



Kaunas University of Technology
Faculty of Mechanical Engineering and Design

Development of a Customizable Heated Module for Rotary 3D Printing

Master's Final Degree Project

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Project author

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Supervisor

Kaunas, 2024



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Mechatronics (6211EX017)

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Kaunas, 2024



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1. Title of the Project

Development of a Customizable Heated Module for Rotary 3D Printing

(In English)

Rotoriniam 3D spausdinimui skirto individualizuojamo kaitinamo modulio kūrimas

(In Lithuanian)

2. Aim and Tasks of the Project

Aim: to develop a proof-of-concept rotary module with a customizable heated print-drum for integration into a standard extrusion-based additive manufacturing machine.

Tasks:

1. to design a rotary module and a heated print-drum with a customizable conductive cylindrical sleeve;
2. to create thermomechanical finite element models of different print-drum designs and evaluate their heat transfer performance and temperature distribution under working conditions;
3. to manufacture the proof of concept of the rotary module with a heated print-drum, experimentally evaluate the print-drum thermal performance and test printing capabilities;
4. to perform a cost-effectiveness analysis of the designed module and commercially available alternative solutions.

3. Main Requirements and Conditions

MATLAB, SolidWorks, SolidWorks Flow Simulations, thermography ISO 18434-1:2008, parallelism and run-out ISO 230-1:2012.

4. Additional Requirements for the Project, Report and its Annexes

Not applicable

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Mantas Šmatavičius. Development of a Customizable Heated Module for Rotary 3D Printing. Master's Final Degree Project, supervisor Chf. Res. dr. Rolanas Daukševičius; Faculty of Mechanical Engineering and Design, Kaunas University of Technology.

Study field and area (study field group): Production and Manufacturing Engineering (E10), Engineering Sciences (E).

Keywords: additive manufacturing; rotary 3D printing; customizable design; thermography; thermal simulations.

Kaunas, 2024. 61 p.

Summary

Additive manufacturing offers great flexibility in design, customizability, and on-demand manufacturing. However, the current additive manufacturing technologies based on planar material extrusion processes have several limiting factors including poor mechanical properties, rough surface quality, extensive use of supporting structure etc. In recent years advances in non-planar material deposition were made to solve these limitations for producing the tubular structures. This study focused on solving the lack of heated surfaces in rotary 3D printing and suggested the use of conductive sleeves for printing the variable-diameter tubular structures. In this paper heated print-drum design and rotary module for Prusa MK3S 3D printer were developed. The thermal performance of the print-drum was analysed using theoretical and experimental research methods. The printing capabilities were tested. The assembled rotary module with print-drum achieved the 100°C printing surface temperature per 130 seconds and was able to print at 30 mm/s.

Mantas Šmatavičius. Rotoriniam 3D spausdinimui skirto individualizuojamo kaitinamo modulio kūrimas. Magistro baigiamasis projektas, vadovas vyr. mokslo darbuotojas dr. Rolanas Daukševičius; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas.

Studijų kryptis ir sritis (studijų krypčių grupė): Gamybos inžinerija (E10), Inžinerijos mokslai (E).

Reikšminiai žodžiai: adityvi gamyba; rotorinis 3D spausdinimas; individualizuota konstrukcija; termografija; šiluminis modeliavimas.

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Santrauka

Adityviosios gamybos metodai suteikia didelį projektavimo proceso lankstumą, pritaikomumą, galimybę pagaminti pagal poreikį. Tačiau dabartinai adityviosios gamybos metodai, grindžiami medžiagos ekstruzijos principu ant plokščio paviršiaus, turi keletą ribojančių veiksnių, kurie lemia prastas mechanines savybes, nepakankamą paviršiaus kokybę, sunaudoja didelį kiekį pagalbinių medžiagų ir t.t. Pastaraisiais metais buvo padaryta pažanga neplokštuminės medžiagos ekstruzijos srityje, siekiant išspręsti šias problemas, spausdinant cilindrinės formos komponentus. Šame darbe buvo siekiama sukurti kaitinamą cilindrinį spausdinimo paviršių pritaikytą rotoriniam 3D spausdinimui ir buvo pasiūlyta naudoti šilumai laidų apvalkalą skirtą kintamo skersmens cilindrinį komponentų spausdinimui. Šiame darbe buvo suprojektuotas ir pagamintas kaitinamas būgnas ir rotorinis modulis pritaikytas integravimui į Prusa MK3S spausdintuvą. Buvo išanalizuotas spausdinimo būgno šiluminis efektyvumas pritaikant teorinius ir eksperimentinius tyrimo metodus. Taip pat, buvo išbandytos spausdinimo galimybės su rotoriniu moduliu. Sukurtas rotorinis modulis su spausdinimo būgnu per nepilnas dvi minutes pasiekia 100 °C spausdinimo paviršiaus temperatūrą ir suteikia galimybę spausdinti 30 mm/s greičiu.

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List of Abbreviations and Terms

Abbreviations:

ABS – Acrylonitrile Butadiene Styrene;
AM – Additive Manufacturing;
ASA – Acrylonitrile Styrene Acrylate;
CNC – Computer Numerical Control;
I/O – Input/Output;
FDM – Fused Deposition Modelling;
FFF – Fused Filament Fabrication;
HIPS – High Impact Polystyrene
MEX – Material Extrusion;
PA – Polyamide;
PETG – Polyethylene Terephthalate Glycol;
PLA – Polylactic Acid;
PLC – Polycaprolactone;
TPU – Thermoplastic Polyurethane.

Terms:

Print-drum – a mechanical assembly of a rotary 3D printing machine or module. It consists of several parts which include one or more heating elements and provide a designated heating area for additive material deposition.

Sleeve – component or assembly of 3D printed parts used on the print-drum to customize the printing surface.

Introduction

Additive manufacturing (AM) is a novel manufacturing method that enables the production of complex, highly customizable geometries in a single process. In recent years, additive manufacturing was brought up from its original use case of rapid prototyping, and it found applications in small series manufacturing across various industries. Moreover, with the advent of Industry 4.0, additive manufacturing gained a lot of interest from different industry sectors in manufacturing components tailored to customers. However, the current additive manufacturing technologies are restricted by the various process limitations for further implementation in the manufacturing process. The researchers proposed a novel solution to improve the additive manufacturing process based on material extrusion (MEX) by employing a non-planar material deposition. This method involves the utilization of specialized algorithms and software, known as “slicer”, to slice modelled components into non-planar toolpath layers for the additive manufacturing material extrusion machine. Moreover, to achieve the full process capability of non-planar material deposition, specifically designed hardware is required. As a result, this new approach to manufacturing complex geometries promises to reduce the waste produced by supporting structures used in planar 3D printing, enhance the mechanical properties of printed parts, and improve surface quality by reducing the staircase effect seen on the parts. This manufacturing process interested researchers in additively manufacturing tubular structures more efficiently and with improved mechanical characteristics for various industrial or medical applications. In addition to process improvements of non-planar material deposition over the conventional AM MEX, the ability to utilize a variety of filaments with different material properties could enable the additive manufacturing of customizable multi-material, multi-functional tubular structures with tailored layer properties. These properties could include electrical conductivity, piezoelectricity, thermally conductivity, biocompatibility, biodegradability and more. Such tubular components have potential applications in the field of medical devices for example stents, scaffolds, grafts, conduits, and others. However, despite its potential, the non-planar extrusion-based 3D printing hardware lacks some functionality found in standard fused deposition modelling (FDM) machines and has some areas for improvement. This research hopes to open the possibility of improving the hardware of non-planar material deposition on a cylindrical printing surface for thermoplastic and their composite materials by developing the rotary module for a conventional FDM machine with a heated printing surface and a customizable sleeve to allow additive manufacturing of non-uniform cross-section tubular components.

Aim: to develop a proof-of-concept rotary module with a customizable heated print-drum for integration into a standard extrusion-based additive manufacturing machine.

Tasks:

1. to design a rotary module and a heated print-drum with a customizable conductive cylindrical sleeve;
2. to create thermomechanical finite element models of different print-drum designs and evaluate their heat transfer performance and temperature distribution under working conditions;
3. to manufacture the proof of concept of the rotary module with a heated print-drum, experimentally evaluate the print-drum thermal performance and test printing capabilities;
4. to perform a cost-effectiveness analysis of the designed module and commercially available alternative solutions.

Hypothesis: A developed rotary module with a heated print-drum will allow to print materials with a higher thermal expansion coefficient and ensure better adhesion of the first layer.

1. Rotary 3D Printing

Rotary 3D printing or 3D lathe printing is an additive manufacturing (AM) material extrusion (MEX) process which is based on extrusion fused deposition modelling (FDM), fused filament fabrication (FFF) and similar 3D printing techniques. A typical MEX process workflow consists of designing a part in selected computer-aided design (CAD) software, exporting files to a specialised software called “slicer” which cuts exported part geometry into two-dimensional planes and generates a machine code for the designated AM MEX machine to operate. Then 3D printer interprets the given commands and moves the actuators to accomplish tasks by depositing material layer by layer on a flat build surface. However, rotary 3D printing compared to conventional MEX process technologies deposits material on a rotating non-planar, cylindrical build surface. Fig. 1.

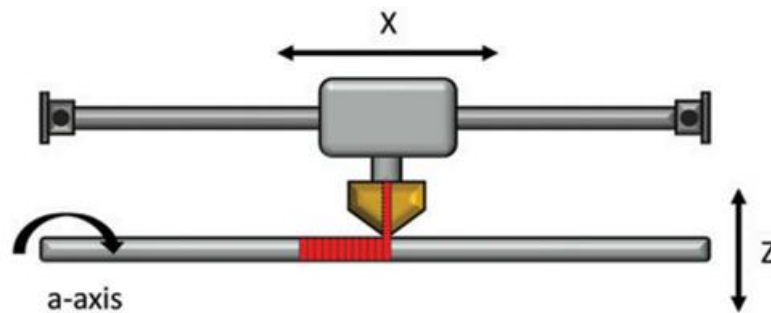


Fig. 1. Description of rotary 3D printer working principle [1]

This process follows the same workflow as mentioned before, but it requires one to possess own specialized machine code generation algorithms, software, and hardware. This technique is mainly focused on producing tree-dimensional parts which exhibit full or partial axial symmetry e.g. gears, propellers, tubular structures, sleeves, stents, etc. The first mention of additively producing three-dimensional solid parts on a rotating cylinder is in the 2009 patent application [2]. This implementation of material extrusion in recent years gained interest from various groups of researchers and 3D printing enthusiasts due to key advantages over conventional planar AM material deposition for producing tubular, variable-size, customizable, thin-wall geometries. The ability to produce tubular shapes with great complexity, design freedom and faster time to market in one manufacturing process is attractive to many fields of implementations from medical implants to industrial applications in the automotive or aerospace sectors.

1.1. Overview of Drawbacks of Conventional AM MEX Process

Components produced by extrusion-based additive manufacturing techniques exhibit reduced mechanical characteristics in comparison to traditionally manufactured counterparts [3-5]. Parts manufactured by conventional manufacturing processes (e.g. injection moulding, CNC machining, etc.) in general tend to have isotropic properties. However, AM material extrusion technologies e.g. fused deposition modelling (FDM), fused filament fabrication (FFF), and fused granular fabrication (FGF) etc. deposit material on a 2D plane layer-by-layer. This manufacturing approach results in parts displaying anisotropic mechanical properties. It is observed that objects printed have diminished performance when the load is applied in parallel to deposited layers. For instance, the study [6] showed that samples of acrylonitrile butadiene styrene (ABS) polymer printed vertically resulted in a tensile strength that is half as large as the samples orientated flat or horizontally. Moreover, ABS samples that were orientated vertically showed about 10% of the yield strength observed in the

samples printed flat or horizontally. Nonetheless, the highest compressive strength is attained when the stress is applied perpendicular to the plane of the deposited material layer [6]. In addition, components 3D printed with thermoplastic polymers under cyclic bending loading experience greater stresses and fatigue failure when specimens are orientated vertically, perpendicularly to the build platform [7]. The decrease in mechanical properties is also evident in parts produced by AM MEX using different materials [8].

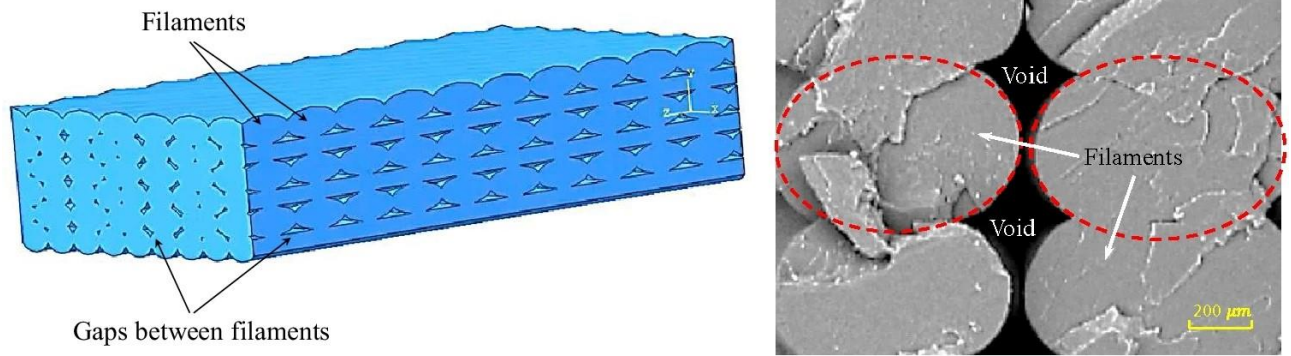


Fig. 2. Voids in the printed specimen [9]

Furthermore, the degree of anisotropy depends on the process parameters employed in extrusion-based additive manufacturing. Material deposition patterns and extruded material volume influence cross-section contact between individual placed molten filament beads. The reduction in the cross-section of filament strands creates voids between deposited layers Fig. 2. The filament adhesion of the component is compromised by the presence of the voids, which results in a decline in strength. [9, 10]. Additional process parameters e.g. printing temperature [11-13], printing speed [11], layer thickness [12-14], raster angle [15, 16], number of contour layers [5], etc. have a substantial impact on the mechanical properties of 3D printed parts. To improve the part characteristics secondary operations could be performed to mitigate MEX AM process variables [15, 17, 18].

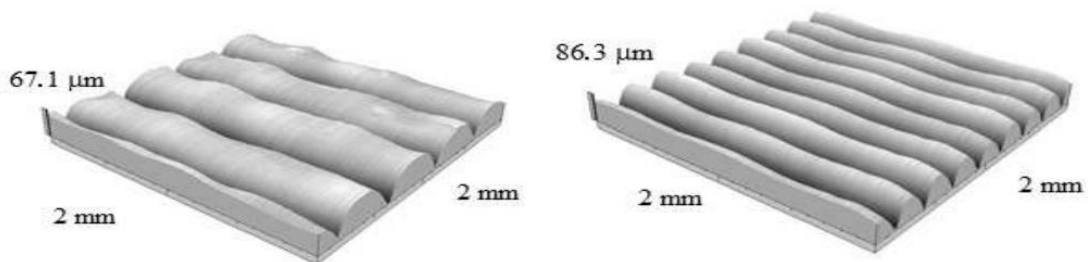


Fig. 3. Surface roughness of horizontal (left) and vertical (right) faces [19]

Another limiting factor of the MEX process is the subpar surface quality Fig. 3. The deposited material inherently creates rough surfaces as a result of the set layer thickness [19]. The staircase effect on the surface is well observed on curved surfaces in the direction of the deposited material layers. To alleviate this issue, layer thickness could be decreased. However, layer height reduction tends to significantly increase the printing time. Another option could be an induction of secondary processing operations. In addition, supporting structures also contribute to low surface quality. The part surfaces built on supporting structures generally have the worst surface quality due to gravity affecting molten material. Supporting structures in practice are used to reinforce overhanging and inclined features that are at an angle of less than 45 degrees. Thus, the use of supporting structures increases printing time, creates waste material, and requires additional operations to remove it.

1.2. Overview of Rotary 3D Printing Advantages Over Planar AM MEX

The study [20] showed the advantage of rotary 3D printing over conventional planar AM MEX for producing functional parts for aerospace applications. The aerofoil produced employing the non-planar AM MEX technique did not require additional support structures and had a better surface finish due to the absence of overhanging geometry features. On the other hand, the aerofoil printed with standard planar FFF with no support structures demonstrated material deformation and loss in detail near overhanging features Fig. 4. Moreover, the components printed from PLA with the rotary 3D printing machine demonstrated 42% higher tensile strength on average over conventional AM MEX [20].

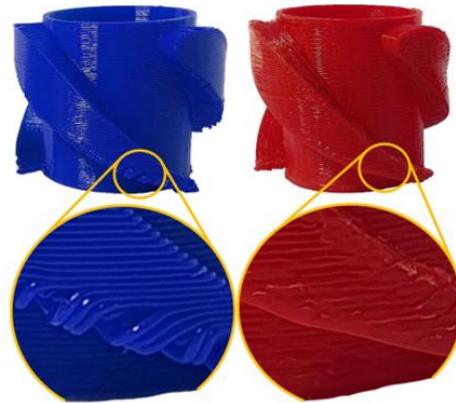


Fig. 4. Aerofoil manufacture without supporting structures using planar MEX (left), rotary 3D printing (right) [20]

Tubular thin-wall structure is another category of part which could take advantage of rotary 3D printing. The study [21] performed a tensile test on thin-wall cylindrical samples manufactured using conventional planar AM MEX and 3D rotational printing Fig. 5. The samples $\text{Ø}10.8 \times 0.4 \times 10$ mm printed from PLA using 5-axis rotary 3D printing demonstrated 14% higher tensile strength on average. Moreover, the study noted that multilateral rotary printing time is faster by 50% compared to standard AM MEX on tubular geometries when different materials are deposited in a radial direction [21].

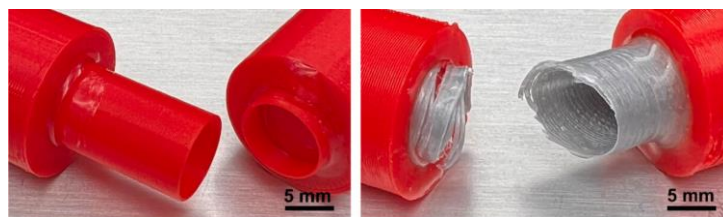


Fig. 5. Tensile test failure results: lateral layer delamination of conventional MEX printing (left), angled layer splitting of rotary 3D printing [21]

A similar study [22] demonstrated the possibility of employing a 4-axis rotary 3D printing machine for manufacturing tubular structures for medical applications. It was able to produce a trachea scaffold from PLC. The tensile test and compressive test were performed on scaffold samples printed using planar and rotary non-planar AM MEX processes. The tubular structures manufactured using rotary 3D printing overperformed the conventional extrusion process in compressive strength by 2.5 times and in tensile strength by 4.7 times. Furthermore, the specimens produced with a non-planar process displayed tighter geometric tolerances [22].

Table 1. Comparison of rotary AM machine specifications and application cases

Field	Application	AM process, technique	Printing materials	No. of DOF	Rotary axis direction	Mandrel modifications	Ref.
Medical	Bioabsorbable stents	Filament-based MEX (FDM)	PLC	2 linear, 1 rotational	Horizontal	-	[23]
	Biliary stents	Plunger-based MEX	PLC, PTX	2 linear, 1 rotational	Horizontal	-	[24]
	Biodegradable smart stents	Plunger-based MEX	PLC	3 linear, 1 rotational	Horizontal	-	[25]
	Bile duct scaffolds	Plunger-based MEX	PLC, GelMA	2 linear, 1 rotational	Horizontal	Heated chamber	[26]
	Cardiovascular stents	Screw-based MEX	PLC, PLLA	3 linear, 1 rotational	Horizontal	-	[27]
	Vascular structures	Plunger-based MEX	Na-Alg	3 linear, 1 rotational	Horizontal	-	[28]
	Vascular scaffolds	Filament-based MEX (FFF)	PLC	2 linear, 1 rotational	Horizontal	-	[29]
	Bio-tubular structures	Plunger-based MEX	Gelatine-alginate solution	3 linear, 1 rotational	Horizontal	-	[30]
	Vascular grafts	Plunger-based MEX	GelMA	2 linear, 1 rotational	Vertical	-	[31]
	Scaffolds	Melt electro-writing (MEW)	PLC	2 linear, 1 rotational	Horizontal	-	[32]
	Bioresorbable stents	Filament-based MEX (FFF)	PLLA	3 linear, 1 rotational	Horizontal	-	[33]
	Tubular scaffolds	Direct ink writing (DIW)	PLC, PGS	3 linear, 1 rotational	Horizontal	-	[34]
	Nerve conduits	Plunger-based MEX	GelMA/PEGDA	3 linear, 1 rotational	Horizontal	-	[35]
	Tracheal grafts	Plunger-based MEX	PLC	3 linear, 1 rotational	Horizontal	-	[22]
	Tubular scaffolds, stents	Melt electro-writing (MEW)	PLC	3 linear, 1 rotational	Horizontal	-	[36]
Clothing	Protective elements	Filament-based MEX (FDM)	PLA	2 linear, 1 rotational	Horizontal	Coton textile substrate	[37]
Printing	Sleeves	Filament-based MEX (FFM)	PLA	2 linear, 1 rotational	Horizontal	-	[38]
Other	Tubular structures	Melt electro-writing (MEW)	PA-12	3 linear, 1 rotational	Horizontal	Heated	[39]

1.3. Rotary 3D Printing Machine Designs and Limitations

The present rotary 3D printing machine designs, in general, can be categorised into two groups: machines purpose-built for rotary 3D printing and machines that have been converted from planar to rotatory printing from existing AM extrusion-based designs. The extent of implementation may differ depending on the selected hardware (Fig. 6.). However, these designs share the same control principles and mechanics. It is observed that (Table 1.) printers have two to three linear degrees of freedom and one rotational degree of freedom to manipulate in three-dimensional space. Nevertheless, in the rotary 3D printing process, usually, only 3 DOF are employed, and in certain implementations, only 2 out of 3 DOF are utilised [32]. Rotary 3D printing machines based on conventional AM MEX designs utilize custom-built rotary axes for individual machines. Some of the designs convert existing linear axes to rotational Fig. 6. a), b), c). This approach does not require for introduction of an additional degree of freedom to utilize the rotational axis and simplifies the control of a potential 4-axis system into a 3-axis one. Contrary to that, in the MEX systems where all 4-axes are used, it is required to ensure movement synchronization between the rotational axis and extruder [27, 28, 35]. Moreover, utilizing 3 DOF for movement allows to reuse of the original hardware and electronics. However, using or integrating into existing AM MEX machine design provides some challenges e.g. limited build volume, constrained geometries, limited I/O number, requirement for a new control algorithm, etc. Thus, the custom-built rotary 3D printer design could be considered.

