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CONTRIBUTIONS TO INCREASING THE QUALITY OF OUTER THREADS OBTAINED THROUGH 3D PRINTING

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Abstract: *This research study presents an exploration into the accuracy of threads produced using the Fused Deposition Modeling (FDM) process. In traditional manufacturing of helical threads adhering to established standards, deformations can occur. These deviations in dimensions often result in departures from radial tolerances and changes in thread shapes. The primary objective of this research is to investigate and characterize these dimensional inaccuracies using image analysis. Additionally, the study aims to address these imperfections partially by implementing a strategy to adjust thread profiles. To achieve this goal, a total of 9 specimens were manufactured using the ZORTRAX M-200 3D printer, varying in flank inclination values and layer thicknesses. These values were selected based on a Taguchi plan. Z-ABS material was utilized in the printing process. The collected data underwent analysis using Minitab software and the Artificial Neural Networks Toolbox within MATLAB, enabling corrective measures to be applied to the printed thread profiles. As an innovative aspect of this study, the paper introduces the utilization of Artificial Neural Networks for analysis and the potential to make necessary adjustments in order to attain profiles that closely align with the desired outcomes.*

Key words: *Additive Manufacturing, Artificial Neural Networks, 3D Printing, Screw, Geometry.*

1. INTRODUCTION

The field of rapid prototyping has witnessed rapid advancements and has gained significant traction across various industries, including automotive, aerospace, electronics, and medicine. Its purpose is to fabricate prototype products and intricate mechanisms. Particularly in the aerospace sector, traditional manufacturing methods have been substituted with additive manufacturing (AM) of lightweight polymer components. Unlike conventional manufacturing techniques, AM, also known as 3D printing, constructs components and parts by layering materials with a predetermined thickness. AM offers enhanced design flexibility, reduced delivery times, and the potential for seamless integration with computer-aided manufacturing (CAM) and computer-aided design (CAD) technologies [1]. While AM was initially predominantly used for prototyping purposes, it has now matured to enable customized mass production of functional parts [2, 3]. Depending on the degree of accuracy of the 3D printer but also of the specific process parameters (material, filament thickness, working temperature, printing speed, layer thickness, degree of filling, etc.), the products obtained have dimensional variations that are within very wide limits. Numerous industrial components manufactured by FDM fall in terms of dimensional tolerances in the precision class IT-09 [4]. Lately, due to the unprecedented development of CAD software, 3D printing has evolved from a niche technology to a widely used technology. 3D printing has also been facilitated by the development of the Internet through the emergence of platforms dedicated to the exchange of precise 3D models and databases that make available to users sets of process parameters specific to a particular configuration [5]. However, due to the diversity of products, these databases are limited. Another modern method of using process parameters is related to the use of AI. This method is still at an early stage of development and is therefore not suitable for productive use [6]. Although AM has many advantages related to the relative short time to reach from the virtual format of the piece to the physical format, it still has many limitations. 3D printing provides a convenient solution for producing parts with complex shapes that are challenging or even unfeasible to manufacture using traditional methods [7, 8]. However, it is important to note that rapid prototyping technologies do not serve as a universal solution for every product-manufacturing issue. Despite the numerous advantages of Fused Deposition Modeling (FDM), including its user-friendly nature, design flexibility, wide material selection, and cost-effectiveness, there are also drawbacks to consider. For instance, FDM exhibits limitations in achieving high accuracy for small parts and intricate details, particularly when manufacturing parts as an assembly [9].

