Machinability Assessment Of 3D-Printed CoCrMo Plate: Influence Of Micro-drill Bit Designs

Mohd Affifudin Abdul Patar[1*], Mohd Azlan Suhaimi[1], Safian Sharif[1], Denni Kurniawan[2], Amrifan S Mohruni[3], and Zhuang Kejia[4]

[1] Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia.
[2] Faculty of Engineering, Universiti Teknologi Brunei.
[3] Faculty of Mechanical Engineering, Universitas Sriwijaya, 30128, Kota Palembang, Sumatera Selatan, Indonesia.
[4] School of Mechanical and electronic Engineering, Hubei Digital Manufacturing Key Laboratory.
[*] Corresponding author. E-mail: affifudinabdulpatar@gmail.com

Received: Oct.17, 2023; Accepted: Dec. 18, 2023

Cobalt chromium molybdenum (CoCrMo) is a hard-to-cut material widely utilized in the fields of medical, biotechnology, and aerospace engineering due to its exceptional combination of properties, including high strength, toughness, wear resistance, and low thermal conductivity. However, some of these attributes of CoCrMo often pose obstacles to its machinability, leading to rapid tool wear and a shortened tool life. Therefore, this paper investigates the impact of different micro drill tool designs (denoted as S and EZ by the manufacturer) with alteration to its point angles with constant machining parameters on the forces and wear when micro drilling CoCrMo. Three-dimensional (3D) printed CoCrMo plates are fabricated using the Selective Laser Sintering (SLS) process, and custom design tool bits with preferred geometries are also prepared. Output forces are measured using a dynamometer, while wear is assessed through optical microscopy. EZ design tool outperforms the S-design tool due to the significantly lower magnitude of thrust forces of 131.86 N at 118° point angle it generates. While S type tool design at the same angle produces 508.72 N thrust force output. Lower forces are anticipated to result in a reduced wear rate for the tool, potentially extending its lifespan. The lowest wear rate was by EZ type tool at 118° with only 0.122 m while S type tool at the same has a maximum average wear of 0.231 . The relationship between forces and wear are directly proportional.

Keywords: Selective Laser Sintering, Micro Drilling, Cobalt Chromium Molybdenum, Tool Wear.

©The Author('s). This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are cited.

http://dx.doi.org/10.6180/jase.202411_27(11).0004

1. Introduction

Cobalt Chromium Molybdenum (CoCrMo) alloy is widely employed in medical applications, particularly in the production of medical devices and surgical implants. This preference is due to its exceptional biocompatibility, high mechanical strength, and chemical resistance [1]. Typically, this alloy is cast and, to a lesser extent, forged to achieve the desired component geometry. Subsequent machining operations are necessary to attain the required geometric tolerances and surface finish. However, similar to other hard-to-machine materials like nickel and titanium alloys, CoCrMo exhibits reduced machinability [2]. Poor machinability is manifested through an increased wear rate and compromised surface integrity of parts and components, directly affecting their performance over their service life. Cobalt is a material used to increase the bonding strength of the diamond cutting tool. It develops and excellent interfacial strength between the atoms. Liao and Axinte [3] reported that bone micro drilling is and increasing demand in the medical industry. A challenge posed by the machining procedure is to control the stability in the drilling operations. We could not theoretically reduce the human error in drilling operations but we could reduce the machining output such as chip and debris formation by choosing the right design for tool [3]. CoCrMo is also well known to be a material with great features to be used as implants in surgical due to its chemical stability.

Numerous studies have been conducted on conventionally manufactured CoCrMo [1, 2, 4–7], but there is limited research on 3D printed variants, particularly within the micro drilling domain. Previous investigations have explored various aspects, including the influence of machining parameters, residual stress, and surface roughness, as well as the effects on surface integrity. CoCrMo is the first alloy made based on cobalt which was founded in 1907 and this material was the first to be considered suitable for dental application, mainly due to the resistance in mouth cavity [8]. Furthermore, cobalt based heart valves were first implanted in 1960s and the lifespans of this material lasted for about 30 years in the organism. Looking at the biomedical view of cobalt chromium superalloy, there are obvious advantages as well as some disadvantages reported by researchers [9–14]. The composition of this alloy enables the fabrication of extremely hard, non-magnetic, wear resistant and heat resistant implants. These implants also have high resistance to corrosion in body fluids. A micro drilling study involving Magnesium (Mg) as a chemically inert metal similar to CoCrMo for biomedical purposes had been conducted by Tools [15]. In the study the tool diameters, cutting speed and feed were varied to verify the appropriate parameters for machining. The outputs from the study were surface integrity involving diameter, burr height and surface roughness. It is found out that as the cutting speed is increased, the burr heights are also increased, this is due to the thermal effect which plasticizes Mg.

