Afyon Kocatepe Üniversitesi Fen ve Mühendislik Bilimleri Dergisi
Afyon Kocatepe University – Journal of Science and Engineering
https://dergipark.org.tr/tr/pub/akufemubid

Araştırma Makalesi / Research Article
DOI: https://doi.org/10.35414/akufemubid.1285987
AKÜ FEMÜBİD **24** (2024) 015901 (166-175) AKU J. Sci. Eng. **24** (2024) 015901 (166-175)

A Study on the Production of Riblet Patterns Providing Micro-scale Flow Control through FDM-type 3D Printers

***Makale Bilgisi / Article Info**
Alındı/Received: 19.04.2023
Kabul/Accepted: 04.01.2024
Yayımlandı/Published: 27.02.2024

FDM-tipi 3 Boyutlu Yazıcılar ile Mikro Ölçekte Akış Kontrolü Sağlayabilen Riblet Desenlerinin Üretimine Yönelik bir Çalışma

Volkan KORKUT[1*], Hürrem AKBIYIK[2]

[1] *Adana Alparslan Türkeş Science and Technology University, Engineering Faculty, Mechanical Engineering Department, Adana, Turkey*
[2] *Adana Alparslan Türkeş Science and Technology University, Faculty of Aeronautics and Astronautics, Department of Aerospace Engineering, Adana, Turkey*

Öz

Bu çalışma, havacılık ve uzay teknolojilerinde kritik öneme sahip olan akış karakterizasyonu uygulamalarına pratik bir alternatif olarak Fused Deposition Modelling (FDM)-tipi eklemeli imalat yöntemini araştırmaktadır. Literatürde, yüksek bütçe gerektiren FDM cihazlarıyla, yüksek boyutsal tutarlılıkta parça imalatı yapılabilmesi üzerine önemli çalışmalar mevcut olmasıyla birlikte; daha erişilebilir, pratik ve esnek bir kullanım imkanı sunan açık-kaynaklı cihazlar ile milimetre-altı riblet geometrileri üretiminin detayları üzerine yürütülmüş araştırmaların sayısı kısıtlıdır. Bu bağlamda çalışmada, mekanik ve yazılımsal olarak modifiye edilebilen bir yazıcı kullanılmış olup, kanat yapısını temsil eden plakalar üzerine, birbirine paralel riblet desenleri üretilmiştir. Ribletler üzerinde mikroskopik inceleme ve ölçümler gerçekleştirilerek, karşılaşılan sorunların çözümüne yönelik araştırmalar yapılmıştır. Gözlemler doğrultusunda, ilk etapta, nozzle-table mesafesi ve nozzle daireselliği gibi donanımsal unsurların homojen bir malzeme ekstrüzyonu açısından önem taşıdığı açığa çıkarılmıştır. Mekanik faktörlerin yanı-sıra, yazılımsal olarak belirlenen çizgi genişliği ve akış oranı parametrelerinin, riblet boyutları üzerinde belirleyici birer etken olduğu gözlemlenmiştir. Özellikle açık-kaynak konseptine dayalı cihazlarda bu parametrelerin kalibrasyonuna yönelik çözümler içeren deneylerin sonucunda; sırasıyla riblet genişliği, ribletler-arası boşluk mesafesi ve riblet yüksekliği olacak şekilde, hata miktarı en fazla %1,83, %1,33 ve %0,19 gibi yüksek doğrulukta riblet profilleri elde edilebilmiştir. Sonuçta, yaygın kullanılan, düşük maliyetli ve modifiye edilebilir yapıdaki FDM cihazlarıyla, bu boyutlarda ve doğrulukta riblet üretimi yapılabilmesine dair bulgular sunulmuştur. Akış kontrolü ve yüzey modifikasyonları alanlarında kullanılan riblet yapılarının havacılık ve uzay endüstrisindeki önemi göz önünde bulundurulduğunda bu çalışma, araştırma-geliştirme faaliyetlerinde kullanılabilecek daha karmaşık yüzey profillerinin, kısa sürelerde, pratik ve efektif bir şekilde üretilebilmesi için kritik bilgileri literatüre kazandırmayı amaçlamaktadır.

Anahtar Kelimeler: *FDM, 3b yazıcı, Akış kontrol, Riblet; Kanat yüzeyi*

Abstract

This study explores the Fused Deposition Modeling (FDM) additive manufacturing method as a practical alternative for flow characterization applications critical in aerospace technology. While there are significant studies in the literature on high-budget FDM devices for manufacturing high-dimensional consistency parts, research focusing on sub-millimeter riblet geometries using more accessible, practical, and flexible open-source devices remains limited. In this study, a printer that can be mechanically and programmatically modified was used to create parallel riblet patterns resembling wing structures on plates. Microscopic examinations and measurements were conducted on these riblets to address encountered issues. Observations revealed that hardware elements such as nozzle-table distance and nozzle circularity are crucial for homogeneous material extrusion. Additionally, it was observed that software-defined parameters like line width and flow rate significantly affect riblet dimensions. Particularly in experiments involving calibration of these parameters in open-source concept devices, riblet width, inter-riblet spacing, and riblet height were achieved with a high accuracy error rate of up to 1.83%, 1.33%, and 0.19%, respectively. Consequently, this study demonstrated the feasibility of producing riblets in this size and precision using widely available, cost-effective, and customizable FDM devices. Considering the significance of riblet structures in aerospace industries for flow control and surface modifications, this research aims to provide critical insights for the practical and effective production of more complex surface profiles in research and development activities.

