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Leakage-proof nozzle design for RepRap community 3D printer

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SUMMARY
The RepRap 3D printer development project is a fast growing, open-hardware initiative relying on the input of hobbyist designers. One of its key components is the printer nozzle. The performance and reliability deficiencies of currently available nozzle designs are common topics in the RepRap community, and our own experience with a RepRap 3D printer has identified a need for improvement in a few particular areas. We set out to eliminate melt leakage, improve thermal isolation, and develop a more effective method of nozzle assembly attachment. Here, we review the issues, describe design efforts, and report results.

KEYWORDS: Finite element analysis; Open hardware; Thermoplastics.

Introduction

Stereolithography, rapid prototyping, and 3D printing are common names for a manufacturing process based on additive manufacturing (see ref. [1] for a review). In contrast to traditional manufacturing processes, 3D printing deposits material layer by layer to form the final part. In fused filament fabrication, small beads of thermoplastic material are extruded to form the layers. Selective laser sintering (SLS) applies powdered material, and then selectively fuses it using a focused laser beam.[2] 3D printing has been available to industry since the early 1980s. In the last ten years, the popularity of 3D printers has grown rapidly as equipment prices have dropped and performance capabilities have improved. Today, 3D printers are essential for rapid prototyping and are being used increasingly to fabricate production components.[2]

From the beginning, the additive 3D printing processes has promised less wasteful and more environmentally friendly alternatives to subtractive fabrication technologies. Traditional cutting processes produce chips, turnings, filings, or shavings that must be removed and reprocessed. For cooling and lubrication, cutting processes use cutting fluids, which present a number of health concerns and must be carefully disposed of to mitigate environmental impacts.[3] 3D printing, on the other hand, applies only the material needed.[4] Unlike other additive processes such as casting or injection molding, 3D printing does not require mold tooling. The 3D printer needs only electricity to operate, making the process clean and environmentally friendly.

Averaging about €16,000, the price for the most common type of 3D printer, which is based on molten polymer deposition, is still too high to make the technology attractive for personal use. Moreover, the current cost of the polymer consumable is about €3 per cubic centimeter, which makes the printing of all but the smallest parts expensive. Seeking more affordable alternatives, enthusiasts of household rapid prototyping have been working to develop low-cost, home-built 3D printing devices, some even capable of self-replication. The pioneer in this area is undoubtedly Adrian Bowyer, the initiator of the RepRap Project, an open-source[1] initiative to develop designs for 3D printers capable of printing most of their own components.[5] RepRap printers use firmware and control software that is commonly distributed with an open-source license, the most popular of which is the GNU General

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[1] http://www.opensource.org/docs/osd

Public License (GPL)[2]. The RepRap open-hardware[3] designs and the open-source software make self-replicating home-built printer technology accessible to a wide group of people.

Unlike commercial products, community 3D printers are developed in collaboration. Enthusiasts from around the world can participate in the project, share improvement ideas, or give and get help as they design, build, and use their new 3D printing devices. However, there is no classical technical support. Instead, online forums serve as the primary source of development and problem solving information.

Although the RepRap Project and similar initiatives provide invaluable tools and assistance to the 3D printer enthusiast, extended community collaboration is not an efficient development approach. It takes effort just to access the correct needed information. For now, home-built 3D printing is the province of hobbyists with strong do-it-yourself skill sets who are not afraid of investing long hours into their project. Despite the fact that RepRap printer assembly itself takes no more than 10 hours,[6] on average, it takes about 6 months to build a reliable working RepRap 3D printer; including initial research, procurement of needed components, assembly, calibration, and performance tuning.

The amount of time needed for a RepRap 3D printer construction is highly dependent on the constructor's skills, the amount of time one can dedicate to the project, and the availability of 3D printer components. The initial printer model choice defines achievable accuracy, costs, serviceability, and capabilities. Based on our experience, printer assembly is relatively quick, taking not more than three days. Components procurement takes about a month. Components ordered from local European sources tend to be shipped within five working days but are more expensive than parts offered by sellers from Asia, where shipping time varies from two weeks to a month and a half. Printer calibration and testing is the most time consuming phase of 3D printer construction. Judging from RepRap forum comments and our own experience, an especially critical part of the calibration process is coordinating molten material flow rate through the printer nozzle with printing speed. This adjustment is especially difficult, because the speed parameters depend on filament type and the object being fabricated.

Following construction and initial calibration, the RepRap printer should be able to produce decent looking objects from a few different thermoplastics. However, if the goal is continuous trouble-free operation, printer development could take much longer. People without engineering skills in Computer Aided Design (CAD) will also require additional time to learn the basics required to build 3D models of the elements they intend to print. Good engineering skills and 3D printer experience can shorten the calibration and fine-tuning of a new RepRap 3D printer remarkably.

This publication will focus on the printer nozzle assembly, assessing its current state of development, describing the main design challenges, and pointing out problems with current designs. The discussion will continue with a detailed description and technical specification for a new low-maintenance design that has been produced and extensively tested by the authors. Photo images of a few printed objects are included to show how well the new nozzle assembly performs.

Basic Operation Principles of a RepRap 3D Printer

All of the current RepRap 3D printer designs are based on the principle of layer-by-layer molten polymer deposition. This implies that motion along the vertical axis, often called the z-axis, occurs in periodic steps. Because of the controllability of material deposition, layer thickness should be less than the diameter of the nozzle orifice. Usually, a layer thickness of around 20–50% of the nozzle orifice diameter is used. The smallest nozzles commonly available for the RepRap community 3D printer have 0.25 mm orifices. The size of filament that can be accurately fed by the polymer feeding mechanism (extrusion forces increase with decreasing orifice size) makes smaller orifice sizes impractical.

The planar motion of the nozzle tip with respect to the work piece (x- and y-axis movement) can be achieved in a number of ways. The most common solutions (7 out of 8) are based on a Cartesian system where the table moves in one direction, along the horizontal y-axis, and the printing nozzle moves in the other two directions, along the horizontal x-axis and the vertical z-axis. See Fig. 1a. The Darwin 3D printer rearranges these motions. The Darwin printing head moves in both horizontal

[2] http://www.gnu.org/licenses/gpl.html
[3] http://www.openhardware.org/

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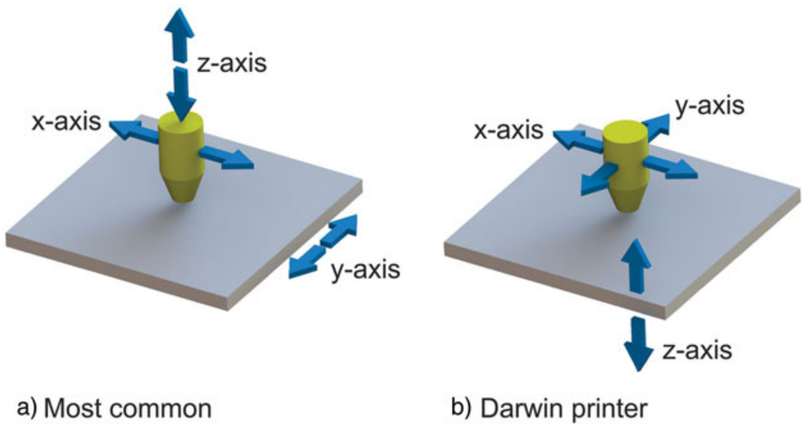

Fig. 1. Typical mechanical arrangements in 3D printers: (a) table moving in horizontal plane along one axis, nozzle moving in the vertical and horizontal planes, (b) table moving along vertical axis, nozzle moving in horizontal plane.

directions, along the x- and y-axes, and the table moves up and down, along the z-axis (Fig. 1b). Solutions using parallel mechanics, such as the delta pick-and-place robot, are also available[4].

Positioning accuracy determines the quality of a 3D printed object. RepRap printers utilize inexpensive 2-phase hybrid NEMA 17 stepper motors with 200 steps per revolution. Recently, micro-stepping controllers (based on the A4988 microchip) that divide each step into a maximum of 16 sub-steps have become available to the community. With these controllers, the same motors can be run with double the resolution, albeit at the expense of torque. Driving the print head or table with the micro-stepped motor gives the RepRap 3D printer a theoretical positioning accuracy of about 0.0118 mm.

The vertical axis is usually screw driven using M8 $\times$ 1.25 screws directly coupled to the stepper motor shaft. Assuming 16-step micro stepping, layer thickness can be controlled to 0.00039 mm accuracy. However, in most setups, the stepper motors used to control the vertical direction are switched off while each print layer is being deposited, which causes the stepper motor to revert to its 200 step per revolution positioning accuracy. This reduced precision results in an actual vertical positioning accuracy of an impressive 0.00625 mm. To avoid variation, layer thickness should be set as a multiple of a single step translation.

Of course, mechanical tolerances can have a large effect on the accuracy of the 3D printer. Since most 3D printer components are produced with unknown accuracy by other 3D printers, it is only possible to estimate the effective accuracy of a specific machine and only after extensive testing. Figure 2 shows an example RepRap 3D printer frame, illustrating how the 3D-printed plastic components are connected using M8 threaded rods. This arrangement makes it possible to compensate, to some extent, for the inaccuracies of the plastic machine components.

The gap between the 3D printer nozzle tip and table is quite small, so the table surface should be flat and level. To achieve a specific layer thickness, table flatness should be at least half of the desired layer height to avoid nozzle-to-table collision. In many designs, table positioning with respect to the nozzle can be adjusted using screws located at the corners of the table. In the design with vertical motion carried out by the printing head, adjustment of the nuts on vertical lead screws allows leveling the x-axis with respect to the table (see Fig. 3).

All stepper motors in the RepRap 3D printers use open-loop control. Therefore, the printer microcontroller needs to calibrate position for each motor at least once upon startup. This is accomplished by homing all the axes to their minimum or maximum positions, depending on hardware configuration. During the homing procedure, motors are driven at constant speed until mechanical or optical end-stops are reached. Homing speed, similarly to the end-stop locations, can be freely adjusted by the end user. Because of the open-loop control, acceleration and speed settings should be adjusted conservatively to avoid pushing the stepper motors and missing steps during operation.

[4] http://reprap.org/wiki/Delta

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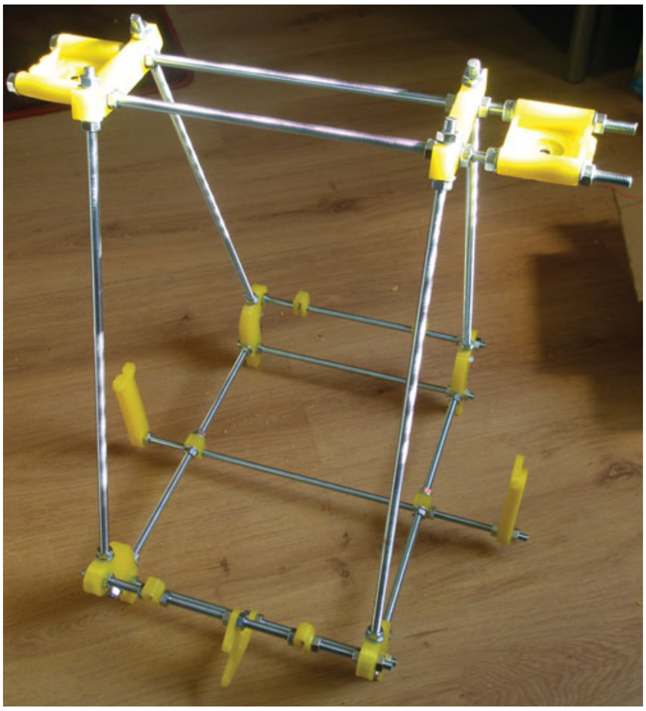

Fig. 2. Typical frame of a RepRap Prusa Mendel 3D printer (photo by authors).

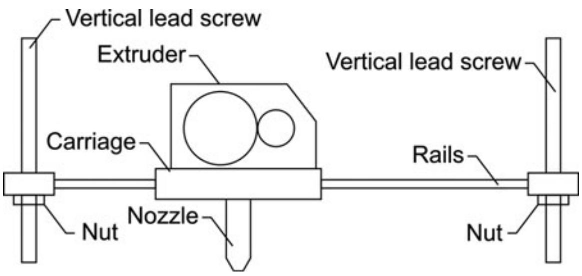

Fig. 3. Schematics of extruder's carriage with horizontal and vertical motion.