The previous studies on micro drilling 3D printed plates were never off CoCrMo. The drill bits designs was the company High Precision Machining Tool (HPMT) [16] own design, which also meant that it has never been used on the application of micro drilling CoCrMo plates. The combination of tool designs and tool point angle variations were also not been used in any studies before. However, to the best of the author's knowledge, there is a lack of references regarding the impact of tool types on micro drilling in 3D printed CoCrMo plates. Krishnan et al. [17] stated that tool designs and drilling parameters are important to improve the tool wear rate when conducting a study on steel multilayer cladding. From the study on drilling magnesium AZ91D alloys, Hassan et al. [18] stated that point angles are an important factor which significantly affect the hole quality.

Therefore, the primary objective of this paper is to provide insight towards the machinability of 3D printed CoCrMo when employing different designs and geometry of micro drill bits using fixed machining parameters. To achieve this objective, a series of micro drilling experiments were conducted under flood cooling conditions until reaching the tool life criterion, defined by the critical value of flank wear or the maximum allowable number of holes drilled. The study closely examines and analyzes output thrust forces and tool wear to ascertain the influence of micro drill tool designs and geometries. The findings of this study will help the drilling operations of 3D-printed CoCrMo Plate in the future by reducing the machining cost and time. This is due to the better design chosen will have a better tool life and machining output.

2. Materials and methodology

The ASTM F1537 cobalt chromium molybdenum alloy was obtained through the selective laser sintering (SLS) additive manufacturing process. The material is fabricated by using Renishaw RenAM 500 3D printer, with parameters of 40μm layer thickness, optimised for single laser per part, continuous laser wave mode and 190m^3/h gas flow rate. Custom plates measuring 60mm $\times$ 60mm $\times$ 4mm were fabricated by the 3D Gens Company in Malaysia, as depicted in Fig. 2 and its chemical composition is as shown in Table 1. This alloy possesses exceptional attributes, including high tensile strength, excellent biocompatibility, corrosion and fatigue resistance, as well as good wear resistance. Two custom-designed uncoated drill bit variants were manufactured by High Precision Machining Tools (HPMT) Company, specifically the S-design and the EZ-design drill bits. Both drill bits were made out of tungsten carbide, shares a common diameter of 2mm, and their features are visually depicted in Fig. 4, with corresponding physical properties detailed in Table 3. The cutting fluid used in this study is water soluble Toyo brand cutting oil which is non-hazardous and environmental friendly. These tools were subjected to identical machining parameters outlined in Table 2.

The reason in comparing two types of tool designs is because each tool has its own distinct features and advantages, the better tool will help in increasing machining efficiency while reducing production cost. A number of previous researchers have concluded that design and geometry of tools gives significant influence to machining output. This is also the reason why different point angles are used, some study shows smaller point angles have more advantage than bigger point angles and vice versa.

Difference in tool designs may or may not influence this result. For each runs, a total of 30 holes are drilled, this is due to the limited material of 3D CoCrMo available out of financial constraints. Figure 3 shows the plate of printed CoCrMo after all runs are completed. Subsequently, the resulting thrust forces and wear patterns were meticulously observed and analysed to determine the superior tool design for micro drilling 3D CoCrMo. Machining operations were carried out using a DMG Mori DMU50 CNC Machine, while force measurements were obtained through the Kistler Type 9554B dynamometer. Tool wear was assessed and observed utilizing the XOPTRON X80 microscope with six times magnification. The tool life criterion is based on the ISO 8688-2 standard. According to this criterion, the limit for tool wear in micro drill bits is set at 0.3mm. Any wear value exceeding this limit is considered a failure. The flank wear of the micro drill bits is specifically taken into consideration. The wear values of the drill bits are measured after every 10 holes drilled, up to the 30th hole.