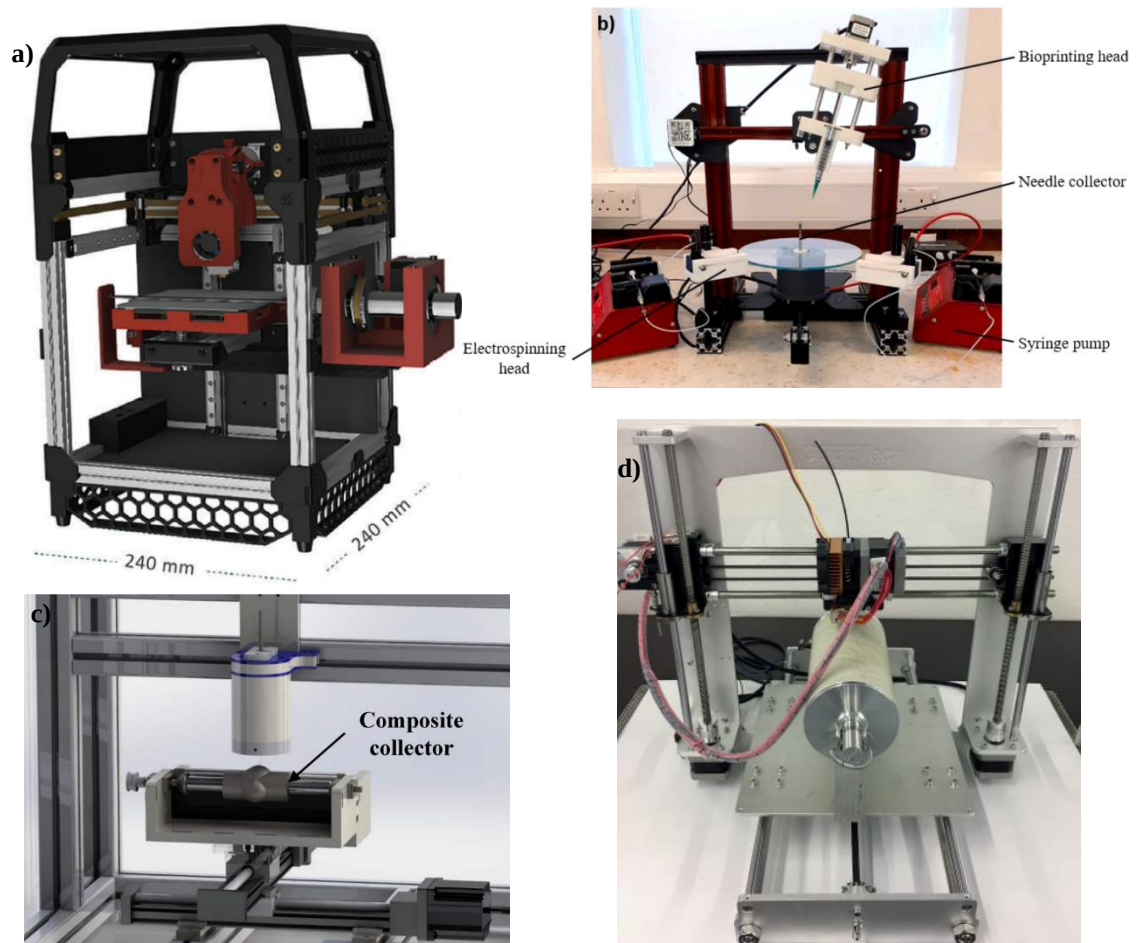


Fig. 6. Rotary 3D printing machine design examples: a) open source MEWron printer with heated cylindrical collector [39]. b) modified Creality3D Ender with a vertical needle collector [31]. c) MEW printer with custom-made composite collector [32]. d) Modified Geeetech Prusa I3A Pro with the fibre-reinforced plastic printing cylinder [38]

Furthermore, the current implementation of rotary 3D printing uses a fixed-diameter cylindrical surface as a printing bed and lacks the heating found in conventional AM MEX machines [40]. The lack of variation in diameter restricts the potential range of shapes that could be printed effectively. The variable-diameter structures could require the use of customized tools or support structures. Moreover, the absence of a heated printing surface limits the variety of materials from which parts can be produced with sufficient adhesion. Most used materials in MEX, for example, ABS, ASA, PLA, PETG etc. and from them derived composites require a heated printing surface to ensure a proper first-layer adhesion to the bed and prevent process failures e.g. “warping”. To mitigate these issues several researchers proposed some ideas on how to solve them. The design proposed by the study [39] investigated heating a cylindrical collector using convection. The printing bed’s heating element was utilised to raise the temperature of the mandrel. In addition, the use of conductive fins on the printing bed was experimented with to improve the heating of the mandrel by researchers. It managed to achieve 95 °C temperature on a 2.5 mm in diameter cylindrical mandrel by setting up the heated bed to 150 °C [39]. However, the use of fins restricted the build volume for parts up to 4.5 mm in diameter (Fig. 7.). The employment of a heated bed for printing larger components requires that a build volume is insulated from the environment to prevent heat loss.

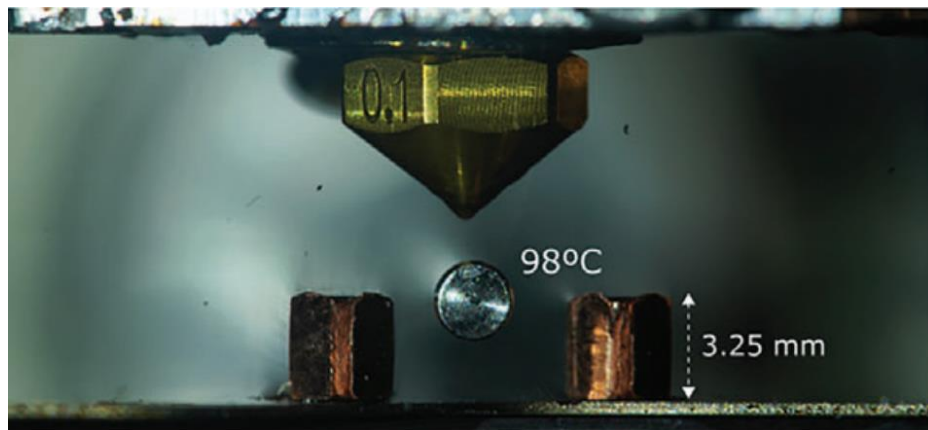


Fig. 7. Mandrel heating by convection [39]

Another study [32] demonstrated MEW printing on a variable diameter, curved surface. It employed a specific build composite collector paced on the mandrel to act as a supporting framework, ensuring accurate deposition of the material strand [32]. Nevertheless, the use of a custom-made collector introduced additional tooling and costs for rotary 3D printing. Thus, a complex part geometry could perplex the design of a collector sleeve, making it difficult to remove a manufactured component from it.

1.4. Path Generation for Rotary 3D Printing

The rotary 3D printing ecosystem is underdeveloped compared to conventional planar MEX. The primary constraint is the lack of specialised software called “slicer” which converts files designed in CAD software into computer numerical control code. The most common language used in 3D printing is G-code. G-code is comprised of a list of instructions that specify process variables: nozzle temperature, bed temperature, actuator position, speed, acceleration etc. To generate a suitable G-code for rotary 3D printing there are several methods. Separate studies [33, 41] experimented with the CAD software Rhino in conjunction with Grasshopper, a visual programming language add-on, to generate a non-planar toolpath. In addition, researchers were able to generate a G-code using

custom MATLAB scripts [23, 38]. However, the slicing was restricted to only fixed-diameter tubular structures. The utilization of MATLAB programs for more complex shape slicing could be insufficient. A more advanced non-planar code generation method for conventional and rotary 3D printers was demonstrated by simulating heat transfer and slicing the object into layers along an isothermal surface line [21]. Furthermore, the research and development on additive rotary toolpath generation for multi-axis AM MEX machines is being investigated by multiple studies [20, 42].

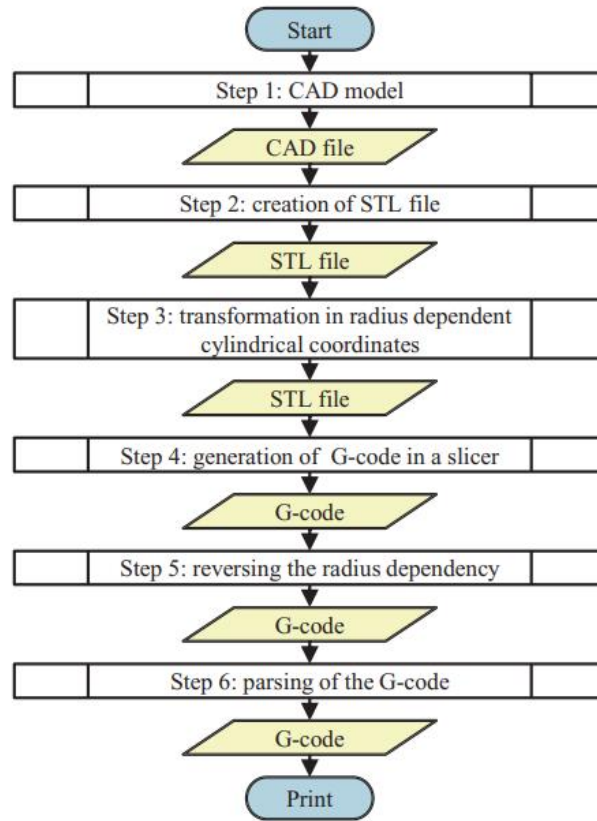


Fig. 8. G-code generation for rotary 3D printing workflow using standard MEX slicing software [43]

Another study [43] proposed a novel technique in which a readily accessible conventional slicing software could be utilised for creating G-code. It involves multiple steps Fig. 8. for modifying meshed object vertices' positions and creating an unwrapped model, then slicing and reassembling G-code [43]. However, despite the advancements in rotary 3D printing toolpath generation methods, the readily accessible number of software options in the market is limited Table 2. compared to conventional AM MEX.

Table 2. Examples of available G-code generation software for the rotary AM process

Program	Module	Availability	Ref.
Siemens NX	NX AM Multi-Axis	Paid	[44, 45]
Autodesk Fusion 360	Additive Multi-Axis Deposition	Paid	[46]
Rhino 8	Grasshopper 3D	Paid	[47]
Cosine Slicer	-	Paid	[48]
5 Axis Slicer	-	Paid	[49]
Cylindrical Slicer	-	Free, open-source	[50]

1.5. Overview of Potential Heating Solutions for Rotary 3D Printing

AM MEX rotary printing lacks the necessary functionality to ensure sufficient first layer and interlayer adhesion. In conventional planar MEX, it is ensured by controlling the build volume temperature [51] or by heating the build surface to a defined temperature. The silicone pad and printed circuit board (PCB) heaters are commonly used in consumer-grade FDM printers Fig. 9. They are based on a physical effect called Joule or resistance heating. The construction of such an element is relatively straightforward. The fin strip or wire of conductive material with specific resistance is patterned and sandwiched between electrically insulating material sheets e.g. glass fiber.



Fig. 9. Examples of heated build platform elements in FDM: silicone pad heater [52] (left), PCB heater (right)

However, alternative heating techniques are being investigated for the MEX process. Dielectric heating is a method in which non-conducted materials are heated by applying an alternating high-frequency electromagnetic field. This technique is distinct in its ability to generate heat in dielectric material. Several studies proposed a solution to improve interlayer adhesion additively manufactured PLA composite components by using microwave heating [52, 53]. Another study demonstrated dielectric heating integrated into the extruder assembly of the MEX machine [54]. Moreover, induction heating could be used to generate heat in the mandrel by inducing an eddy current. Some researchers developed induction systems for similar applications in 3D printing. They were able to integrate the induction coil into the extruder and successfully extrude melted material [55, 56]. Furthermore, induction heating could be utilised to improve the mechanical properties of AM MEX conductive composite materials [57]. In addition, in AM MEX applications (e.g. bio-printing) where materials require not only heating but also cooling elements based on the Peltier effect could be used [58, 59]. However, the application of heating based on dielectric, induction or Peltier effect creates complications for integrating into existing AM MEX machine hardware and requires extensive modifications of electronics, control etc. Moreover, the lack of standard components available for rotary printing could require custom manufacturing of devices based on these heating methods which could be costly and time-consuming. Thus, for this study, a heater element based on Joule heating was selected.

1.6. Chapter Summary

The conventional planar additive manufacturing material extrusion process is unsuitable for printing thin-wall, tubular geometries due to poor mechanical properties, subpar surface quality, necessity of supporting structures and secondary operations. Rotary 3D printing is a novel method used for depositing material in a non-planar manner. However, this printing technique has some limitations: fixed diameter mandrel with limited shape customization capability and no direct printing surface heating. Moreover, rotary printing has a limited variety of freely available “slicing” software for file preparation.

2. Development of Heated Print-drum and Rotary Module

This chapter is dedicated to the theoretical development of the customisable rotary 3D printer module. The several designs of heated mandrel which are called print-drum in this paper are proposed to be evaluated for rotary 3D printing. Furthermore, the selected design is incorporated into the rotary module for the designated AM MEX machine (FDM printer).

2.1. Development of Heated Print-drum

To assess the functionality of print-drum for rotary 3D printing, the design needs to achieve and maintain the target temperature across the printing surface throughout the whole printing time. The proper temperature of the build surface ensures consistent first-layer adhesion and prevents early process failures. Moreover, the heating up time to the desired temperature is important for process efficiency. The faster the heating-up cycle time reduces downtime for manufacturing and increases the output of the machine.

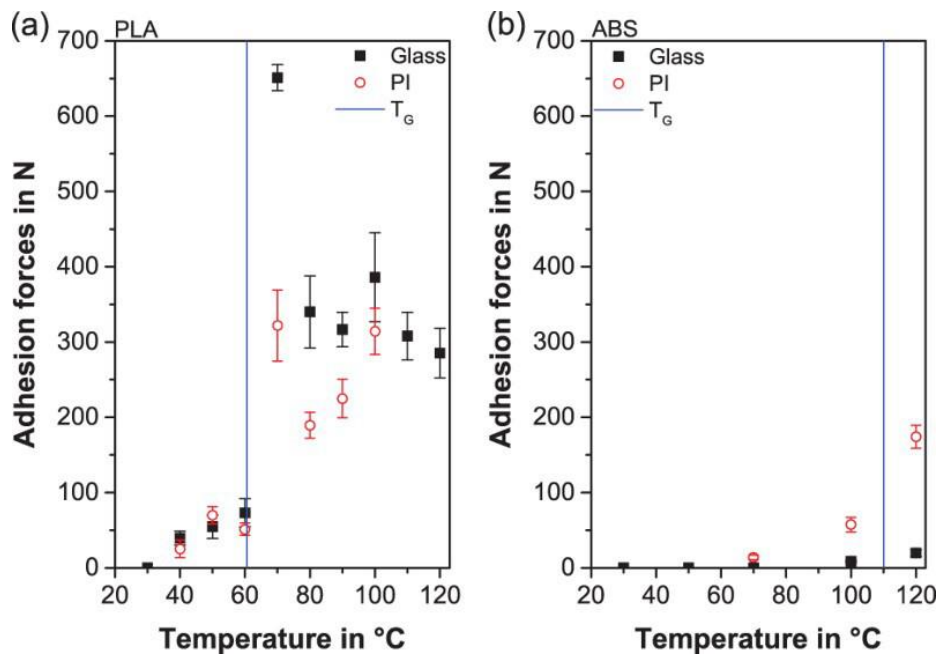


Fig. 10. ABS and PLA first-layer adhesion force depending on build surface temperature and material [53]

In the literature, it was found that the heated surface set temperature value depends on the material which is used in the AM MEX process. The optimal heated build surface value for achieving sufficient adhesion is usually around the glass transition temperature of the material used in FDM [53, 54]. Moreover, the adhesion strength between the build surface and the first layer of deposited material depends not only on the heated bed temperature but as well from which material is used on the top of the printing surface (Fig. 10) [53]. Furthermore, another study [55] demonstrated that adhesion between layers improves when the bed temperature is close to the material glass transition temperature. In addition, it was noted that void size reduces at elevated temperatures [55].

The temperature settings for the heated bed vary based on the material used in the MEX process as mentioned before. To determine the temperature range required for the intended print-drum designs to be utilized in the rotary 3D printing process, the general bed temperature settings of several FDM “slicer” software for commonly used materials were investigated. The temperature presets are shown

in Table 3. Therefore, it was decided that the proposed print-drum designs must attain a minimum temperature of 100 °C.

Table 3. Bed temperature presets for thermoplastic materials in different FDM “slicer” software [56-58]

Material	PrusaSlicer	UltiMaker Cura	ideaMaker
PLA	60 °C	60 °C	60°C
ABS	100 °C	80 °C	100 °C
PETG	85 °C	85 °C	60 °C
HIPS	100 °C	-	100 °C
TPU	50 °C	0 °C	60 °C
PA	105 °C	40 °C	-
ASA	105 °C	-	100 °C

2.1.1. Development of Parametric Model of Heating

This subchapter focuses on the creation of an equation-driven heating element model to evaluate the thermal performance of a variety of print-drum designs. This parametric model is based on a resistance wire cylindrical helix heater. The required heating element model can be determined by several characteristics, which include the required nominal power, the resistivity of the wire, the diameter of the wire, the internal diameter of the helix for the mandrel of the print-drum, and the length of the helix for the printing zone. In addition, the length of the wire for connectors could be configured. The parametric model (Fig. 11) was defined in SolidWorks software using equations functionality.

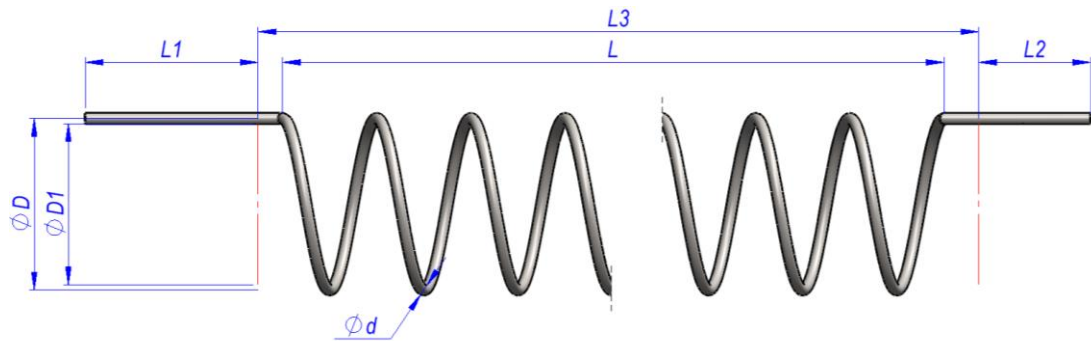


Fig. 11. Heating element model scheme

The required nominal power, P (W) and voltage, U (V) are input in this model. Moreover, the power supply is a constant voltage, then the current, I (A) is given by:

$$I = \frac{P}{U} \quad (1)$$

The resistance, R (Ω) is calculated by using Ohm's law:

$$U = I \cdot R \quad (2)$$

The length of the resistance wire, l (mm) is calculated by:

$$l = \frac{R}{R_l} \quad (3)$$

Note that, R_l is the resistivity of the wire (Ω/mm). The calculation of the helix length, L (mm) and diameter, D (mm) from provided inputs are expressed as:

$$D = D1 + d \quad (4)$$

$$L = L3 - d \quad (5)$$

Note that $D1$, $L3$, d (mm) are input values describing the diameter of the mandrel, the length of the printing zone and the diameter of the wire. The resistance wire length of the cylindrical helix curve, l is given by:

$$l = \frac{L}{P} \cdot \sqrt{(\pi \cdot D)^2 + P^2} \quad (6)$$

The pitch, P (mm) is expressed by rearranging Eq.6:

$$P = \sqrt{\frac{(\pi \cdot D)^2}{\frac{l^2}{L^2} - 1}} \quad (7)$$

To the helix end at the same angle as it started, the number of turns, N must be a positive integer. Furthermore, to include the additional length of contacts, the N must be rounded down to the closest whole number. N is defined as:

$$N = \frac{L}{P} , [N] \quad (8)$$

And the new helix length, L_n (mm) becomes:

$$L_n = N \cdot P \quad (9)$$

The new helix curve length, l_n (mm) is calculated by inserting L_n in Eq.6. The total length of resistance wire, l_t (mm) is given by:

$$l_t = l_n + L1 + L2 \quad (10)$$

Note that, lengths $L1$ (mm) and $L2$ (mm) are input values for contacts. The total resistance of the heating element, R_t (Ω) is calculated by rearranging Eq.3 and it becomes:

$$R_t = R_l \cdot l_t \quad (11)$$

The required current, I_r (A) for the heating element and power P_r (W) is calculated by formulas derived from Ohm's law. (Eq.12, Eq.13)

$$I_r = \frac{U}{R_t} \quad (12)$$

$$P_r = R_t \cdot I_r^2 \quad (13)$$

2.1.2. Design of Print-drum

Six designs were proposed to be evaluated based on the principle of Joule heating. Principal design schematics are shown in Fig. 12. All designs included these base requirements: mounting shaft of $\varnothing 10$ mm, and printing surface of $\varnothing 14 \times 100$ mm. Three of the designs were based on the resistance wire model created in the previous subchapter. Other print-drum designs were based on commercially available $\varnothing 6 \times 20$ mm 30 W at 12V heating cartridges used in 3D printers.