Keywords: *FDM, 3d printing, Flow control, Riblet, Airfoil surface*

**Sorumlu Yazar/Corresponding Author: Volkan KORKUT* *e-posta/e-mail: vkorkut@atu.edu.tr*

1. Introduction

Flow control has critical importance in terms of aerospace and aeronautical engineering technologies. The flow field can be manipulated by either the overall wing geometry or by modifying the airfoil’s surface. It has been observed that riblet patterns created on the wing surface provide significant benefits in critical areas such as controlling the flow direction, delaying flow separation, and reducing drag. Furthermore, there are important studies indicating that microscale riblet patterns improve flow characterization.

In the study conducted by Walsh and Weinstein (1978), it was noted that achieving a 10% reduction in drag on an aircraft body could result in annual savings of hundreds of millions of dollars from flights. It was additionally suggested that this reduction could be achieved by implementing riblet structures with various shapes, including rectangular, V-shaped, or razor-blade profiles. The enhancement in flow performance was attributed to variations in riblet height and spacing, which were adjusted according to changes in the riblets' cross-section. Subsequently, it was suggested that not only conventional shapes but also bio-inspired riblet models, such as surfaces mimicking shark skin textures, could effectively reduce surface drag by up to 8% (Walsh 1983). Dai et al. (2019) further explored the impact of shark-skin-like riblets on flow characteristics, employing additive manufacturing techniques to replicate the texture of shark skin. Riblet arrays were manufactured with different orientation angles on a substrate to investigate their impact on variations in fluid drag. Despite the limited information available regarding the device configuration and printing process, the study demonstrated that the orientation of the riblet array significantly influences flow characteristics. This finding opens avenues for future studies to investigate different riblet placement angles on surfaces. In another study conducted by Bechert and Bartenwerfer (1989), the investigation focused on the location, orientation, and geometry of riblets within flow boundaries. The riblets were designed as grooves, and subsequently, the orientation angle of these grooves in a specific area at the flow outlet section was increased compared to the rest of the boundary layer. The geometrical design and varying orientation within the same flow boundary resulted in a significant drag reduction of around 10%, thereby enhancing the overall flow performance. The aforementioned studies represent some of the earliest examples demonstrating comprehensive tests and measurements regarding riblets' geometry, encompassing both primitive and bio-inspired specific shapes. Moreover, the design of riblet arrays, which involves the spacing between riblets (including individual riblet sizes) and the orientation angle(s) of the riblet array, underwent thorough examination. A common observation across these studies is the substantial enhancement in flow performance achievable through modifications in riblet design and its placement within flow boundaries. At this point, various methods to produce surface patterns of desired dimensions and geometries on which the flow will occur, have become a major research topic in the literature. In this context, the issue of how different riblet designs can be manufactured in real life has become a major research topic spanning from the past to the present day, and its significance has been increasingly recognized as also subjected in this study.

In recent times, a range of microscale riblet manufacturing techniques have proven to be effective. For instance, Bechert et al. (1997) employed precision milling to produce small riblets in trapezoidal and triangular shapes on a plexiglass surface. They reported that the manufactured riblets were sufficiently small and the results were qualified due to the precision of the CNC milling machine. However, it was noted that it took nearly two weeks to prepare one successful sample. This was attributed to the material characteristics, which are limited to being machined at low material removal rates, as well as to the machine hardware that requires low-speed stepper motors, thus extending processing times. In the end, drag-reducing surfaces were successfully obtained, but due to the low production capacity, only a few models could be tested. Likewise, in the study by Chen et al. (2013) aiming for the same objective, microscale riblets were produced through successive machining and casting methods. To begin, a master with microchannels was created using an ultra-precise lathe. Subsequently, a polymer resin was poured onto this master and cured. The solidified layer was then machined once more to attain the desired depth of the riblet geometries. Finally, the processed material was separated from the master and subjected to tests. Consequently, herringbone-type riblets with over 95% dimensional consistency were successfully produced. However, the high installation/operation cost of the extremely precise devices used, as well as the chemical-based processes requiring multiple stages such as molding and curing, are limiting factors in terms of flow control studies. In addition, processes based on material removal such as turning and milling (Walsh and

Lindermann 1984, Denkena et al. 2010), or plastic deformation such as rolling (Hirt and Thome 2007), require expensive machinery and cutting/shaping tools. Another method involves the production of highly precise riblet patterns using lithographic processes employing various solvents and etchants (Marentic and Morris 1992, Bixler and Bhushan 2013, Jung and Bhushan 2010, Brennan et al. 2010). Nonetheless, these processes entail time-consuming steps like curing and heating, and may carry potential risks of contamination, harmful gas emissions, and exposure to UV light.

In the mentioned studies, high-precision riblet geometries have been produced using mechanical and/or chemical processing methods based on chip removal. However, it has been observed that almost all of these studies necessitate multiple process steps, demanding considerable time and effort to complete the procedures. Furthermore, it has been noted that high-cost chip removal devices with micrometer precision capabilities and the necessary electronic components for their monitoring are crucially required in almost all these endeavors. Additionally, harmful solvents and gas emissions used in chemical processes are found to be limiting factors in riblet production. In the quest to minimize these barriers, a next-generation production technique known as Fused Deposition Modeling (FDM), also referred to as 3D printing, offers promising advantages. One of the foremost advantages is the utilization of only the required amount of material without material waste, unlike traditional chip removal methods (Gibson et al. 2010). Moreover, the availability of a variety of materials suitable for FDM production, such as Polylactic Acid (PLA), enables environmentally friendly and non-hazardous production, promoting environmental sustainability (Sin et al. 2012). Furthermore, the direct transfer and fabrication of digitally prepared models to the device dramatically reduce process steps compared to traditional methods (Vyavahare et al. 2020).