Functional Description and Design Challenges

The nozzle assembly of a RepRap 3D printer includes the parts responsible for safely melting and precisely applying the printed polymer.[4,7] It is part of the printer's extruder and critical to print quality. Typically, a polymer filament of around 3 mm diameter is forcibly fed into the hot dispensing nozzle of the assembly where it melts. The molten polymer exits the nozzle through a hole that is about 0.25–0.5 mm in diameter. In a good nozzle assembly, the temperature is held constant at about 200°C. The temperature varies depending on the type of polymer used, and it is typically in the range of 190–230° C. The nozzle tip must be shaped so it does not disturb what has been previously applied, but must still lay down each new polymer layer efficiently and precisely. If the nozzle tip is tilted with respect to the printed object, motion in different directions will produce different layer thicknesses and cross sections. To reduce sensitivity for the vertical alignment of the nozzle, the tip should be conically shaped, and the area of the tip should be minimized. The hot parts of the nozzle assembly must be thermally insulated from the mostly plastic components that make up the remainder of the extruder.

The main components of a RepRap nozzle assembly are the dispensing nozzle, a heater for the nozzle, a filament guide, and a mounting block. The nozzle in some designs is brass, because of its good machinability and relatively low (for metals) thermal conductivity.[8] With a simple thermal barrier, a brass nozzle can be made as a single piece. Some other designs use aluminum for the hot end and other materials such as stainless steel or Polyether ether ketone (PEEK) to set up the thermal

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isolation between the hot aluminum end and the cold end components of the print nozzle assembly. Many RepRap printers use PEEK as the mounting block material to thermally insulate the heated parts. Although PEEK offers good thermal endurance and low heat conductivity, PEEK mounting blocks often lose structural integrity and deform after long exposure to heat and the load caused by the extrusion forces.

Fine polymer filament is fed into the nozzle assembly with substantial force, so a filament guide is needed to prevent buckling. The preferred filament guide material is Polytetrafluoroethylene (PTFE), because it offers good high-temperature performance, and because its low-friction surface guides the filament smoothly with minimal resistance. PTFE begins to lose mechanical integrity as it nears 220°C, however, so care must be taken to keep it below that temperature. A small fan or radiator can be used to cool the PTFE filament guide to ensure mechanical stability as long as the heated nozzle parts are not affected.

Resistance heating of the nozzle is typical for RepRap 3D printers. The most common and least expensive resistance heater blocks use off-the-shelf resistors as their heating elements. Simple and effective, they are made by inserting resistors into holes drilled into the block material and securing them with silicone or sodium silicate as a sealant. However, the maximum operating temperature for these resistors is 235°C, which is close to the ideal operating temperature of the metal dispensing nozzle (≈190°C for Polylactic Acid and 230°C for Acrylonitrile Butadiene Styrene). Working so close to their maximum temperature can result in overheating or early failure. Another limitation is that the resistors most commonly used are rated for only 3 W of power dissipation. In the most common designs, they must withstand more than 24 W of power during the nozzle warm-up process.

Heating elements that can resist significantly higher temperatures can be made from Nichrome wire, which has a maximum operating temperature of about 900°C. The challenge in making heaters using Nichrome wire is to provide adequate galvanic isolation. When properly designed, however, the Nichrome wire heater offers a more reliable alternative to resistor-based heating elements. Solutions based on using the heating cartridges used in soldering irons are also becoming popular.

Even though, 3D printer nozzle function is relatively complex, the dimensional tolerances of the designs can be relatively loose and still provide good print accuracy. For instance, nozzle length variation can be compensated for by offsetting the vertical axis end-stop. The mounting block dimensions need only be precise enough to allow for screw connection to the x-axis carriage and provide sufficient room between the linear bearings. This means that oversized mounting holes can be hand drilled. The nozzle inner diameter must be 0% to 20% greater than the polymer filament diameter. Tighter tolerances will reduce molten polymer backflow and reduce the length of the heat-affected zone, which has a positive effect on molten polymer flow control. Looser tolerances can lead to poor filament feeding or even filament binding, buckling, and breakage. Nozzle external diameters have little effect on performance and increasing them even by one or two millimeters will not cause problems. Nozzle necking sections added as heat flow inhibiters might require tighter tolerances (within 10% of the wall thickness), because they must be of minimal diameter and still withstand the extrusion forces.

A very thin drill bit is used to fabricate the orifice in the nozzle tip; therefore, care must be taken to ensure roundness. Roundness within 10% of the orifice diameter is sufficient. As a rule of thumb, a lathe produces very good quality orifices, stationary drills give good quality, and hand drilling leads to poor results. Orifice positioning with respect to the center axis of the nozzle tip influences the shape of the extruded molten polymer. When the nozzle is exactly perpendicular with respect to the table, an offset orifice will have marginal effect. However, an inclined nozzle will produce different extrusion profiles depending on the nozzle travel direction as indicated in Fig. 4; where the nozzle orifice depicted is 0.5 mm in diameter, the tip diameter is 2 mm, and the layer thickness is 0.2 mm. A 2° nozzle incline will result in a 17.5% layer thickness change. Decreasing the diameter of the nozzle tip decreases the tolerance requirement for the vertical alignment of the nozzle.

Commercial 3D Printers

Mechanically, the RepRap 3D printers are similar to the commercial 3D printers offered, for instance, by Z-Corp or Stratasys. All are based on Cartesian robotics. Both Z-Corp and Stratasys use the same motion approach as the RepRap Darwin 3D printer (previous Fig. 1b). Linear motion and extrusion

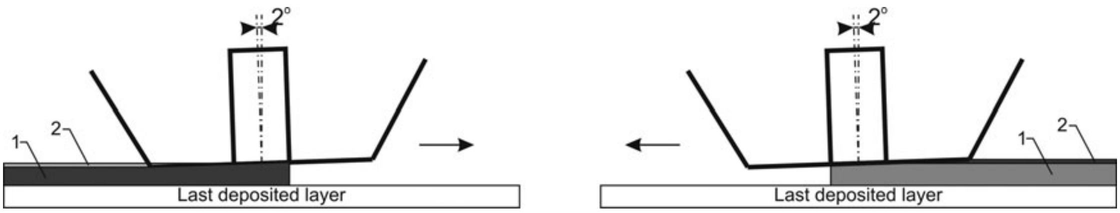

Fig. 4. Error in layer thickness produced by nozzle tilted of 2° depending on nozzle travel direction: 1—layer produced by correctly aligned nozzle, 2—layer produced by tilted nozzle.

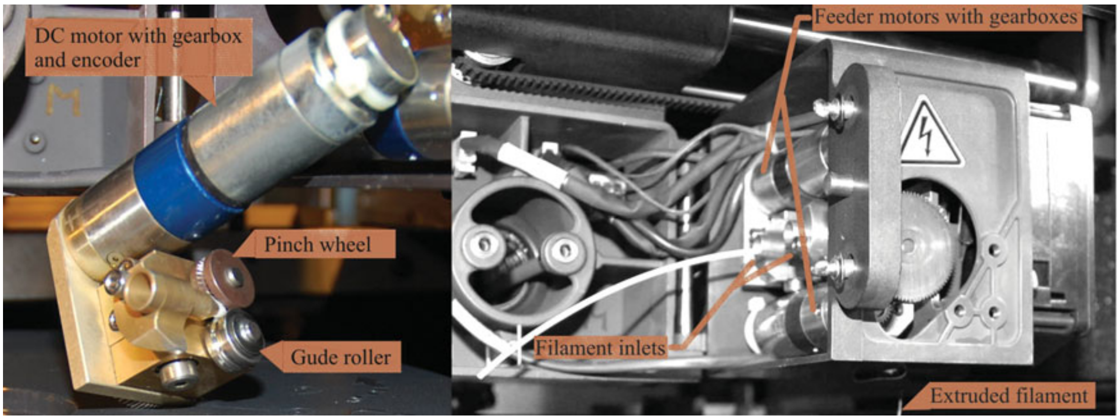

Fig. 5. Stratasys printing head disassembled (photo by authors).

is realized in commercial 3D printers using either stepper motors or DC motors with encoders. Apart from design sophistication, a closed heated printing chamber and filament extruder design are the most visible construction differences between commercial and hobby 3D printers. The closed heated chamber results in less deformation of the printed objects due to non-uniform thermal shrinkage of the deposited material. It also shields the printing process from external disturbances and contamination.

Printing nozzle designs differ considerably between different 3D printer models. For instance, the printing head in Stratasys 3D printers uses only one material for the liner, nozzle, and heating elements. Moreover, these three functions are fulfilled using just two components. The liner and heater are a single element, and the nozzle is a replaceable second element. The liner/heater is divided into two halves held together with screws. This simplifies the cleaning process. The feeding mechanism for the Stratasys 3D printer is, however, much more complex than in RepRap printers. The entire mechanism is metal. The RepRap extruder is made mainly out of plastic. In addition, the Stratasys printing head is a dual head unit that allows switching between a support material and the main polymer print material. Two DC geared motors with encoders are used to feed the main or support filament material to either of two distinct nozzles as indicated in Fig. 5. Like the RepRap extruder, the Stratasys extruder relies on friction between the feeding roller and filament to hold and feed the filament.

Review of Popular Designs

For today's RepRap 3D printer, there are approximately 40 different nozzle assembly designs. Details are available from the reprap.org website. Most of these designs are optimized to dispense polymer filaments such as Acrylonitrile Butadiene Styrene (ABS) or Polylactic Acid (PLA).[7] However, there are also designs that work with ceramic materials, various pastes, or polymer granules. In this paper, the focus will be on designs that are fed polymer filament to dispense molten polymer. The five most important designs, those commonly included with prepackaged RepRap printer model kits, and typical DIY approaches are considered.

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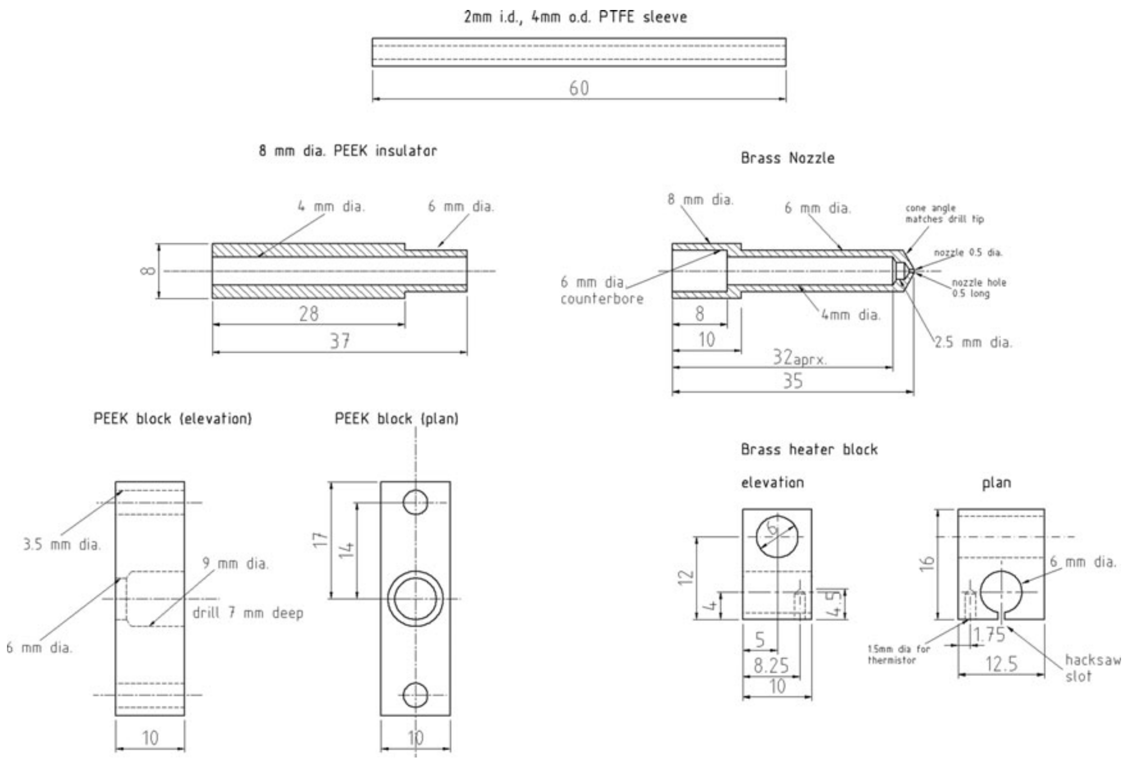

Fig. 6. Part drawings of the Universal Mini Extruder nozzle assembly. Source: http://www.reprap.org/wiki/File:Mini-extruder-hot-end-drawings.png, author: Adrian Bowyer.