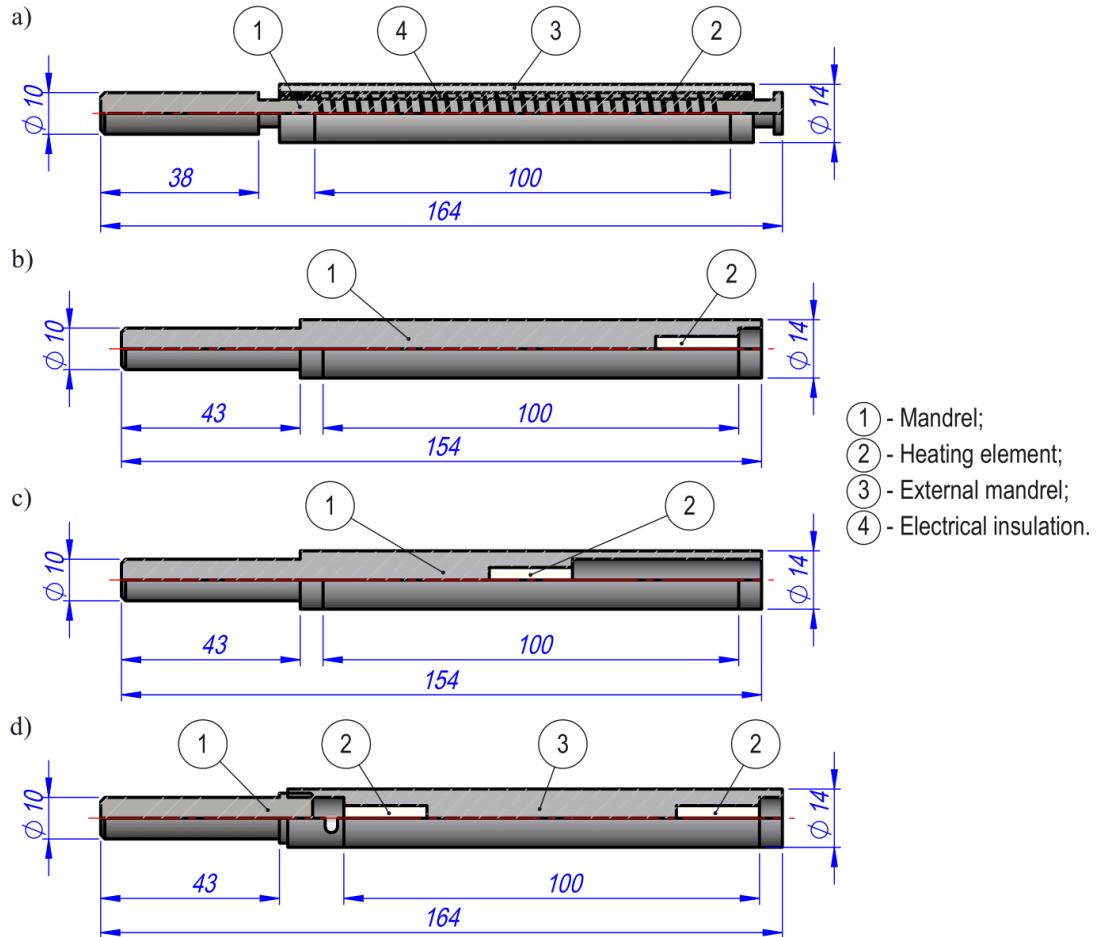


Fig. 12. Schematic of different print-drum designs: a) 30W/45W/60W Resistance Coil Heater; b) 30W Heat Cartridge 1; c) 30W Heat Cartridge 2; d) 60W Heat Cartridge 3

A description of each design and parameters is provided below:

- 30W Resistance Coil Heater (30WRCH): general dimensions are $\varnothing 14 \times 164$ mm. Heating element is based on $\varnothing 0.5 \times 866.3$ mm wire with 4.81Ω resistance, nominal power 29.95 W at 12V. The heating element is placed across the entire printing surface with a pitch of 3 mm.
- 45W Resistance Coil Heater (45WRCH): general dimensions are $\varnothing 14 \times 164$ mm. The heating element is based on $\varnothing 0.5 \times 579.5$ mm wire with 3.22Ω resistance, nominal power 44.76 W at 12V. The heating element is positioned along the whole printing area with a pitch of 4.6 mm.
- 60W Resistance Coil Heater (60WRCH): general dimensions are $\varnothing 14 \times 164$ mm. The heating element is based on $\varnothing 0.5 \times 427.2$ mm wire with 2.37Ω resistance, nominal power 60.73 W at 12V. The heating element spans the full printing surface with a pitch of 6.2 mm.
- 30W Heat Cartridge 1 (30WHC1): general dimensions are $\varnothing 14 \times 154$ mm. The heating element of $\varnothing 6 \times 20$ mm 30W is used. It is placed in an opposite direction to the mounting shaft, at the far end of the printing surface.

- 30W Heat Cartridge 2 (30WHC2): general dimensions are $\text{Ø}14 \times 154$ mm. 30W heating cartridge is placed in the middle of the build area.
- 60W Heat Cartridge 3(60WHC3): general dimensions: $\text{Ø}14 \times 164$ mm. Two $\text{Ø}6 \times 20$ mm 30W heaters are employed. These cartridges are located at the opposite ends of the designated heating area.

2.2. Theoretical Evaluation of Print-Drum Designs

Initial thermal simulations were carried out using the SolidWorks Simulations software package. However, it was noted that SolidWorks Simulation lacks an accurate representation of thermal convection depending on object surface geometry and only the general value of convection coefficient could be designated. To achieve more precise results of the thermomechanical model it was decided to utilize the SolidWorks Flow Simulation add-on.

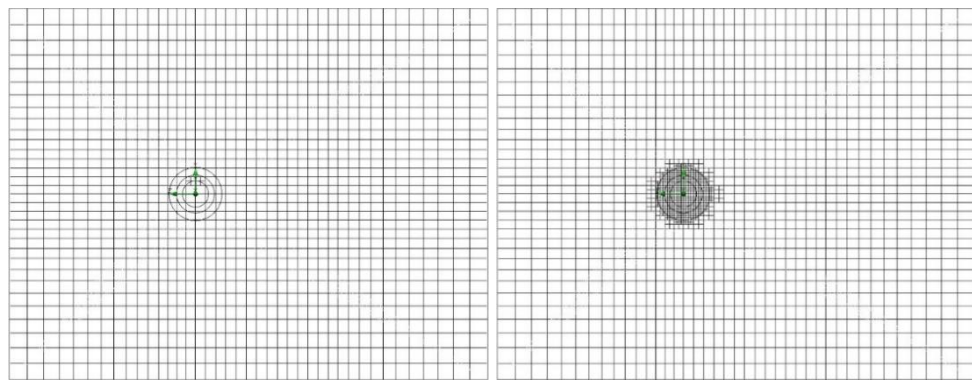


Fig. 13. Cross-section comparison between default global mesh (left) and default global mesh with local mesh refinement (right)

To acquire accurate data and minimize the required computational resources to run computational fluid dynamics equations, experimentation with global analysis settings was performed. These results were observed:

- Default global mesh: it is not sufficient for studies which analyse designs based on resistance coil heaters due to the small diameter of the wire. With the addition of level 2 and level 1 local mesh refinement for solid cells and fluid cells containing solids (Fig. 13), maximum temperature values were 5°C higher than default mesh settings. However, the time required to run a transient state study was doubled. Further, an additional increase in mesh density did not significantly change the result values.
- Computational domain size: automatically determined computational domain proven to be sufficient for selected designs. The size increase of the computational domain by two times was tested. The time required to compute the simulation was 2.4 times greater than using the default size. Moreover, the reduction in temperature was negligible. In addition, reducing the computational domain of the CFD analysis with refined mesh by 2 times reduces computational time by 35%. However, the result values were higher by 2°C and it was decided not to reduce the computational domain.
- Iteration step size: 1s intervals are sufficient to calculate the transient-state thermal simulation. Tests were carried out with four different step size settings: auto, 0.25s, 0.5s, 1s. Results were almost identical and additional computational resources and time were not justified for smaller iteration step size.

2.2.1. Steady-State Thermal Analysis Setup

Steady-state thermal analysis is required to evaluate the potential achievable heating maximum and minimum temperature in a different print-drum design. Moreover, it is important to assess the required material properties for future print-drum manufacturing. Materials used in steady-state CFD simulation were from the SolidWorks Flow Simulations materials library: steel 5135 (specific heat – 466 J/(kg·K) at 293 K and 529 J/(kg·K) at 473 K, thermal conductivity – 41 W/(m·K) at 293 K and 38 W/(m·K) at 473 K), steel stainless 302 (specific heat – 500 J/(kg·K), thermal conductivity – 16.3 W/(m·K)), aluminium 6061 (specific heat – 895 J/(kg·K) at 250 K and 953.9 J/(kg·K) at 300 K, thermal conductivity – 147.5 W/(m·K) at 250 K and 155.5 W/(m·K) at 300 K) and nichrome (specific heat – 460 J/(kg·K), thermal conductivity – 13.4 W/(m·K) at 293 K and 17 W/(m·K) at 573 K). However, for designs based on resistance coil heater custom E-glass fiber material was created: specific heat – 810 J/(kg·K) at 296 K and 1030 J/(kg·K) at 473 K; thermal conductivity – 1.3 W/(m·K) at 300 K and 2 W/(m·K) at 873.1K. Specific materials applications in the print-drum designs are shown in Fig. 14.

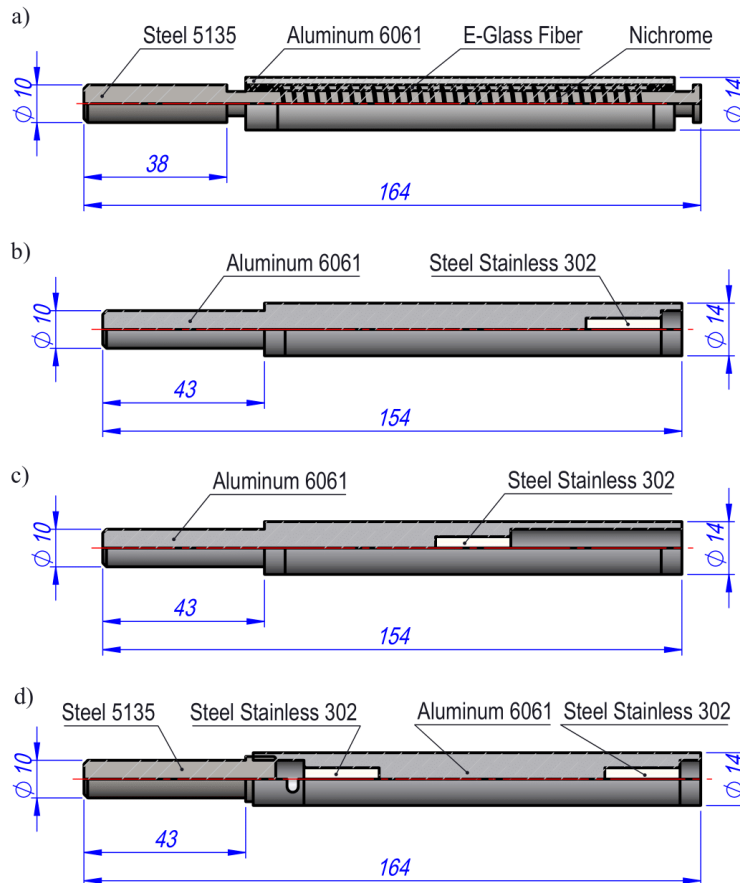
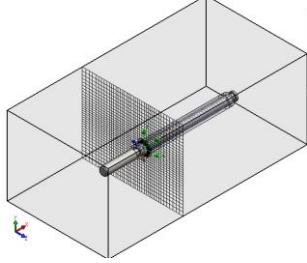
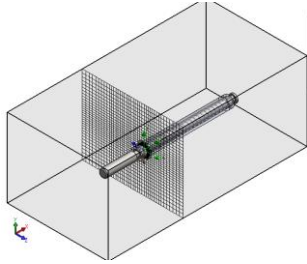
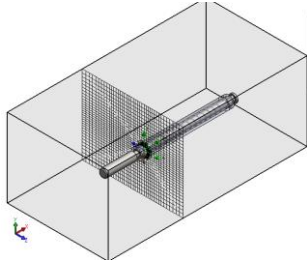
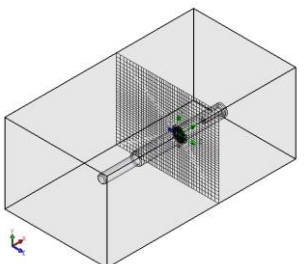
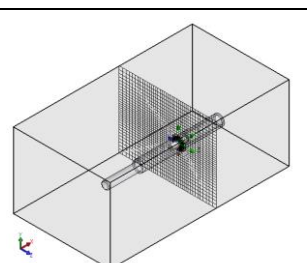
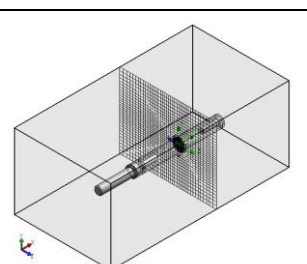


Fig. 14. Schematic of materials used in different print-drum designs: a) 30W/45W/60W Resistance Coil Heater; b) 30W Heat Cartridge 1; c) 30W Heat Cartridge 2; d) 60W Heat Cartridge 3

Moreover, the default ambient fluid was selected to be air at a temperature of 20 °C. The initial ambient pressure is to be at 101325 Pa. The initial temperature of solid materials was 20 °C. For the solid surfaces in contact with air Ra 3.2 surface roughness was applied. Moreover, gravity and ambient fluid velocity of 0.1 m/s to all designs were applied to imitate room conditions. The default computational domain size was kept for all steady-state thermal simulations. However, the default global mesh of level 3 refinement was not sufficient for all solids. The local mesh was applied with additional level 2 refinement for solid cells and level 1 for fluid cells containing solids. The

volumetric heat source was applied to the bodies with steel stainless 302 and nichrome materials. The heat transfer through rotation was neglected due to the low emissivity of metal surfaces. Specific parameters used in each study are depicted in Table 4.

Table 4. Steady-state thermal simulation parameters

Design name	Mesh Information	Loads	Image
30W Resistance Coil Heater	Total cells: 262229 Fluid cells: 143628 Solid cells: 118601 Fluid cells contacting solids: 21178	Gravity: -Y, 9.81 m/s ² Ambient velocity: -Z, 0.1 m/s Volume heat source: 29.95 W	
45W Resistance Coil Heater	Total cells: 259737 Fluid cells: 143040 Solid cells: 116697 Fluid cells contacting solids: 21096	Gravity: -Y, 9.81 m/s ² Ambient velocity: -Z, 0.1 m/s Volume heat source: 44.76 W	
60W Resistance Coil Heater	Total cells: 259297 Fluid cells: 143410 Solid cells: 115887 Fluid cells contacting solids: 21102	Gravity: -Y, 9.81 m/s ² Ambient velocity: -Z, 0.1m/s Volume heat source: 60.73 W	
30W Heat Cartridge 1	Total cells: 225354 Fluid cells: 134640 Solid cells: 90714 Fluid cells contacting solids: 19842	Gravity: -Y, 9.81 m/s ² Ambient velocity: -Z, 0.1m/s Volume heat source: 30 W	
30W Heat Cartridge 2	Total cells: 221590 Fluid cells: 141616 Solid cells: 79974 Fluid cells contacting solids: 23780	Gravity: -Y, 9.81 m/s ² Ambient velocity: -Z, 0.1m/s Volume heat source: 30 W	
60W Heat Cartridge 3	Total cells: 231980 Fluid cells: 137208 Solid cells: 94772 Fluid cells contacting solids: 21494	Gravity: -Y, 9.81 m/s ² Ambient velocity: -Z, 0.1m/s Volume heat source: 2×30 W	

2.2.2. Transient-State Thermal Analysis Setup

Transient-state thermal simulations were performed for all designs to investigate the performance under working conditions. Moreover, it is important to select the correct position for the thermistor to be placed. Two different locations were selected for thermistors: L and R, depicted in Fig. 15. The initial conditions were the same as in steady-state thermal simulation. The target temperature was selected to be 100°C. The volumetric heat source was constrained to turn off then the thermistor reached the target temperature, the dead band of the target value was 1°C. The simulation duration was restricted to 300 seconds with 1-second iteration steps. Gathered data was aggregated using SolidWorks Flow Simulations provided analysis tools. Further data analysis was performed using MATLAB by employing the “stepinfo” function.

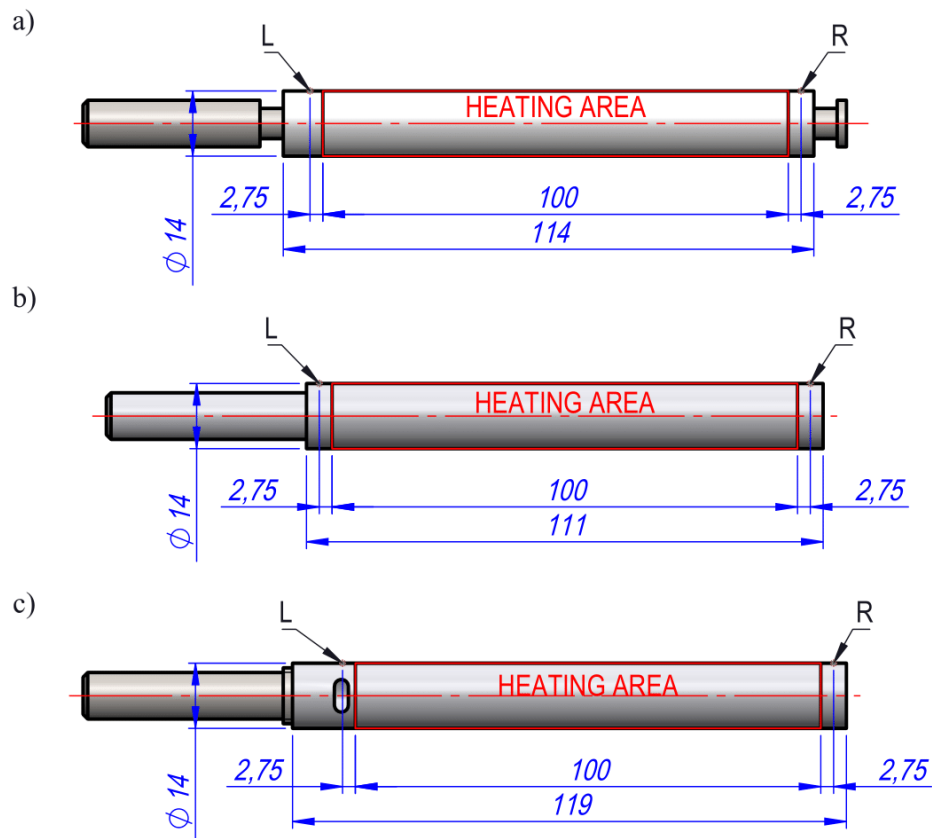


Fig. 15. Thermistor positions L and R in different print-drum designs: a) 30W/45W/60W Resistance Coil Heater; b) 30W Heat Cartridge 1/2; c) 60W Heat Cartridge 3

2.2.3. Preliminary Results and Discussion for Selecting Print-Drum Design

The results from the steady-state study showed that all proposed print-drum designs can reach temperatures above 100 °C. Overall, the highest temperatures were achieved by 60WRCH and 60WHC3 designs, subsequently, the lowest temperatures were attained by the 30WRCH print-drum. In addition, the steady-state thermal simulation showed that the maximum temperatures in all proposed print-drum designs were reached on the surfaces of the heating element. Furthermore, the minimum temperatures in all designs were measured at the end of the $\Phi 10$ mm shaft. The minimum temperatures recorded range from 226.9 °C to 462.2 °C depending on the design of the print-drum. This could indicate that a substantial amount of heat is transferred via conduction from the heating zone to the end of the shaft. The highest difference between the overall minimum temperature and

the minimum temperature of the heating area is achieved by 60WRCH (140.3 °C) and 45WRCH (102.2 °C). This indicates that these designs have the highest thermal insulation of Ø10 mm shaft from the heating area. Furthermore, the maximum temperatures of the heating area in all designs were recorded at the furthest point from Ø10 mm shaft. The maximum and minimum recorded temperature values for all surfaces of the print-drum and designated heating area are presented in Table 3.

Table 5. Steady-state thermal simulation results

Design name	All surfaces		Printing surface	
	Min, °C	Max, °C	Min, °C	Max, °C
30WRCH	226.92	324.58	294.02	312.61
45WRCH	304.37	456.09	406.54	433.37
60WRCH	379.68	599.54	519.93	559.2
30WHC1	270.26	344.57	284.4	343.05
30WHC2	283.96	331.14	299.01	323.79
60WHC3	462.20	536.36	504.81	534.92

However, the transient-state thermal analysis revealed that not all suggested designs, with defined thermistor locations, could reach a stable temperature of 100 °C within a timeframe of 300 seconds (Fig. 16). The 30WHC1 and 30WHC2 designs with thermistor position L showed the highest temperature overshoot for thermistor among all designs and were not able to achieve $\pm 2\%$ settling time (Table 6). Furthermore, 30WHC1 recorded the highest average printing surface temperature of 127.7 °C (Fig. 17), maximum printing surface temperature of 160.4 °C (Fig. 18) and minimum printing surface temperature of 109.7 °C (Fig. 19).