FDM systems enabling the efficient production of functional parts can be utilized in various domains such as rapid tooling, architectural modeling, and in-place repairing (Huang et al., 2013; Rayna et al., 2016). Moreover, they facilitate the production of components catering to the aerospace industry, which often involves highly complex geometries (Zaman et al., 2019; Hossain et al., 2014; Guduru et al., 2020). However, significant engineering effort is required to produce parts with high geometric consistency. This is due to the multitude of process (printing) parameters, such as layer thickness, line width, build orientation, printing speed, nozzle diameter, and temperature, which need to be harmonized (Dey and Yodo 2019). Moreover, the FDM device's motion accuracy, extrusion rate, layer-to-bed distance, and nozzle circularity must meet adequate precision requirements, and if not, various modifications and calibration processes are necessary (Geng et al. 2019, Tymrak et al. 2014).

Especially when producing micro-scale structures through open-source and custom-built FDM devices, a more detailed consideration of these factors is necessary. The same conditions apply for the production of micrometer-sized riblet structures via the FDM method, which is an effective surface modification technique in the aerospace and aeronautical fields. The lack of sufficient studies in the literature regarding criteria for producing riblets through the FDM method, capable of providing distinct flow characterization, motivates this study. In this context, a series of experiments have been conducted with the aim of effectively adapting the FDM method, which offers advantages of shorter production periods, lower budgets, minimum material consumption, and high dimensional consistency, to riblet fabrication. The objective of this study is to provide critical information regarding the production of riblet structures through 3D printers, which can be effectively used in various research and development activities.

2. Material and Methods

In this section, a serie of tests were conducted in order to examine the producibility of the micro-scale riblets and grooves by using an open-source, custom-built FDM device.

Firstly, the CAD model of ribleted flat surfaces was designed in the digital environment. Representing the wing, the dimensions of both the flat surfaces and the riblets were planned to be within the limits of hardware and the built size of the device. In the Figure 1, images of the flat plates having a riblets and grooves on the top surface is represented. Regarding the printing process, it is necessary to ensure the minimum scale that the device is capable of. This is because common 3D printing processes may suffer from deformations such as under or over-extrusion, uneven deposition, and structural problems in the extrusion hardware (Gordeev et al. 2018). These factors significantly affect the print quality. Fortunately, there are numerous guides and troubleshooting instructions available owing to open-source communities (Int. Ref. 1-3).

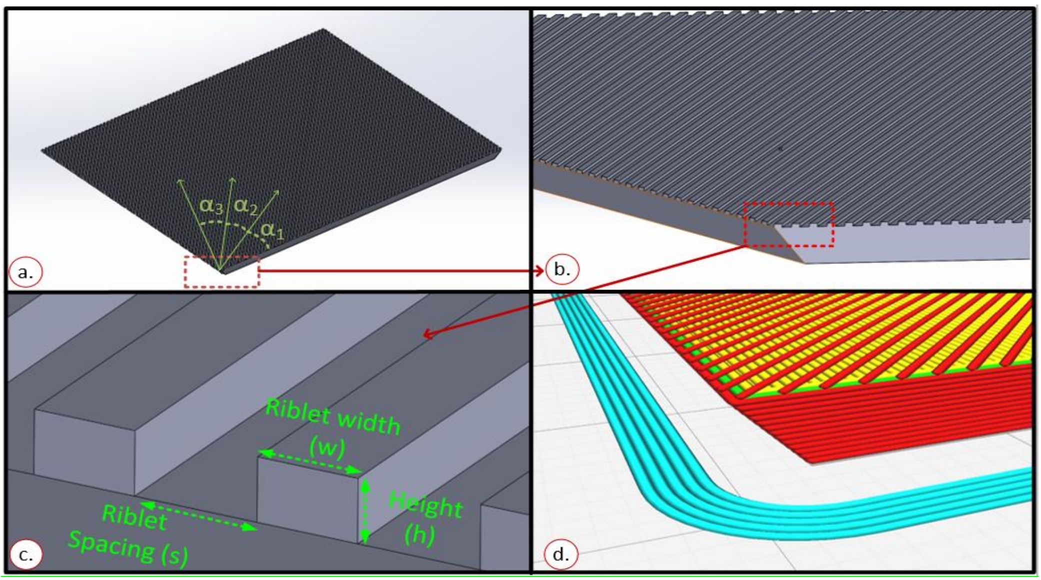

Figure 1. Flat plates a. Isometric view of the plates in CAD software. b) Magnified image of plate. c) Description of the riblet dimensions. d) Image of the plates in the slicer software

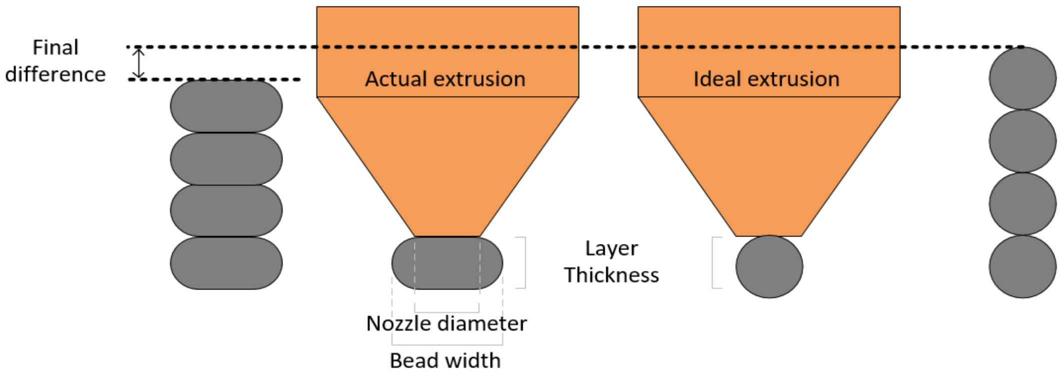

Figure 2. Comparison between the actual and ideal deposition heights

However, further investigation is required to identify possible issues when working at a sub-millimeter level. Examining the extrusion conditions can serve as a starting point to assess the device's capabilities.