Design 1 – The Universal Mini Extruder

The nozzle assembly of the Universal Mini Extruder[5] uses a brass nozzle with a brass heater block tightly fitted near its outlet end. The mounting block is PEEK. There is a filament guide made of two parts: an outer insulating PEEK housing, which screws into the brass nozzle, and an inner PTFE sleeve for low-friction filament feeding. Part drawings for the nozzle assembly of the Universal Mini Extruder are shown in Fig. 6.

This was the only evaluated design the authors have not tested experimentally. The PTFE sleeve is fitted loosely into the nozzle to provide a smooth non-stick surface for filament guidance. The nozzle design does not include a mechanical lock to keep the PTFE tube in place. However, this particular nozzle is part of the whole printing unit, and the extruder body keeps the PTFE sleeve from retracting together with the filament. The PEEK insulator and brass nozzle are connected by sliding one into the other. Following final assembly into extruder, the insulator block is compressed against brass nozzle.

Design 2 – Longboat Prusa Nozzle

The nozzle assembly used in the RepRap Longboat Prusa[6] extruder is probably the most common nozzle assembly design. It consists of a brass nozzle and heating block, a PTFE filament guide, and a PEEK mounting block. See Fig. 7. All components screw together. The heater block is simple to manufacture by cutting a piece of brass plate, then drilling nozzle, resistor, and thermistor holes, and finally, tapping the thread for the nozzle. The nozzle and PTFE liner must be turned on a lathe. The PEEK mounting block can be cut from a bar of material, and then all the holes can be drilled. The only parts that need to be done precisely are the nozzle and the thread on the PTFE liner. The outer diameter of the brass nozzle is M6 threaded, and inner thread for the filament guide is threaded to M7. Screwing the filament guide and brass nozzle together should form a primary seal on the screw interface, and a secondary seal on the flat interface surface between the liner and the nozzle collar. Extrusion force is transmitted through the flange at the top of the nozzle to the mounting block. The

[5] http://www.reprap.org/wiki/RepRap_Universal_Mini_Extruder, author: Adrian Bowyer
[6] http://www.reprap.org/wiki/LongboatPrusa, author: James Walsh

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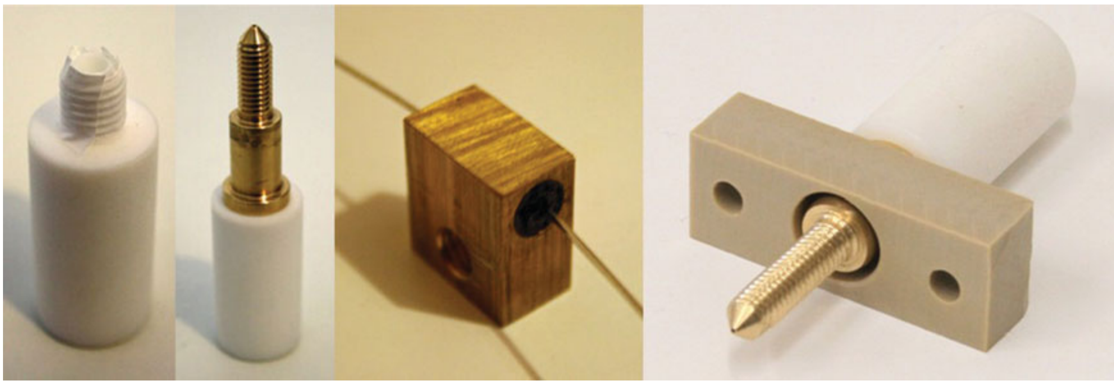

Fig. 7. Photos of nozzle assembly parts for Longboat Prusa extruder. Source: http://www.reprap.org/wiki/LongboatPrusa, author: James Walsh.

external threads of the brass nozzle are long enough to allow for some up and down adjustment of the heater block. A clear benefit of this design is the relative simplicity of the parts, making them easy to fabricate. Longboat Prusa nozzle parts are also widely available for purchase. The mounting block is made out of PEEK, and its design is almost identical to the one in the universal mini extruder.

Testing of this nozzle design revealed several problems. First, the seal between the nozzle and the PTFE liner did not remain tight, allowing the molten polymer to begin leaking in as little as a few hours of operation. Wrapping the filament guide threads with PTFE sealing tape did little to improve the situation, and the nozzle assembly never operated leak-free for more than a few days. Secondly, the pressure from the brass nozzle flange eventually deformed the supporting contact surface of the PEEK mounting block, shearing off the PTFE threads of the filament guide. Finally, over time, the heat of the nozzle deformed the entire mounting block resulting in the misalignment of the dispensing nozzle. Therefore, the viscoelastic behavior of the PEEK mounting block under combined thermal and structural loading results in deformations over time that exceed RepRap 3D printer polymer layer thicknesses.[17] Testing carried out by the authors revealed downwards PEEK mounting block deformation of 1 mm in only a few hours of printer operation. This is five to ten times larger than the printer's extruded layer thickness.

Design 3 – The J Head Nozzle

The J Head nozzle design[7] combines the heater block and the dispensing nozzle into a single component. Heating power is provided by an inserted single power resistor or a heater cartridge. See Fig. 8. The design also combines the filament guide and mounting block. Prior to this publication, the J Head nozzle has gone through five stages of development. Currently, the heated nozzle is aluminum, either 2024 or 7075. The nozzle screws into the PEEK mounting block and filament guide. According to the designer, leakage may occur at the interface between the metal and the PEEK. This was also confirmed by research on RepRap forums. PTFE sealing tape may be wrapped around the mating threads to reestablish the seal. This design is lightweight, compact, and comprises only two parts that must be machined.

Design 4 – Arcol.hu nozzle v.4.1.1

This design is based on aluminum and stainless steel parts. The heater construction is similar to other RepRap designs with a hole for a heating resistor and a smaller hole for a thermistor. The most interesting part of this design is the stainless steel barrel used as heat separator between the hot end and cold end parts. The wall thickness of the stainless steel separator is only 0.07 mm, making it relatively difficult to manufacture. A large radiator at the top of the nozzle efficiently removes heat so the cold components remain at a safe-to-touch temperature during operation. Inside the radiator, there is an 11 mm long PTFE guide sleeve. The PTFE sleeve is secured from one side by the top

[7] http://www.reprap.org/wiki/J_Head_Nozzle, author: Brian Reifsnyder

Fig. 8. J Head nozzle, PEEK filament guide (black), and aluminum heater block with resistors. Source: http://www.reprap.org/wiki/J_Head_Nozzle, author: Brian Reifsnyder.

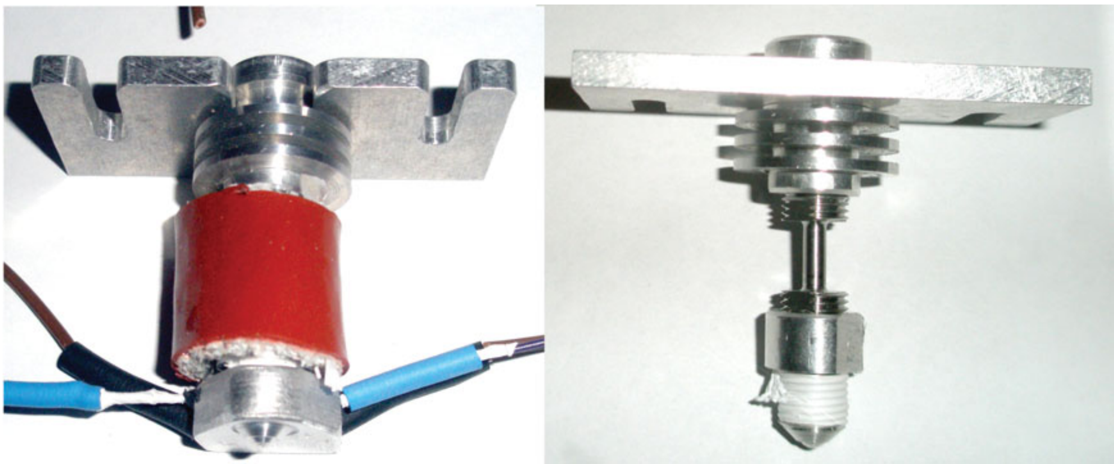

Fig. 9. Arcol.hu nozzle; fully assembled on the left, without the heater and insulator on the right (photo by authors).

surface of the stainless steel barrel and from the other by a brass set screw. Sealing of the nozzle relies on tight contact between flat metal surfaces. One of the weaknesses of this design is the low bending resistance of the thermal barrier. The author of the design mentioned that occasionally it can fracture if the nozzle hits the table or printed object. The nozzle has a 0.5 mm orifice. The Arcol.hu nozzle is shown in Fig. 9. The heater part is easy to manufacture. The nozzle component is also of a relatively simple construction, but requires a lathe for production. The radiator part is yet another component that must be manufactured on a lathe. Most challenging might be the fabrication of the stainless steel thermal barrier. An internal hole must be drilled first, and then the external diameter must be machined and threaded. Only as the final operation is the neck section machined.

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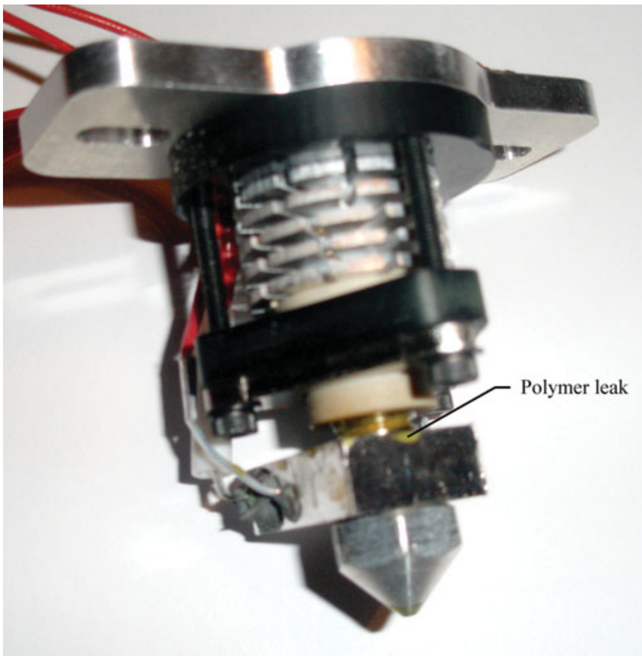

Fig. 10. RepRap 2.0 printing nozzle, polymer leak on the PEEK-Aluminum interface after 3 hours of operation (photo by authors).

Design 5 – Farynozzle 2.0/ LulzBot/Budaschnozzle/RepRap hot end 2.0

This design appears under several names. And there are small differences between versions; mostly in terms of radiator design and material for the supports. This design relies on PEEK as an insulator between the hot and cold ends of the nozzle unit. Heater block, nozzle, and barrel are made of aluminum. The liner element is PTFE. However, the PTFE liner in this design is attached by compressive force created between two wooden supports. To keep the PTFE liner cool, aluminum radiator fins are stacked on its outer diameter surface. In the evaluated design, the holder element was aluminum. The supports were phenolic plastic. The PEEK element is threaded to connect with the barrel. On the other end of the PEEK insulator, there is a support flange. The nozzle is available assembled and in DIY kits. We purchased the assembled version.

Before first use, all connections between components were inspected. The heating resistor had 0.1 mm clearance with respect to the heater block hole. This gap was filled with sodium silicate to improve thermal contact. The PEEK-to-aluminum connection was also checked, and it seemed tight. However, after an initial extrusion test of the nozzle with PLA filament, a leak on the PEEK-aluminum interface was detected (see Fig. 10). The nozzle comprises a relatively large number of components; however, all the components are relatively simple to manufacture. The threaded part of the connector can be made from an aluminum screw or threaded rod by trimming it to size and drilling a hole. All the support shelves are simple elements, which can be laser cut or cut using mechanical means. The PEEK element and nozzle end must be machined on a lathe. Also, sides must be machined into the nozzle to form a grip for a wrench. Each radiator fin is a separate sheet metal product, which can be mechanically cut.

