 mm, and a_p = 2 mm. The highest value of Fy component had the experiment nr. 1 with the cutting parameters, which are already mentioned above. The last component of cutting force – Fz reached the highest value in the experiment nr. 4 with cutting parameters v_c = 400 m.min^{-1}, f_z = 0.25 mm, and a_p = 1 mm. The total cutting force has similar values in experiments nr. 1, 2 and 3. To compare cutting forces of two different milling cutter, there was used a conventional milling cutter. In the following graph (Fig.5) are depicted total cutting forces of the both materials, Duraluminium and POM-C during milling with conventional milling cutter and Onyx milling cutter head.

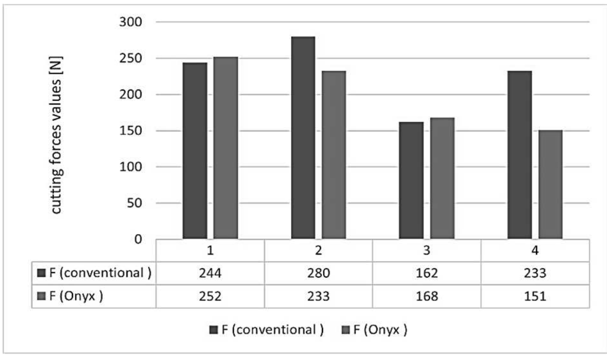

Fig. 5 *Average of maximum cutting forces of when machining Duraluminium using conventional cutter and Onyx milling head*

As the graph shows, the differences between total cutting forces were quite low. The experiment nr. 4 (35.2%) and nr. 2 (16,8%) show variation.

6 Conclusion

The presented article was focused on the analysis of cutting forces during milling using additive-produced milling head. Although vibration measuring was not included during machining, it can be assumed their influence on the cutting forces and quality of surface.

Based on experimental results of direct measurements of machining force components with a dynamometer during milling of POM-C material, it can be summarized:

- The highest values of the cutting-forces-components were: Fx = 396 N, Fy = 393 N, Fz = 354 N and total cutting force F =582 N. All these highest values of total cutting force and components were recorded in experiment nr. 5, which means that during maximal selected cutting parameters (v_c = 400 m.min-1,f_z = 0.25 mm, and a_p = 1 mm) were detected the highest cutting force.

For machining of Duraluminium, the following values are recapitulated:

- The highest values of the cutting-forces-components were: Fx = 137 N and Fy = 393 N in experiment nr. 1, Fz = 154 N in experiment nr. 4 and total cutting force F =252 N in experiment nr. 1.

For comparison, a conventional milling head was used for machining to record its cutting forces. The difference between total cutting forces of conventional and additive-produced milling head were quite low (experiment nr. 4: 35.2 % and nr. 2: 16.8 %). The main cause of achieved forces was a low Onyx milling head vibration due to its low mass and density in comparison to mechanical properties of conventional milling cutter.

The article presented the application of additive technologies (3D printing) on a modified conventional milling head made of non-metallic composite materials. According to the chosen materials, it is a form of practical verification of its mechanical properties, because of the fact that Onyx with reinforcing fibers has mechanical properties (stiffness, strength, but not resistance to higher temperatures) comparable to steels (from which conventional milling heads are routinely made). At the same time, a comparison with a similar conventional milling head was made to demonstrate that such an application of a composite milling tool is possible. The use of data is important for the further research of additive-produced milling tools, because of possibilities of the coating, different composite tool material using and vast number of various tool shapes.

Acknowledgement
This article was funded by the University of Žilina project 313011ASY4 – "Strategic implementation of additive technologies to strengthen the intervention capacities of emergencies caused by the COVID-19 pandemic."

References

[1] LEAL-MUÑOZA, E., DIEZ, E., PEREZ, H., VIZAN, A. (2018). Accuracy of a new online method for measuring machining parameters in milling. In: *Measurement*, Vol. 128, pp. 170-9, ISBN 0263-2241

[2] MEHDI K, ZGHAL A. (2012).Modelling cutting force including thrust and tangential damping in peripheral milling process. In: *Int J. Mach. Mach. Mater.*; Vol. 12, Nr. 3, ISBN 17485711

[3] WAN ,M., YIN, W., ZHANG, W.H. (2016). Study on the correction of cutting force measurement with table dynamometer. 9th Int. Conf. on Digital Enterprise Technology-DET2016 "Intelligent Manufacturing in the Knowledge Economy Era" *Procedia CIRP*, Vol. 56, pp.119-123

[4] DANIS, I.; MONIES, F.; LAGARRIGUE, P.; WOJTOWICZ, N. (2016).Cutting forces and their modelling in plunge milling of magnesium-rare earth alloys. In: *Int. J. Adv. Manuf. Technol.*, Vol. 84, pp.1801–1820, ISSN 02683768

[5] MONIES, F.; DANIS, I.; LAGARRIGUE, P.; GILLES, P.; RUBIO, W. (2016). Balancing of the transversal cutting force for pocket milling cutters: Application for roughing a magnesium-rare earth alloy. In: *Int. J. Adv. Manuf. Technol.*, Vol.89, pp. 45–64., ISSN 02683768