When considering the extrusion conditions, parameters such as the flow rate, motion accuracy in all axes, and the roundness of the nozzle orifice play a significant role in determining the final quality of the part. In the Figure 2, the comparison between the ideal and actual deposition conditions is represented. It is an expected result that the deposition height in deposited material to be slightly less than the digital model height. The reason can be attributed to the shear strength reduction in the polymer materials when they are heated up to the semi-molten phase (Bhalodi et al. 2019). At this condition, the softened material tends to be squeezed between bottom surface of the nozzle outlet and the deposition platform. As a result, the extruded bead cannot find enough time to regain its circular shape and cools down in a near elliptical profile.

In macro-scale (≥ millimeters) printing processes, this dimensional error may be overlooked, but it is still a subject that needs to be addressed in micro-scale deposition processes. It is important to at least reveal the amount of height variation in the final product. Only in this way, micro-fabrication processes performed by FDM devices can be successful. The fact that the difference between the digital value and the actual elevation obtained can also be affected by factors such as electromechanical noise and other variables caused by friction in various areas should also be taken into consideration (Korkut and Yavuz 2020). In Table 1, printing parameters of the plates are given. In the following Figure 3, six printed samples having various riblet patterns are represented.

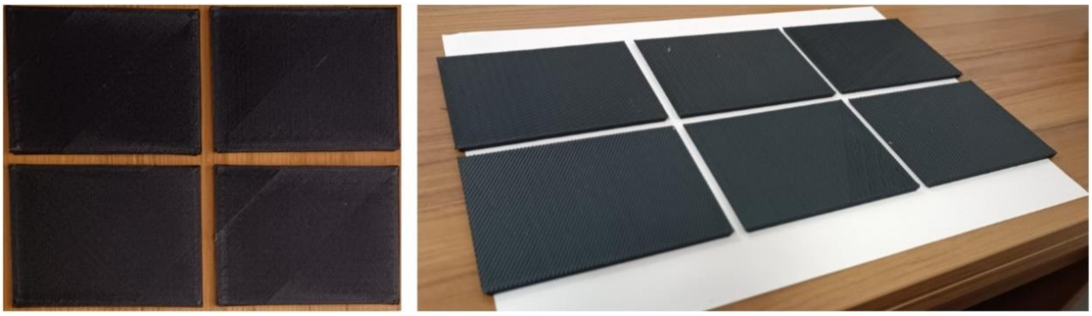

Figure 3. Initially printed pre-testing sample plates (left), The image of selected plates (right)

Table 1. The printing parameters of the plates and riblets

Printing Parameters	Value	Unit
Line (road) width:	0.4	mm
Layer (riblet) height:	0.2	mm
Number of layers:	13	
Nozzle diameter:	0.4	mm
Bed temperature:	65	°C
Nozzle temperature:	205	°C
Base material	PLA	
Print speed:	60	mm/s
Riblet orientation (angle):	30° / 60°	

As a result of production, photographs of different regions of the models have been taken through a digital microscope. Measurements were made on the captured photographs using ImageJ software, and comparisons were made between digital and actual dimensions. The microscopic examinations of the produced samples and their corresponding regions in the real samples as indicated in the digital model (Figure 1) are presented in Figure 4. Polylactic Acid (PLA) was selected as the printing material, and the slicing was set with a line width of 0.4 mm. In addition, the total thickness of the plate was set to 2.6 mm with a unit layer thickness of 0.2 mm, and the nozzle and print bed temperatures were configured as 205 °C and 65 °C, respectively. The sample production was carried out in two separate sessions. In the first stage, the quality of the obtained sample was evaluated in general. At this stage, some factors that are likely to be encountered during the printing process were examined. These include prominent surface defects, extrusion errors, circularity distortions in the nozzle's orifices, issues commonly encountered in mass-manufactured nozzles.

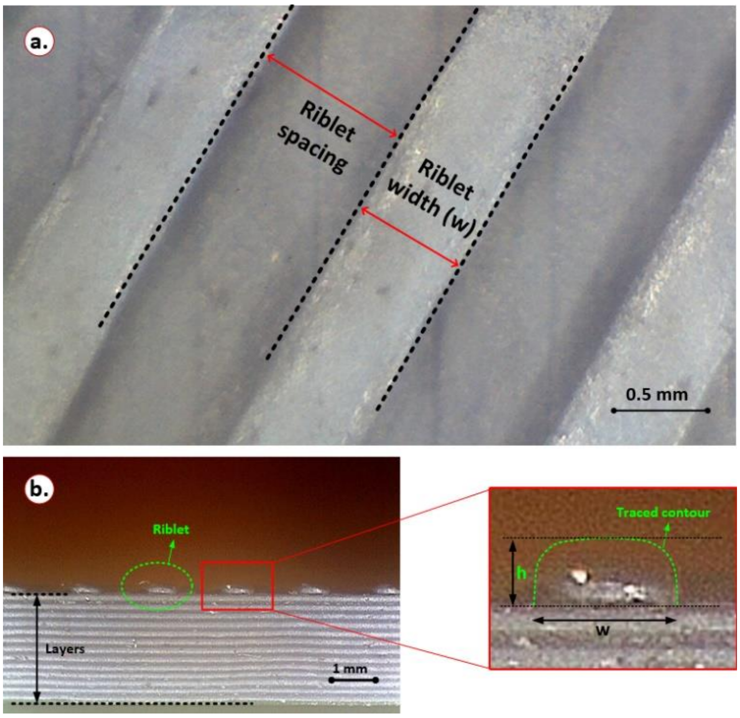

Figure 4.a. Top view of the microscopic photoshoot of a sample **b.** The front view of the same sample, (Riblet height: h, width: w)

In the second stage, the study focused on testing the conditions for producing microscale riblet patterns with high dimensional consistency, which was identified as the primary subject. The results were evaluated using microscopic images and image processing software.