DIY designs

Most other nozzle assembly designs are DIY approaches that rely on readily available materials and parts, such as gas nozzles, glass tubes, screws, etc. The main advantages to these designs are their low cost and that they are easy to fabricate using simple tools. Their biggest disadvantage, in general, is a lack of refinement. They have not benefited from the constant incremental design improvements made available through community collaboration. Furthermore, the basic tools used to fabricate the DIY nozzle assemblies can often lead to a loss of precision that adversely affects printing performance. Resistors are the most common source of heating power for the DIY designs. Occasionally, Nichrome

Fig. 11. PTFE liner failure. Source: http://forums.reprap.org/read.php?1,124652,124784, photo by Pierre le Vrai.

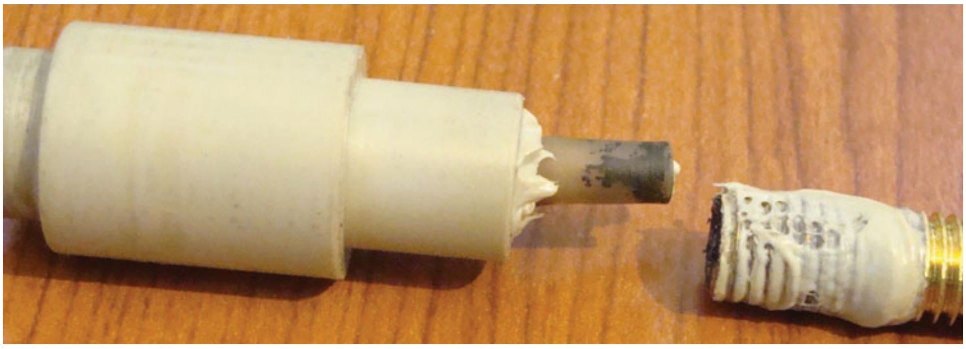

Fig. 12. PEEK liner to mounting block of J-Head nozzle failure. Source: http://reprapforum.pl/component/kunena/47-ekstruder-wytlaczarka-plastiku/423-peek-vs-teflon-ciekawy-przypadek.html, photo by Unique Design.

wire is used. The number and wide variety of DIY designs makes evaluation difficult, and little is known about the performance of such designs.

The Proposed Nozzle Assembly Design

Based on RepRap community commentary and our own 3D printing experiences, the major problem with current nozzle assembly designs seems to be reliability. While the nozzle assemblies are affordable and relatively easy to build, they must be serviced or rebuilt at frequent and unpredictable intervals. Catastrophic failures of the designs are also common.

Common problems

One of the common failure modes is polymer leakage at the interface between the metal nozzle and the PTFE filament guide. This can result from structural failure at their connection, which opens up a leak path, or from the failure of the seal itself. Polymer leakage not only makes a mess, but it also affects the flow of polymer through the nozzle tip adversely affecting print quality. The second common failure mechanism is structural failure of the PEEK mounting block at temperature, which results in movement of the dispensing nozzle tip. If this movement occurs while printing, the part being printed will most likely be ruined. For small tip displacements, the polymer deposition track will shift. For larger displacements, the nozzle can even crash into previously dispensed and hardened polymer tracks. Figures 11 and 12 show typical nozzle components failures.

Problems with nozzle heating circuitry can be a third possible source of failure. Common 3 W resistors used as the heat source are overdriven up to 24 W, which results in their short lifetime. A strong extruder is important to print speed and accurate and consistent polymer flow through the nozzle tip. However, if heating power is lost while printing, and polymer solidifies in the nozzle, the

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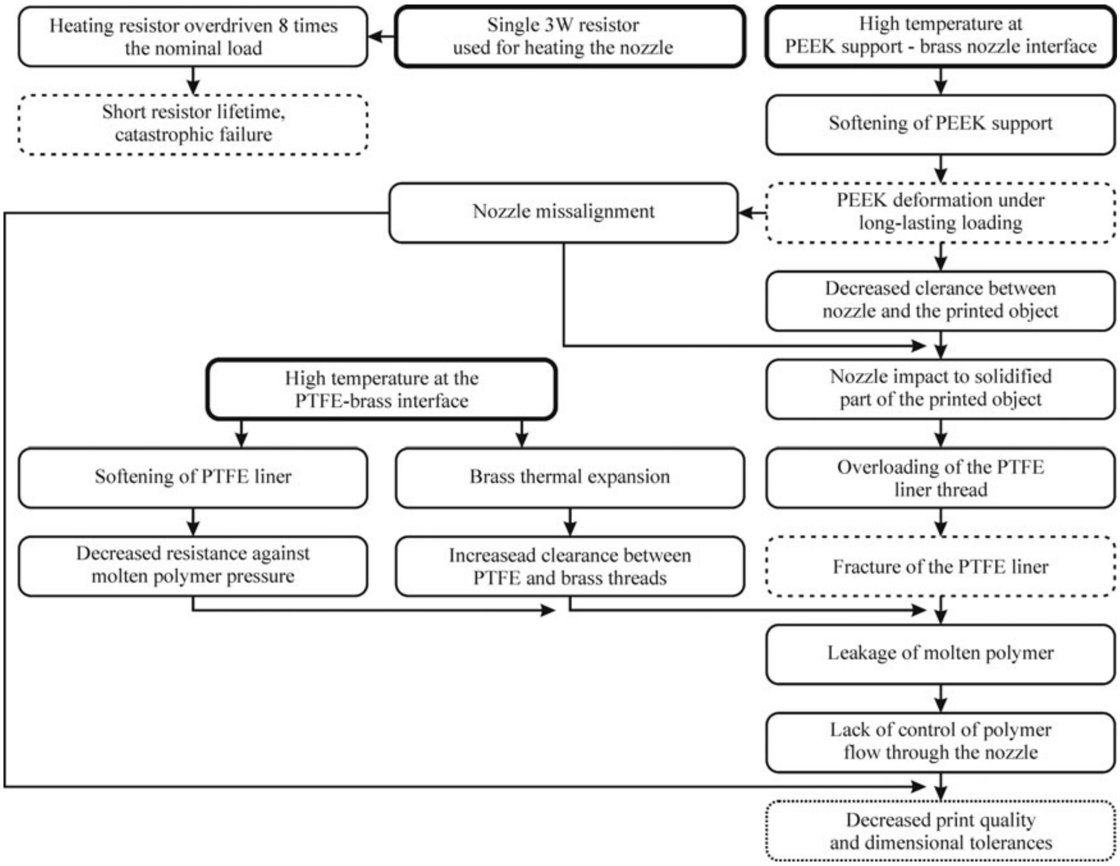

Fig. 13. Failure mechanisms of the printing head.

filament feeding force of the extruder pushing against the immovable polymer can damage the nozzle assembly. The common failure mechanisms are presented in Fig. 13.

PEEK mounting block failure analysis

While the genesis of the leakage problem is simple, the PEEK mounting block failure mechanism is rather complex. First, high-performance polymers can be subdivided into families based the type of bonding between the aromatic rings.[10] Secondly, based on their mechanical and thermal properties and their performance in various technical applications, polymers can be roughly divided into four main groups: commodity polymers, mid-range polymers, high-performance polymers, and ultra-polymers. Within each of these groups, the available polymers are further classified into semi-crystalline and amorphous types.

Selecting the material for the nozzle-mounting block of a 3D printer focuses on two important questions. What are the thermal requirements of the application? And, how is structural integrity affected by the simultaneous application of mechanical and thermal loading? The selected nozzle-mounting block material must combine high thermal durability with mechanical strength, which for polymers depends on viscoelastic behavior. Another important consideration is how the material insulates or conducts heat. Therefore, the comparison of different polymer options begins by analyzing the relevant thermal data; clarifying numerical values for melting point, glass transition temperature, heat deflection temperature, continuous use temperature (mechanical with possible impacts), creep strength, thermal conductivity, and coefficient of thermal expansion.

To analyze polymer component life as a function of mechanical loading, polymer compressive strength and the frequency load pulsation must be known. If load pulsation frequency is greater than 10 Hz, the fatigue strength of a polymer material can decrease significantly. The prediction of fatigue strength for an arbitrary load frequency, temperature, and stress ratio for polymer composites, including PEEK-based materials, has been discussed in a previous publication.[11]

Table I. Average values for the most critical material properties of different PEEK grades.

Material property	Unfilled PEEK	Glass-fiber reinforced PEEK	Carbon-fiber reinforced PEEK	Graphite and PTFE alloyed PEEK
Tensile strength (MPa)	110[b]	190/ 69/ 42[c]	262/ 96/ 62[c]	141 /58 / 34[c]
Tensile modulus (GPa)	3.7	12	26	14
Compressive strength at 200°C (MPa)	N/A	55	69	N/A
Melting point (°C)	343	343	343	343
Glass transition temperature (°C)	143	143	143[d]	143
Heat deflection temperature (°C)	156	335	342	315
Thermal conductivity (W/mK)	0.29	0.30	0.95	0.87
Continuous use temperature (°C)[a]	82	104	93	82

[a]Mechanical with impacts.
[b]Yield strength at room temperature.
[c]Break strength at room temperature/ at 275°C/ at 275°C.
[d]Can be elevated up to 162°C with special treatments.

Based on the literature, available ultra-polymers that might be appropriate nozzle-mounting block materials include the polyaryletherketone (PAEK) family of plastics,[9,12] which include polyetherketoneketone (PEKK) and polyetheretherketone (PEEK), and perfluorosulfinic acid (PFSA).[13] Each of these polymers offers excellent or at least good thermal properties, but typically, PAEK is used where good chemical stability is also a requirement. PFSA is the choice when an unusually low friction material is needed. PEKK and PEEK are both suitable. Since it offers more commercially available grades, PEEK was selected for evaluation in this study. The commercially available PEEK grades can be classified into four main groups: unfilled PEEK, glass-filled PEEK, carbon-filled PEEK, and carbon fiber reinforced PEEK with graphite and polytetrafluoroethylene (PTFE) lubricants.

The glass or carbon fiber content in filled PEEK can vary, but ∼30% is typical. The addition of glass fibers reduces the rate of thermal expansion and creep and increases flexural modulus. Therefore, glass-filled grades are ideal for applications where more strength at temperature is needed. Carbon-filled PEEK offers higher compressive strength and better thermal conductivity (more than 3 times higher) than unreinforced PEEK grades. Adding PTFE and graphite lubricants lowers the coefficient of friction.

The average values of the most critical material properties for different PEEK grades are presented in Table I. The values are based on material tests carried out according to existing ISO-standards. Within each PEEK grade, there are several subgrades available for tuning specific mechanical or thermal properties according to the requirements of the application. The information in the table suggests that unfilled PEEK does not have sufficient compressive strength near the hot nozzle to support it reliably over time in the face of the elevated temperature, load pulsation, and continuous and compressive loading of an operating 3D printer. To solve this problem, a more appropriate filled-PEEK grade could be selected, better ways to transfer heat away from the critical area could be designed, limits could be imposed on load pulsation frequency, or thermal load could be reduced by shortening nozzle heating intervals.

The loading cycle seen by the mounting block for the 3D printer nozzle varies with the type of part being printed and the print speed settings. For a common 65 mm/s printing speed, the loading pulsation frequency is around 0.6 Hz for a part with a moderate level of detail. More part detail will lead to a higher pulsation frequency; however, the upper limit is directly related to the maximum achievable acceleration of the printing nozzle. Therefore, loading pulsation frequencies of more than a few cycles per second are not possible.