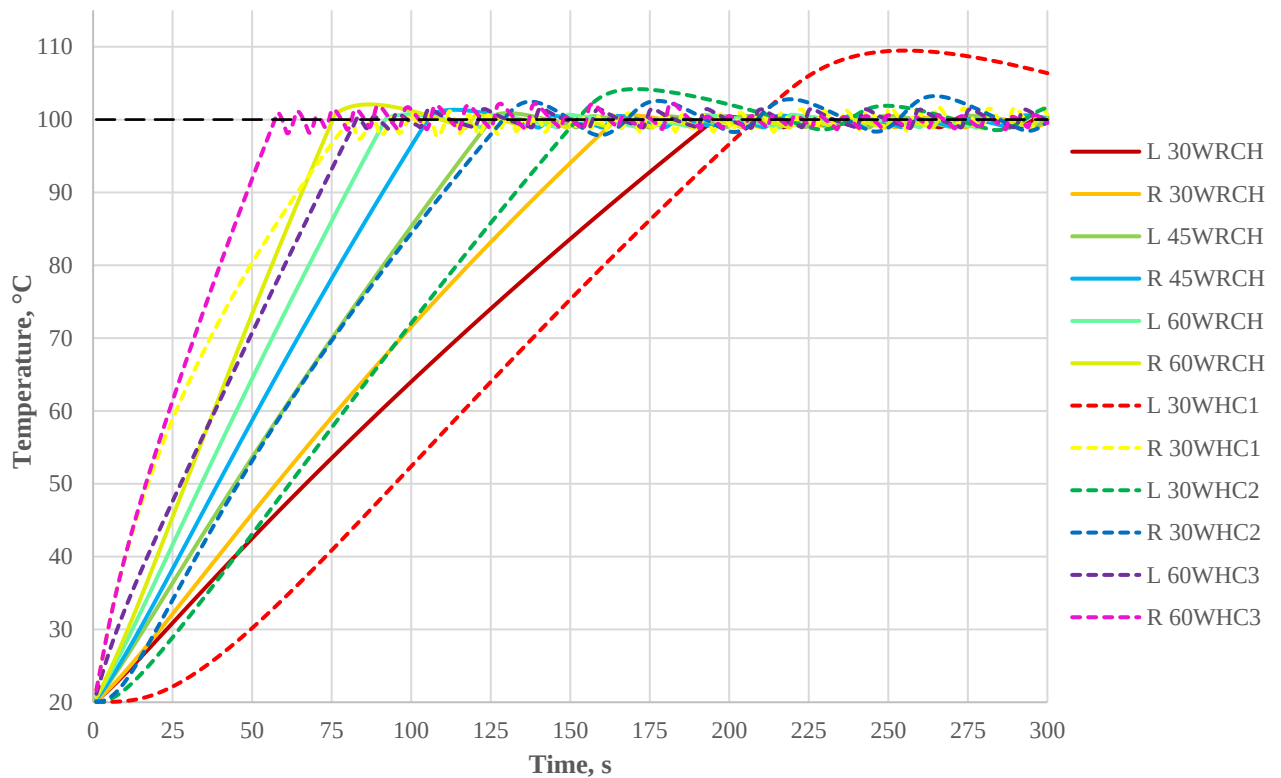
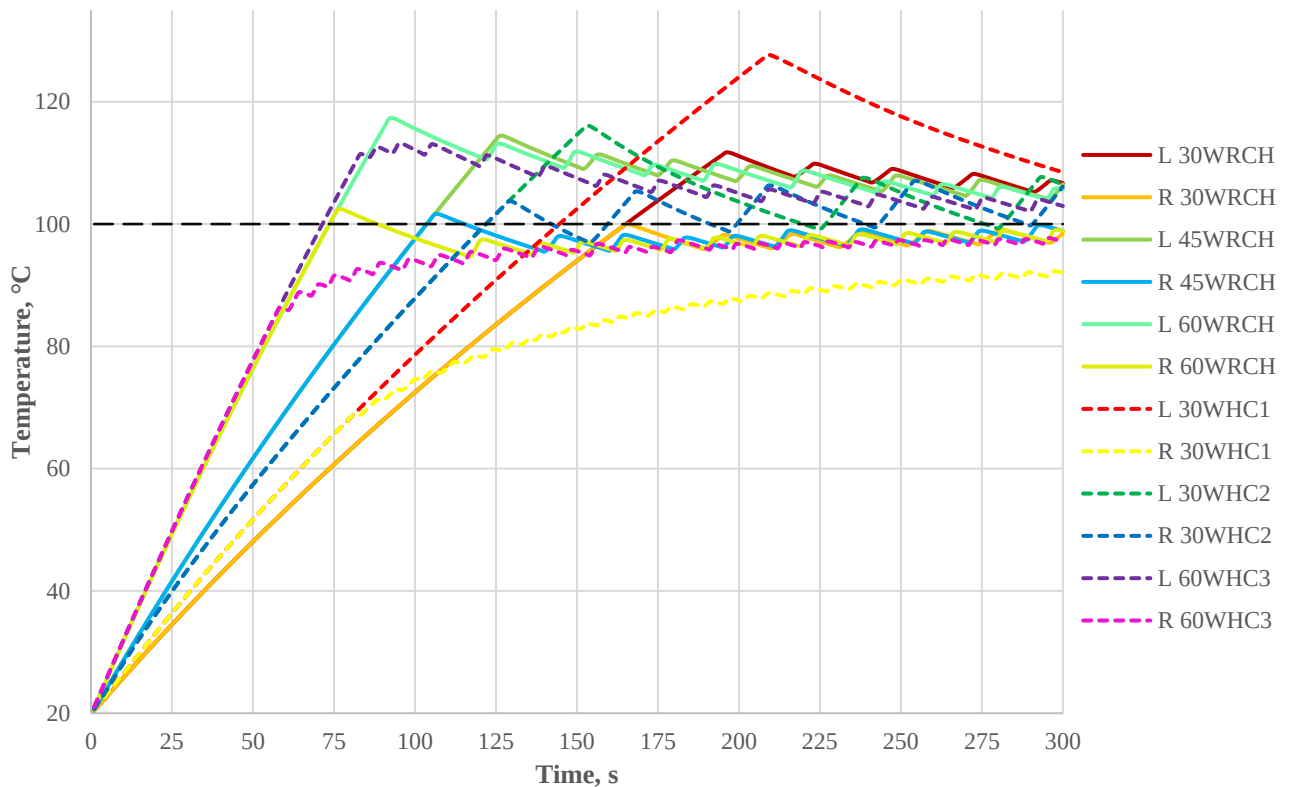


Fig. 16. The temperature recorded by the thermistor in L and R positions for different print-drum designs

Table 6. Step response characteristics of the thermistor

Configuration name	Rise time ($t_{r\ 10-90\%}$), s	Settling time ($t_{s\pm 2\%}$), s	Overshoot, %	Undershoot, %	Peak, °C	Peak time, s
L 30WRCH	153.67	190.82	0.51	0.00	100.40	199
R 30WRCH	127.58	160.49	0.73	0.00	100.58	169
L 45WRCH	98.05	122.31	1.11	0.00	100.88	130
R 45WRCH	81.63	102.92	1.68	0.00	101.34	114
L 60WRCH	71.87	89.93	0.90	0.00	100.72	99
R 60WRCH	58.48	96.15	2.60	0.00	102.08	87
L 30WHC1	144.18	-	11.86	0.13	109.47	255
R 30WHC1	63.53	298.21	2.11	0.00	101.68	298
L 30WHC2	113.14	-	5.24	0.12	104.19	171
R 30WHC2	96.29	277.15	4.03	0.11	103.22	265
L 60WHC3	67.66	80.96	1.86	0.00	101.48	141
R 60WHC3	46.26	184.08	2.88	0.00	102.30	182

Moreover, it was noticed that print-drum thermal performance differs depending on the selected position of the thermistor. The temperature distribution in the printing area for print-drums with a thermistor placed in the R position (except for the 30WHC2 design) tended to be around the target temperature and below. The maximum printing surface temperature for the designs with R thermistor hovered around 100 °C (Fig. 18). The average temperature (Fig. 17) and the minimum temperature (Fig. 19) on the printing surface were below the desired temperature when the thermistor reached the settled state.

**Fig. 17.** Average printing surface temperature

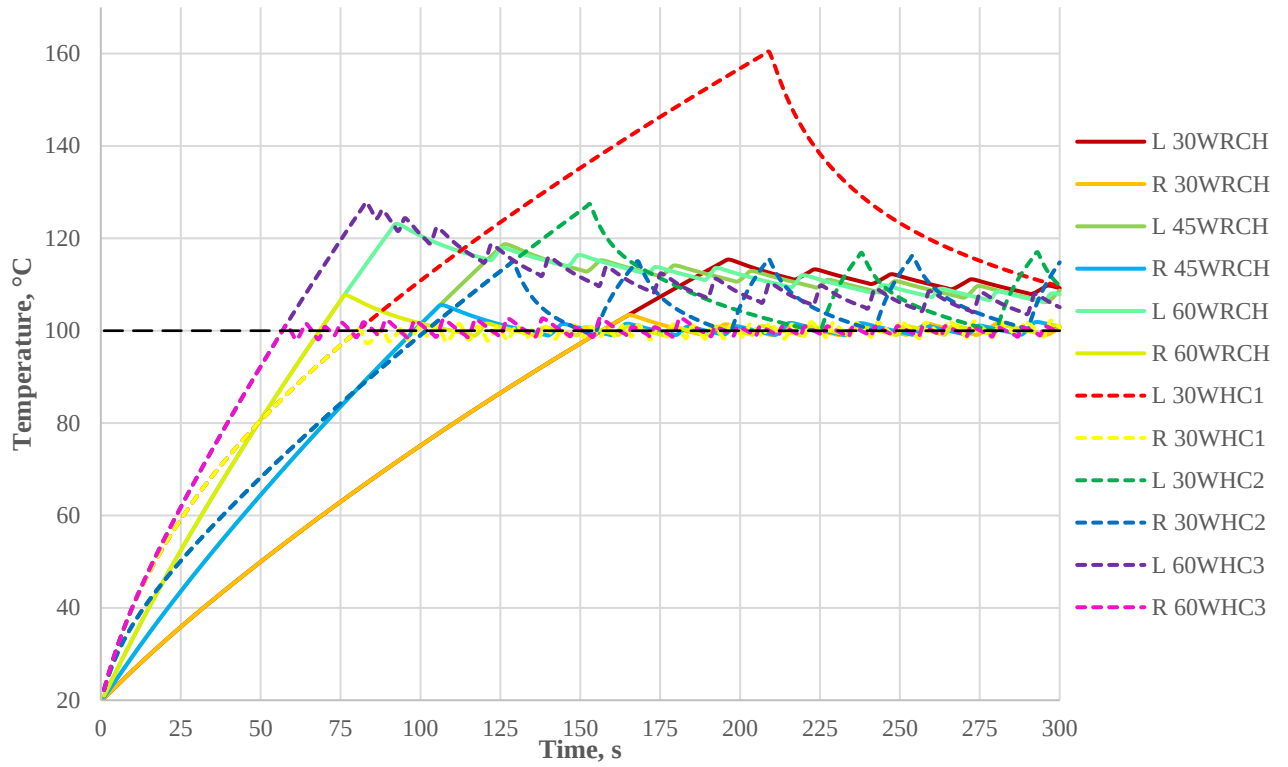


Fig. 18. Maximum printing surface temperature.

Conversely, the print-drums which reached the settled state with the thermistor positioned in the L position exhibited opposite behaviour. The minimum printing surface temperatures were around 100 °C (Fig. 19). When the thermistor reached a settled state, the average temperature (Fig. 17) and the maximum temperature (Fig. 18) on the printing surface exceeded the target temperature.

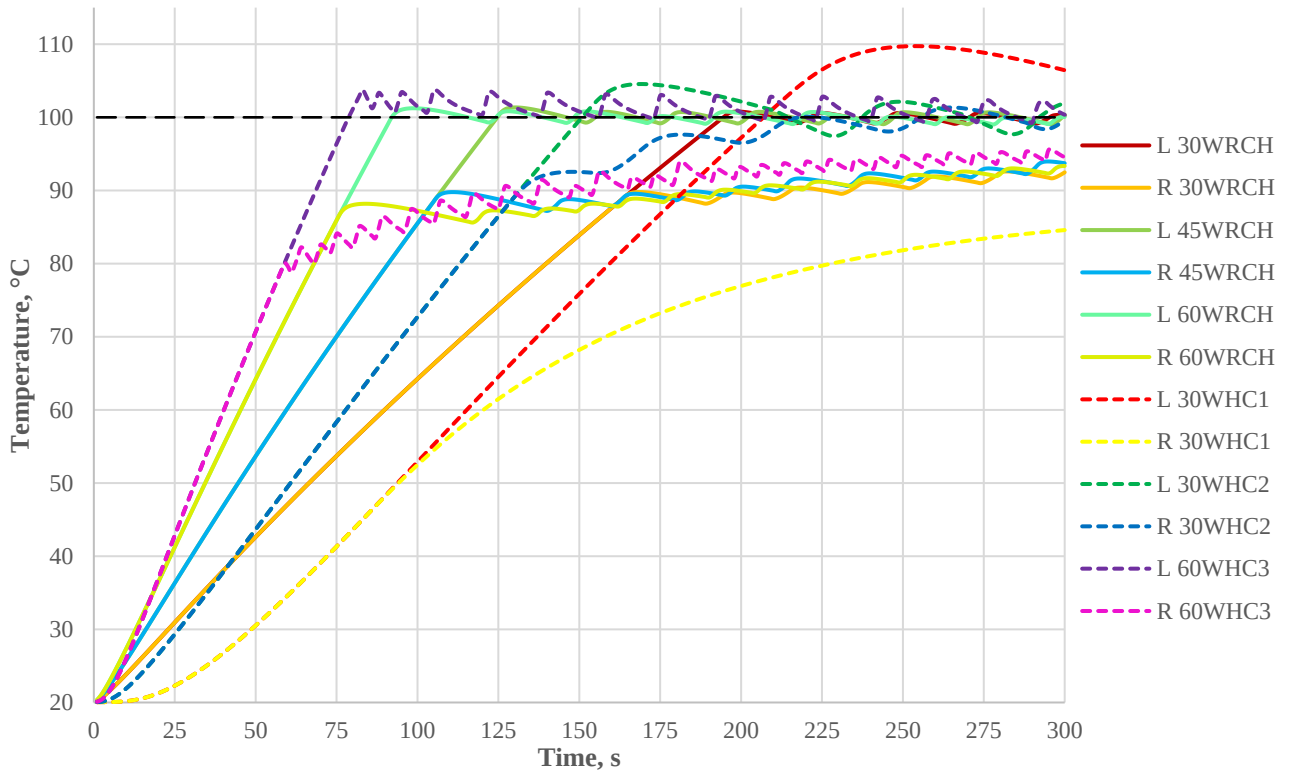


Fig. 19. Minimum printing surface temperature.

These observations were made based on the results of the steady-state and transient-state CFD thermal analysis:

- The R position for the thermistor tended to result in a printing surface temperature that was lower than target the desired target value. Thus, the lower temperature might not be sufficient to achieve proper adhesion between the deposited material and the build surface.
- The print-drum designs based on heater cartridges had poor printing surface insulation from mounting features. This could lead to undesired heat conduction to external components.
- The proposed designs with 60W heaters displayed the quickest rise and settling time. However, temperatures achieved in the steady-state study were from 379.7 °C to 599.5 °C and in case of hardware malfunction could cause severe damage to the equipment.

After evaluating the settling and observations, the 45WRCH print-drum design with the thermistor placed in the L position was selected to be implemented in the rotary module for the Prusa MK3S 3D printer.

2.3. Development of Rotary Module

This subchapter focuses on the development and integration of the rotary module with heated print-drum for the Prusa MK3S FDM 3D printer from Prusa Research a.s. (Fig. 20.). This additive manufacturing machine has a build volume of 250×210×210 mm, has a heated bed, a single extruder, three stepper motors for 3 linear axes and works from a 24V AC/DC power supply. In early development, it was decided that no major modification should be performed on the printer, and the rotary module must be an auxiliary equipment. Moreover, the rotary module should incorporate as many standardised components as possible, while custom parts should be made from readily available manufacturing methods. Finally, the design of the rotary module should be low-cost.



Fig. 20. Prusa MK3S FMD 3D printer

2.3.1. Mechanical Parts

The rotary module was developed to enable the utilisation of customizable print-drum designs with a three-jaw drill chuck. The drill chuck was selected from the power drill due to its price. It can hold any cylindrical mandrel from 1,5 mm to 13 mm in diameter. The drill chuck is fixed on the custom-

made spindle from S355JR steel (Appendix 1). The spindle is mounted into two DIN 625 – 6000 radial bearings. The rotational movement to the spindle from the motor is transferred by two pulleys and the belt. The pulleys utilised were identical to those used on the Prusa MK3S. The belt was selected to be of 2GT-200 due to the immediate availability. The stepper motor was chosen similar to those used in Prusa MK3S. The stepper motor model 17HS19-2004S1 from STEPPERONLINE Inc. was available and compatible with the microcontroller used in Prusa MK3S. Moreover, the bed of the rotary module was made from two Profile5 20×40 mm aluminium extrusions from item Industrietechnik GmbH (Appendix 2). Aluminium extrusions were selected due to fast and customizable mounting options, variety of sizes, availability, as well as its ability to easily accommodate additional components. In addition, the positioning bracket was designed to ensure that the rotary module would be placed parallel to the x-axis and normal to the nozzle. Furthermore, the head stock (Appendix 3), tail stock (Appendix 4), and positioning bracket (Appendix 5) were designed to be manufactured by using AM MEX. These parts are fixed to the bed by a combination of DIN 7991 M5×12, DIN 912 M4×12 bolts and Profile5 T-slot nut M4 from item Industrietechnik GmbH. To ensure that the rotary module is fixed firmly to the bed of Prusa MK3S the neodymium magnets were selected. The E1000/NEO from Eclipse Magnetics Ltd were available and offered 75 N pull force with mounting holes. Eight of these magnets were designed to be mounted on the bed by DIN 9771 M3×10 bolts and Profile5 T-slot M3 nuts. The design of the rotary module for Prusa MK3S and its component placement is shown in Fig. 21. The General dimensions of the rotary module are 309×101×149 mm.

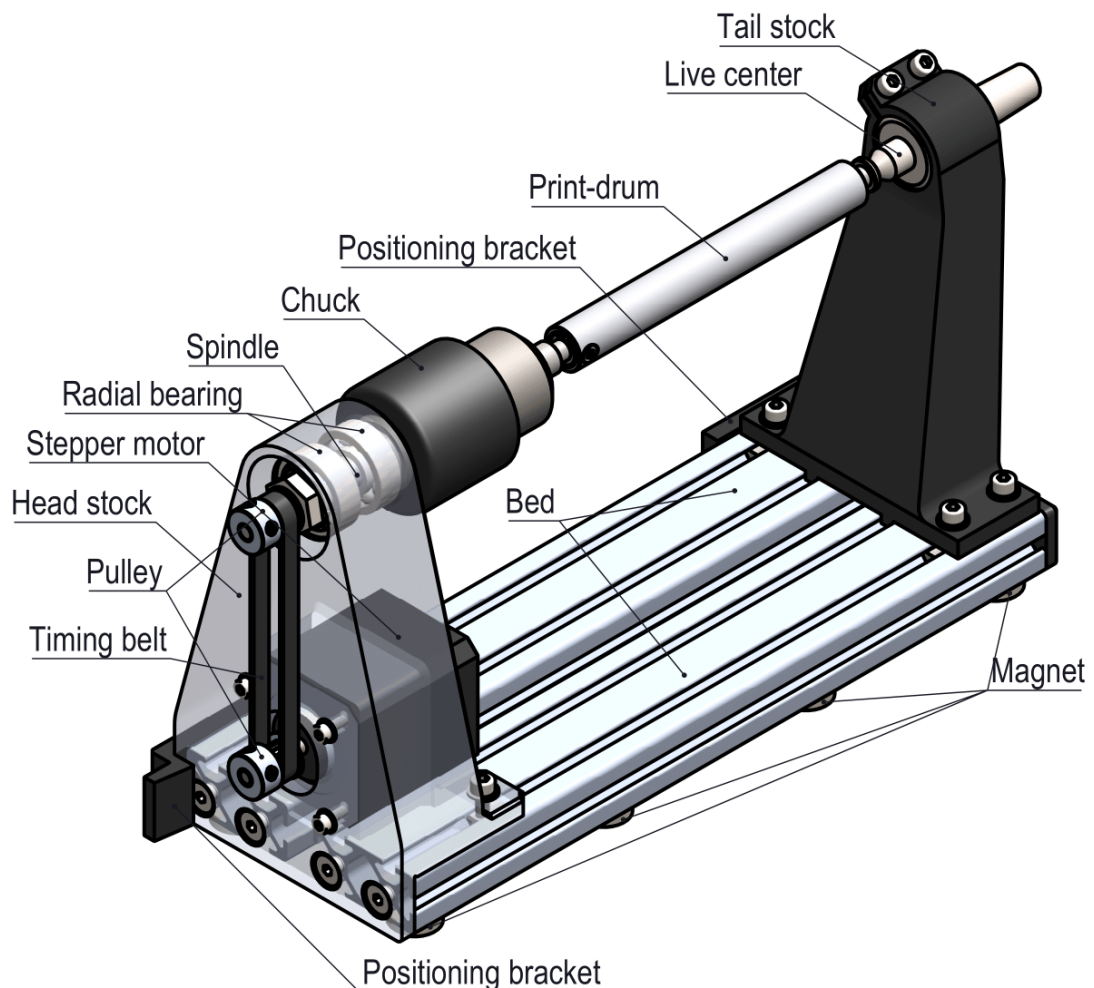


Fig. 21. The design of the rotary module and components

The design of the print-drum was based on a 45W resistance coil heater with thermistor position L. The general dimensions of the print-drum were kept the same. The theoretical maximum build volume of the rotary module is $\varnothing 157 \times 71.5 \times 100$ mm Fig. 22. The drawings for the mandrel and external mandrel are shown in Appendix 6-7. However, some of the materials used in thermal analysis for print-drum were not available to be manufactured from. Materials with similar thermal conductivity coefficients and specific heat values were selected. The external mandrel was made from EN AW-6082 T6 instead of 6061 aluminium alloy. The mandrel was machined from S355JR structural steel as a substitute for steel 5135 used in thermal analysis. In addition, the TG-200 0.2 mm of thickness E-glass fiber from UAB “PLASTENA” was used as an electrical insulator. The heating element was made of nichrome (Cr20Ni80) $\varnothing 0.5$ mm wire with 5.551 Ω/m resistivity from UAB “Eltechnika”. The eternal mandrel with mandrel was joined by two ISO 14581 M3 $\times$ 6 bolts.