3. Results and Discussion

In the first step of the experimental study, two samples were produced with riblet orientation angles of 30 and 60 degrees, respectively. When these samples were examined under a microscope, various problems were observed in material deposition. In Figure 5(a), it was observed that the lines within the regions highlighted in red were thinner than expected, indicating under-extrusion errors. Similarly, over-extrusion marks were found at different points on the samples as shown in (b). It should be noted that over-extrusion affects both the line thickness and the height of the material. Hence, it was observed that as the nozzle finished one layer and transitioned to the next, friction occurred with the upper surface of the preceding layer, leading to the deformations visible in (c). The fact that the radius of the deformed area was very close to the diameter of the nozzle's bottom surface serves as evidence that the aforementioned situation occurred. It was concluded that the mentioned problems were hardware-related since they occurred at specific points rather than overall. Therefore, the orifice, which is the most important region that determines the extrusion form, was subjected to microscopic examination. As a result of the examination, significant distortions in the circularity of the current nozzle were detected, and it was replaced with another nozzle (h) that had a sufficiently smooth circularity (d). After the replacement process, two more samples were produced under the same printing conditions and examined under a microscope. As a result of the upgrade, it was observed that the aforementioned problems were significantly eliminated (e, f, g). After resolving the problem in the orifice region, the second stage of the experiments was initiated. In this stage, 6 samples were produced and the dimensional consistency of the riblets on the samples were examined.

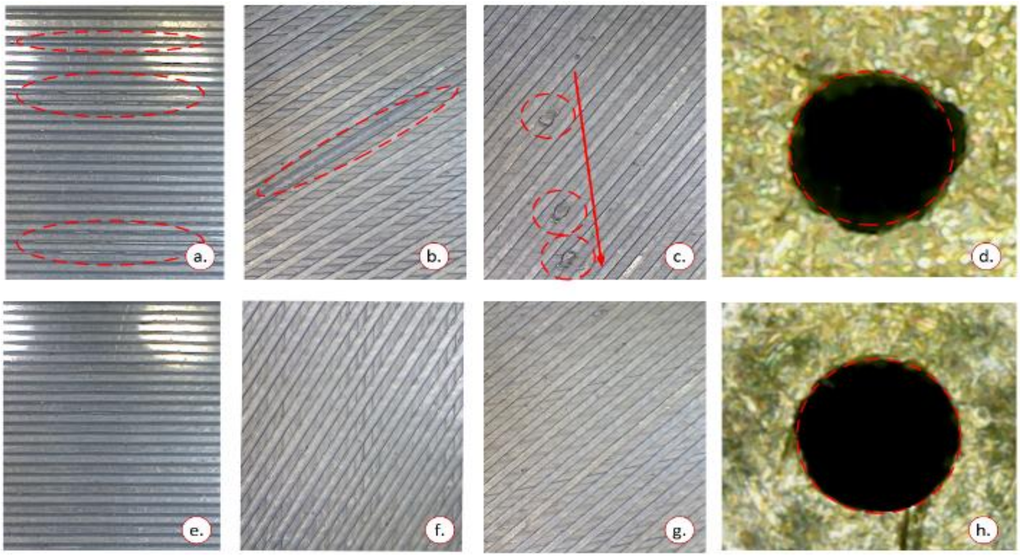

Figure 5.a. Under-extrusion regions, **b**. over-extrusion region, **c.** drag marks occured during the nozzle travel, **d.** distorted roundness, **(e, f, g.)** images taken from the equivalent regions of the primary samples, **h.** orifice with a good roundness.

Table 2. The dimensional properties of the riblets on the surface of the sample printed in the 2nd stage

Sample No.	Riblet Angle (°)	Riblet Width, w (mm)	w-Error (%):	w-Std. Dev.	Riblet Spacing, s (mm)	s-Error (%)	s-Std. Dev.	Riblet Height, h (mm)	h- Std. Dev.
1	60	0.437	9.25	0.008	0.442	11.60	0.015	0.252	0.005
2	60	0.423	5.83	0.017	1.105	10.50	0.011	0.248	0.003
3	30	0.422	5.42	0.019	0.470	6.00	0.003	0.251	0.016
4	60	0.419	4.67	0.022	0.479	4.20	0.003	0.254	0.232
5	30	0.417	4.25	0.013	0.970	2.97	0.033	0.254	0.011
6	60	0.407	1.83	0.010	0.507	1.33	0.010	0.256	0.190

Each measurement was calculated as the average of 3 different measurements from random locations of the samples, and standard deviations and error measurements were made based on these measurements. As each dimension presented a standard deviation below 2% for the width, 3.5% for the spacing, and 3% for the height, it was interpreted that the problem was not caused by the hardware itself, but rather by the flow rates specified in the slicer software. Therefore, in every session of sample manufacturing, flow rate parameter was re-adjusted based on the repetitive calibration process provided in the Equation 1 (Korkut and Yavuz 2020);

$$Required\ flow\ rate\ value = \left(\frac{Line\ width\ value}{Measured\ line\ width}\right) x (Flow\ rate\ in\ slicer) \quad (1)$$

Implementing the flow rate calibration based on Equation 1 significantly enhanced the accuracy of the width of extruded lines per unit of time. The graph illustrating the reduced error values is provided in Table 2 and visualized in Figure 6. The definitions of the measured dimensions can be referenced in Figure 4.