Failure may also occur at PEEK-to-metal interfaces because of abrasion. Based on laboratory tests of reciprocating sliding wear and abrasion, unfilled PEEK exhibits low scuffing resistance and high rate of wear, indicating that it could be susceptible to abrasion-induced failure.[14] Carbon-fiber reinforced PEEK, on the other hand, offers low scuffing resistance but higher sliding and micro abrasive wear resistance. Furthermore, the presence of the carbon fibers seems to enhance abrasion protection by minimizing plastic deformation. The addition of PTFE and graphite to carbon-fiber-reinforced PEEK results in a sharp decrease in the friction coefficient and an increase in scuffing and

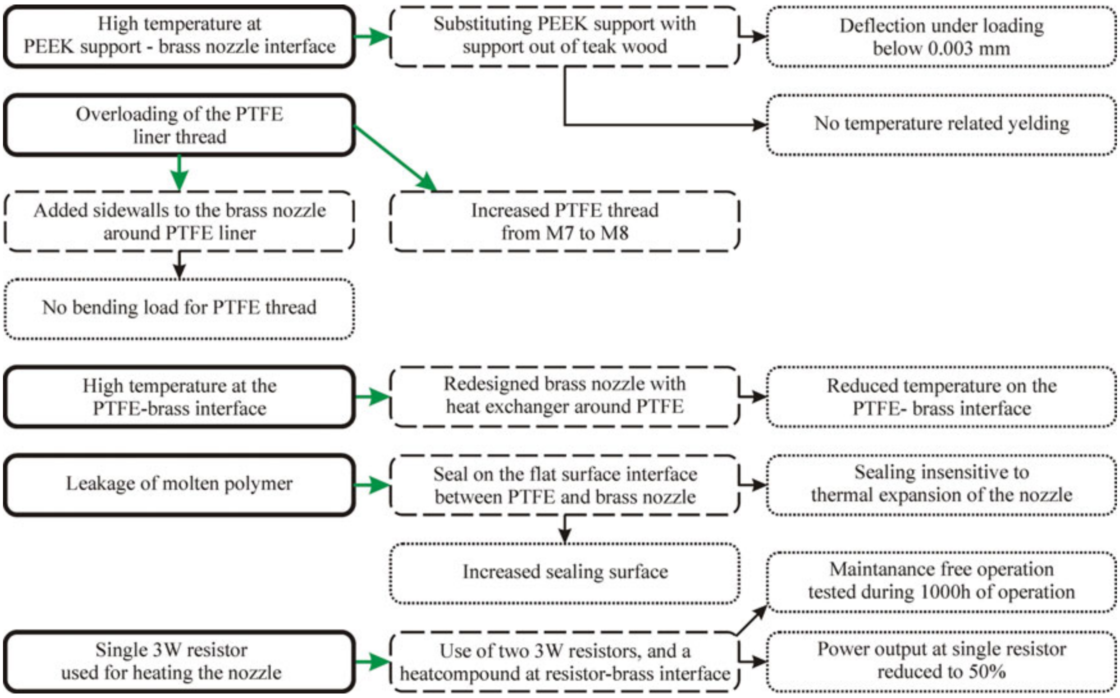

Fig. 14. Problems, solutions and achieved improvements.

abrasion resistance. The reciprocating sliding wear and abrasion tests reveal an almost non-measurable wear rate.[14]

Other novel material options could be considered for the mounting block of the 3D polymer extrusion printer. For example, the advanced properties of modern nanomaterials could offer a solution. One possibility would be to tune the thermal conductivity and mechanical properties of PEEK by embedding single-walled carbon nanotubes (SWCNT).[15]

Proposed solutions

The authors have addressed the first three of the common design failure modes: sealing failure leading to polymer leakage, loss of structural integrity of the PEEK mounting block, and the resistor based heating circuitry. The summary of problems and solutions is presented in Fig. 14.

Three design aspects of the Longboat Prusa nozzle assembly contribute to the unreliability of the seal between the PTFE filament guide and the brass nozzle. First, although interference is designed into the threaded connection, there is still, typically, some clearance between the mating threads. This clearance changes with temperature due to the differential heat expansion of the brass and PTFE materials. Secondly, the threaded connection is not only a seal. It must also serve as a structural connection subject to substantial stresses, which can result in the deformation or tearing of the PTFE material. Finally, the PTFE loses strength with increasing temperature, making it even less resistant to applied structural stresses and the pressures being exerted by the molten polymer as it is being extruded.

The clearance between mating threads can be minimized or eliminated by winding a couple layers of PTFE tape around the outer thread before joining the two parts. However, this can make it more difficult to screw the two parts together, and because the threaded PTFE neck of the filament guide is fragile, the neck can be damaged or twisted off during assembly. Furthermore, as a structural connection, the threaded joint must support the tensile forces produced by the pressurized molten polymer and any incidental transverse forces that might be incurred while printing. Because of its fragility, these forces can result in failure of the PTFE.

Adding supporting sidewalls to the brass nozzle keeps it from bending and torqueing the threaded neck of the PTFE filament guide, which should prevent structural failure (see Fig. 15). Increasing the threaded diameter of the PTFE neck should also provide a strength benefit. Finally, moving the

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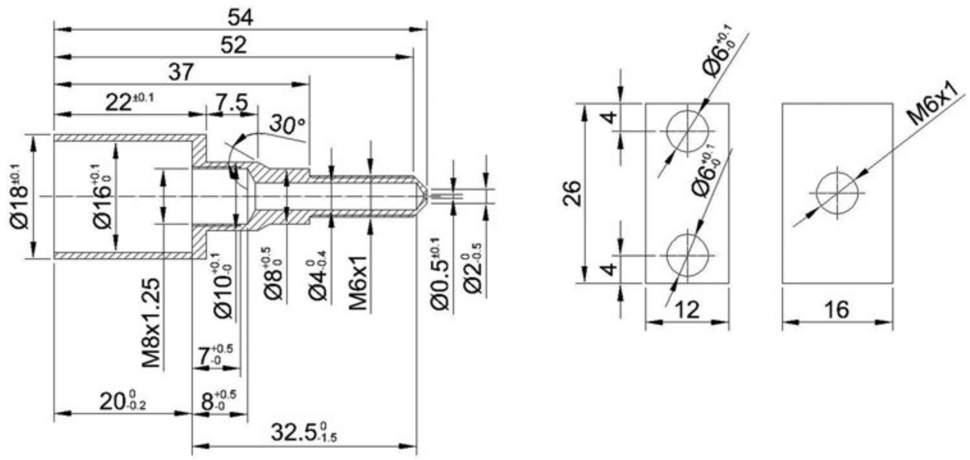

Fig. 15. Brass nozzle and heater block for proposed nozzle assembly design.

sealing function away from the threaded interface and providing a more traditional sealing feature should increase the reliability of the seal.

With the addition of supporting sidewalls, the flange diameter of the brass nozzle increases. The larger diameter provides an appropriate flat surface that can be sealed with a suitable gasket. Gore® TR is expanded PTFE and resistant up to 270°C. It is soft, easy to cut, and makes an excellent sealing gasket. Rather than using an M7 threaded joint with PTFE tape as a seal, the threaded connection between the PTFE neck and the brass nozzle can be increased in size and become the more commonly used M8 threaded connection.

Testing has revealed that the most commonly used extruder (Wade's Geared Extruder) is capable of transmitting nearly 150 N of force into a cold nozzle assembly. For the standard Longboat Prusa nozzle assembly, the contact surface area between the nozzle flange and the PEEK mounting block is around 35 mm^2. A force of 150 N acting on that contact surface area results in a pressure of 4.3 MPa. The highest nozzle temperatures reached while printing are between 200 and 230°C, more than 60°C above the glass transition temperature of PEEK (≈143°C). At this elevated temperature, PEEK exhibits viscoplastic behavior.

The increased flange diameter of the brass nozzle that comes with added sidewalls also reduces surface pressure acting on the mounting block. With an outer diameter of 18 mm and a 10 mm neck diameter (to accommodate the larger M8 internal threads), the contact surface area between the nozzle and mounting block increases by 500% to 176 mm^2. This reduces contact surface pressure from 4.3 MPa to 0.9 MPa. For better thermal endurance, Teak wood can be used instead of PEEK as the mounting block material. Teak does not deform plastically with increasing temperature. In addition it does not lose structural integrity at elevated temperatures as polymers do.

These ideas have been incorporated into the authors' proposed new nozzle assembly design. Figures 15 and 16 are part drawings for the new design. Figure 15 shows the brass nozzle with the new supporting walls (inner diameter Ø16 and outer diameter Ø18) and the increased thread size (M8) for the PTFE to brass connection. The heater block shown is expanded in comparison to the original design. Figure 16 shows the PTFE filament guide with a more robust neck and the new gasket seal. The drawing of the new Teak mounting block is on the right. All free dimensions should be fabricated within +1 mm tolerance. The proposed new nozzle assembly drawing, Fig. 17, illustrates how the components work together to mitigate both sealing problems and the structural deficiencies of existing nozzle assembly designs. This figure also presents assemblies of other reviewed designs. Figure 18 presents the picture of the new nozzle assembly (excluding the support block) and separate machined parts.

An indirect result of the design changes is that the new sidewalls of the brass nozzle will convect heat, which should help to reduce PTFE temperature. Adding a small fan to the 3D printer aimed at the upper parts of the nozzle assembly will magnify this effect. However, the heating resistors will need to provide more power to compensate for the heat power lost through convection.

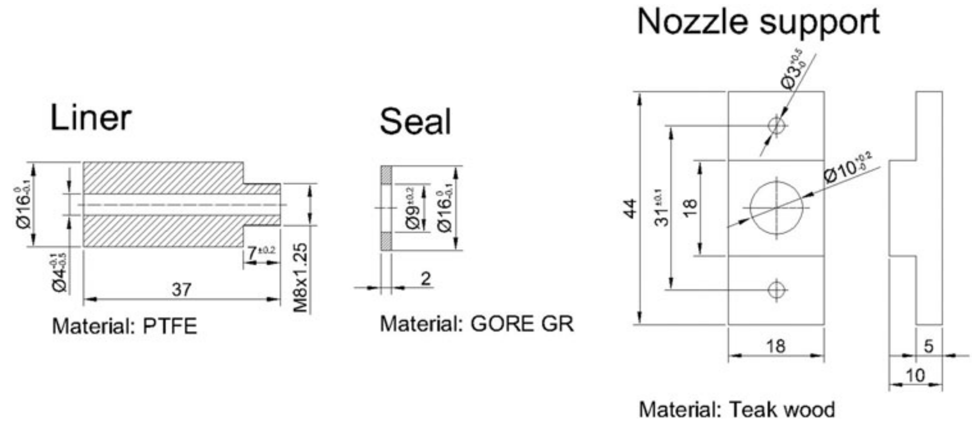

Fig. 16. Liner, seal, and nozzle mounting block for proposed nozzle assembly design.

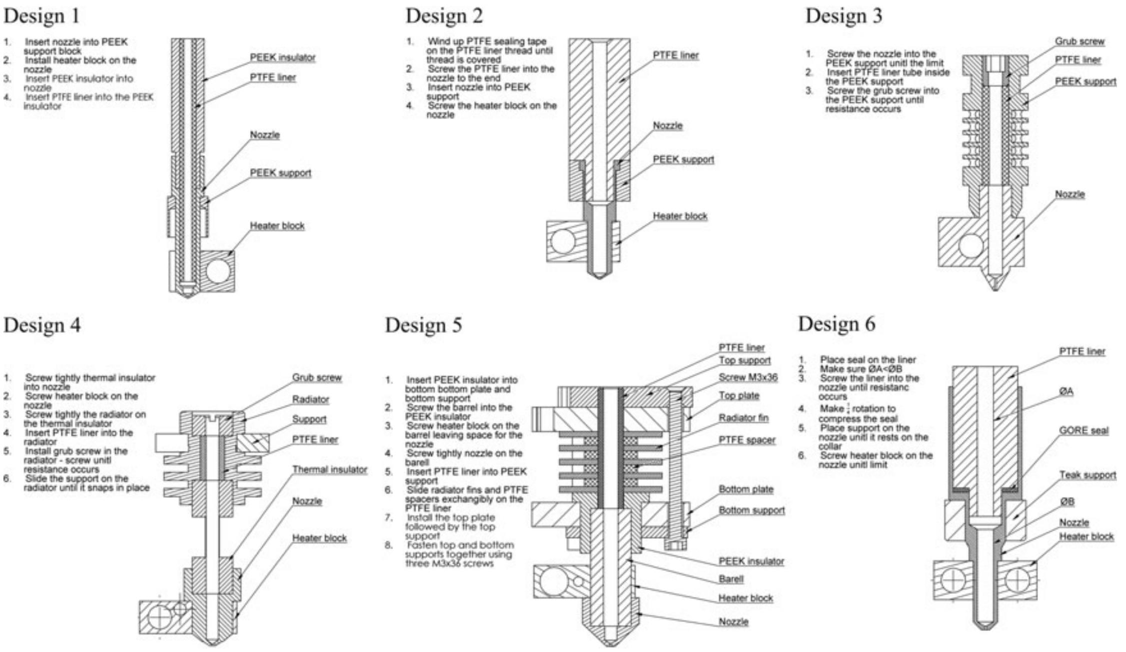

Fig. 17. Assembly of the tested nozzle designs.