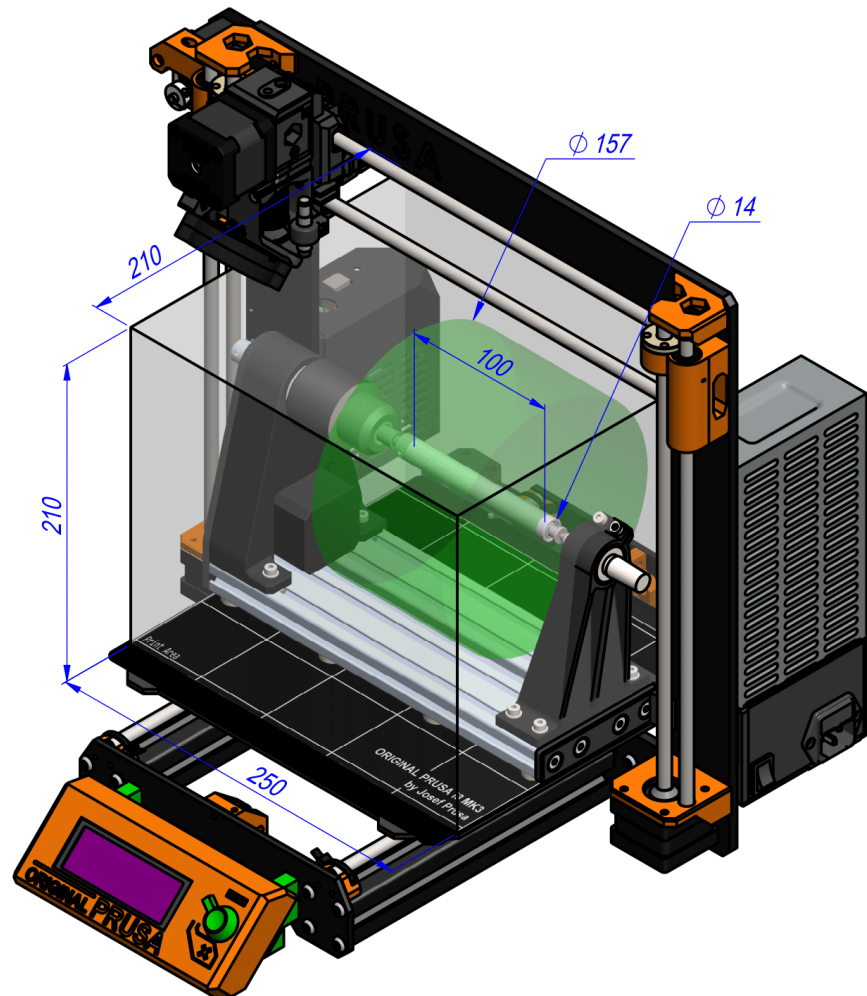


Fig. 22. Build volume of the rotary module (green) inside the build volume of Prusa MK3S (grey)

2.3.2. Electrical Components

The requirement of making the rotary module a separate piece of equipment from the Prusa MK3S 3D printer necessitates the use of additional hardware to control the heating process. To accommodate the requirements of the heating element, an Arduino Mega 2560 microcontroller with RAMPS 1.4 modular board shield was selected. These components are popular among the 3D printer hobbies due to their low price. In addition, the RerRapDiscount Full Graphic Smart Controller a dot LDC display was selected to be used in combination with previous components. Moreover, it allows to monitor

the temperature of the thermistor. It can be utilized to directly set the target temperature for the heating element and has an additional button which is used as an emergency stop button. The thermistor ATH100K1R25 from Analog Technologies Inc. was selected due to the small size of $\varnothing 1.25 \times 2$ mm and the wide operating temperature range from -40 °C to 270 °C. To power the whole system a 201W 12V power supply S-201-12 from STEPPERONLINE Inc was employed. To circumvent problems with rotary axis synchronization, the selected stepper motor, of the NEMA 17 type, is directly connected to the microcontroller board of the Prusa MK3S. It is connected to the Y-axis. The general wiring diagram is shown in Fig. 23. To run the temperature control algorithms and enable the functionality of the controller, a custom configuration of Marlin firmware [59] for the rotary module was uploaded to the Arduino Mega microcontroller.

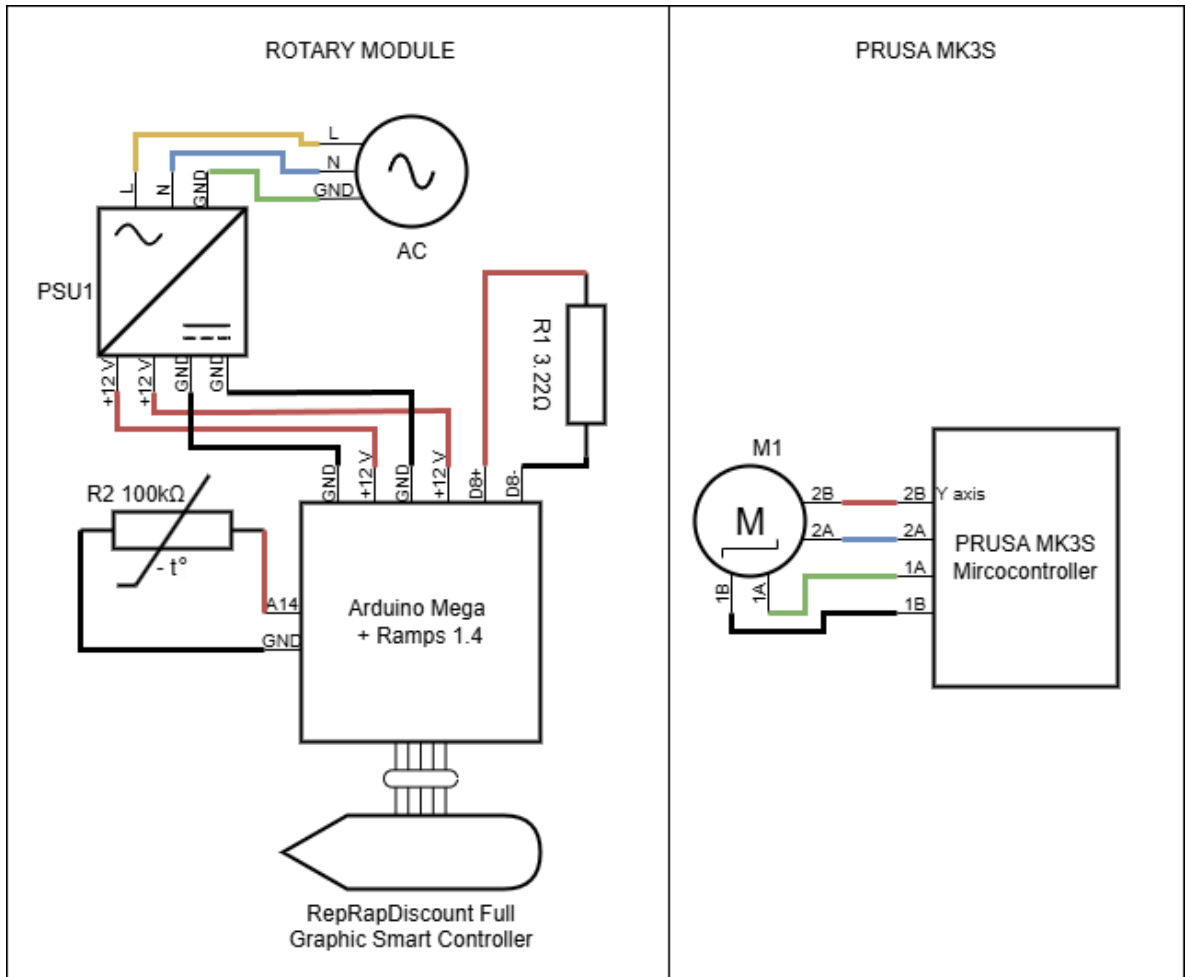


Fig. 23. General wiring diagram

2.4. Chapter Summary

In this chapter, the theoretical thermal performance of six different print-drum designs was evaluated by utilising the SolidWorks Flow Simulation software add-on. The 45W resistance coil heater print-drum design with thermistor position L was selected based on the performed CFD steady-state and transient-state thermal study analysis results. In addition, the rotary module was designed as additional equipment for the Prusa MK3S FDM printer to enable rotary 3D printing. It was developed with a theoretical $\varnothing 157 \times 71.5 \times 100$ mm build volume. The standard mechanical and electrical components were selected for the rotary module to enable the rotational moment of the print-drum, and control temperature.

3. Experimental Thermographic Analysis

To perform temperature measurements using thermography on the metallic surface is difficult, due to the low emissivity of a material and high reflectivity of radiated energy in the infrared spectrum. However, the emissivity of the object can be improved by applying additional coatings or by adding thin pieces of material e.g. tape, film, etc. with known value of emissivity. In this case, an extra layer of coating could not be applied due to the nature of being a permanent solution and it was decided to use a tape to temporarily increase the emissivity of the machined aluminium surface. Nevertheless, most manufacturers do not provide the emissivity value for their products. Thus, it was decided to measure the emissivity of three different materials which are commercially readily available.

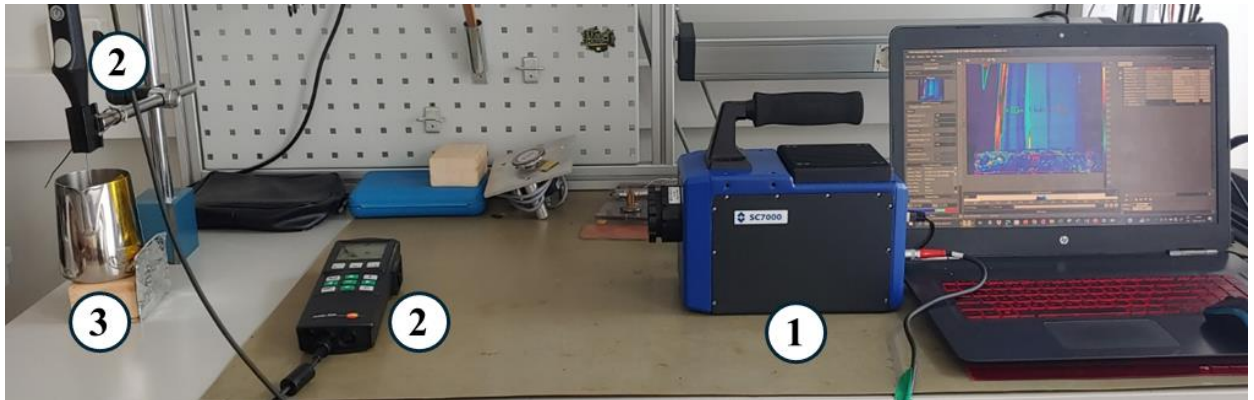


Fig. 24. Experimental setup for measuring reflected apparent temperature and emissivity (1 – FLIR SC7500; 2 – Testo 950 with NiCr-Ni probe; 3 – observed object.)

The emissivity of three different tapes was measured: tesa® 53988 black colour soft PVC insulation tape, tesa® 4323 yellow colour general-purpose paper masking tape and PPI 701 brown transparent colour polyimide self-adhesive masking tape from PPI Adhesive Products Limited. To determine the emissivity of selected adhesive tapes, experimental measurements following ISO 18434-1:2008 standard [60] were carried out. The reflector method described in the standard was used to evaluate the reflected apparent temperature (T_{ref}) and the contact method was used to determine the emissivity of the specimens. The experimental setup is depicted in Fig. 24. The FLIR SC7500 infrared camera with a 50 mm lens and testo 950 temperature measuring instrument with NiCr-Ni immersion probe was used to measure temperature directly. The adhesive tapes were applied on a stainless-steel cup. A cup was used to hold hot boiling water to simulate the elevated temperatures of the print-drum. The data from the thermal imaging camera was processed using ReseacherIR software from Teledyne FLIR LLC. Measured values are displayed in Table 7. and a graphical representation is displayed in the Fig. 25.

Table 7. Measured values using thermography and thermistor

Material	Temperature, °C	
	FLIR SC7500	testo 950
Stainless steel cup	39,1	84,6
PPI 701	63,1	
tesa® 53988	81,1	
tesa® 4323	71,9	

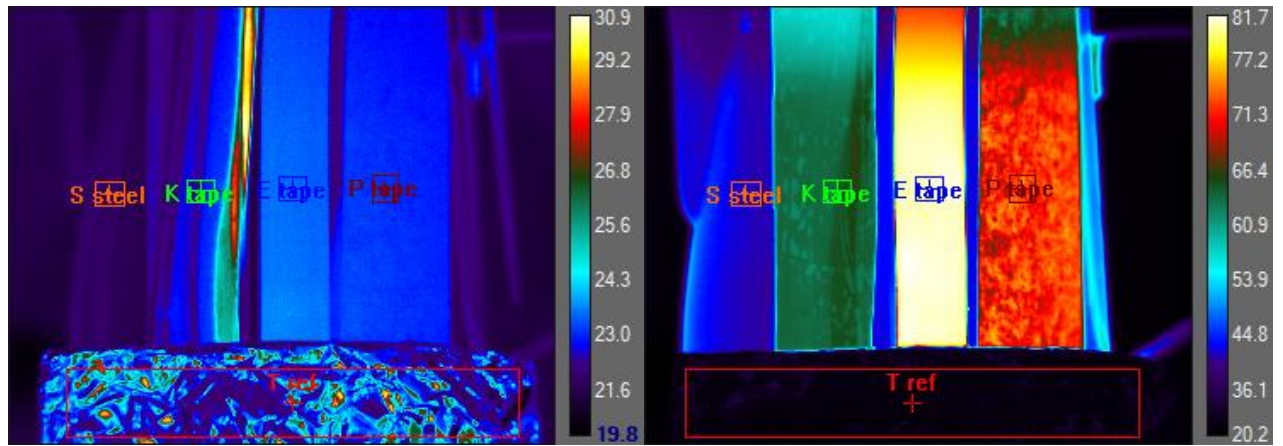


Fig. 25. Temperature distribution with ROI's (T_{ref} – reflected temperature; S steel – stainless steel cup; K tape – PPI 701; E tape – tesa® 53988; P tape – tesa® 4323): before pouring boiling water (left); after pouring boiling water (right)

It was measured that the average T_{ref} was at 22.9 °C. Moreover, the emissivity values for each material were obtained by using the built-in emissivity calculator in the ReseacherIR software. The emissivity values for selected materials were calculated after correcting the apparent temperature value and providing the measured temperature with a Testo 950 probe. The emissivity for different materials were determined as follows: stainless steel – 0.151; PPI 701 – 0.499; tesa® 53988 – 0.903; tesa® 4323 – 0.680. The tesa® 53988 black colour soft PVC insulation tape was selected as the material to improve emissivity and to be used in further experimental thermography measurements due to the highest value of emissivity.

3.1. Evaluation of Print-drum Thermal Performance Using Default PID Values

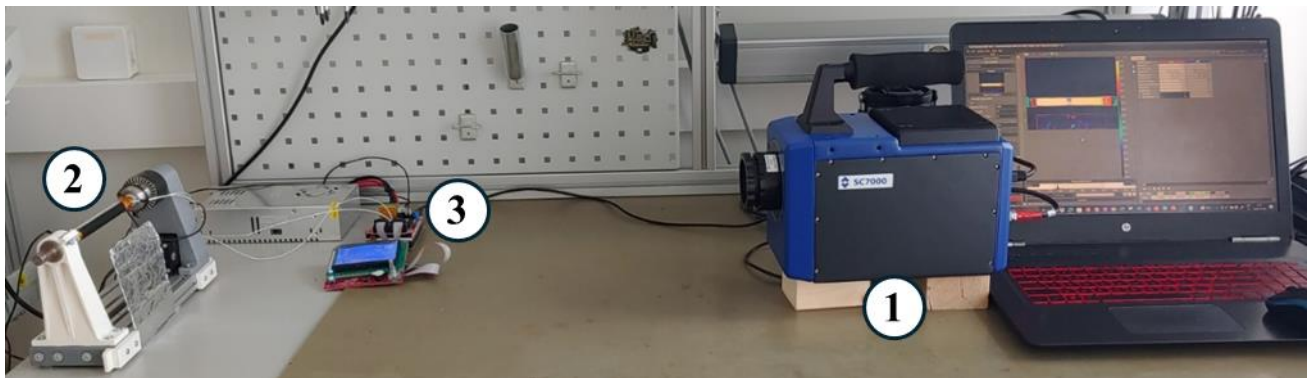


Fig. 26. Experimental setup for measuring reflected apparent and the print-drum temperature (1 – FLIR SC7500; 2 – rotary module with print-drum; 3 – control unit of the rotary module)

To assess the heating process of the assembled print-drum in the rotary module, the temperature distribution measurements were performed using thermography. The tesa® 53988 insulation tape was applied through the length of the print-drum heating zone to improve the emissivity. The setup of the experiment was comparable to the one used in a prior study and is depicted in Fig. 26. The maximum, minimum and total average temperatures were quantified during the heating process. The duration of the measuring was 300 seconds, and the target temperature was 100 °C. The default proportional-integral-derivative (PID) controller values utilized in the Marlin firmware for this test were as

follows: $K_p = 10.00$; $K_i = 0.023$; $K_d = 305.4$. Measured values are displayed in Fig. 27 and the step response characteristics of measured values are summarized in Table 8.

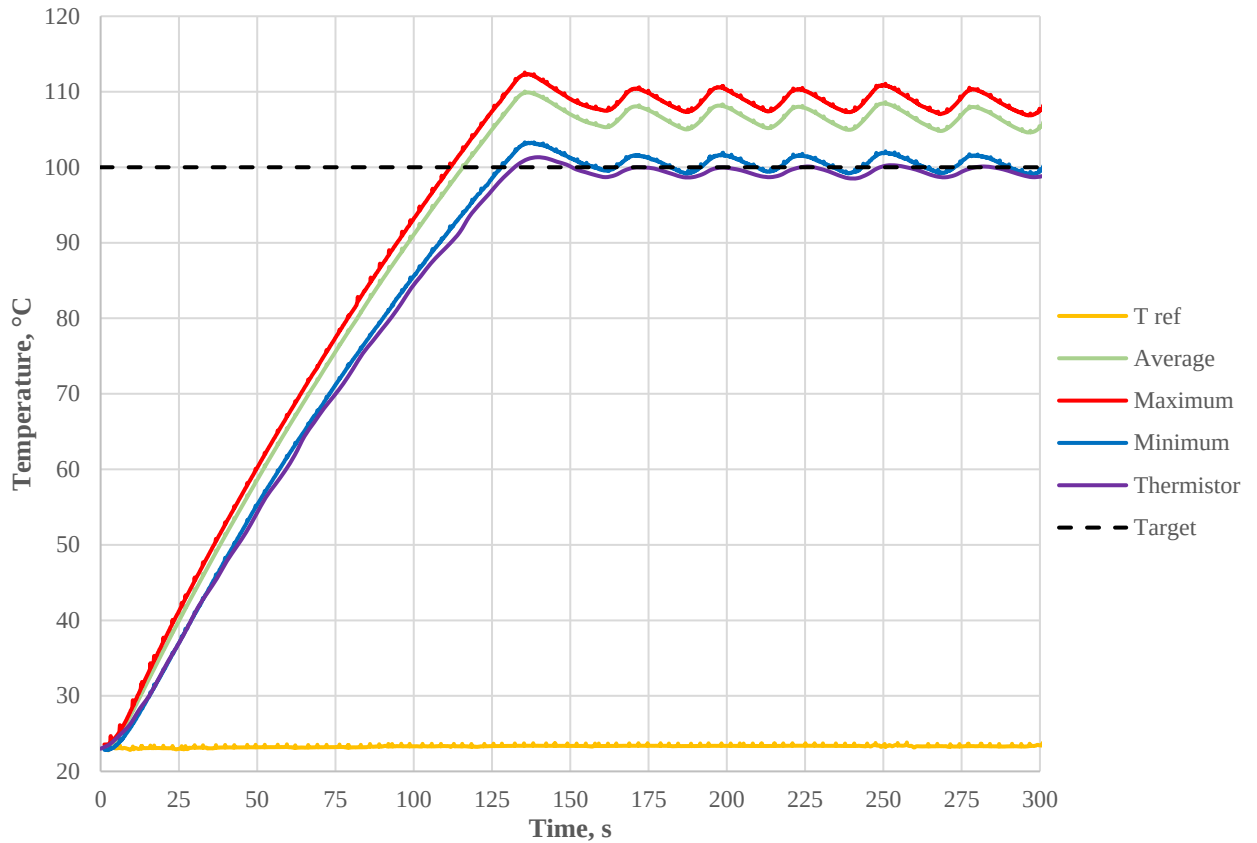


Fig. 27. Measured results during the heating process with the default PID controller

Table 8. Step response characteristics of measured temperatures with default PID controller

Temperature name	Rise time ($t_{r\ 10-90\%}$), s	Settling time ($t_{s\pm 2\%}$), s	Settling time ($t_{s\pm 5\%}$), s	Overshoot, %	Undershoot, %	Peak, °C	Peak time, s
Thermistor	99.60	128.17	123.34	1.73	0.00	101.55	139.50
Average	88.59	-	-	13.03	0.00	110.25	134.27
Maximum	85.97	-	-	16.30	0.00	112.77	134.27
Minimum	96.17	-	118.79	4.29	0.22	103.52	134.27

It was determined that the average T_{ref} was at 23.31 °C during the measurement. The results showed that the heating time for the print-drum was 128 seconds and the peak temperature measured with the thermistor was 101.6 °C. However, as was predicted by the CFD thermal model, the maximum and the total average temperatures in the heating area were above the target value. The average settled value within $\pm 5\%$ range for total average temperature was 106.6 °C and the average maximum temperature – 108.9 °C.

3.2. Evaluation of Print-drum Thermal Performance Using Calibrated PID Values

The possible improvements in heating time and temperature stability were investigated by calibrating the PID controller. The PID controller values were optimized utilizing the built-in autotuning feature of the Marlin firmware. The process consisted of heating and cooling the print-drum to 100 °C for 8 cycles. The determined PID values by the firmware tool were as follows: $K_p = 26.79$; $K_i = 2.06$; $K_d =$

232.59. The temperature values of the print-drum with a calibrated PID controller are shown in Fig. 28. Measured results during the heating process with a calibrated PID controller. The step response characteristics of recorded values are summarized in Table 9.