When utilizing Fused Deposition Modeling (FDM) for producing intricate regions like threaded surfaces, undesired defects such as dimensional errors, shape discrepancies, and positional inaccuracies may arise. Previous studies emphasize that quantifying these defects becomes increasingly challenging as the complexity of the geometry being fabricated intensifies. Recognizing that FDM manufacturing inherently entails dimensional errors, certain researchers suggest exploring alternative Additive Manufacturing (AM) processes like Stereolithography (SLA) or Selective Laser Sintering (SLS) [3However, Fused Deposition Modeling (FDM) remains a preferred choice for many manufacturers due to its significantly lower equipment and software costs. Nevertheless, when producing parts using FDM, helical threads created in accordance with standard guidelines (such as ISO 68-1) have a tendency to deform during the manufacturing process [10]. These dimensional imperfections commonly involve violations of radial tolerances and frequently result in distorted thread profiles. As a result, achieving successful threaded connections using FDM often necessitates looser tolerances than standard requirements [10, 11]. One of the factors that restrict the utilization of Additive Manufacturing (AM) in the production of certain components is the limited information available regarding the formation of threaded surfaces [12]. The work makes a comparison between the quality of a threaded surface manufactured by FDM compared to the same surface also manufactured by FDM, followed by an adjustment of the surface using a cutting tool. Also, to minimize errors due to deposits in consoles of the material on the flanks of the thread, the work proposes additional cooling of the part during the AM process. In their research, Elkaseer et al. [1] examined the impact of various parameters within the 3D printing process on surface quality, specifically focusing on surface roughness, when producing inclined surfaces at different angles. Thus they conclude that the roughness of the surface depends on the angle of inclination of the surface and the thickness of the layer. The paper [10] proposes a method by which the ratio between the thread step and the layer thickness is calculated so that it is an integer multiple. Since the vast majority of printers do not have the possibility of continuously adjusting the layer thickness, the proposed method cannot always be applied. Also, depending on the value of the ratio between the pitch size and the thickness of the layer, the shape of the thread flank section may vary from the theoretical form. At the same time, a higher or lower accuracy of the thread tip or the bottom of the thread can be achieved.

The same work studied the influence of layer thickness on the diameter of the thread tip and on the diameter of the thread bottom. The results presented demonstrate that modifying the layer thickness from 0.3 mm to 0.15 mm results in improved dimensional accuracy for the two parameters. In [5] is presented another method of improving the quality of the profiles of the threaded surfaces, namely the manual rolling method in which a specific device is used. The main advantages of the process consist in the bulk repositioning of the material, which means that there is no loss of material (and no interruption of the fibers), but also an increase in the surface quality and an improvement of the screw properties. Another way to improve the accuracy of threaded surfaces is to use a post-processing operation that corrects the profile obtained by FDM [5]. Unfortunately, during this post-processing operation, an additional amount of material is removed, which will lead to a decrease in the properties of the product manufactured by FDM. The objective of this paper is to analyze and characterize dimensional inaccuracies in printed threads by utilizing a profile projector to examine their profiles. Additionally, the study investigates the implications of these defects and proposes a strategy to partially compensate for them. This compensation strategy involves modifying the tooth flank geometry by adjusting the thread angle with a coefficient angle, aiming to minimize the deviation from the nominal angle.

2. THE SPECIMENS USED IN THE STUDY

In carrying out the case study, the screws were made using the method of threading by 3D printing considering their strength and the fact that they do not require further processing.
To conduct the case study, screw-type parts were designed with specific dimensions (ranging from M10 to M24) and a geometry of moderate complexity. These parts were then printed in order to gather valuable insights on how the input parameters of the 3D printing process influence the geometric characteristics of the component [13].

The study started from the analysis of 15 screws printed by FDM, with a range of diameters between 12 and 24 mm, using variable layer thicknesses: 0.09, 0.14 and 0.19 mm. These are relatively small screws, which makes them ideal for case study, as no large amount of raw material is needed for printing.

The parts were printed in an upright position, without support so as not to further affect the quality of the surface after removing the support. Figure 1 illustrates an example of the specimen drawings.

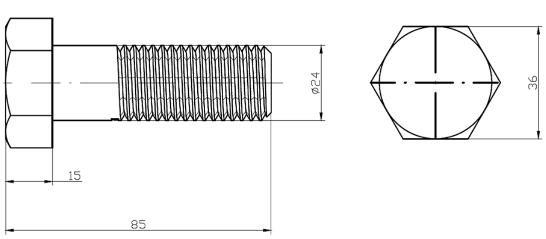


Fig.1. The specimen drawing

The process of transforming a design into a 3D printed object comprises three primary phases: computer-aided design (CAD), slicing, and printing. These phases are depicted in Figure 2.