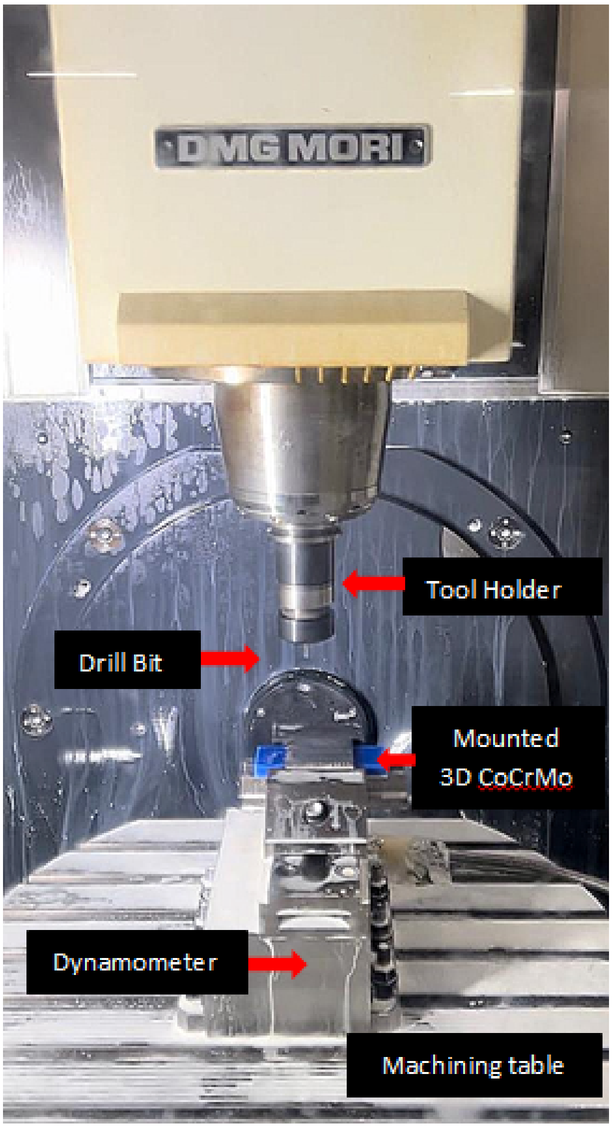


Fig. 1. Machining Experimental Setup of Micro Drilling

3. Results and discussion

The machinability of 3D printed CoCrMo using different drill tool designs was assessed based on the output thrust forces. Table 4 presents the average output thrust forces derived from tool design S, while Table 5 provides the average output thrust forces from tool design EZ. The findings are detailed and discussed as follows:

3.1. Thrust Forces

From the tabulated tables, it is evident that S-design tools exhibit a reduction in force when the point angle decreases from 140° to 130°, but there is a sharp increase when it further decreases to 118°. On the other hand, EZ-design tools display a consistent trend of decreasing force values as the point angles of the tools decrease from 140° to 118°. These trends can be attributed to the specific geometries and designs of the drill bits. This phenomenon can be elucidated by referencing the work conducted by Dang et al. [19], which explored drilling composite materials. According to their study, when the point angle of a drill bit is small, the cutting edge becomes longer, and the contact area between the cutting edge and the material becomes smaller. A smaller contact area between the tool and the material results in more dispersed force distribution and higher thrust forces.

However, this is not the case for EZ-design tools. The results indicate that as the point angles decrease, the thrust forces also gradually decrease. This outcome can be attributed to the unique design of EZ-design tools, which incorporate a chisel design that reduces thrust load and enhances biting performance [16]. Additionally, EZ-design drill bits feature effective clearance and gashing, which serves to reduce cutting forces. Fig. 5 provides a visual comparison of the force outputs between both tool designs.

3.2. Tool Wear

Tool wear is a critical aspect considered in this investigation of the machinability of 3D-printed CoCrMo. In drilling operations, wear on the flanks of the tools is typically of primary concern. The wear trends for S-design tool runs are illustrated in Table 6, while Table 7 presents the wear changes observed for EZ-design tools. Observations and measurements of wear were conducted after drilling every 10 holes until reaching the 30th hole.

Table 1. Chemical Composition of 3D Printed CoCrMO

Specimens	Brand	Manufacturer	Co	Cr	Mo	Si	Mn	Fe
LS CoCr	Cobalt Chrome	3D Gens	$60-65\%$	$26-30\%$	$5-7\%$	$<1\%$	$<1\%$	$<1\%$

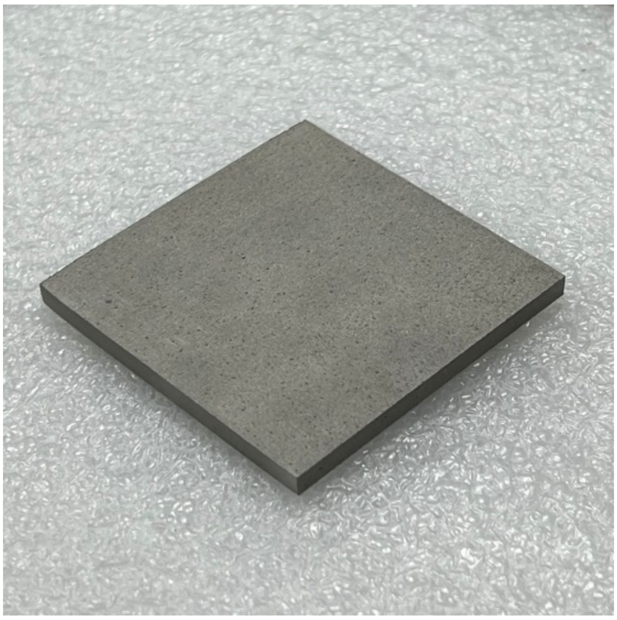


Fig. 2. 3D Printed CoCrMo (Before Machining)