As the chart suggests, calibrating an open-source, custom-built device can be game-changing in terms of improving dimensional accuracy in the prints. That is, a reduction from near 12% to 1% can be achieved only by adjusting a simple but effective flow-rate parameter as can be derived from the Figure 6. In relation to the riblet width (w), the average measured extruded line widths in the final specimen (#6) were 0.407 mm, with the lowest error value of 1.83%. Despite the gradual adjustment of the flow-rate parameter, the measured line widths were slightly greater than the nozzle diameter (0.4 mm). This issue can be attributed to the tendency of the softened lines deposited on the build platform to swell due to the compressive forces exerted by the nozzle tip, as illustrated in Figure 2. Geng et al. (2019) discussed a correlation between deviation in line width and the principle of mass conservation, indicating that the mass of the entering filament into the extruder must equal the mass of the exiting (deposited) lines. Considering this principle and accounting for the compressive forces of the nozzle tip, it can be inferred that the lines are slightly compressed from the lateral regions, resulting in an expansion of the width size.

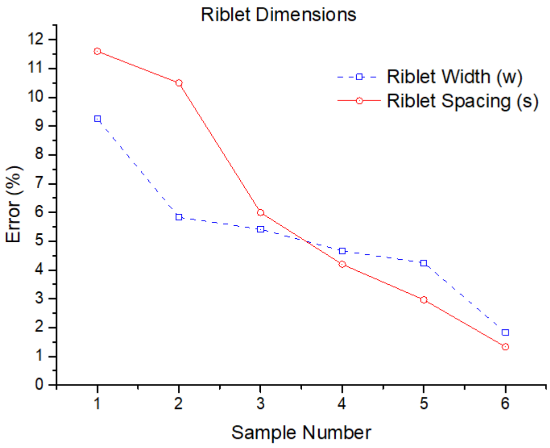

Figure 6. Gradual decrease in the amount of dimensional error measured in the riblet dimensions.

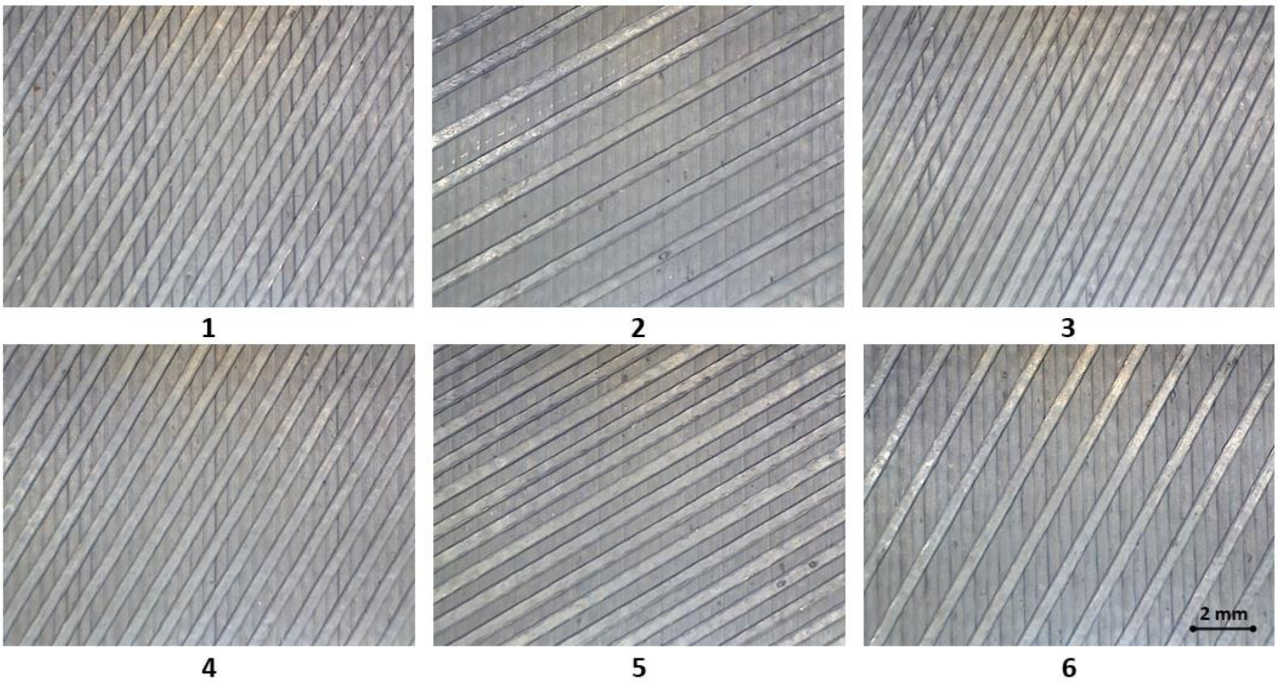

Figure 7. Microscopic images of the successfully printed riblets and channels

In the examinations of the riblet heights found in the second layer of the plate, average riblet height was measured to be 0.256 mm which is slightly higher that the value (0.2 mm) defined in the slicer software. This can be attributed to the fact that no other layer was deposited after the final layer containing riblets. In other words, since the nozzle does not pass over the same point again after completing a riblet, the semi-molten material tends to regain its cylindrical shape due to the dominance of surface tension over viscous stresses, thus forming a cylindrical groove. In actuality, each riblet line is deposited individually without direct contact with adjacent lines. Due to the absence of bonding between the riblets, the surface energy of the extrudate causes the line profile to reform into a more circular shape, resulting in a slight increase in the height of the lines. This phenomenon aligns with findings from the studies conducted by Bhalodi et al. (2019) and Frankel (1945).

As mentioned earlier, this phenomenon is usually negligible at macro levels. Nonetheless, it is crucial to closely consider this occurrence and adjust the top layer parameters accordingly. This involves implementing a series of calibration methods, such as flow rate calibration, to achieve the desired sizes in microscale fabrication operations.