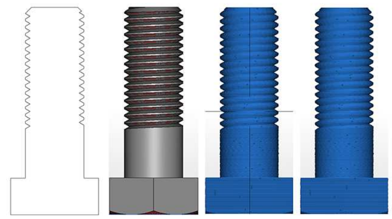


Fig.2. Sketch of the model, CAD model, STL

To create a digital input, the design needs to be modeled in a CAD software, and then exported as a stereolithography file (STL), which is the standard format for importing into the slicer. This process is illustrated in Figure 3. This is a discretization of CAD parts, in which the geometry is discretized into triangles that make up a mesh [14].

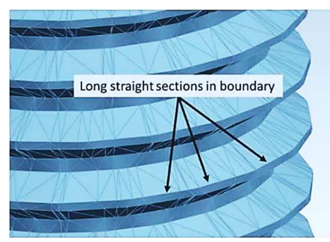


Fig.3. Linearizing the geometry of a CAD drawing into an STL file

The geometry sampling of the surfaces in the x-y direction remains identical to the STL surfaces. However, in the z-direction (layer by layer), as depicted in Figure 4, the geometries exhibit lower accuracy [15].

Fig.4. The slicing of an inclined plane

The 3D specimen is created using Catia V5 software, and subsequently, the 3D model is imported into Z-Suite software to generate the code necessary for the Zortrax M200 3D printer. This process is illustrated in Figure 5.

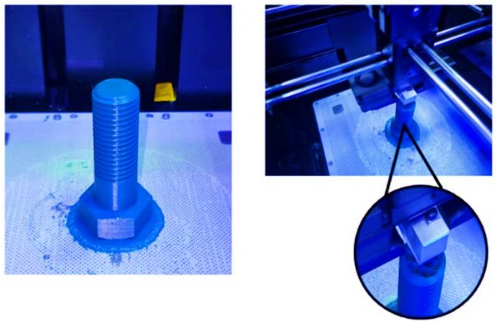


Fig.5. The screw during the 3D printing process

The commonly employed slicing software (Z-SUITE) captures the geometry's contour at the middle layer position and endeavors to align it with the nozzle tool paths and the designated filament width. However, since the contour maxima are influenced by material flow and solidification during plastic extrusion rather than being modeled based on the STL geometry, there can be a discrepancy between the maxima of an inclined printed surface and the corresponding CAD part. This gap is illustrated in Figure 6 [15].

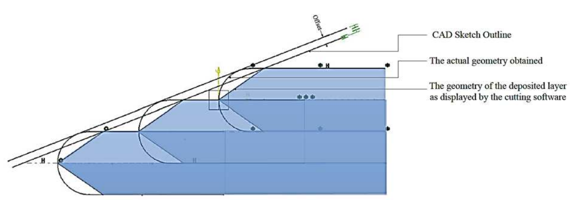


Fig.6. Offset sketch between the ideal geometry and the printed one due to the deposition of the middle layer

The layering effect and resultant gaps are somewhat predictable when dealing with inclined planes, where the plastic is extruded onto a solid base. However, for suspended sections, the effect becomes more unpredictable as the plastic is extruded partially on a solid base and partially in the air. This phenomenon is depicted in Figure 8 [16].

There are additional factors contributing to these defects, including:

- Thermal contraction (as shown in Figure 7).
- Nozzle movements that can disturb the material that has been extruded before it solidifies.
- Structural deformation during the printing process (as depicted in Figure 8).
- The slicing of the model, which is dependent on the height of the deposited layer.