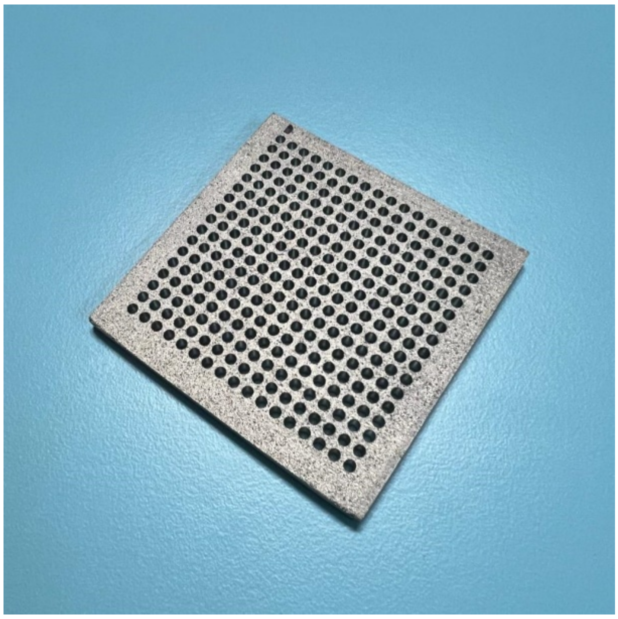


Fig. 3. 3D Printed CoCrMo (After Machining is completed)

Table 2. Machining Parameters

Factors	Values
Cutting Speed	50 m/min
Feed Rate	0.1 m/min
Tool Designs	S and EZ
Tool Geometry (Point Angle)	$118°, 130°, 140°$
No of Holes Drill	30 holes
Depth of Hole	4 mm (through)
Cooling Method	Flood

Table 3. Drill Bit Design Features [16]

S Design Features	EZ Design Features
Wider Chip Pocket	Split Point Design
Straight Edge Profile	C-Flute Shape
Bigger K-Value	Effective Clearance and Gash
Corner Chamfer Edge	Corner Chamfer on point design

Analysing the results from both tools, the wear trends mirror the trends observed in the thrust force outputs. Specifically, for tool design S, wear decreases as the point angle decreases and increases abruptly as the point angle further decreases to 118°. Conversely, for EZ design tools, the trend shows a gradual decrease in wear values as the point angles of the tools decrease from 140° to 118°. These phenomena can also be attributed to the specific geometries and designs of the drill bits.

From a geometrical perspective, S-design tools are engineered with wider chip pockets that enhance and facilitate chip evacuation [16]. Furthermore, S-design tools feature a straight edge profile that produces shorter chips, preventing them from jamming within the tool cavities, as they can be easily flushed away by the flood coolant. On the other hand, EZ design tools incorporate a C-flute shape design that enhances chip evacuation and reduces the likelihood of chip jamming. This chip pocket design improves the chip ejection rate during machining. Barbosa et al. [20] have reported that chip interactions with tools are crucial, as friction between chips, the rake face, the machined surface, and the tool flank face contributes to increase machining temperatures. Elevated temperatures, in turn, promote a higher wear rate of tools. Fig. 6 offers graphical comparisons of wear changes between both tool designs.

The progression of wear for tool Design S can be observed in the figures provided in Table 8, while Table 9 illustrates the wear progression for tool Design EZ. Changes in wear are recorded from left to right in the table from point angle 140° to 130° to 118°. When viewing from top to bot-

Table 4. Tool Design S Average Thrust Force Output

Run	Hole No	Speed (m/min)	Tool (S)	Force Average	Run Force Average (N)
1	10 20 30	50	1 (140°)	261.69 281.54 277.81	273.68
2	10 20 30	50	2 (130°)	206.85 206.29 213.84	209.00
3	10 20 30	50	3 (118°)	497.65 518.87 509.64	508.72