[6] SAPTAJI, K.; GEBREMARIAM, M.A.; AZHARI, M.A.B. (2018).Machining of biocompatible materials: A review. In: *Int. J. Adv.Manuf. Technol.*, Vol. 97, ISBN 2255–2292

[7] SOUTIS C. (2005). Fibre reinforced composites in aircraft construction. In: *Prog Aerosp. Sci.*;Vol. 41, Nr.2, pp.143–51. ISSN 03760421

[8] ŠAJGALÍK, M.; KUŠNEROVÁ, M.; HARNIČÁROVÁ, M.; VALÍČEK, J.; CZÁN, A.; CZÁNOVÁ, T.; DRBÚL, M.; BORZAN, M.; KMEC, J. (2020). Analysis and Prediction of the Machining Force Depending on the Parameters of Trochoidal Milling of Hardened Steel. In: *Applied Sciences*, Vol. 10, No. 5, pp. 1788, ISSN 20763417

[9] LI, Y.; ZHENG, G.; ZHANG, X.; XU, R.(2019). Cutting force, tool wear and surface roughness in high-speed milling of high-strength steel with coated tools. In: *J. Mech. Sci. Technol.*, Vol.33, pp.5393, ISSN 19763824

[10] COCOCCETTAA, N.M., PEARLA, D., JAHANA, M.P., MAB, J.(2020). Investigating surface finish, burr formation, and tool wear during machining of 3D printed carbon fiber reinforced polymer composite. In: *Journal of Manufacturing processes,* Vol. 56. pp. 1304-1316, ISSN 15266125

[11] SADÍLEK, M., KOUSAL, L., NÁPRSTKOVÁ, N., SZOTKOWSKI, T., HAJNYŠ, J.(2018). The Analysis of Accuracy of Machined Surfaces and Surfaces Roughness after 3axis and 5axis Milling. In*: Manufacturing Technology*. Vol. 18, No. 6, ISSN 1213–2489

[12] MAREK, M., NOVÁK, M., ŠRAMHAUSE, K.. (2019). The Impact of Changes in Feed Rate on Surface. In: *Manufacturing Technology*. Vol. 19, No. 3, ISSN 1213–2489

[13] CALZADA, K.A., KAPOOR, S.G., DEVOR, R.E., SAMUEL, J., SRIVASTAVA, A.K. (2012).Modeling and interpretation of fiber orientation-based failure mechanisms in machining of carbon fiber-reinforced polymer composites. In: *J. Manuf. Processes*, Vol. 14, No.2, pp.141–9, ISBN 978-0-7506-8287-9

[14] DU, J., GENG, M., MING, W., HE, W., MA, J. (2021). Simulation machining of fiber-reinforced composites: a review. In: *Int J. Adv. Manuf. Tech.*, Vol. 117, No.1-2, pp. 1-15, ISSN 02683768

[15] KOPLEV A. (1980). Cutting of CFRP with single edge tools. In: *Proc. Adv. Compos. Mater.*, Vol. 14, No.4, pp. 371-376, ISBN 1597605

[16] MUKHYOPADHYAY, M.(2004). *Mechanics of composite materials and structures.*, 2nd ed. Hyderabad: India; ISBN 8173714770

[17] BARBERO, E.J.(2008).*Introduction to composite materials design*. 2nd ed. London: New York; ISBN 9781138196803

[18] HOCHENG, H, TSAO, C.C.(2006*)*.Effects of special drill bits on drilling-induced delamination of composite materials. In: *Int. J. Mach. Tools. Manuf.*; Vol 46, No. 12-13. pp. 1403-1416. ISSN 08906955

[19] PALANIKUMAR, K., PRAKASH, S., SHANMUGAM, K. (2007). Evaluation of delamination in drilling GFRP composites. In: *Mater. Manuf. Process*. Vol. 23, pp. 858-864, ISSN 10426914

[20] DEMENG, C., ISHAN, S., PEIDONG, H., PING, G., KORNEL, E.F.(2014). Machining of carbon fiber reinforced plastics/polymers: a

literature review. In: *J. Manuf. Sci. Eng.* Vol. 136. No. 3, ISSN 10871357

[21] GROFČÍK, L.(2019). *3D Printed Tool Holder Prototype Design.* Diploma thesis.Žilinská univerzita v Žiline.

[22] Mark two desktop [Online], [Visited 23.32023]: https://markforged.com/3d-printers/mark-two

[23] Mark two desktop [Online], [Visited 23.32023]: https://static.markforged: static.markforged.com

[24] Material Onyx [Online], [Visited 23.32023]: https://plmgroup.eu/articles/material-guide-markforged-onyx/

[25] POM-C material: [Online], [Visited 23.32023]: www.techplasty.sk

[26] POM-C material properties: : [Online], [Visited 23.32023]: https://enkop.eu/

[27] Duraluminium: [Online], [Visited 23.32023]: www.alfun.cz

[28] Duraluminium: [Online], [Visited 23.32023]: www.ehlinik.cz

[29] Duraluminium material properties: [Online], [Visited 23.32023]: https://material-properties.org/

[30] Dynamometer KISTLER 9225A [Online], [Visited 23.32023]: www.kistler.com