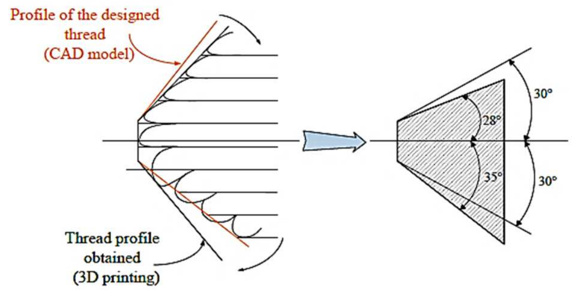


Fig.7. Pattern contraction during printing

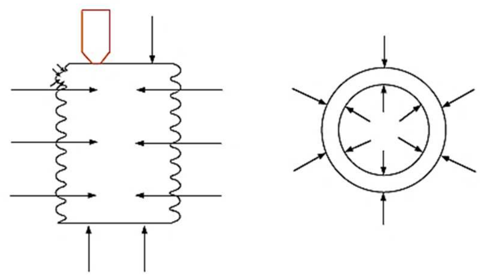


Fig.8. Pattern contraction during printing

When dealing with inclined surfaces, the hydraulic pressure from the extrusion nozzle can cause the previously deposited layer to deform temporarily, leading to an abnormally thicker layer in that particular area. However, this deformation returns to its original state once the nozzle moves past it (as depicted in Figure 9). Consequently, the deposited layer ends up being positioned higher compared to a layer deposited on a solid base [17]. This increase in layer height can further impact the nozzle pressure when it passes through those areas in subsequent layers, resulting in a progressive increase in size with each new layer added.

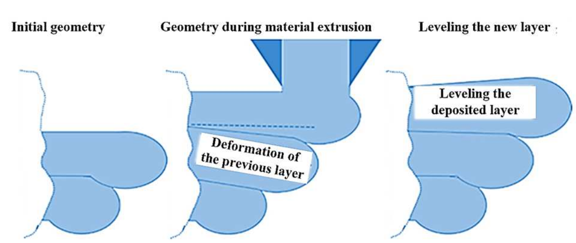
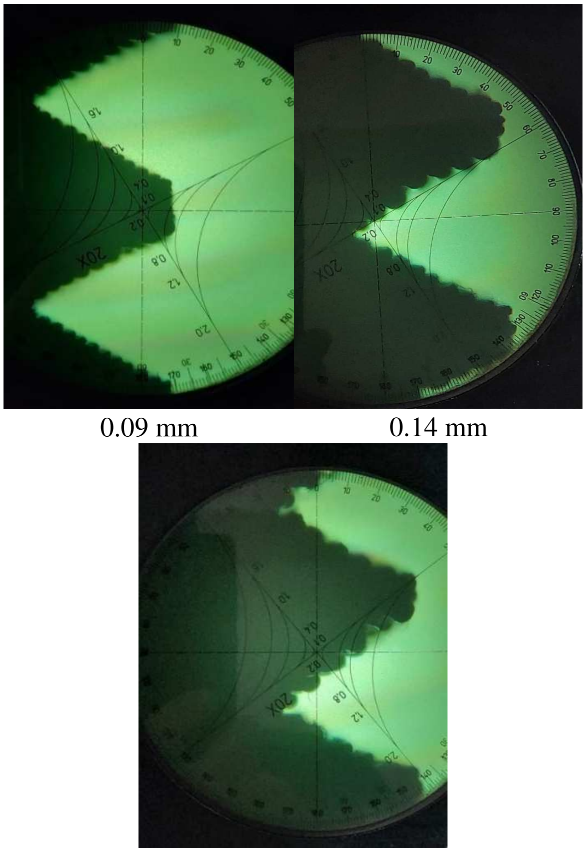


Fig.9. Deformation and levelling of the layer during extrusion

After the printing process was completed, each screw was analysed using a profile projector with a vertical optical system to observe any non-conformities of the screw thread. As an e.g., the projection of M24 can be seen in Figure 10.