Table 5. Tool Design EZ Average Thrust Force Output

Run	Hole No	Speed (m/min)	Tool (EZ)	Force Average	Run Force Average (N)
1	10 20 30	50	4 (140°)	180.26 194.90 159.84	178.33
2	10 20 30	50	5 (130°)	129.69 132.59 137.41	133.23
3	10 20 30	50	6 (118°)	133.17 138.60 123.80	131.86

Table 6. Tool Design S Average Wear Output

Run	Hole No	Speed (m/min)	Tool (S)	Wear
1	10 20 30	50	1 (140°)	0.165 0.176 0.185
2	10 20 30	50	2 (130°)	0.067 0.071 0.089
3	10 20 30	50	3 (118°)	0.187 0.206 0.231

Table 7. Tool Design EZ Average Wear Output

Run	Hole No	Speed (m/min)	Tool (EZ)	Wear
1	10 20 30	50	1 (140°)	0.179 0.220 0.274
2	10 20 30	50	2 (130°)	0.087 0.115 0.129
3	10 20 30	50	3 (118°)	0.091 0.114 0.122

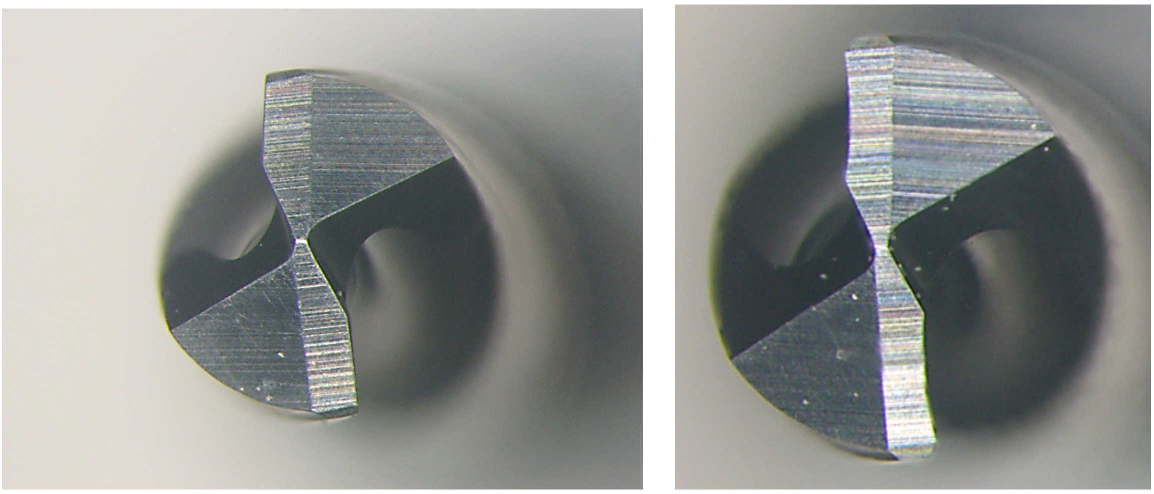


Fig. 4. Drill Designs; S (Left) EZ (Right)