Another noteworthy detail is the observation that alterations in orientation angle and riblet spacing do not notably compromise the dimensional precision in the riblet sizes as the final outcome. In Figure 7, the sections of the samples produced as a result of both hardware and software improvements are presented. In the images, it can be observed that significant errors related to extrusion have been eliminated. Furthermore, based on Table 2 and Figure 6, it has been concluded that dimensional errors can be gradually reduced to an ignorable level. At this point, critical findings regarding the micro-scale fabrication with FDM printers have been obtained.

This situation holds particular importance for studies within the aerospace field. One reason for this is the commercial nature of devices used for similar purposes, as highlighted in studies by Dai et al. (2019), Bhushan and Caspers (2017), Uriondo et al. (2015), where these devices are noted to be either unsuitable for necessary modifications or costly. In contrast, as indicated in sources such as Pearce (2012, 2014), and Tymrak et al. (2014), custom-built devices available at significantly lower costs can be easily modified in terms of both hardware and software. Furthermore, while open-source FDM devices enable the production of high-quality parts, the number of studies conducted for small geometries applicable in aerospace research and flow control applications appears limited. This study may serve as a bridge between these two extremes.

4. Conclusion and Future Studies

In this study, the production of riblets, which is critically important in flow control and drag reduction efforts in the aerospace industry, has been investigated using FDM type additive manufacturing device. The findings provide compelling evidence that open-source devices are capable of performing this production. Notably, it was observed that in open-source and custom-built devices, careful consideration of the distance between the nozzle tip and built platform, as well as the circularity of the orifice, is crucial as these factors substantially impact print quality. In addition, flow-rate calibration has been identified as a critical printing parameter that depends on the precision of both the device and the printed part sizes. This can be associated with the decreasing error rate due to sequential adjustments made before each sample.

Besides, it has been revealed that if all mechanical components responsible for axial movements and the extrusion process, along with digital parameters, are properly calibrated, the riblet spacing and orientation angle do not significantly affect print quality. In cases where similar production processes for surface modifications are required, this finding is crucial in demonstrating that these two parameters can be freely experimented with various combinations in different studies.
To conclude, this study aimed to contribute critical findings to the literature on riblet production that can be realized through open-source 3D printers, rather than requiring expensive devices and processes. In the future studies, it is planned to produce riblets of different sizes and shapes, and to experimentally test the flow control and drag reduction capabilities of ribletted surfaces.

Declaration of Ethical Standards
The authors declare that they comply with all ethical standards.

Credit Authorship Contribution Statement
Author 1: Resources, Research, Experiments, Visualization, Writing
Author 2: Research, Experiments, Analysis, Writing

Declaration of Competing Interest
The authors have no conflicts of interest to declare regarding the content of this article.

Data Availability
All data generated or analyzed during this study are included in this published article.

Acknowledgement

This research article was supported by the laboratories of Adana Alparslan Türkeş Science and Technology University, Faculty of Engineering, Mechanical Engineering Department and Faculty of Aeronautics and Astronautics, Department of Aerospace Engineering.

References

Bechert, D. W., Bruse, M., Hage, W., Van Der Hoeven, J. G. T. and Hoppe, G., 1997. Experiments on drag-reducing surfaces and their optimization with an adjustable geometry. *Journal of Fluid Mechanics*, **338**, 59–87. https:/www.doi.org/10.1017/S0022112096004673

Bechert, D., and Bartenwerfer, M., 1989. The Viscous Flow on Surfaces with Longitudinal Ribs. *Journal of Fluid Mechanics*, **206,** 105–129. https://www.doi.org/10.1017/S0022112089002247

Bhalodi, D., Zalavadiya, K., and Gurrala, P. K., 2019. Influence of temperature on polymer parts manufactured by fused deposition modeling process. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, **41(3)**, 113. https://doi.org/10.1007/s40430-019-1616-z

Bhushan, B., Caspers, M., 2017. An overview of additive manufacturing (3D printing) for microfabrication. *Microsystem Technologies*, **23**, 1117–1124. https://doi.org/10.1007/s00542-017-3342-8

Bixler, G. D. and Bhushan, B., 2013. Fluid drag reduction with shark-skin riblet inspired microstructured surfaces. *Advanced Functional Materials*, **23(36)**, 4507–4528. https://doi.org/10.1002/adfm.201203683

Brennan A. B., Baney R. H., Carman M. I., Estes T. G., Feinberg A. W., Wilson L. H., Schumacher J. F., 2010. Surface Topographies for Non-Toxic Bioadhesion Control. United States Patent no. 7, 650, 848.

Chen, H., Rao, F., Shang, X., Zhang, D., and Hagiwara, I., 2013. Biomimetic drag reduction study on herringbone riblets of bird feather. *Journal of Bionic Engineering*, **10(3)**, 341–349. https://doi.org/10.1016/S1672-6529(13)60229-2

Dai, W., Alkahtani, M., Hemmer, P. R., and Liang, H., 2019. Drag-reduction of 3D printed shark-skin-like surfaces. *Friction,* **7(6)**, 603–612. https://doi.org/10.1007/s40544-018-0246-2

Denkena B., Kohler J., Wang B., 2010. Manufacturing of functional riblet structures by profile grinding. *Cirp Journal of Manufacturing Science and Technology*, **3**, 14. https://doi.org/10.1016/j.cirpj.2010.08.001

Dey, A., and Yodo, N., 2019. A systematic survey of FDM process parameter optimization and their influence on part characteristics. *Journal of Manufacturing and Materials Processing,* MDPI Multidisciplinary Digital Publishing Institute, **3(3)**, 64. https://doi.org/10.3390/jmmp3030064

Frenkel J., 1945. Viscous flow of crystalline bodies under the action of surface tension. *Journal of Physics,* **9,** 385–395.