0.09 mm 0.14 mm

0.19 mm

Fig.10. View of M24 screw using the profile analyser

As a result of the measurements made, there was a difference between the designed and obtained dimensions. In addition to the dimensional deviation, a distortion of the thread profile is also observed.

To attain satisfactory dimensional accuracy, the approach of printing the screws in an upright position proves effective. This method entails printing inclined planes at 30° and protrusions at 60°. In the specific case under consideration, three different layer heights of 0.09 mm, 0.14 mm, and 0.19 mm will be employed for printing these components.

As a compensation method, this article aims to test the effect of a concept involving the modification of the tooth flank geometry by increasing or decreasing the thread angle with a coefficient, aiming to minimize the deviation from the nominal angle. The proposed method consists of two steps:

Step 1: The threads are initially created with the nominal flank incline values, and deviations from these values are evaluated (Figure 11);

In *Step 2* (Figure 12), based on the analysis of the results obtained in the previous step, corrections for the X and Y angles are determined. The approach illustrated in Figure 12 provides a simple and practical solution for compensating errors that may arise during the 3D printing of components. This change should lead us to results closer to the standard values of a 30° thread flank angle to be achieved.

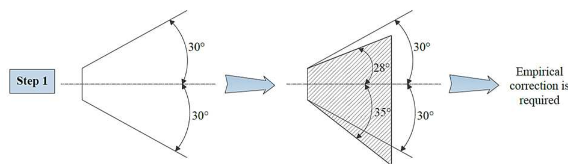


Fig.11. Preliminary determination of errors obtained compared to nominal values

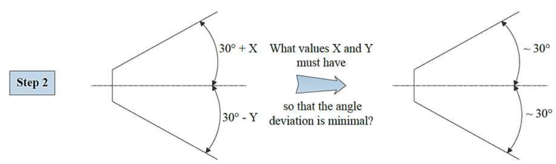


Fig.12. Presentation of the proposed angle compensation method

3.THE CAS STUDY: EXPERIMENTAL INVESTIGATIONS

3.1 Data planning and analysis with Minitab

To validate this strategy, an experimental plan of Taguchi type was suggested, which was created utilizing the Minitab software. The plan employed was L9 (3^3), incorporating three variables: layer thickness, upper angle correction and lower angle correction. The strategy was applied to the M24 screw to save time and material, but also due to the fact that its geometry is more easily visible due to its proportions [9].

With three input parameters (deposited layer thickness, upper angle correction and lower angle correction), the Minitab software generated an experimental plan containing nine experiences.

The experimental data plan can be found in table 1.

Table 1

The data used for the experiment

Exp. No.	Layer thickness	Upper angle correction	Lower angle correction
1	0,09 mm	32°	26°
2	0,09 mm	33°	27°
3	0,09 mm	34°	28°
4	0,14 mm	32°	27°
5	0,14 mm	33°	28°
6	0,14 mm	34°	26°
7	0,19 mm	32°	28°
8	0,19 mm	33°	26°
9	0,19 mm	34°	27°

The printed parts, with the corrections applied, can be found in Figure 13.

Fig.13. 3D printed parts with flank correction

A regression analysis was realized: input parameters (layer hight, upper angle correction and lower angle correction) versus output parameters (the upper and lower obtained angles of the flank), Figure 14.

3.2 Analysis of the data using the Artificial Neural Network Toolbox in MATLAB

The MATLAB Artificial Neural Network Toolbox was utilized to import the data. Using the data presented in Table 5.8, an Artificial Neural Network (ANN) was trained. The input data set consisted of a matrix with dimensions 9x3, while the output data set was represented by a vector with dimensions 3x1. The training process was performed using the Neural Network Toolbox in MATLAB.

In Figure 14, we can observe from the Pareto chart and the main effects plots that the input parameters do not have a significant influence on the output parameter. Additionally, on the histogram, it is evident that the distribution is not close to a normal one.