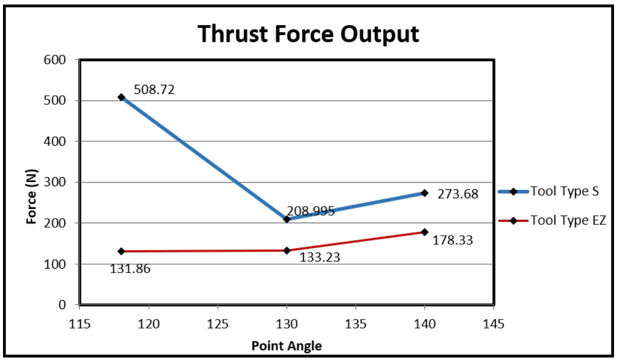


Fig. 5. Force output comparisons between tool designs

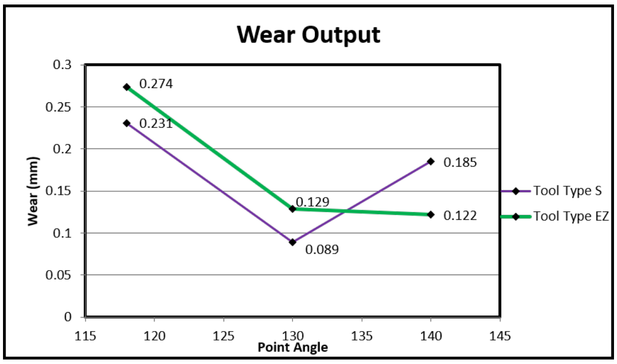


Fig. 6. Wear output comparison between tool designs

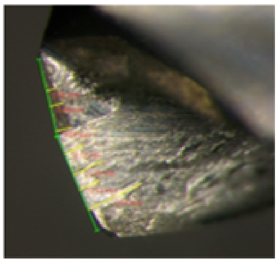
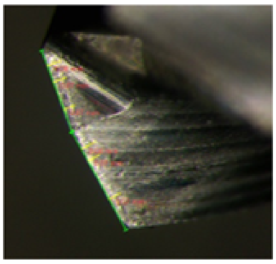
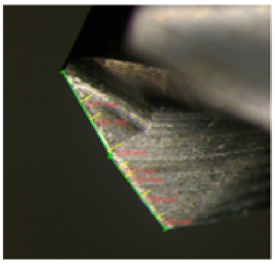
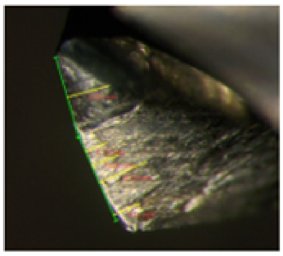
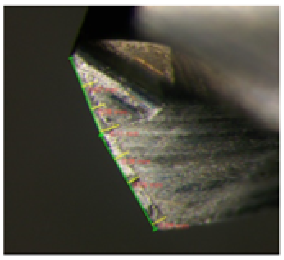
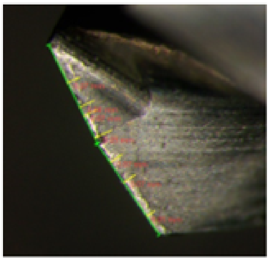
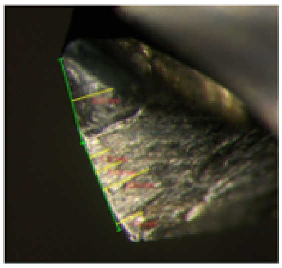
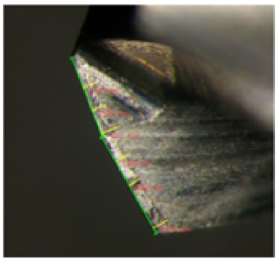
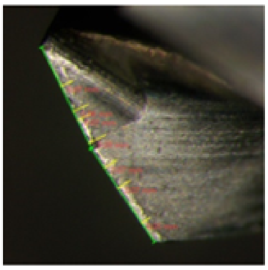
tom shows the wear changes as the material were drilled at the 10th hole to 20th hole and to the 30th hole. The observation and measurement of tool wear are recorded by using XOPTRON optical microscope with eight times magnification measured with the built in software.

The summarized data of average thrust forces and wear output for both tool designs are presented in Table 10. Notably, the trends in force and wear exhibit a proportional relationship; when the force increases, wear also increases, and vice versa.

4. Conclusion

This paper presents an experimental study aimed at investigating the impact of different micro drill tool designs on the machinability of selective laser sintered (SLS) advanced manufactured cobalt chromium molybdenum (CoCrMo) alloy plates, utilizing a flood cooling method. The primary objective of this experiment is to determine the more suitable tool design for micro drilling SLS CoCrMo plates. It is evident that the EZ design tool outperforms the S-design tool due to the significantly lower magnitude of thrust forces it generates of only 131.86N as compared to S type tool which generated a force magnitude of 508.72N.The difference in force output percentage of these two tools shows S tool generates 385% greater in force when compared to EZ type tool design. Lower forces are anticipated to result in a reduced wear rate for the tool, potentially extending its lifespan. Evidently showing from the average wear output after drilling 30 holes. EZ tool at 118°, having an average wear value of only 0.122 mm, while S type tool has an average wear magnitude of 0.231 mm. The increase in value is almost twice the wear magnitude of EZ tool. For further exploration of micro drilling performance with both tool designs (S and EZ), future research should consider varying machining parameters such as cutting speed, feed rate, and cooling methods. These parameter variations may provide valuable insights for optimizing the micro drilling process of CoCrMo alloys.

Table 8. Wear Progression of Tool Design S on SLS COCrMo

Tool S	140°	130°	118°
10^{th} Hole			
20^{th} Hole			
30^{th} Hole			

Acknowledgement

The authors would like to express their gratitude and acknowledgements for the financial support provided by Universiti Teknologi Malaysia under UTM High Impact Grant (HIR) with grant No: Q.J130000.2409.08G37 and Q.J130000.5024.09G98.