The mounting block was made from Teak, as this particular wood is easily obtainable from many hardware shops; if not as raw material, then as inexpensive board-like products, which can be transformed into the mounting block using simple tools. Another benefit of the material is that it does not split or chip when being drilled. Teak is a hard material that retains mechanical stiffness over a wide range of temperatures up to the point where it burns. The auto-ignition temperature for large specimens is in the range of 254–530°C.[16] As tested by the authors, heating up the nozzle to 250°C and keeping the temperature steady for an hour did not cause the Teak to ignite or burn; therefore, it is assumed to be a safe choice.

The use of two 3 W 12 Ω resistors instead of one 6 Ω resistor was dictated by practical space limitations; and because the nozzle acts as a large heat exchanger, the resistors can be overdriven to some extent. Heat sink compound (thermal grease) between the resistors and the heater block increases thermal conductivity. To retain the resistors, high temperature silicone is applied at the openings of the resistor cavities. Reducing the power dissipated by a single resistor to 50% prolongs life. In over 1,000 hours of printing, including constant operation for a one-week period at temperatures above 190°C, the resistors functioned without fault or failure.

The liner element is similar to the one in the Longboat Prusa design, and it can be manufactured on a lathe in one setup. First, the external profile needs to be turned, and the smaller end must be

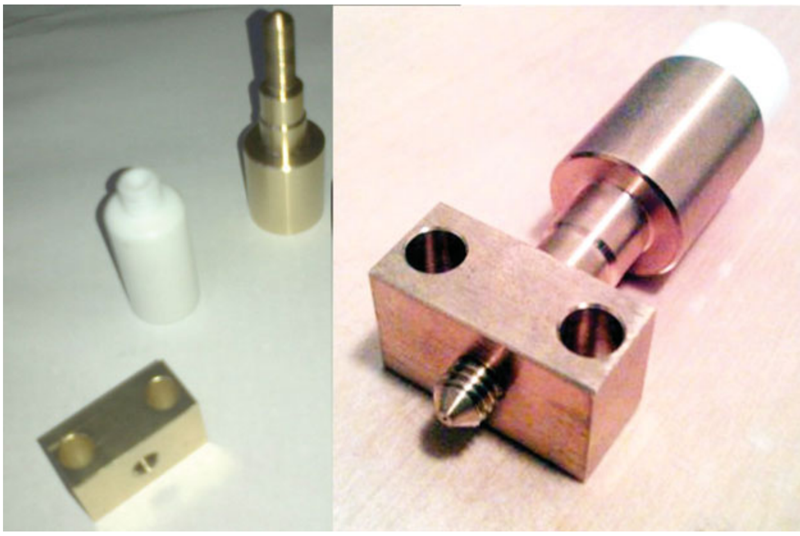

Fig. 18. New nozzle design, machined parts are shown on the left, and assembled unit is shown on the right (photo by authors).

threaded. Then, the hole inside is drilled. Finally, the element must be cut to size. The seal is cut from a larger sheet using a punch. The heater and mounting block are cut from a larger block of material, and then a drill finishes the parts. The heater block also requires tapping the thread for the nozzle. Nozzle fabrication must be done on a lathe. It is made from a bar of brass. The fabrication requires two clamping operations: one when producing the internal profile and one when the material is cut to the final nozzle length.

The large bore is milled to produce a flat sealing surface. Then, a support tool must be built with a shape that resembles the inside of the nozzle, including the M8 thread. This support is screwed into the nozzle, and the object is clamped using the support tool. Finally, the external profile of the nozzle can be turned, the M6 thread cut, and the orifice hole drilled. This newly proposed design was fabricated using a standard large size lathe without any numerical control; therefore, it should not be a problem to reproduce the components in other workshops.

Thermal and structural analysis was carried out for this proposed nozzle assembly design. The results of the simulation are presented later in the thermal analysis section.

Print quality

The proposed new nozzle assembly was tested by printing a number of objects on a Longboat Prusa RepRap 3D printer, which operates under control of Sanguinololu control board with Sprinter[8] firmware. Repetier-Host V0.90C[9] was used as printing control software. Slicing of the models was done using Skeinforge[10], for complex objects, and Slic3r[11], for simple geometries. Print quality was good with little need for post-printing cleanup. Figure 18 shows a printed herringbone gear as taken from the printer. The gear meshed well with a second one, allowing for rather smooth torque transmission. Some post-print cleanup was needed of the octopus shown by Fig. 19: the body of the octopus is an overhanging feature. Finally, the electrical connector-shielding box was printed as a test case for bridging gaps and large-scale object printing. See Fig. 20. The box is 80 mm in diameter and 40 mm tall. It was printed in the orientation shown on the left hand side of Fig. 20. All items produced as part of this study were printed using PLA thermoplastic. No support material was used for any of the 3D printing.

Printed part surface quality is directly related to filament dimensional stability and the accuracy of the filament feeding mechanism. Those parts performed well during testing, and no artifacts

[8] http://reprap.org/wiki/Sprinter
[9] http://www.repetier.com
[10] http://fabmetheus.crsndoo.com/wiki/index.php/Skeinforge
[11] http://slic3r.org/

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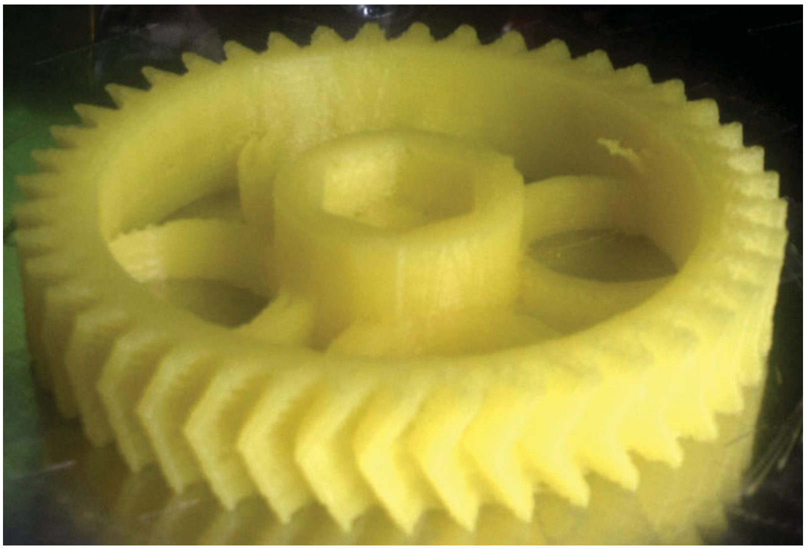

Fig. 19. Herring-bone gear printed with the proposed nozzle assembly (as printed) (photo by authors).

Fig. 20. Octopus printed with the proposed nozzle assembly (photo by authors).

related to their performance were observed. Infill of the narrow spaces on the walls of the electrical connector-shielding box from Fig. 20 did not cause any difficulties. The polygonal approximation of its circular shape is a software artifact related to triangular mesh size. The pattern does not depend on the orientation of the part on the printer.

Thermal Analysis

A steady state thermal analysis representing extrusion of PLA and ABS has been carried out for each of the evaluated nozzle designs: 1) the Universal Mini Extruder, 2) the Longboat Prusa, 3) the J Head, 4) the Arcol.hu v.4.1.1, 5) the RepRap 2.0, and 6) the introduced Longboat Prusa improvement. For the PLA polymer, the assumed extrusion temperature at the nozzle tip was 190°C. The ABS nozzle tip temperature was 230°C. Nozzle assembly temperatures peak at rest, because the molten polymer inside the nozzle is essentially at its maximum steady state temperature. Therefore, the FEA thermal

Table II. Material properties used in the simulations.

Parameter	Brass	Teak	PTFE	PEEK	Aluminum	Phenolic plastic
Young's modulus [GPa]	100	13	0.5	3.9@20° C 0.2@200°C	69	2.41
Poisson's ratio	0.33	0.3	0.46	0.4	0.33	0.39
Thermal conductivity [W/(m·K)]	110	0.25	0.25	0.24	200	0.26
Specific heat [J/(kg·K)]	390	2400	1200	1850	900	1900

Table III. Experimental steady-state results based on the chosen duty cycle and heater resistances.

Design	1	2	3	4	5	6
Duty cycle	Not tested	24%	12%	24%	24%	24%
Steady state temperature		122°C	148°C	183°C	160°C	152°C
Heater resistance		11.0 Ω	5.2 Ω	6.2 Ω	6.8 Ω	5.6 Ω

analysis modeled the hot nozzle at rest to understand its temperature distribution, especially near the PTFE or PEEK filament guide and the metal nozzle interfaces. The model results were verified by comparing the calculated temperatures to a number of measured temperatures using an infrared thermometer.

The internal surfaces of the nozzle assemblies were assumed adiabatic, because heat flow is negligible between the nozzle and molten polymer, which is at essentially the same temperature. Heat power was input through the surfaces of the power resistor holes in the heater block. The material properties used in the simulations are shown by Table II.

The geometry for each of the presented designs was modeled with SolidWorks 2013 SP4.0 3D CAD software. Heat power was left as an independent variable and adjusted until the temperature at the tip of the nozzle model reached the desired criterion within 0.1°C accuracy. Convection coefficient for the nozzle assembly was determined using a combined experimental and thermal analysis method.

Each test nozzle was connected to a Sanguinololu RepRap controller board and placed on a support. The Sprinter controller firmware was modified to operate the nozzle at 24% duty cycle using Pulse Width Modulation (PWM).[18] The target temperature in the host software (Repetier-Host V0.90C) for the nozzle was set up to be 220°C. The duty cycle was chosen so the nozzle would settle into steady state well before reaching the target temperature excluding any control algorithm influence on the results. Steady state was achieved when the nozzle temperature sensor settled for five minutes with oscillation less than 1°C. The steady-state temperature and calculated power then were used along with the thermal analysis to determine the convection coefficient required to reach the temperature measured in the experiment.

All the evaluated designs, except the first, were tested experimentally. The first nozzle was not available to the authors. The steady-state test results are presented in Table III. The duty cycle had to be reduced for the J-Head nozzle, because of its highly efficient ceramic heater element. The finest mesh setting was used for the thermal analysis resulting in a maximum element size of 1.05 mm.

The voltage provided by the power supply was measured prior to adjusting the duty cycle. It measured 12.37 V. Given voltage U, duty cycle η, and heater resistance R, the actual power P delivered to the nozzle can be estimated using the following equation.

$$P = \eta \frac{U^2}{R} \tag{1}$$

Convection coefficients determined in the simulation were 15.92 W/m^{2}K for the Longboat Prusa nozzle, 13.39 W/m^{2}K for the J-Head nozzle, 18.53 W/m^{2}K for the Archol.hu nozzle, 9.71 W/m^{2}K for the RepRap hot end 2.0, and 12.63 W/m^{2}K for the new introduced design. For the universal mini extruder nozzle, the convection coefficient was assumed equal that of the Longboat Prusa nozzle, since the two designs are similar.

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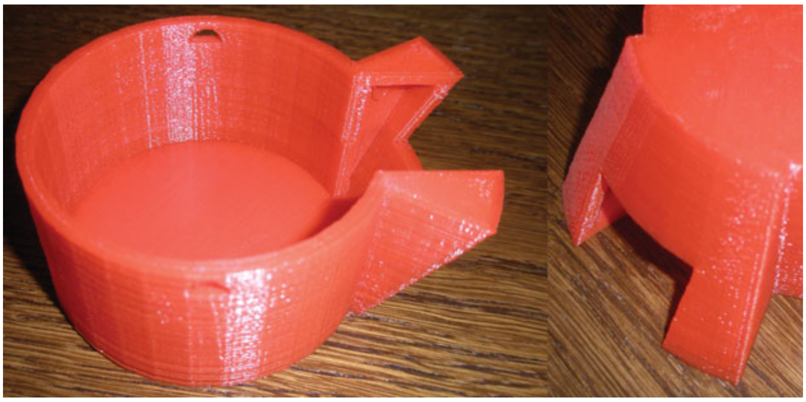

Fig. 21. Shield for an electrical connection box (photo by authors).