Regression Equation

Lower angle = 14,6 - 1,7 Layer thickness + 0,050 Upper angle correction + 0,500 Lower angle correction

Coefficients

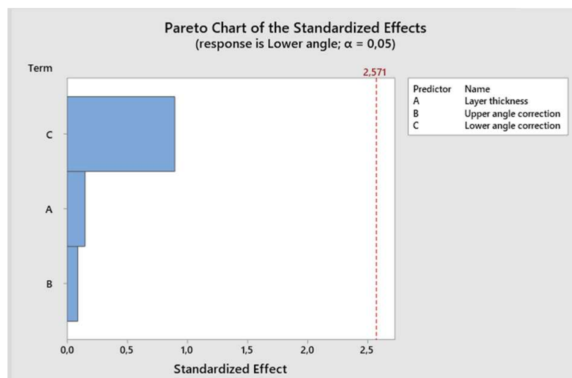
Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	14,6	23,9	0,61	0,566	
Layer thickness	-1,7	11,2	-0,15	0,887	1,00
Upper angle correction	0,050	0,558	0,09	0,932	1,00
Lower angle correction	0,500	0,558	0,90	0,411	1,00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
1,36715	14,28%	0,00%	0,00%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	1,5567	0,51889	0,28	0,840
Layer thickness	1	0,0417	0,04167	0,02	0,887
Upper angle correction	1	0,0150	0,01500	0,01	0,932
Lower angle correction	1	1,5000	1,50000	0,80	0,411
Error	5	9,3456	1,86911		
Total	8	10,9022			



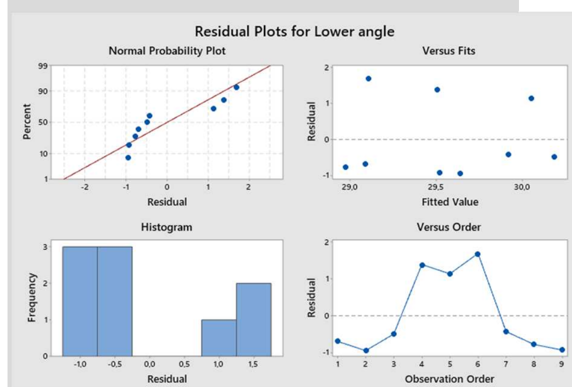


Fig.14. Rapport of regression analysis generated by Minitab software for “Lower angle”

Regarding the "Upper angle" parameter, by analyzing Figure 15, we can observe from the Pareto chart that the "Layer thickness" and

"Upper angle correction" parameters have a significant influence on the output parameter.

Regression Equation

Upper angle = -17,6 + 44,33 Layer thickness + 1,850 Upper angle correction - 0,583 Lower angle correction

Coefficients

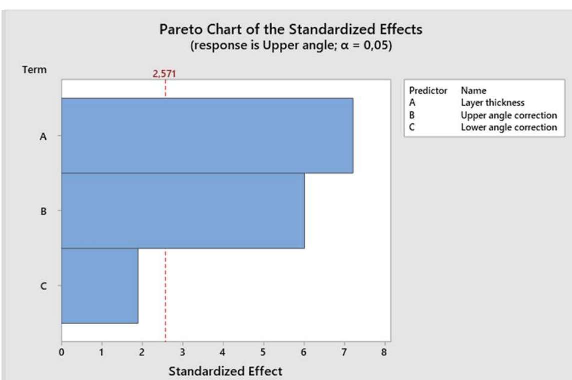
Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-17,6	13,2	-1,34	0,238	
Layer thickness	44,33	6,16	7,20	0,001	1,00
Upper angle correction	1,850	0,308	6,01	0,002	1,00
Lower angle correction	-0,583	0,308	-1,90	0,117	1,00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0,753879	94,82%	91,72%	82,69%

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	52,058	17,3528	30,53	0,001
Layer thickness	1	29,482	29,4817	51,87	0,001
Upper angle correction	1	20,535	20,5350	36,13	0,002
Lower angle correction	1	2,042	2,0417	3,59	0,117
Error	5	2,842	0,5683		
Total	8	54,900			