References

[1] S. Baron, E. Ahearne, P. Connolly, S. Keaveney, and G. Byrne, (2015) *"An Assessment of Medical Grade Cobalt Chromium Alloy ASTM F1537 as a" Difficult-to-Cut (DTC)" Material"* **The Proceedings of MTTRF**:

[2] H. A. Zaman, S. Sharif, D.-W. Kim, M. H. Idris, M. A. Suhaimi, and Z. Tumurkhuyag, (2017) *"Machinability of cobalt-based and cobalt chromium molybdenum alloys-a review"* **Procedia Manufacturing *11***: 563–570. DOI: 10.1016/j.promfg.2017.07.150.

[3] Z. Liao and D. A. Axinte, (2016) *"On monitoring chip formation, penetration depth and cutting malfunctions in bone micro-drilling via acoustic emission"* **Journal of Materials Processing Technology *229***: 82–93. DOI: 10.1016/j.jmatprotec.2015.09.016.

[4] R. Hamidon, N. Zulkefli, R. Saravanan, Z. Zailani, M. Bahari, S. Zakaria, and H. Azmi. "Effect of Different Cutting Conditions on Tool Wear and Chip

Table 9. Wear Progression of Tool Design EZ on SLS COCrMo

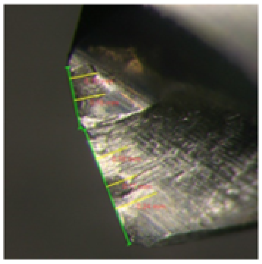
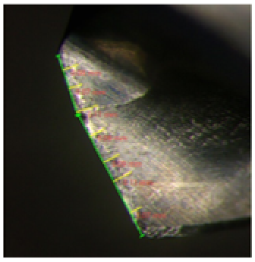
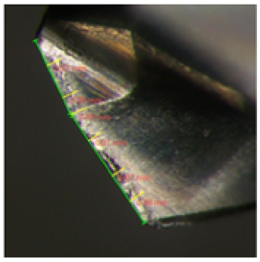
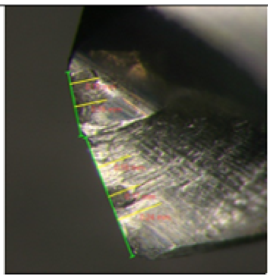
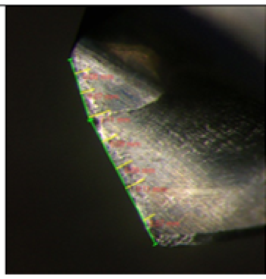
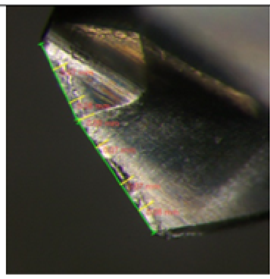
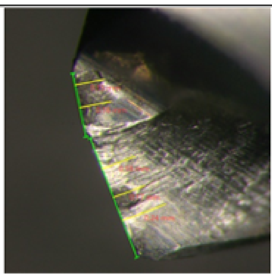
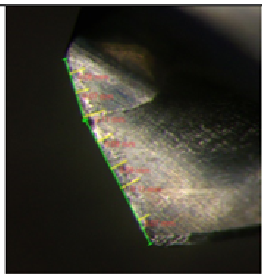
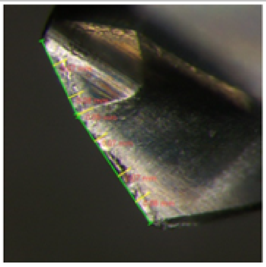
Tool EZ	140°	130°	118°
10th Hole			
20th Hole			
30th Hole			

Table 10. Comparison between S DESIGN tool and EZ DESIGN tool

Tool Design	S (140°)	EZ (140)	S (130°)	EZ (130°)	S (118°)	EZ (118°)
Average Force	273.68	178.33	208.995	133.23	508.72	131.86
Average Wear	0.185	0.274	0.089	0.129	0.231	0.122

Formation in Drilling of Cobalt Chromium Molybdenum”. In: *Intelligent Manufacturing and Mechatronics: Proceedings of SympoSIMM 2020*. Springer. 2021, 391–400. DOI: 10.1007/978-981-16-0866-7_34.

[5] M. Hasan, J. Zhao, and Z. Jiang, (2017) *“A review of modern advancements in micro drilling techniques”* **Journal of Manufacturing Processes 29**: 343–375. DOI: 10.1016/j.jmapro.2017.08.006.

[6] A. Arjunan, J. Robinson, A. Baroutaji, A. Tuñón-Molina, M. Martí, and Á. Serrano-Aroca, (2021) *“3D printed cobalt-chromium-molybdenum porous superalloy with superior antiviral activity”* **International Journal of Molecular Sciences 22**(23): 12721. DOI: 10.3390/ijms222312721.