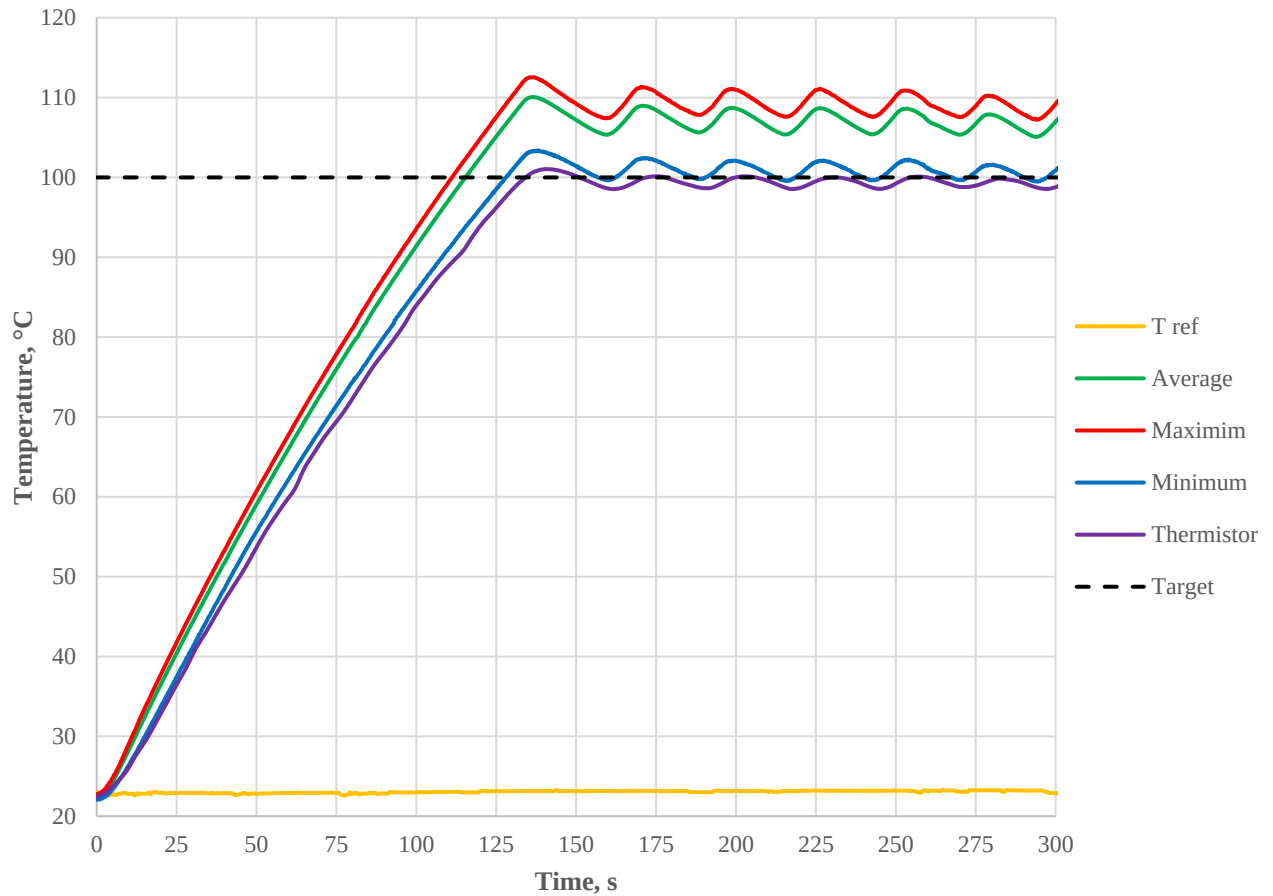


Fig. 28. Measured results during the heating process with a calibrated PID controller

Table 9. Step response characteristics of measured temperatures with calibrated PID

Temperature name	Rise time ($t_{r\ 10-90\%}$), s	Settling time ($t_{s\pm 2\%}$), s	Settling time ($t_{s\pm 5\%}$), s	Overshoot, %	Undershoot, %	Peak, °C	Peak time, s
Thermistor	100.64	129.89	124.84	1.29	0.05	101.00	139.50
Average	89.09	-	-	12.97	0.00	110.06	136.80
Maximum	86.47	-	-	16.18	0.00	112.55	136.00
Minimum	97.11	-	120.17	4.33	0.49	103.36	138.40

The results show that the average T_{ref} was at 23.05 °C during the period of measurement. The temperature distribution within the print-drum is displayed in Fig. 29. The calibrated PID controller values did not improve the required heating to reach 100 °C. Moreover, results were comparable to measured data with the default PID controller. The settling time was increased by almost 2 seconds and the peak temperatures were a bit lower. In addition, the average settled value within the $\pm 5\%$ range was about 0.5 °C higher. It was calculated that the total average temperature was 107,05 °C and the average maximum temperature – 109.28 °C. Thus, print-drums thermal performance did not significantly change with calibrated PID controller.

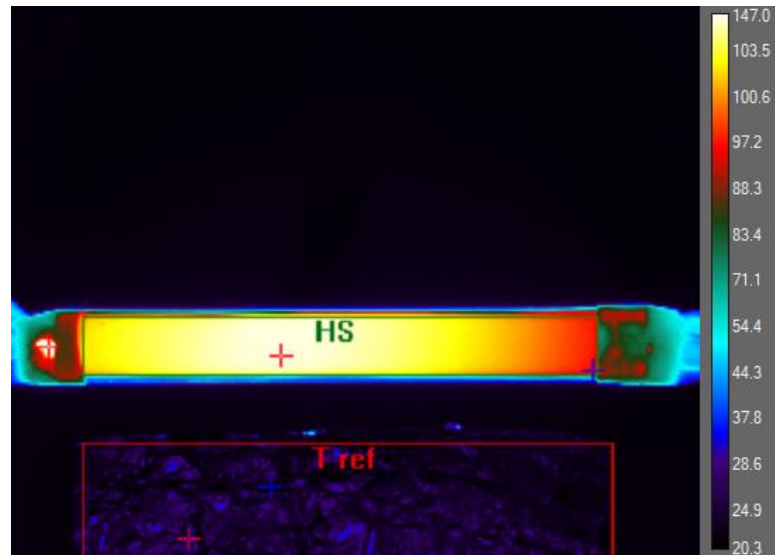


Fig. 29. Temperature distribution on the print-drum when $t = 129,89$ s. (T_{ref} – reflected temperature; HS – heated surface)

3.3. Comparison of Experimentally Measured and Theoretically Calculated Data

Simulated and manufactured print-drum performance was almost identical (Fig. 30.). The main difference was that the rise time and the peak time of the theoretical system were faster than the physical one. Moreover, the actual print-drum experienced lower maximum and average peak temperatures than in the CFD thermal simulation (Table 10.). The measured average and the maximum temperature settled averages were lower. However, the settled average temperature difference between the theoretical and physical systems ranged from 0.13 °C to 0.96 °C. These discrepancies could be attributed to several factors:

- Utilized CFD thermal simulation study did not consider the thermal radiation.
- Additional resistance from the wiring was not accounted for.
- The heating element was formed by hand, and the coil pitch could have some variation in it.

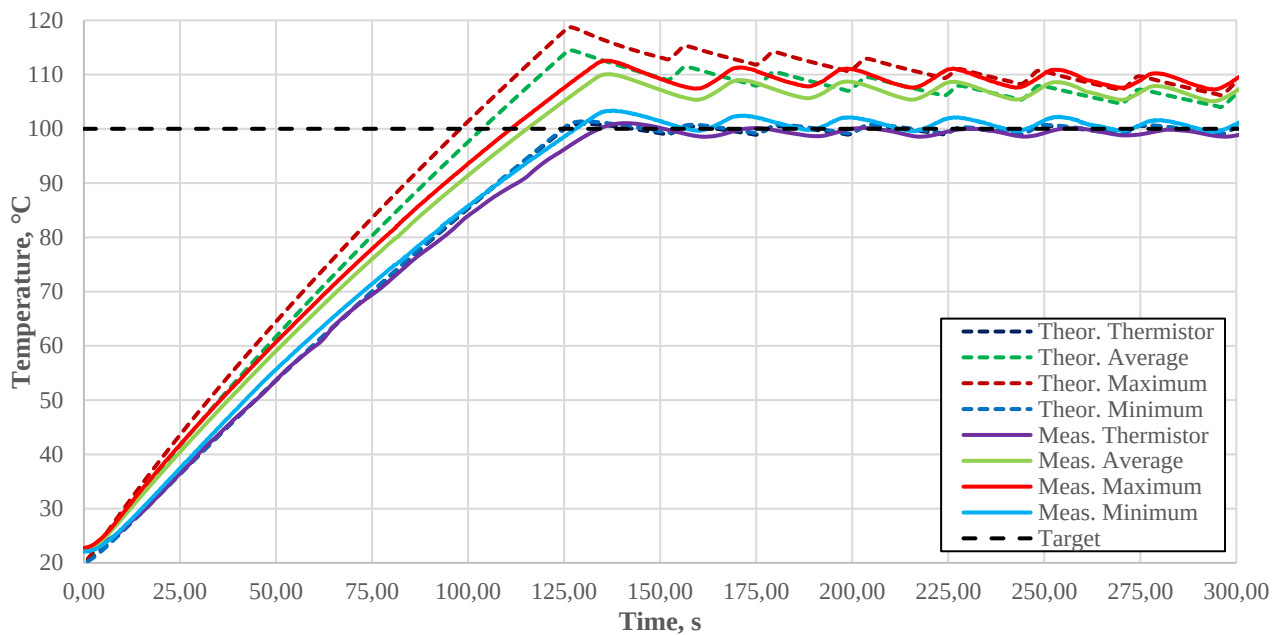


Fig. 30. Theoretically and experimentally measured data comparison

Table 10. Step response characteristics comparison between theoretical and experimental studies (red colour – higher value than; blue colour – lower value than)

Temperature name	Rise time (t_r 10-90%), s	Settling time ($t_s \pm 2\%$), s	Settling time ($t_s \pm 5\%$), s	Overshoot, %	Undershoot, %	Peak, °C	Peak time, s	Average settled (avg. $y_{final} \pm 5\%$), °C
Theor. Thermistor	98.05	122.31	118.15	1.11	0.00	100.88	130.00	99.86
Theor. Average	82.32	-	-	18.09	0.00	114.44	127.00	107.72
Theor. Maximum	78.12	-	-	23.40	0.00	118.69	127.00	110.24
Theor. Minimum	97.51	-	117.77	1.70	0.00	101.35	130.00	99.99
Meas. Thermistor	100.64	129.89	124.84	1.29	0.05	101.00	139.50	99.46
Meas. Average	89.09	-	-	12.97	0.00	110.06	136.80	107.05
Meas. Maximum	86.47	-	-	16.18	0.00	112.55	136.00	109.28
Meas. Minimum	97.11	-	120.17	4.33	0.49	103.36	138.40	100.91

3.4. Cylindrical Run-Out and Parallelism Measurement Results

In AM MEX it is important to ensure that the printing surface is in parallel to the nozzle and the distance between them is kept the same. The excessive variation in distance between the surface and the nozzle could lead to such process failures for example: the nozzle crashing into the build surface, uneven material deposition, material jamming, first layer adhesion failure etc. To prevent these problems from happening in the rotary module during 3D printing, the parallelism between an axis and the plane and the cylindrical run-out must be measured. The measurements were carried out according to the ISO 230-1:2012 standard [61]. The measurements were taken in position A near the chuck and in position B close to the live center (Fig. 31). The measurements were taken 100 mm apart. The dial indicator with 10-micron graduation was used. The measured results are shown in Table 11.

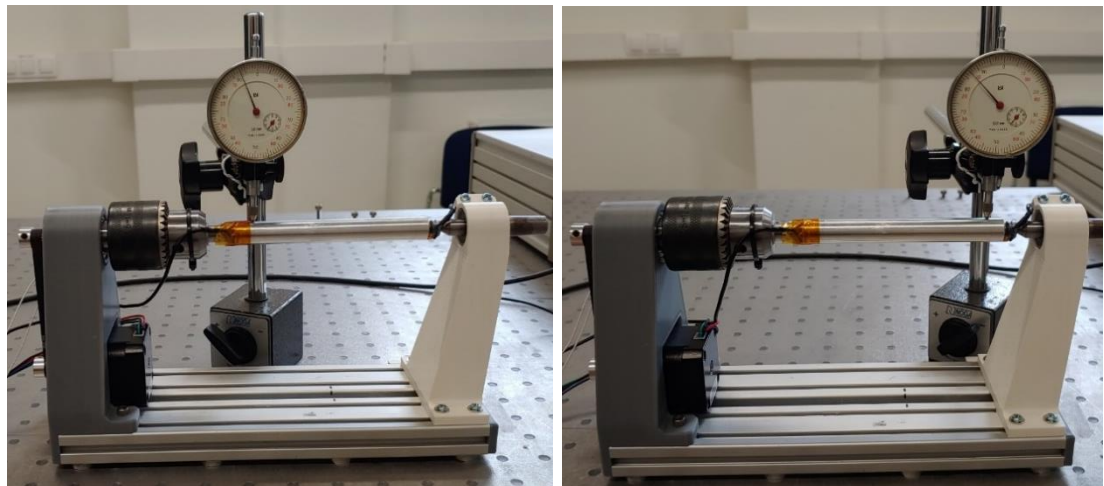


Fig. 31. Parallelism and circular run-out measuring setup: position A (left); position B (right)

Table 11. Measurement of parallelism between an axis and a plane

Angle	Position A	Position B
0°	0 µm	-60 µm
90°	-60 µm	-40 µm
180°	-10 µm	+40 µm
270°	+50 µm	0 µm

Measurements showed that the print-drum was parallel to the datum plane within a 0.06 mm tolerance zone. However, measured circular run-out exhibited significantly poorer results. At position A, it measured 0.11 mm, while at position B, it reached a 0.10 mm tolerance zone. Thus, it was determined that these inaccuracies do not allow 3D print thinner first layer thickness than 0.2 mm.

3.5. Development of the 3D Printing Process Procedure for Rotary Module

As stated, before the selection of the AM MEX printing software capable of preparing G-code for rotary 3D printing is limited. It was decided to try to use the original Prusa MK3S “slicer” software called PrusaSlicer to generate the G-code for the designed rotary module. The first issue was that the home positions of the rotary module and the Prusa MK3S were not at the same point. The homing procedure for the Prusa MK3S is required every time, when it starts to print a new file, due to the lack of closed system controls for the stepper motors. This problem was solved by offsetting the point from which the printer would start to print after homing all its axes with the G92 command. Moreover, it is needed to have a pause before the start of material deposition to place the rotary module on the Prusa MK3S printing bed. This functionality was achieved by utilizing the M0 G-code command. In addition, the Y-axis stepper motor of Prusa MK3S needed to be disconnected, to connect the stepper motor from the rotary module during the pause. To achieve this safely, stepper motors had to be disabled. This was accomplished by the M18 command. Lastly, the steps per millimetre were needed to be corrected for the rotary module. This parameter describes how many steps the stepper motor rotates to move the linear axis by 1 millimetre. The required parameter was calculated by utilizing Eq.12. The Written G-code for the rotary module is provided in the Fig. 32 and the rotary 3D printing process diagram is shown in the Fig. 33.

$$\text{steps per mm} = \frac{180^\circ}{\alpha \phi \pi R} \quad (14)$$

Where: α is a stepper motor step angle (°); ϕ – stepper motor driver micro stepping ratio; R – printing surface radius (mm).

```

M862.3 P "[printer_model]" ; Printer model check
M862.1 P[nozzle_diameter] ; Nozzle diameter check
M115 U3.13.3 ; Tell printer latest fw version
G90 ; Use absolute coordinates
M83 ; Extruder relative mode
M92 Y100; Set steps per millimetre for Y-axis
G28 W; Home all axis
G92 E0 X-108 Y0 Z-137.6 ; Set a new home position
G1 X0 Y105 Z25 ; Move axis
M18 ; Disable all stepper motors
M104 S[first_layer_temperature] ; Set extruder temperature
M109 S[first_layer_temperature] ; Wait for extruder temperature
M0 Click to continue ; Stop printer and wait
G1 X0 Y105 Z0 ; Move axis
M92 Y72.76 ; Set steps per millimetre for Y-axis (rotary axis)

```

Fig. 32. Start G-code of the rotary module for Prusa MK3S

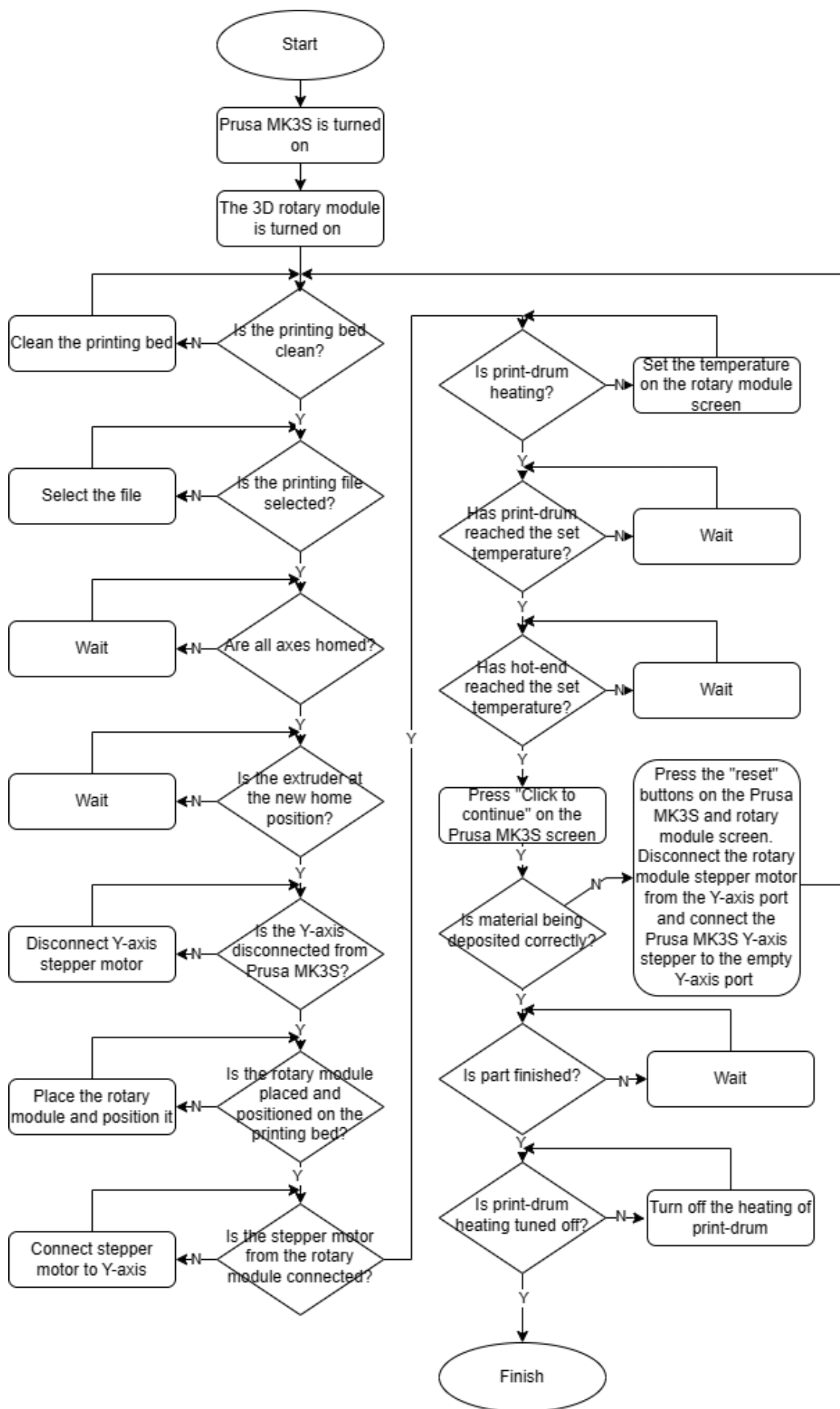


Fig. 33. Rotary 3D printing process diagram for rotary module and Prusa MK3S

3.6. 3D Printing with Rotary Module

To test the printing capabilities of the rotary module with a heated print-drum, the example of the sleeve was designed using SolidWorks. Firstly, the part was designed as it should look manufactured. Then the model was flattened around the axis of rotation and the difference in length between the inner and outer edges along the Y-axis was adjusted to be equal to the arc length of the print-drum. The G-code of the part was generated using PrusaSlicer (Fig. 34).

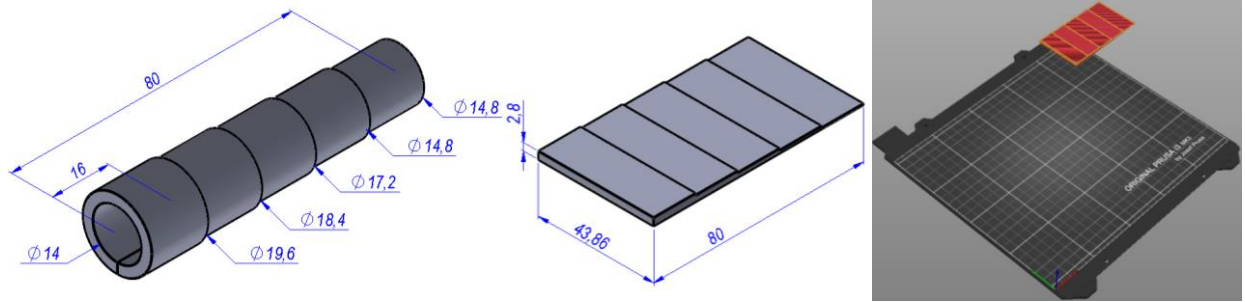


Fig. 34. Part preparation for the rotary 3D printing: a cylindrical part is designed in CAD (left); a flat pattern of the part is made in CAD (middle); a flat pattern is “sliced” in PrusaSlicer (right)

The sleeve was printed from PLA with a modified “Original Pusa i3 MK3S & MK3S+” printer settings template at 0.2 mm layer thickness. The part was sliced to have a solid rectilinear infill with 3 perimeters. Skirt and brim features were removed. The default speed values were reduced: perimeter, infill, solid infill, top solid infill, travel speeds were reduced to 30 mm/s, and the first layer speed was lowered to 15 mm/s. The temperature of the print-drum was set to 60 °C. The total printing time was 44 minutes. It was found that part could be printed faster, however, the printing speed was limited due to the wiring design of the print-drum. At higher speeds, print-drum power cables and thermistor wires would interlace together with external components. In addition, the designed wiring solution was proven to interfere with extruder assembly and restrict the building surface length to 85 mm (Fig. 35.). Moreover, it was observed that part 3D printed on a rotary module exhibited increasing under-extrusion with each additional layer in the rotational Y-axis direction. It was determined that this was caused by an increase in the travel distance of the extruder.