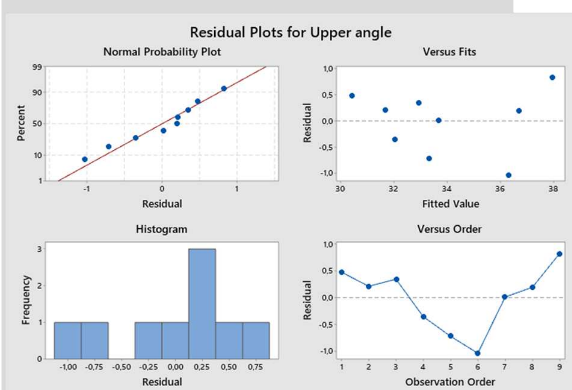


Fig.15. Rapport of regression analysis generated by Minitab software for "Upper angle"

The neural network architecture in this study comprised an input layer, a hidden layer, and an output layer. The inputs for the Artificial Neural Network (ANN) were the thickness of the deposited layer, the correction of the upper angle, and the correction of the lower angle [18].

The connections between the input layer, hidden layer, and output layer were represented by weights (w) and biases (b), which are considered as parameters of the ANN. For the training process, 70% of the available data sets were selected, while 15% of the data sets were used for testing and another 15% for validation [9, 18, 19].

The specific network architecture employed in this study included three input neurons corresponding to the input parameters, two output neurons corresponding to the output parameter, and ten neurons in the hidden layer. The selection of ten neurons in the hidden layer was determined empirically and depicted in Figure 16.

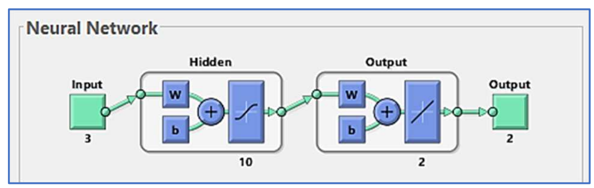


Fig.16. The ANN architecture

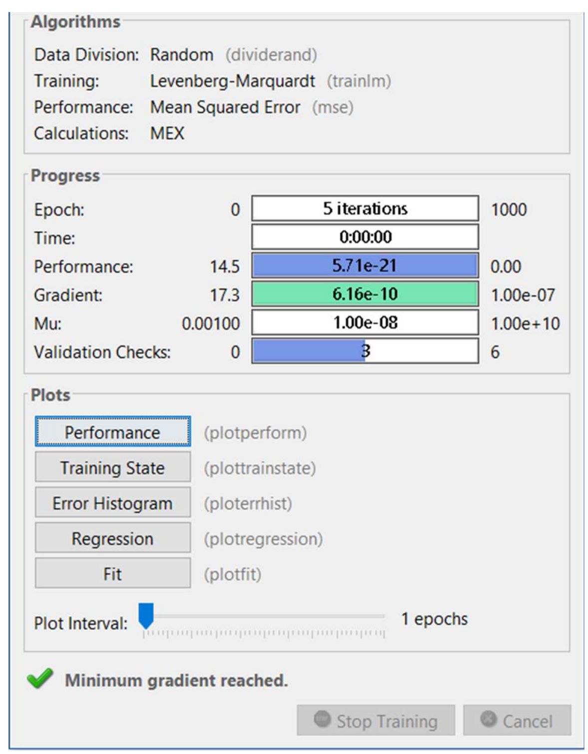
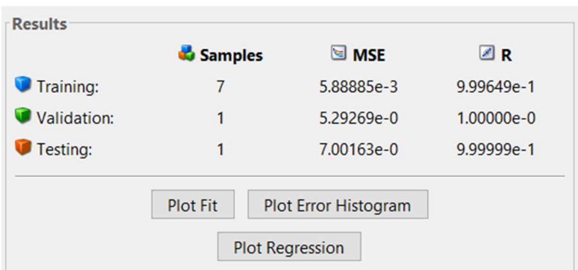


Fig.17. Training the neural network

The Artificial Neural Network (ANN) was trained using the "Levenberg-Marquardt" backpropagation algorithm, which is known for its effectiveness in network training. The training process involved iterative steps. In this particular study, the network was trained for 5 iterations, as shown in Figure 17.