[7] A. Barazanchi, K. C. Li, B. Al-Amleh, K. Lyons, and J. N. Waddell, (2020) *“Mechanical properties of laser-sintered 3D-printed cobalt chromium and soft-milled cobalt chromium”* **Prosthesis 2**(4): 28. DOI: 10.3390/prosthesis2040028.

[8] , (1984) *“COBALT CHROME: High-Carbon, High Chromium Die Steel, Type D5”* **Alloy Digest 33**(8): TS–427. DOI: 10.31399/asm.ad.ts0427. eprint: https:

//dl.asminternational.org/alloy-digest/article-pdf/33/8/TS-427/366437/ad_v33_08_ts-427.pdf.

[9] A. Standard et al., (2011) *"Standard Specification for Wrought Cobalt-28Chromium-6Molybdenum Alloys for Surgical Implants"* **ASTM International: West Conshohocken, PA, USA**:

[10] C. T. Wanniarachchi, A. Arjunan, A. Baroutaji, and M. Singh, (2022) *"Mechanical performance of additively manufactured cobalt-chromium-molybdenum auxetic meta-biomaterial bone scaffolds"* **journal of the mechanical behavior of biomedical materials *134***: 105409. DOI: 10.1016/j.jmbbm.2022.105409.

[11] P. V. Vaidya, A. Dutta, S. Rooj, R. Talukdar, K. Bhombe, V. S. Seesala, Z. Q. Syed, T. K. Bandyopadhyay, and S. Dhara, (2023) *"Design modification of surgical drill bit for final osteotomy site preparation towards improved bone-implant contact"* **Heliyon *9***(6): DOI: 10.1016/j.heliyon.2023.e16451.

[12] A. G. C. Presotto, J. M. Cordeiro, J. G. C. Presotto, E. C. Rangel, N. C. da Cruz, R. Landers, V. A. R. Barao, and M. F. Mesquita, (2021) *"Feasibility of 3D printed Co–Cr alloy for dental prostheses applications"* **Journal of Alloys and Compounds *862***: 158171. DOI: 10.1016/j.jallcom.2020.158171.

[13] C. Han, Y. Yao, X. Cheng, J. Luo, P. Luo, Q. Wang, F. Yang, Q. Wei, and Z. Zhang, (2017) *"Electrophoretic deposition of gentamicin-loaded silk fibroin coatings on 3D-printed porous cobalt–chromium–molybdenum bone substitutes to prevent orthopedic implant infections"* **Biomacromolecules *18***(11): 3776–3787. DOI: 10.1021/acs.biomac.7b01091.

[14] M. Pizzi, F. De Gaetano, M. Ferroni, F. Boschetti, and M. Annoni, (2023) *"A Deep-Hole Microdrilling Study of Pure Magnesium for Biomedical Applications"* **Micromachines *14***(1): 132. DOI: 10.3390/mi14010132.

[15] H. P. M. Tools. 2023.

[16] M. Sorgato, R. Bertolini, A. Ghiotti, and S. Bruschi, (2023) *"Tool wear assessment when drilling AISI H13 tool steel multilayered claddings"* **Wear *524***: 204853. DOI: 10.1016/j.wear.2023.204853.

[17] V. Krishnan, J. V. John, and R. Girimurugan, (2023) *"Optimization of drilling parameters in vertical machining centre drilling on magnesium AZ91D alloy under dry condition with Taguchi design"* **Materials Today: Proceedings**:

[18] M. Hassan, J. Abdullah, A. Mahmud, and A. Supran, (2018) *"Effect of drill geometry and drilling parameters on the formation of adhesion layer in drilling composite-metal stack-up material"* **Journal of Mechanical Engineering (JMechE)** (2): 90–98.

[19] J. Dang, G. Liu, Y. Chen, Q. An, W. Ming, and M. Chen, (2019) *"Experimental investigation on machinability of DMLS Ti6Al4V under dry drilling process"* **Materials and Manufacturing Processes *34***(7): 749–758. DOI: 10.1080/10426914.2019.1594254.

[20] A. Barbosa, L. Oliveira, G. S. Bobrovinitchii, R. Guimarães, S. Crespo, and M. Filgueira. "Processing and mechanical properties of PM processed Fe-Cu-Co alloys". In: *Materials Science Forum*. ***591***. Trans Tech Publ. 2008, 247–251. DOI: 10.4028/www.scientific.net/msf.591-593.247.