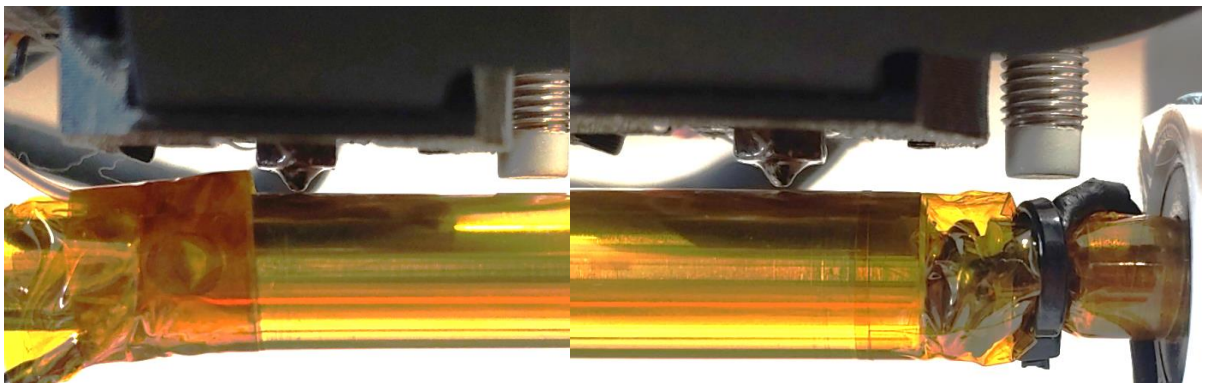


Fig. 35. Extruder interference with elements of the print-drum

However, there was an attempt to solve the under extrusion in the rotational Y axis by slicing the model without adjusting the flattened CAD model and calculating the steps per millimetre for each layer. The individual layer steps per millimetre were calculated by employing Eq.15. Nevertheless, another problem was found which would shift the beginning point of the next layer from the previous

one and layers would be misaligned in the rotational Y-axis direction. Thus, rotary 3D printing with PrusaSlicer was proven to be challenging.

$$steps\ per\ mm_n = \frac{180^\circ}{\alpha\phi\pi(R + t(n - 1))} \quad (15)$$

Where: α is a stepper motor step angle ($^\circ$); ϕ – stepper motor driver micro stepping ratio; R – printing surface radius (mm); t – layer thickness (mm); n – layer number.

3.7. Print-drum Thermal Performance with Customizable Sleeve

An example of a customisable sleeve was a rotary 3D printed from composite PLA thermoplastic material filled with carbon black particles from Protoplant Inc. The part was printed using the same settings described in the previous subchapter. The duration of the measurements was 600 seconds, and the sleeve was heated to 60 $^\circ\text{C}$. Measured values are shown in Fig. 36 and the response characteristics of measured variables are summarized in Table 12.

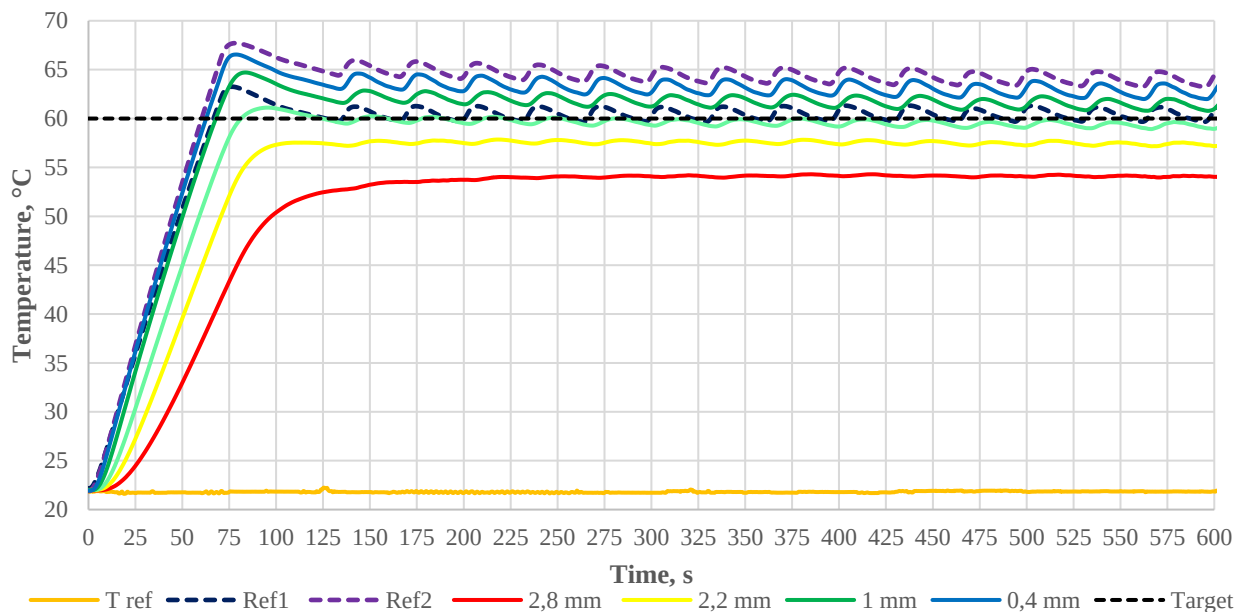


Fig. 36. Measured temperatures of variable thickness sleeve

Table 12. Step response characteristics of measured temperatures

Temperature name	Rise time ($t_{r\ 10-90\%}$), s	Settling time ($t_{s\pm5\%}$), s	Peak, $^\circ\text{C}$	Peak time, s	Average settled (avg. $y_{final\pm5\%}$), $^\circ\text{C}$
Ref1	50.65	94.30	63.26	76.80	60.47
Ref2	50.76	98.23	67.72	78.67	64.50
2.8 mm	75.29	123.45	54.30	385.07	53.96
2.2 mm	58.57	85.88	57.86	217.87	57.50
1.6 mm	54.06	75.04	61.12	95.20	59.67
1.0 mm	50.77	98.48	64.71	83.47	61.81
0.4 mm	50.11	99.42	66.55	78.67	63.21

The average Tref was 21,81 $^\circ\text{C}$ during the period of measurement. The results showed that the temperature difference on the print-drum between the reference 1 zone (Ref1) and the reference zone 2 (Ref2) was about 4 $^\circ\text{C}$. The print-drum reached the printing temperature within 65 seconds.

However, not all regions of the sleeve managed to reach the target temperature. The lowest average settled temperatures were measured on the sleeve regions with wall thickness of 2.8 mm and 2.2 mm to be at 54 °C and 57.5 °C respectively. In addition, the measured regions with wall thickness from 1.6 to 0.4 mm reached the 60 °C target temperature within 95 seconds.

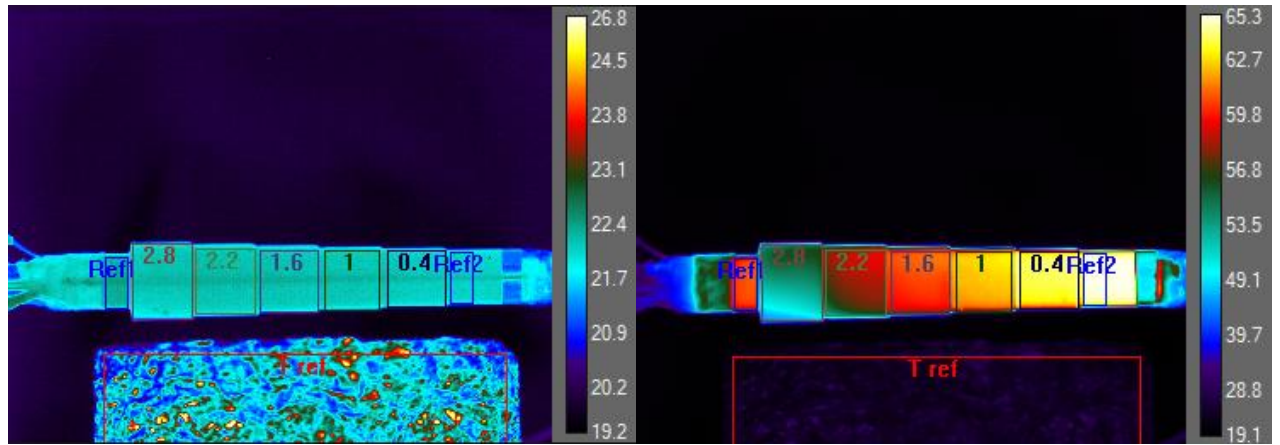


Fig. 37. Temperature distribution: $t = 0s$ (left); $t = -123.5s$ (right)

3.8. Chapter Summary

After assembling the rotary module and the 45W resistance coil heater print-drum the thermal performance and printing capabilities were evaluated experimentally. To perform the experimental thermographic analysis and obtain the accurately measured surface temperature of the print-drum the emissivity needed to be improved. The emissivity of the three different adhesive tapes was measured in accordance with the ISO 18434-1:2008 standard. It was measured that PVC insulation tape had the highest emissivity value of 0.903 and it was used to enhance the emissivity of the print-drum in the thermal performance analysis. The heating performance of the 45W resistance coil heater print-drum design with thermistor position L was evaluated using the default PID controller values provided by the firmware and after the calibration of the PID controller. However, the PID controller value calibration did not result in any improvements. The print-drum settled to the target temperature of 100 °C in 130 seconds with an average temperature of 107 °C. At this temperature, the difference between the maximum and the minimum values on the printing surface was about 9 °C. The difference between the theoretically and experimentally obtained settled average temperatures ranged from 0.13 °C to 0.96 °C, resulting in a relative error of $\pm 0.9\%$. In addition, the parallelism and circular run-out measurements were performed following the ISO 230-1:2012 standard to determine the quality of the printing surface. It was measured that the printing surface was parallel within the 0.06 mm tolerance zone and exhibited the circular run-out of 0.1 mm which meant that the first layer thickness could not be thinner than 0.2 mm. Moreover, the printing capabilities were examined by using the Prusa MK3S 3D printer and PrusaSlicer software. The custom start G-code and rotary 3D printing process sequence for the Prusa MK3S were developed. A printing speed of 30 m/s was achieved. However, the printing surface length was reduced to 85 mm from 100 mm due to wiring interference with external components. Printed parts experienced under-extrusion with the increase of the layer number due to limitations of the PrusaSlicer software. Furthermore, after designing and printing a sample of a customizable sleeve out of composite PLA filament the thermal performance was evaluated. It was observed that a target temperature of 60 °C was achieved on the surfaces of the sleeve with wall thickness from 0.4 to 1.6 mm. The measured temperatures on surfaces with wall thickness from 2.2 to 1.6 were not able to reach the target temperature.

4. Economical Aspects of the Developed Rotary Module

This chapter focuses on the economic aspects of the developed rotary module with a heated print-drum system. The cost of the components will be calculated, including the price of parts which were produced by additive manufacturing. Moreover, the cost-effectiveness analysis will be performed in comparison to commercially available solutions to evaluate the economic benefits of the manufactured module.

4.1. Bill of Material Cost Calculation for Rotary Module

To evaluate the cost-effectiveness of the rotary module total cost of components needed to be calculated. To manufacture the parts designed for the AM MEX Raise3D Pro2 printer and ideaMaker software was used. The parts were made free of charge. However, the price was needed to perform the analysis. The utilized software provided the key information on how much material was needed and how long the manufacturing process would be. Moreover, it provided price estimation for these parts (Fig. 38). Nevertheless, it was decided to calculate the part price:

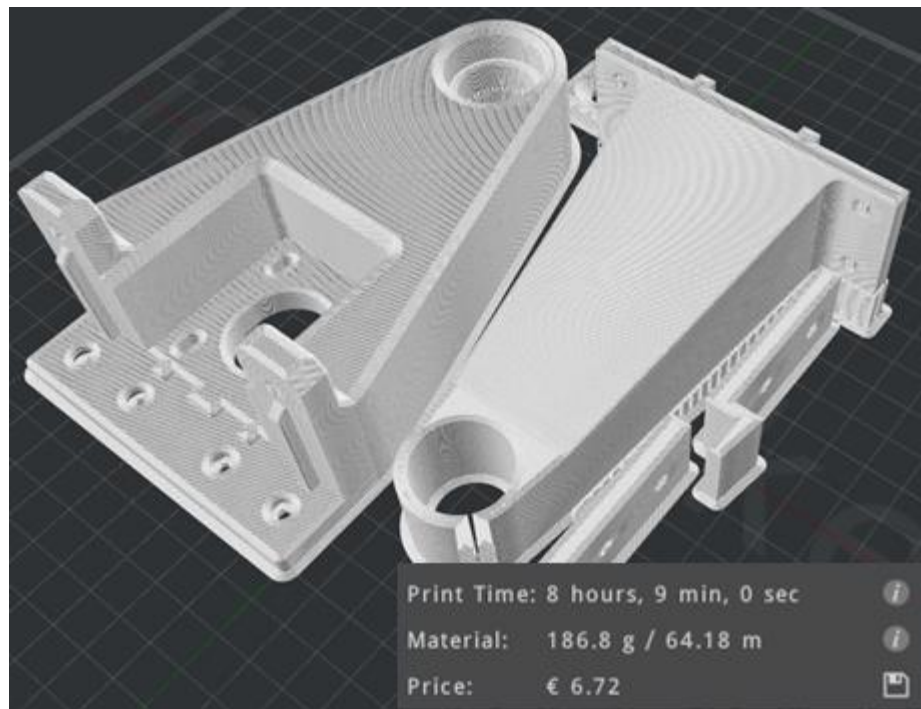


Fig. 38. Provided printing time, material, and cost calculations by ideaMaker “slicing” software

The machine hourly cost rate was calculated by using Eq.16 to be 2,80 €/h. The hourly manufacturing rate was estimated by using these assumptions:

- The machine was operating on average 16 hours per day, every workday through the year.
- The initial cost of Raise3D Po2 was around 3300 € and it was expected to operate it for 5 years.
- Raise3D Po2 required 600W power and operated at 90% efficiency, energy costs around 0.19 €/kWh.
- Employee hourly rate was around 13€ and spent maintaining the 3D printer around 3 hours per working day.
- The printer required 1m² to work, and the monthly rent price was 10 €/m².

$$C_{HMR} = \frac{C_e + C_d + C_L + C_R}{t_M} \quad (16)$$

Where: C_e is an energy cost (€); C_d – depreciation cost (€); C_L – labour cost (€); C_R – rental space cost (€); t_M – machine working time per year (h.).

The parts were printed from Rosa3D High Speed PLA which cost 20,58 € without VAT, and by using Eq.17 it was calculated that the material cost was about 3,83 €

$$C_m = m \cdot c_m \quad (17)$$

Where: m – required quantity of material (kg); c_m – material cost (€/kg).

By employing previously calculated variables, the production cost for the rotary module parts was calculated to be about 26,66 € without VAT, To calculate the production cost Eq.18 was used.

$$C_p = C_m + t_p \cdot C_{HR} \quad (18)$$

Where: C_p is a production cost (€); C_m – material production cost (€); t_p – printing time (h.); C_{HR} – hourly manufacturing rate (€).

Unlike parts manufactured by AM MEX, other components were bought, and the prices were known. The total cost of the rotary module is listed in Table 13.

Table 13. Bill of material cost

Component	Description	Quantity	Price without VAT
MS002.01.00.001	Spindle	1	109.22 €
MS002.01.00.002	Bed extrusion	2	20.00 €
MS002.01.00.003	Head stock	1	26.66 €
MS002.01.00.004	Bed bracket	1	
MS002.01.00.005	Tail stock	1	
MS002.01.00.006	Positioning bracket	2	
MS002.02.00.001	Mandrel	1	128.91 €
MS002.02.00.002	External Mandrel	1	64.51 €
17HS19-2004S1	Stepper Motor	1	9.43 €
Arduino MEGA 2560	Microcontroller	1	22.00 €
RAMPS 1.4	Board shield	1	5.62 €
RepRarDiscount Full graphic Smart Controller	Display	1	11.73 €
S-201-12	Power Supply	1	17.14 €
Miracon LIGTH DUTY 1/2" 1,5-13 mm	Drill Chuck	1	5.87 €
ATH100K1R25	Thermistor	1	5.39 €
Extra components	Bolts, nuts, bearings, cables etc.	-	20.00 €
Total:			446.48 €

4.2. Cost-effectiveness Analysis

A cost-effectiveness analysis was conducted to evaluate how the developed rotary module compares to similar products in the market. The Snapmaker 2.0 rotary module [62], manufactured by Snapmaker HK Limited was selected as the comparator. This module is an add-on for the 3D printers offered by Snapmaker. It has a build volume of Ø136×170 mm, offers a chuck which has a clamping range from 1 to 30mm, can reach a maximum 45 °/s angular speed, ensures 0.2° angular precision

and costs 679 € [62]. However, it does not have a heated bed and does not provide a mandrel to be used as the printing surface. For this cost-effectiveness analysis, it is assumed that this module uses Ø14mm mandrel for printing. On the other hand, the designed rotary module in this study was tested for printing 30mm/s linearly which means it could reach around 246 °/s angular speed. Moreover, the developed rotary module uses stepper motors with a 1.8° step and utilizes 1:16 micro-stepping which allows to achieve the theoretical 0.1125° angular precision. Nevertheless, the designed module has a narrower clamping range. The criteria and parameters of cost-effectiveness analysis are listed in Table 14.

Table 14. List of parameters

Criteria	Designed rotary module	Snapmaker 2.0 Rotary Module
Price, €	446.48	679.00
Build volume, mm ³	1920534.13	2443373.69
Maximum angular speed, °/s	246	45
Angular precision, °	0.1125	0.2000
Heated surface size, mm ²	4398.2	0.0
Clamping range, mm	11.5	29.0

The effectiveness was calculated by dividing the cost of the module by the criteria value. However, for angular precision, the criteria were divided by the cost of the module due to a lower inverse relationship. The calculated cost-effectiveness value for each criterion is shown in the table below (Table 15). The analysis demonstrated that the design module offered lower prices per parameter in the 3 out of 5 criteria and was more cost-effective than the commercial solution.

Table 15. Cost-effectiveness analysis results (red colour – lower cost efficiency; blue colour – higher cost efficiency)

Criteria	Designed rotary module	Snapmaker 2.0 Rotary Module
Build volume, €/mm ³	2.32E-04	2.78E-04
Maximum angular speed, €/°/s	1.82	15.09
Angular precision, °/€	2.52E-04	2.95E-04
Heated surface size, €/mm ²	0.10	-
Clamping range, €/mm	38.82	23.41

4.3. Chapter Summary

The developed design proved to be cost cost-effective solution in three out of five categories when compared to the analysed commercial alternative. Moreover, the FDM manufacturing cost of the custom components produced by the Raise3D Pro2 printer was calculated to be 27 €. The total cost of the bill of materials was calculated to be 446.5 €.

Conclusions

1. The rotary module with a customizable heated print-drum was designed to be installed as additional equipment in the Prusa MK3S 3D printer to enable the additional capabilities to additively manufacture more complex, variable-diameter tubular components by utilizing the non-planar material deposition method. The total dimensions of the rotary module are 309×101×149 mm, the print-drum – Ø14×164 mm. It was designed to have a printing volume of Ø157×71.5×100 mm with a Ø14×100 mm heated surface. The customizable conductive sleeve was designed to be printed utilizing the rotary module by using conductive composite filament. It enables the capability to quickly tailor the shape of the print-drum for a specific tubular structure by utilizing a single additive manufacturing process.
2. Six different print-drum designs based on resistance heating wire and commercially available heater cartridges were evaluated through multiphysics finite element modelling. After the comparative computational study was performed, out of the six proposed designs, the 45W resistance coil heater print-drum design with thermistor position L was determined to be the most effective design based on favourable temperature distribution properties, settling time and safety. Moreover, the thermomechanically simulated values and behaviour of temperature profiles reflected the experimentally measured data. The relative settled temperature error between the values simulated and measured with the thermal imaging camera was ±0.9%.
3. The designed print-drum and rotary module was manufactured and assembled by using commercially available components and custom-designed parts. The print-drum was able to reach 100 °C printing surface temperature. The relative settled temperature difference between cold and hot spots on the printing surface was 8%. The average settled temperature was 107 °C with a target value of 100 °C. Moreover, the heating time to 100 °C was about 130 seconds. Printing speeds up to 30 mm/s were achieved. However, it was measured that the print-drum has a 0.1 mm circular run-out which limited the minimum thickness of the first layer to 0.2 mm. In addition, it was found that the printing surface length was limited from 100 mm to 85 mm due to the selected wiring solution.
4. The cost-effectiveness analysis was performed, and it was calculated that the total cost to manufacture the rotary module with the heated print-drum for Prusa MK3S is 447 €. The developed hardware for rotary 3D printing offers better cost-effectiveness together with improved functionality and performance in terms of build volume, angular speed and heated surface size compared to similar commercially available solutions.

Recommendations

This research developed a proof-of-concept rotary module with a customizable heated print-drum for the commercially available planar material extrusion additive manufacturing machine. It provided additional hardware capability for standard FDM printers in terms of rotary 3D printing. However, the manufactured module with a heated print-drum is not the definitive solution and additional improvements and research could be done. The suggestions for future study and enhancements are listed below.

1. All proposed print-drum designs based on resistance heating wire displayed significant temperature gradients on the printing surface. In the case of the manufactured print-drum, it was about 9 °C difference between cold and hot spots when the target temperature was 100 °C. To reduce the temperature difference within the printing surface a variable pitch heating element or better thermal insulation of the print-drum could be investigated.
2. The printing speed and printing surface length were restricted by the implemented wiring solution. Moreover, the developed rotary module could not achieve continuous 360 ° rotation due to the same problem. The implementation of sliding contacts in the print-drum could be evaluated.
3. The majority of conventional FDM machines have an auto-bed levelling feature which allows them to compensate for the uneven surface of the build plate. The implementation of this feature in rotary 3D printing could improve the process and reduce the precision requirements of print-drum.
4. The study only evaluated the thermal performance of one filament for the customizable sleeve. Different materials and composite filaments e.g. thermoplastics filled with metallic fillers could be examined. Moreover, the adhesion between different sleeve and part materials might be measured to understand the practical utility of the sleeve.
5. The study did not consider the reusability of the rotary 3D printed sleeve for further manufacturing process. The different locking mechanisms or fixturing methods could be developed to enable the utilization of previously produced sleeves.
6. The employed file preparation method for rotary 3D printing by utilizing PrusaSlicer software proved to be challenging. The alternative G-code generation methods or the development of additional capabilities for rotary 3D printing in standard FDM software could be investigated.