The steady-state thermal analysis results are presented in Figs. 21 and 22 for PLA and ABS extrusion conditions, respectively. Only PEEK and PTFE components and the thermal barriers are shown with temperatures indicated at characteristic points. The results indicate that nozzle designs 4 and 6 (Arcol.hu v.4.1.1 and improved Longboat Prusa) should perform well for PLA extrusion. Especially good thermal isolation can be seen in design 4, which keeps the PTFE liner just a few degrees above room temperature. Design 6 transmits a significant amount of heat through the brass barrel around the PTFE element to the upper parts of the liner. Nozzle designs 3 and 5 (J Head and RepRap 2.0) have a PEEK mounting block component screwed onto an aluminum hot end component. The region adjacent to the threads operates at close to the nozzle tip temperature. The temperatures at this interface are significantly higher than the glass transition temperature for PEEK. This elevated temperature may result in failure with time.

Nozzle designs 1 and 2 (Universal Mini Extruder and Longboat Prusa) use PEEK for the mounting block. For design 1, the highest temperature at the brass-to-mounting block interface is 173°C (see Fig. 21a). For design 2, the temperature reaches 174°C (see Fig. 21b). Both conditions may lead to excessive deformation of the PEEK under load. In design 1, deformation of the mounting block will not cause immediate damage to the liner element. The PTFE liner terminates in the melt chamber of the nozzle and will always be the same temperature as that of the melted polymer. It is however not subjected to any significant structural loading. However, for design 2, structural failure of the mounting block transmits part of the load through the fragile PTFE liner.

Raising the temperature at the nozzle tip to 230°C, which is good for working with ABS plastic, highlights even more possible design flaws. In design 1, the temperature of the brass nozzle to PEEK mounting block interface increases to 209°C (see Fig. 22a), which can further reduce the structural rigidity of the PEEK. A similar effect can happen to the mounting block to nozzle interface in design 2. However, both designs maintain low temperatures at the cold end, which contacts the plastic extruder components (see Figs. 22a and 22b). Design 3 shows minimal increase in temperature around the thin radiator part of the mounting block (see Fig. 22c). Nevertheless, the temperature of its mounting block to hot end interface remains above the PEEK glass transition temperature, which may lead to a loss of structural stability.

Design 4 performs well, keeping the PTFE component near room temperature (see Fig. 22d). The thin-walled stainless steel insulator shows good thermal barrier performance allowing for a 136°C (see Fig. 23d) temperature drop along its length. Design 5, maintains good thermal separation between the hot and cold ends (see Fig. 22e), however as in nozzle design 3, the mounting block to metal interface is exposed to temperatures above the PEEK glass transition temperature. Finally, the improved Longboat Prusa nozzle design 6 shows satisfactory thermal insulation performance (see Fig. 22f). The maximum calculated temperature for the brass-PTFE interface is 212°C (see Fig. 23f). The model predicts essentially uniform heater block temperatures, so a temperature sensor to control heater power can be placed at any convenient location within the heater block. The PTFE liner is exposed to high temperatures along its length up to the point where the nozzle collar ends. This leads to elevated temperatures of around 72°C to 82°C (see Fig. 23f) on the cold end where contact is made with the extruder body. These temperatures are not high enough to damage the extruder body.

Table IV. Heating power in Watts required for keeping the nozzle in thermal steady state.

Design	1	2	3	4	5	6	Average
PLA printing (190°C)	3.982	5.543	4.655	6.095	6.495	8.285	5.843
ABS printing (230°C)	4.947	6.890	5.784	7.564	8.060	10.280	7.254

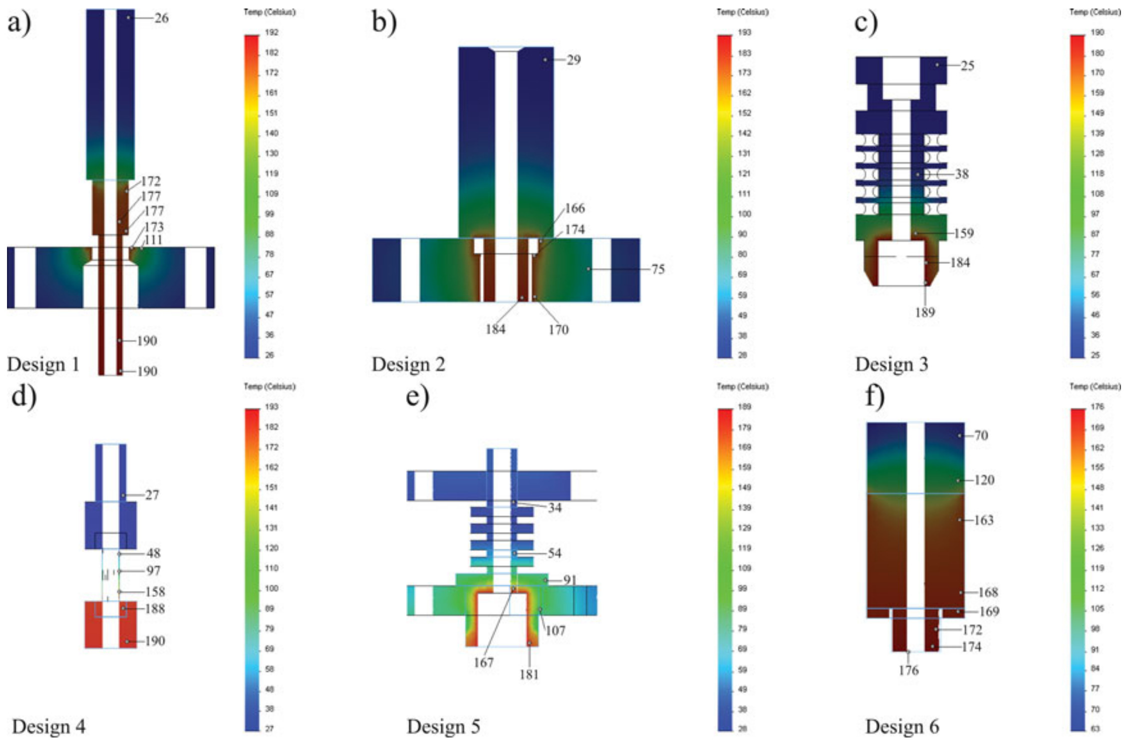

Fig. 22. Simulated heat distribution inside PEEK and PTFE parts and thermal barriers for PLA extrusion.

The thermal analysis also gave an estimate of steady-state power consumption for each of the nozzle designs. The results are presented in Table IV. The improved Longboat Prusa nozzle design consumes the most power, while the Universal Mini Extruder consumes the least. Actual power consumption will be higher, because the energy required to melt the polymer was not considered in the computations. Only convection losses were considered.

Structural Analysis

A structural analysis was carried out for the six evaluated designs to determine nozzle deflection under extreme extrusion conditions; defined as 150 N of force applied by the polymer filament pushed through the nozzle. This analysis reveals stress levels within the most fragile nozzle components to indicate likely failure areas. Each nozzle design was modeled as an assembly, with components connected using a surface-to-surface contact definition. Threaded connections were modeled as connected meshes of the two bodies creating a rigid joint. Under mounting blocks, washers were modeled as elements rigidly attached with sliding boundary condition applied under the washers. For the J Head nozzle design, a sliding support was added under the upper flange of the PEEK mounting block. To restrain horizontal movement, radial motion constraints were applied to the upper cylindrical components of the nozzles. This constraint was applied to the liner elements for designs 1, 2, and 6. For design 3, the neck was used as the horizontal movement constraint. Finally, for designs 4 and 5, the constraint was applied to the upper part of the inside of the filament bore. External force was applied to the final cone section on the inner part of each nozzle. Structural analysis used thermal results from ABS extrusion simulation to account for PEEK material softening.

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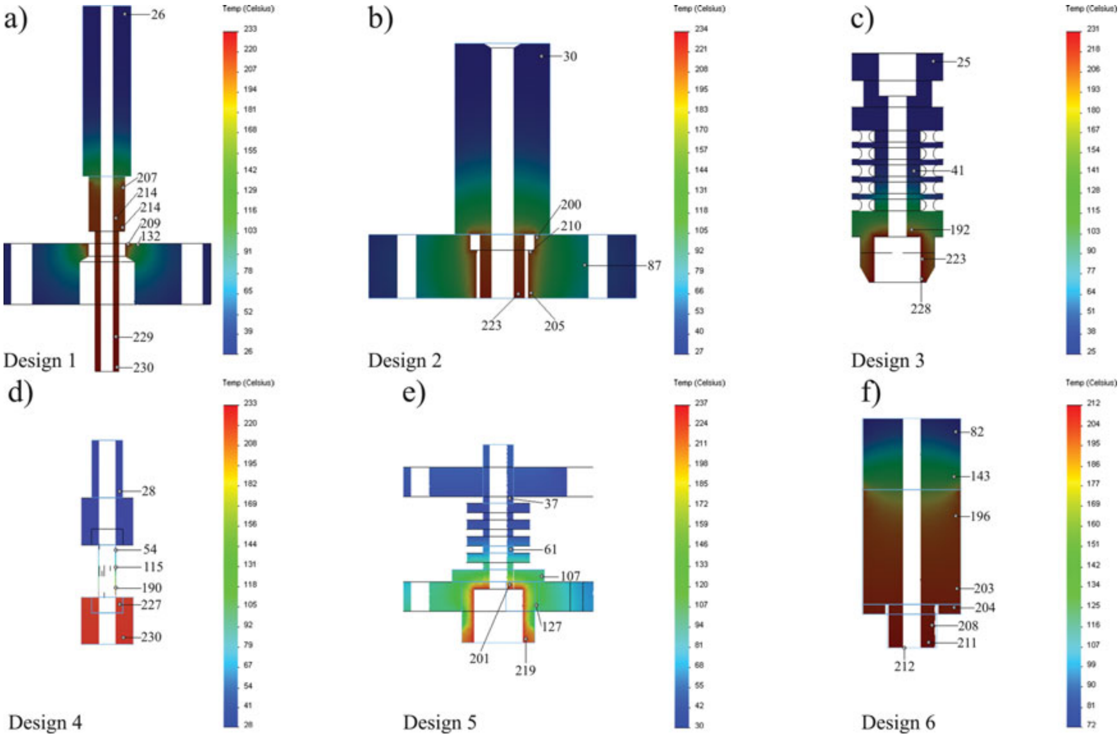

Fig. 23. Simulated heat distribution inside PEEK and PTFE parts and thermal barriers for ABS extrusion.

Figure 24 shows the deflection under load calculated for each of the six designs. The simulation is considering PEEK material softening related to the increase of material temperature, however it does not account for viscoelastic behavior of PEEK. The nozzle designs utilizing a PEEK mounting block exhibit similar deflections under extreme loading conditions to other supports. Therefore, it can be concluded that the mechanism of structural failure of PEEK supports in RepRap nozzles, known from experiments, is solely a result of viscoelastic behavior of PEEK polymer, and the reduction in polymer structural rigidity is a secondary cause.

Figure 25 shows the stresses calculated for the weakest areas of each design. For design 1, the PEEK mounting block is the weakest component. Stresses at its neck do not exceed 10% of the PEEK yield strength at room temperature; however, at the elevated temperatures seen while printing, structural failure is likely to occur. Design 2 experiences higher stresses at the interface between the PEEK mounting block and brass nozzle. The stress at the thread between the PTFE liner and the brass nozzle, exceeds 25 MPa. The yield strength of PTFE, depending on the grade, is between 2 to 9 MPa. This clearly indicates that fracture of the PTFE liner is imminent in such situation. Design 3, which uses a PEEK mounting block, experiences relatively low stresses near the aluminum threaded region of the nozzle. PEEK ultimate strength is in the range 110 to 262 MPa, which means that this design should be safe in terms of extrusion stresses. Stresses within the radiator structure of the block are at maximum 10.8 MPa, which is safe considering the moderate thermal loading conditions in this region.

The load bearing components in design 4 are metal. The weakest component is the thermal barrier made out of stainless steel with a wall thickness of only 0.07 mm. The stresses within the thin-walled component can reach 124 MPa, which assuming only tensile load should be still safe. However, this component might bend if the nozzle runs into previously printed and solidified polymer. The PTFE liner used in design 4 does not carry any mechanical load attributed to the dynamics of the extrusion process. Design 5 experiences low stresses in its most fragile components. The PTFE components are not exposed to load during the extrusion process. Finally, the improved Longboat Prusa nozzle design, design 6, experiences minimal stress in its wooden mounting block and no operational stresses at all in the PTFE liner.