Geng, P, Zhao, J., Wu, W., Ye, W., Wang, Y., Wang, S., Zhang, S., 2019. Effects of extrusion speed and printing speed on the 3D printing stability of extruded PEEK filament. *Journal of Manufacturing Process,* **37**, 266–273. https://doi.org/10.1016/j.jmapro.2018.11.023

Gibson, I., Rosen, D. and Stucker, B., 2010. Additive manufacturing technologies, 3D printing, rapid prototyping, and direct digital manufacturing, SE, *Springer,* New York, NY, 107-112.

Gordeev, E. G., Galushko, A. S., and Ananikov, V. P., 2018. Improvement of quality of 3D printed objects by elimination of microscopic structural defects in fused deposition modeling. *PLoS ONE*, **13(6)**, e0198370. https://doi.org/10.1371/journal.pone.0198370

Guduru, K. K., and Srinivasu, G., 2020. Effect of post treatment on tensile properties of carbon reinforced PLA composite by 3D printing. *In Materials Today: Proceedings,* **33**, 5403–5407. https://doi.org/10.1016/j.matpr.2020.03.128

Hirt G., Thome M., 2007. Large area rolling of functional metallic micro structures. *Production Engineering,* **1**, 351-356. https://doi.org/10.1007/s11740-007-0067-z

Hossain, M. S., Espalin, D., Ramos, J., Perez, M. and Wicker, R. 2014. Improved Mechanical Properties of Fused Deposition Modeling-Manufactured Parts Through Build Parameter Modifications. *Journal of Manufacturing Science and Engineering, Transactions of the ASME*, **136(6),** 061002. https://doi.org/10.1115/1.4028538

Huang, S., Liu, P., Mokasdar, A., and Hou, L., 2013. Additive manufacturing and its societal impact: a literature review, *International Journal of Advanced Manufacturing Technology*, **67**, 1191–1203. https://doi.org/10.1007/s00170-012-4558-5

Jung, Y. C. and Bhushan, B., 2010. Biomimetic structures for fluid drag reduction in laminar and turbulent flows. *Journal of Physics Condensed Matter*, **22(3)**, 035104. https://www.doi.org/10.1088/0953-8984/22/3/035104

Korkut V. and Yavuz H., 2020. Enhancing the tensile properties with minimal mass variation by revealing the effects of parameters in fused filament fabrication process, *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, **42(10),** 525. https://doi.org/10.1007/s40430-020-02610-0

Marentic F. J., Morris T. L., 1992. Drag reduction article, United States Patent no. 5, 133, 516.

Pearce, J. M., 2012. Building research equipment with free, open-source hardware, *Science*, **337**, 6100, 1303–1304. https://doi.org/10.1126/science.1228183

Pearce, J. M., 2014. Open-Source Lab: How to Build Your Own Hardware and Reduce Research Costs, *Elsevier*, New York, USA, 1-5.

Rayna, T., and Striukova, L., 2016. From rapid prototyping to home fabrication: how 3D printing is changing business model innovation. *Technological Forecasting and Social Change*, **102**, 214–224. https://doi.org/10.1016/j.techfore.2015.07.023

Sin, L. T., 2012. *Polylactic Acid:* PLA *Biopolymer Technology and Applications*, William Andrew, Boston, MA, USA. 57-66.

Tymrak, B., Kreiger, M. And Pearce, J., 2014. Mechanical properties of components fabricated with open-source 3-D printers under realistic environmental conditions. *Materials and Design* **58**, 242–246. https://doi.org/10.1016/j.matdes.2014.02.038

Uriondo, A., Esperon-Miguez, M. and Perinpanayagam, S. 2015. The present and future of additive manufacturing in the aerospace sector: A review of important aspects. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, **229(11),** 2132–2147. https://doi.org/10.1177/0954410014568797

Vyavahare, S., Teraiya, S., Panghal, D. and Kumar, S., 2020. Fused deposition modelling: a review, *Rapid Prototyping Journal*, Emerald Group Holdings Ltd., **26(1),** 176-201. https://doi.org/10.1108/RPJ-04-2019-0106

Walsh M. J. and Lindemann A. M., 1984. Optimization and application of riblets for turbulent drag reduction. *22nd Aerospace Sciences Meeting*, Reno, NV, American Institute of Aeronautics and Astronautics Meeting Papers, *New* York. https://doi.org/10.2514/6.1984-347

Walsh M. J., 1983. Riblets as a viscous drag reduction technique. *American Institute of Aeronautics and Astronautics Journal,* **21(4)**, 485–486.

Walsh, M.J. and Weinstein, L.M., 1978. Drag and Heat Transfer on Surfaces with Small Longitudinal Fins. *11th Fluid and PlasmaDynamics Conference*, American Institute of Aeronautics and Astronautics Meeting Papers, New York, 1161. https://doi.org/10.2514/6.1978-1161

Zaman, U. K., Boesch, E., Siadat, A., Rivette, M. and Baqai, A. A. 2019. Impact of fused deposition modeling (FDM) process parameters on strength of built parts using Taguchi's design of experiments. *International Journal of Advanced Manufacturing Technology*, **101(5–8)**, 1215–1226. https://doi.org/10.1007/s00170-018-3014-6

Internet References

1- AI-powered developer platform. https://github.com/, (17.04.2023)

2- Simplify3D, Print Quality Troubleshooting Guide. https://www.simplify3d.com/resources/print-quality-troubleshooting/, (17.04.2023)

3- DeRuvo, J., 2019. Simplify3D Troubleshooting: Common Questions Answered. https://all3dp.com/2/simplify3d-troubleshooting-the-most-common-questions-answered/, (17.04.2023)