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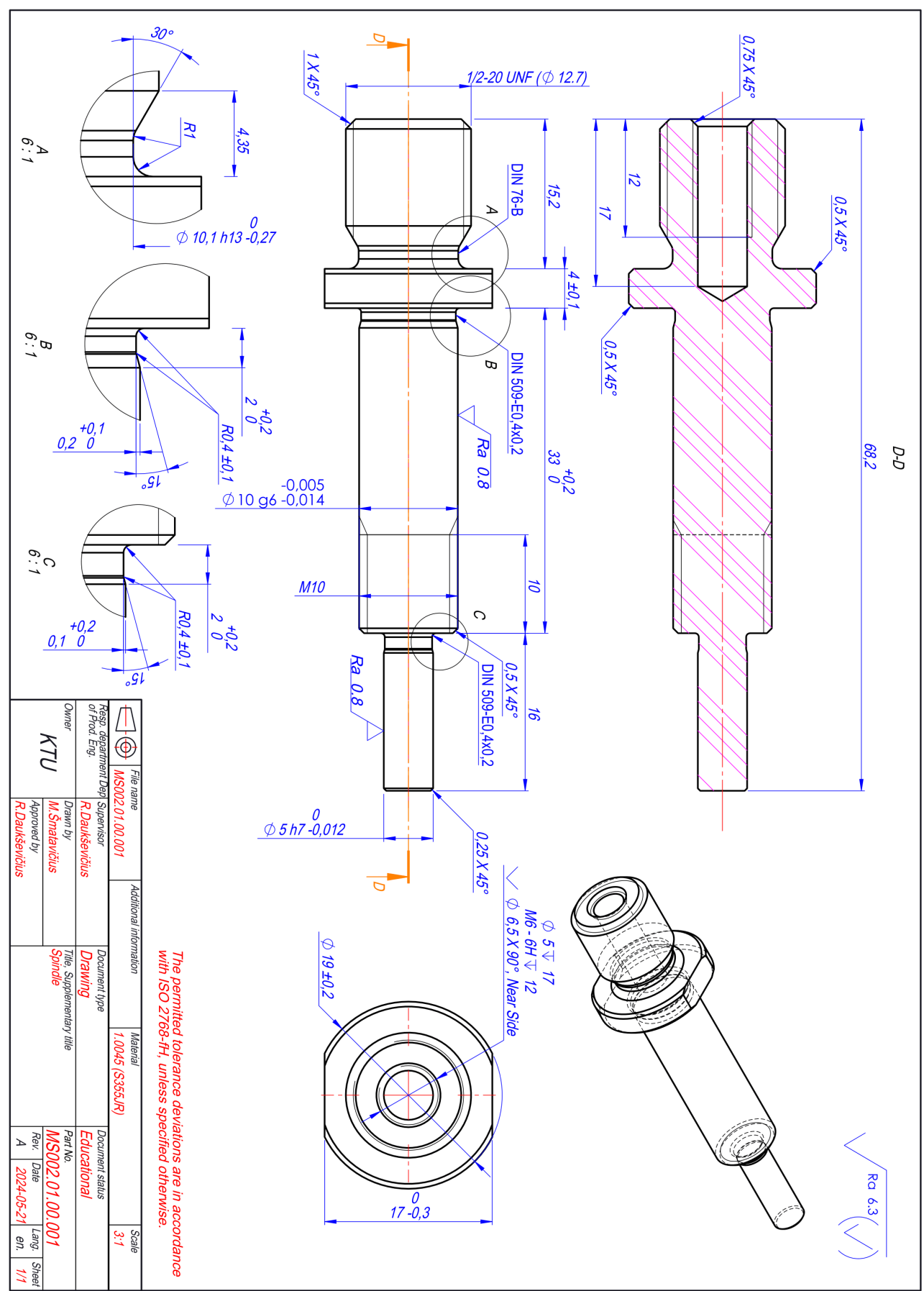
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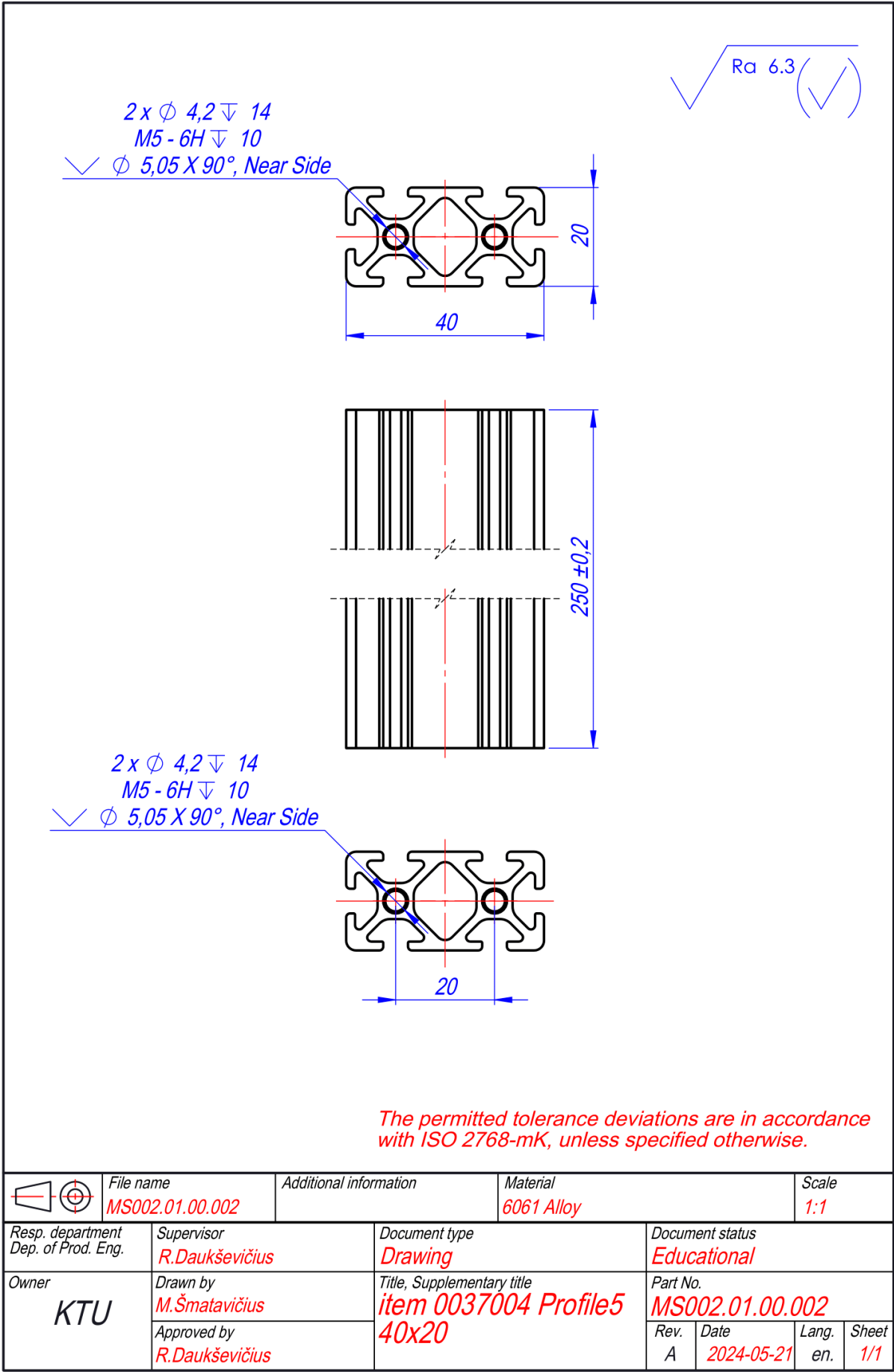
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Appendices

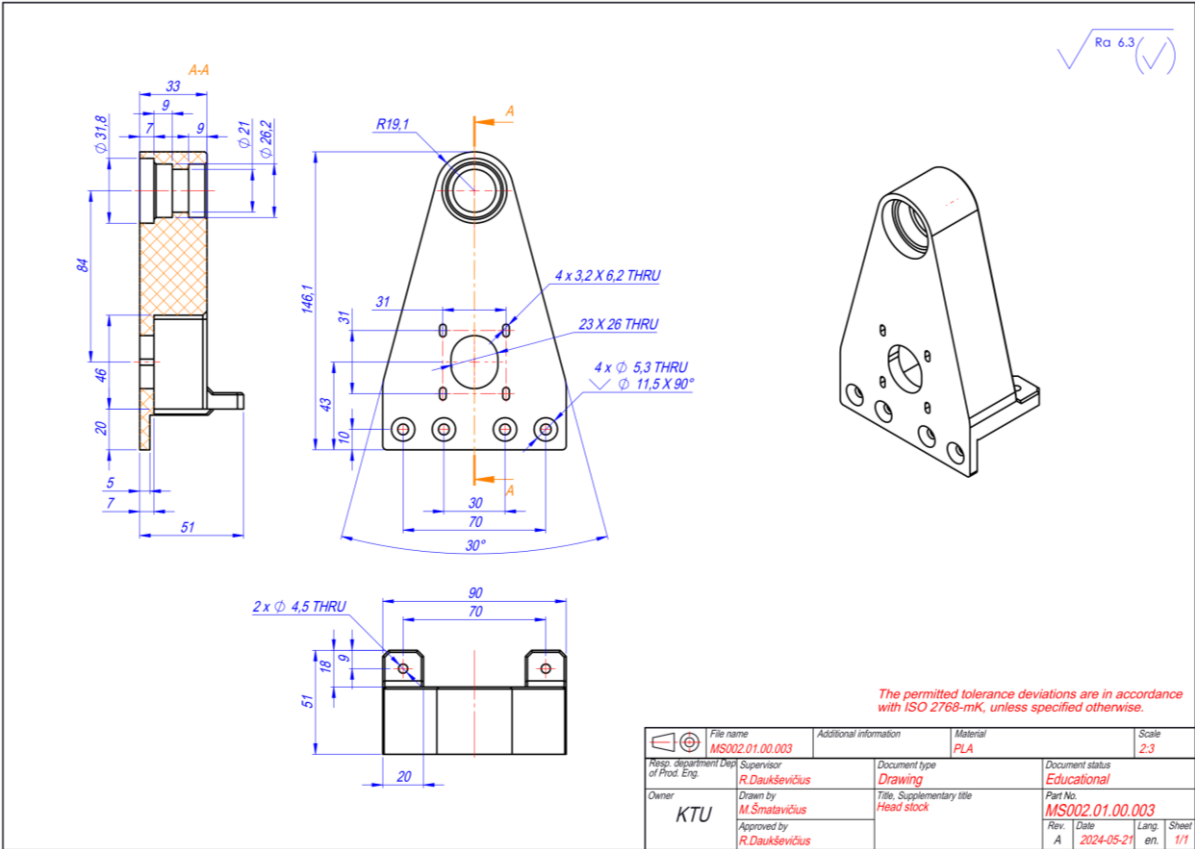
Appendix 1. Drawing of the Spindle



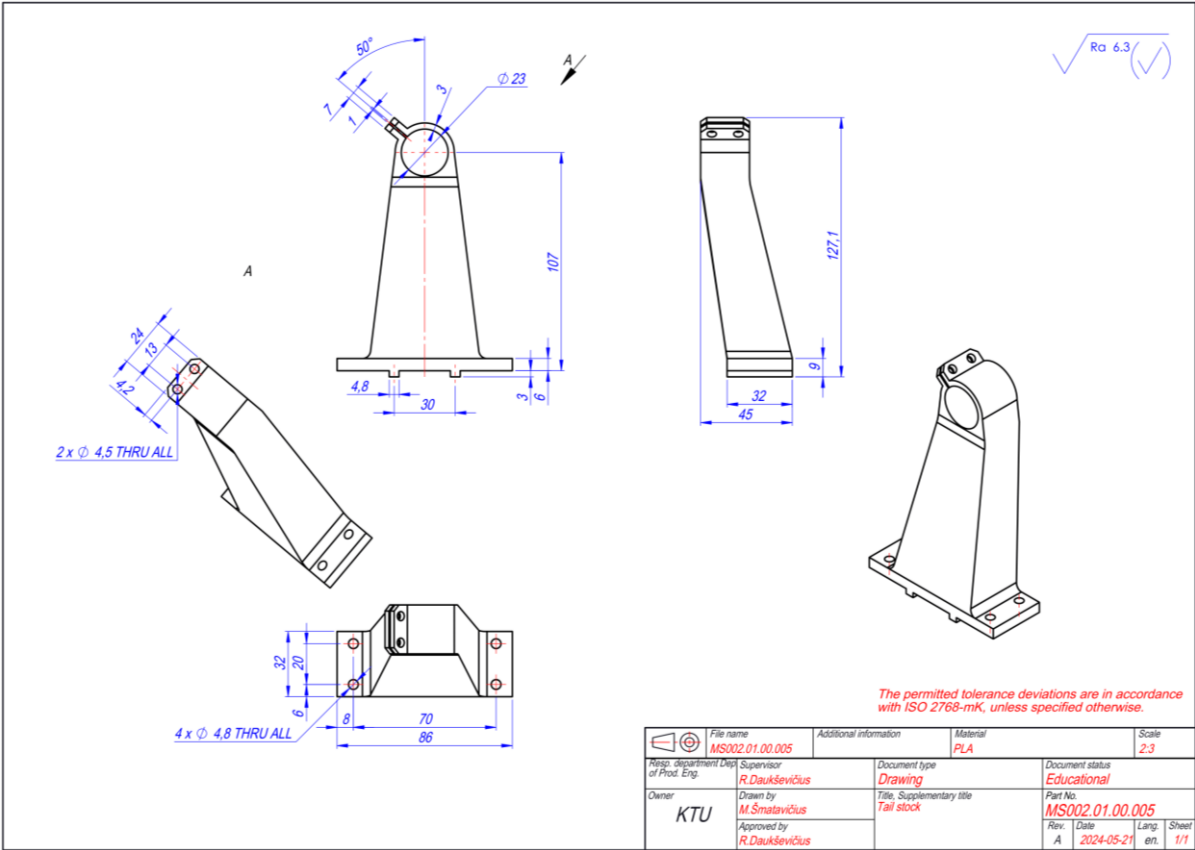
Appendix 2. Drawing of the Bed Extrusion



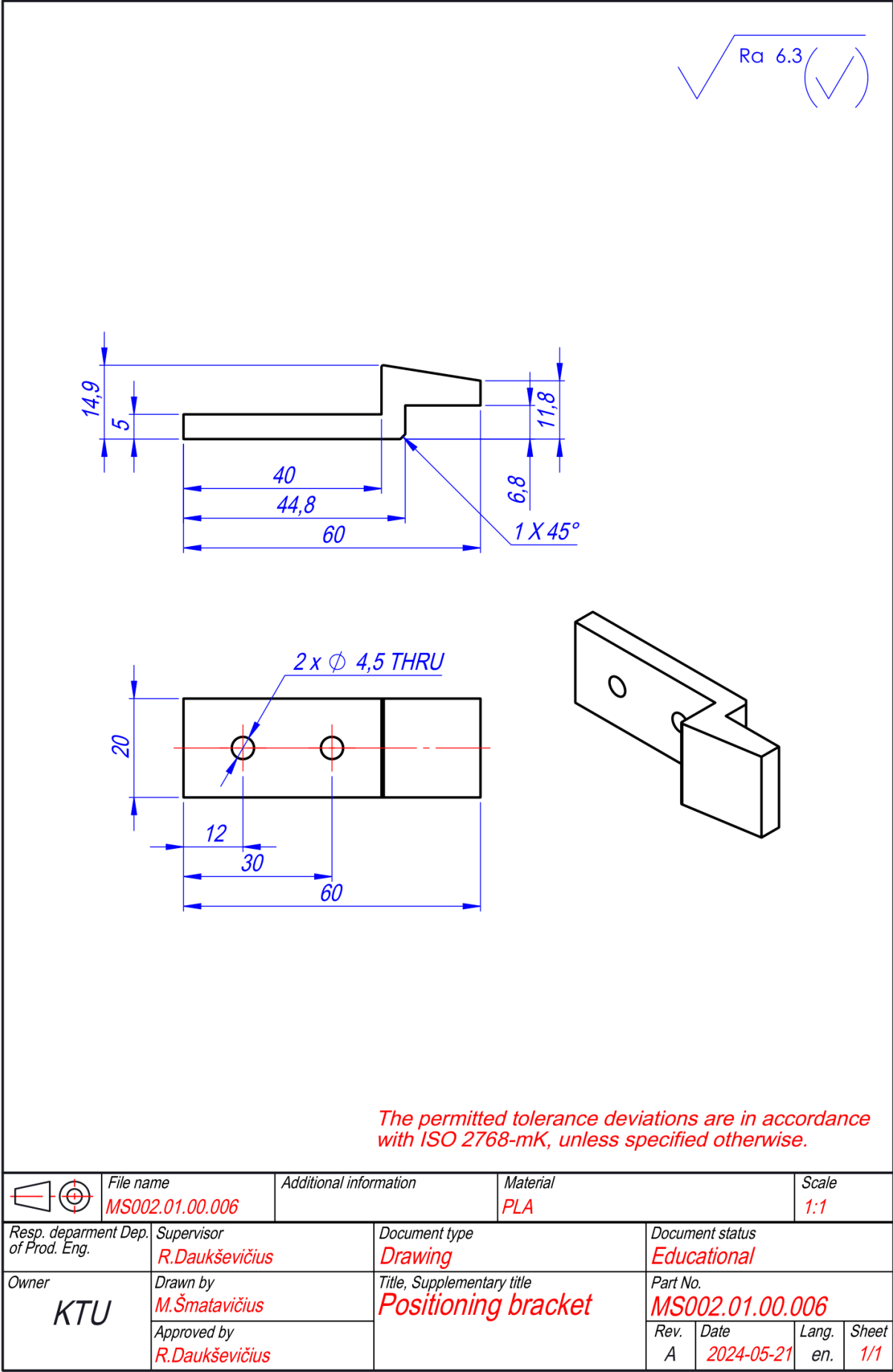
Appendix 3. Drawing of the Head Stock



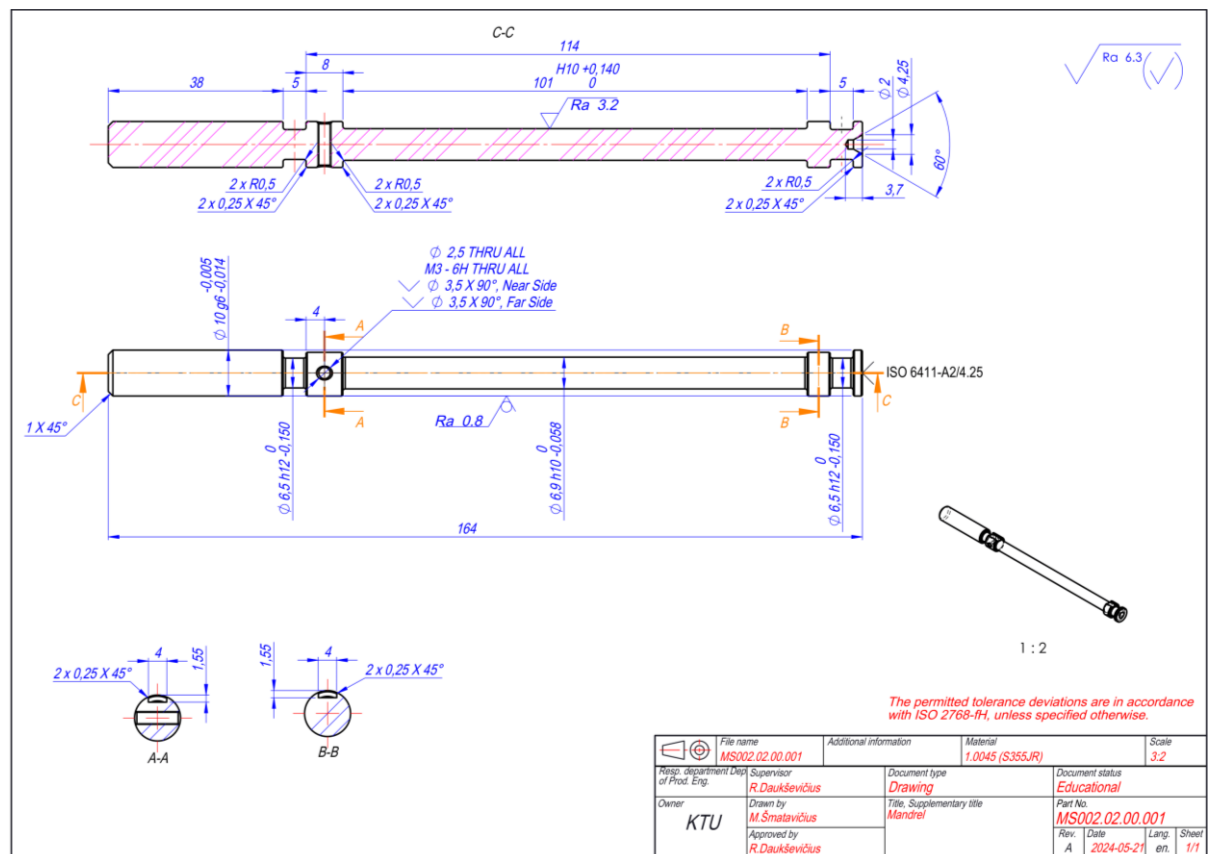
Appendix 4. Drawing of the Tail Stock



Appendix 5. Drawing of the Positioning Bracket



Appendix 6. Drawing of the Mandrel



Appendix 7. Drawing of the External Mandrel