After completing the training process, the "Train network" window displayed the values for R^2 (coefficient of determination) and MSE (mean square error), as shown in Figure 18. These metrics provide an evaluation of the performance and accuracy of the trained network.


Results

	Samples	MSE	R
Training:	7	5.88885e-3	9.99649e-1
Validation:	1	5.29269e-0	1.00000e-0
Testing:	1	7.00163e-0	9.99999e-1

Fig.18. The results of network training, testing and validation

Once trained, the network can be utilized by the designer to obtain advice or simulate new parameters. By inputting a new set of data that corresponds to a different situation, the network can provide a response or prediction. The results given by the network for the new input data can be observed in Table 2 [9]. This enables the designer to make informed decisions based on the network's outputs in various scenarios.

Table 2.

New parameters simulated with ANN

INPUT	
Layer thickness	0.19 mm
Upper angle correction	33 °
Lower angle correction	29 °
OUTPUT	
Upper flank	34.1252 °
Lower flank	31.2787 °

4. CONCLUSIONS

When printing threads, the layer thickness plays a crucial role as an essential parameter, as shown in Figure 15. To ensure proper operation, it is preferable to use smaller layer thickness. Threads larger than M12 can be efficiently printed using 0.2 mm layers, while smaller threads should be printed using even thinner layers.

Dimensional accuracy decreases as the thickness of the deposited layer increases, as highlighted in Figure 10.

Due to the nature of material flow and solidification during plastic extrusion, the contour extremities of a printed inclined surface may exhibit a gap compared to the corresponding CAD part. This is because the extremities are not precisely modelled according to the STL geometry. Furthermore, the size of this gap tends to increase with the angle of inclination.

There are other factors contributing to errors in the printing process. Thermal shrinkage, for instance, can cause dimensional discrepancies between the printed object and the intended design. Additionally, nozzle movements can affect the already extruded material before it fully solidifies, leading to further distortions. Other sources of errors include structural deformations during printing and the segmentation of the model, which is influenced by the height of each deposited layer.

We printed and measured nine pieces following an established measurement plan, subsequently centralizing the obtained values. After adjusting these values, they were analyzed using MINITAB software to determine the influence of input parameter variations on them. Following regression analysis, regression equations were established for both the upper flank and the lower flank. Data analysis was performed using the Artificial Neural Network Toolbox in MATLAB.

The method presented offers a straightforward solution for mitigating errors that occur during 3D printing of components. By implementing this approach, it is expected that the results will approach the desired standard values of 30° for each side of the thread. While specific numerical values may vary between different machines, the overall trend is expected to be similar for the Fused Deposition Modeling (FDM) process as a whole. This method addresses both fundamental errors and errors dependent on layer height, contributing to improved accuracy in printed components.

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Contribuții privind creșterea calității filetelor exterioare obținute prin imprimare 3D

Lucrarea prezintă un studiu privind precizia dimensională a filetelor obținute prin FDM. Filetele elicoidale proiectate în conformitate cu standardele normale, tind să își modifice forma atunci când sunt fabricate. Aceste abateri dimensionale includ în mod obișnuit atât toleranțele privind diametrul exterior dar mai ales profilul filetului. Acest studiu își propune să caracterizeze astfel de abateri dimensionale prin analiza imaginii și să încerce să compenseze parțial defectele prin utilizarea unei strategii care modifică profilul filetului. În acest scop, au fost imprimate cu imprimanta 3D Zortrax M-200 un număr de 9 exemplare cu diferite valori ale înclinării flancurilor. Combinația de valori a fost stabilită conform unui plan Taguchi. Z-ABS a fost folosit ca material. Datele au fost analizate cu software-ul Minitab și cu Artificial Neutral Networks Toolbox de la MATLAB

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