Table V. Heat expansion coefficients.

Material	Heat expansion coefficient [μ m/mm°C]
Brass	0.0180
Aluminum	0.0230
Stainless steel	0.0701
PEEK	0.0114
PTFE	0.0750

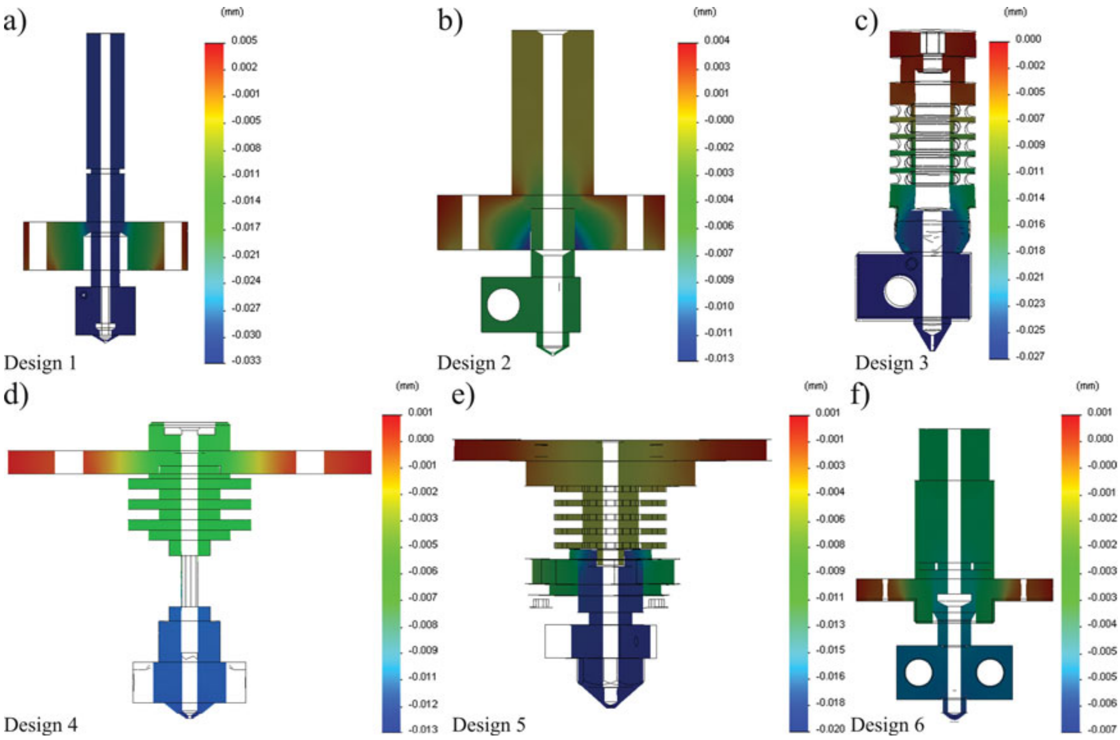

Fig. 24. Vertical displacements of the nozzle designs under test loading of 150 N.

Leakage paths

As an extreme condition, the thermal analysis results for printing ABS can be used to predict possible leakage paths in the evaluated nozzle designs. The thermal expansion coefficients for contacting materials are presented in Table V. For design 1, the interface between the brass nozzle and the PEEK liner is the only possible leak path for molten polymer. For design 2, the PTFE liner-to-brass nozzle interface is the possible source of leakage. Design 3 could possibly leak between the PEEK mounting block and aluminum hot end. For design 4, there are theoretically two possible leakage paths, one between the stainless steel heat barrier and the hot end, and one between the heat barrier and the cold end. In design 5, three possible leakage paths exist, one between the PTFE liner end and the aluminum threaded connector, a second between the PEEK thermal barrier and the aluminum threaded connector, and a third between the nozzle and the threaded connector. Because the threaded connector and nozzle are made of the same material, thermal expansion does not play a role in the sealing of this joint, so this path will be neglected. The flat face-to-face connection between the PTFE and threaded connection seal depends only on the surface quality and pressure between them, which can be adjusted by tightening three screws. Since the contact faces are flat, differences in thermal expansion will not affect the sealing capabilities of this joint. High temperature softening of the PTFE might actually improve the seal. Finally, in design 6, one leakage path is possible between the PTFE liner and the brass nozzle. Table VI gives summary of the possible leakage paths and clearance changes at the leakage path interfaces due to thermal expansion of the interface materials.

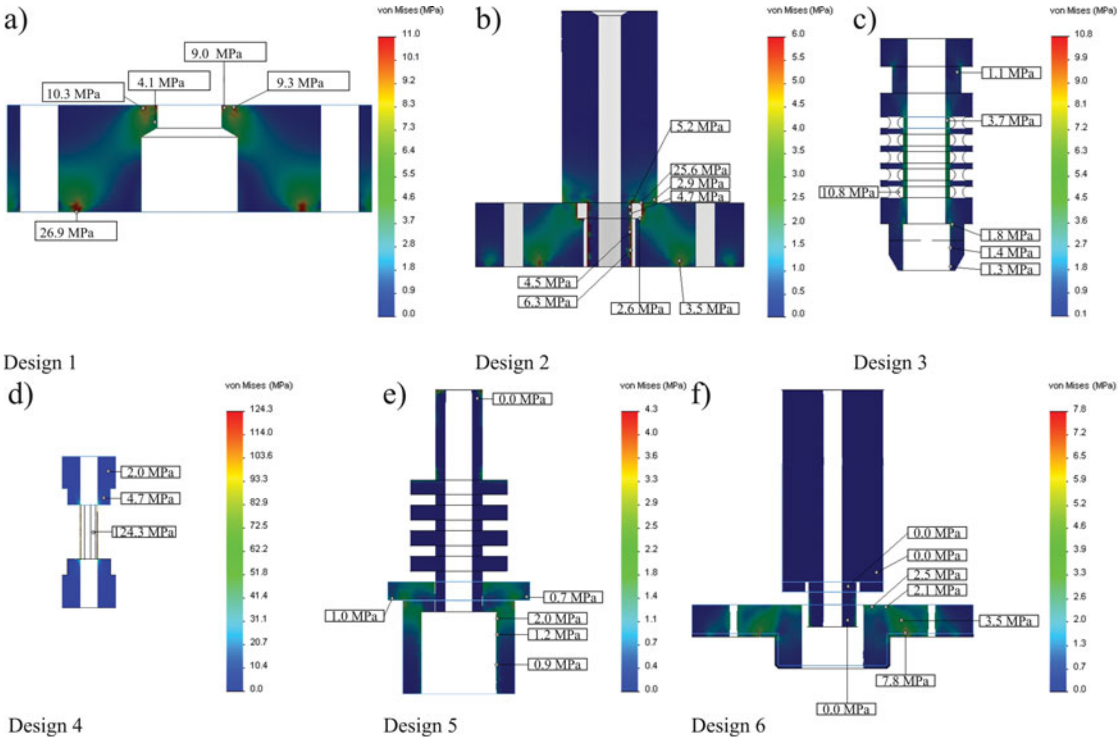

Fig. 25. Von Misses stresses in the weakest parts of the presented nozzle designs.

Analysis of the thermal diameter changes in the seal interfaces shows that only design 1 develops a leak path due to thermal expansion when it heats up. In design 2, the difference in expansion between the brass and PTFE materials will not sufficiently tighten the connection if M7 thread tolerances, which can accommodate a variation of up to 0.65 mm, are considered. Design 3 requires tight dimensional tolerances between the aluminum nozzle thread and the PEEK mounting block. Heat expansion tightens the threaded connection, but it is only a small fraction of the nominal M8 thread tolerance, which is 0.812 mm.

A thread sealant should be used. In design 4, sealing between parts is achieved by direct contact of flat surfaces. No sealing agent is used between the aluminum and stainless steel component faces. If the surface quality of the mating faces is adequate, the threaded connection will not become a leak path. Design 5 might experience the same problems as design 3 in terms of sealing between the aluminum and PEEK components, what agrees with experimental results. The connection tightens with increasing temperature, but the large thread diameter comes with tolerances significantly larger than the maximum expected thermal movement. Finally, in design 6, the threaded connection will most likely not be leak proof, but testing has demonstrated that the large flat seal surfaces provide a good seal for leak-free operation. If the dimensional tolerance for the 16 mm diameter part of the liner is kept within −0.05 mm and the nozzle collar within +0.05 mm, an additional seal will be formed between the wide part of the PTFE liner and the brass collar.

Conclusions

This study identified and addressed the design problems most commonly reported for RepRap 3D printer polymer extruders. Here, the authors began by presenting the construction of typical design solutions and discussing the inherent weaknesses and strengths of each. Evaluating a popular material choice for the nozzle-mounting block, PEEK, suggested the plastic is not the best material choice for long-term reliable extruder performance. A new and improved nozzle assembly design was introduced that uses Teak wood instead of PEEK for the mounting block. Drawings sufficient to fabricate the new design have been included.

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Table VI. Clearance change at leakage path interfaces due to thermal expansion of the interface materials.

Design 1 – PEEK liner inside brass nozzle, interface diameter 6 mm, ΔT = 195°C	
Outer part: Brass nozzle	+21.06 μm
Inner part: PEEK liner	+13.37 μm
Difference	+7.69 μm (loosening of the connection)
Design 2 – PTFE liner inside brass nozzle, interface diameter 7 mm, ΔT = 204°C	
Outer part: Brass nozzle	+25.70 μm
Inner part: PTFE liner	+107.10 μm
Difference	−81.40 μm (tightening of the connection)
Design 3 – aluminum hot end inside PEEK mounting block body, interface diameter 8 mm, ΔT = 210°C	
Outer part: PEEK mounting block	+23.52 μm
Inner part: aluminum nozzle	+38.64 μm
Difference	−15.12 μm (tightening of the connection)
Design 4 – stainless steel heat barrier inside cold end aluminum radiator, interface diameter 10 mm, ΔT = 10°C	
Outer part: Aluminum radiator	+2.30 μm
Inner part: Stainless steel barrier	+7.07 μm
Difference	−4.77 μm (tightening of the connection)
Design 4 – stainless steel heat barrier inside hot end aluminum nozzle, interface diameter 10 mm, ΔT = 208°C	
Outer part: Aluminum nozzle	+47.84 μm
Inner part: Stainless steel barrier	+145.81 μm
Difference	−97.97 μm (tightening of the connection)
Design 5 – aluminum threaded connector inside PEEK mounting block, interface diameter 10 mm, ΔT = 208°C	
Outer part: PEEK mounting block	+23.71 μm
Inner part: aluminum connector	+47.84 μm
Difference	−24.13 μm (tightening of the connection)
Design 6 – PTFE liner inside brass nozzle, interface diameter 8 mm, ΔT = 208°C	
Outer part: brass nozzle	+21.06 μm
Inner part: PTFE liner	+177.80 μm
Difference	−88.92 μm (tightening of the connection)
Design 6 – PTFE liner inside brass nozzle collar, interface diameter 16 mm, ΔT = 184°C	
Outer part: brass nozzle	+52.99 μm
Inner part: PTFE liner	+220.80 μm
Difference	−168.81 μm (tightening of the connection)

The result of a thermal analysis gives a better understanding of the operational environment for each nozzle assembly component and validates the design assumptions for the assembly. As a component critical to long-term printer function and reliability, the nozzle structural rigidity was studied in particular, and its structural performance at temperature was described. Finally, extended testing was conducted to verify and validate the new nozzle assembly design. To demonstrate satisfactory performance, examples of parts printed using the new nozzle prototype were presented. The new nozzle assembly performed well as expected. The Teak mounting block also performed well, and Teak can be considered a suitable material for the mounting block of a RepRap 3D printer. Simulation results for the Arcol.hu nozzle design show that this design is promising in terms of thermal insulation of the hot and cold ends of the nozzle, however the same thermal barrier, is also the most fragile part of the design and can be damaged easily in case of nozzle collision. Design marked as RepRap 2.0 failed on the PEEK-to-aluminum interface leaking melted polymer already at 200°C after only 3 hours of physical tests. All of the tested nozzles allowed to extrude PLA polymer without jamming related to solidification of the polymer inside the thermal barrier.

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