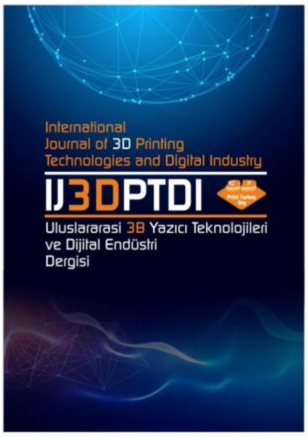

ULUSLARARASI 3B YAZICI TEKNOLOJİLERİ
VE DİJİTAL ENDÜSTRİ DERGİSİ

INTERNATIONAL JOURNAL OF 3D PRINTING
TECHNOLOGIES AND DIGITAL INDUSTRY

ISSN:2602-3350 (Online)

URL: https://dergipark.org.tr/ij3dptdi

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Yazarlar (Authors): Özgün Selvi*, Murat Yetim, Samed Yiğit Çırnık Hasan Fehmi İlter, Muhammed Enes Akan, Temel Tomaç

Bu makaleye şu şekilde atıfta bulunabilirsiniz (To cite to this article): *Selvi Ö., Yetim M., Çırnık S.Y., İlter H.F., Akan M.E., Tomaç T. "Design and Production of Multi Material 3D Printer For Soft Robotic Structural Elements" Int. J. of 3D Printing Tech. Dig. Ind., 5(2): 227-236, (2021).*

DOI: 10.46519/ij3dptdi.955494

Araştırma Makale/ Research Article

Erişim Linki: (To link to this article): https://dergipark.org.tr/en/pub/ij3dptdi/archive

DESIGN AND PRODUCTION OF MULTI MATERIAL 3D PRINTER FOR SOFT ROBOTIC STRUCTURAL ELEMENTS

Özgün Selvi*, Murat Yetim, Samed Yiğit Çırnık
Hasan Fehmi İlter, Muhammed Enes Akan, Temel Tomaç

*Çankaya University, Engineering Faculty, Mechanical Engineering Department, Ankara, TURKEY

* *Corresponding Author: ozgunselvi@cankaya.edu.tr*

(**Received:** 21.06.2021; **Revised:** 15.07.2021; **Accepted:** 11.08.2021)

ABSTRACT

With the latest technology, the development and interest in soft robots have gained speed. Flexible robots are generally produced by the casting method. This traditional production method has difficulties in the production of complex geometries such as, sharp corners, thin structures, cavities, pipelines and use of multi-materials. Also a new mold is needed for each product in the casting method and the mold costs are quite high. In additive production method, no mold is needed. Design can be produced at any time. When it comes to the production of a small number of special parts, faster production is achieved compared to the casting method. Therefore, present study aims to design and produce a multi-material 3D printer capable of printing non-conductive and conductive rapidly curing silicone that can be used in soft robotics and medical simulators. The electrical conductivity was achieved by mixing silicone and graphite powder. The parts in the printer are also produced by the additive manufacturing. Test pieces were printed using the produced 3D printer. Specific tests on produced parts produced have been carried out to determine mechanical and electrical properties. Technical data such as strength, elasticity, electrical conductivity have been obtained.

Keywords: Soft Robotics. Additive Manufacturing. 3D Printers. Multi-Material Printing. Conductive silicone printing

1. INTRODUCTION

Soft robots are a variation of robots that can imitate movements of living things and are produced from suitable materials. The branch of science dealing with such robots is called soft robotics. It determines the compatibility of soft robot systems, their flexibility, which constantly and frequently respond and undergo local deformation. Flexible robots can be used in areas that are restricted and difficult to work, unlike conventional robots. Main components of soft robots are sensors and actuators. Sensors detect and react to physical factors such as heat, motion, humidity, pressure. An actuator is a machine element that moves or controls a system or mechanism. Examples of actuators and sensors used in soft robotic systems are shown in Table 1.

Table 1. Examples of actuators and sensors

Actuators	Sensors
Fiber-Reinforced Actuators [12]	Egain Sensors [21]
Pneumatic Artificial Muscles [13]	TakkTile Sensors [22]
SDM Fingers [14]	Smart Braids Sensors [23]
Dielectric Elastomer Actuators [15]	TacTip Sensors [24]
Combustion-Driven Actuators [16]	Pneumatic Sensor [25]
Manipulator [17]	Textile Silicone Hybrid Sensor [26]
Soft-Bending Actuators [18]	
Soft Grippers [19]	
PneuNets Bending Actuators [20]	

Traditionally silicone soft robots are produced by the casting method. A mold is needed for each part. Since the produced molds have a limited lifespan, new ones must produce periodically. Mold production is a costlier and laborious process than the production of the part. This traditional production method has difficulties in the production of complex geometries such as, sharp corners, thin structures, cavities, pipelines and use of multi-materials. Also a new mold is needed for each product in the casting method and the mold costs are quite high. The production of objects designed by a virtual environment in a 3D limited space layer by layer is called additive manufacturing [5]. The usage areas of 3D printers are increasing today, as they can be integrated into almost every field. As a result, various printing technologies have emerged. These printing types can be given as selective laser sintering (SLS), direct ink writing (DIW), shape deposition modeling (SDM), fused deposition modeling (FDM), inkjet printing. SDM is a robust free-form manufacturing process; it is built from top to bottom, rather than removing excess material from specific objects. It is achieved by layering the lining material and the required finished material [33].

Detailed examination of the economics of additive manufacturing (SLS) by Atzeni and Salmi [27] show that after a certain threshold additive manufacturing will be cheaper than the traditional manufacturing method. In additive production method, no mold is needed. Design can be produced at any time. When it comes to the production of a small number of special parts, faster production is achieved compared to the casting method. The lack of need for using a core in additive manufacturing decreases the labor time and also helps to produce parts that cannot be achieved by casting method. Many studies have been conducted on flexible robots from past to present. Detailed examination of design, fabrication, and control of the soft robots by Daniela and Micheal [4] showed that soft robots could be applied in various areas of use. Soft robots easy integration with body tissues help people in difficult working conditions. Flexible robots are suitable for use in applications such as biomedical applications, exploration missions in areas that are difficult to move. Apart from these, there is more than one type of soft robot according to their usage areas. Examples of robotic muscles, climbing, edible robots, wearable robots, prosthetic robots, and flexible gripper robots are soft robots. Robotic muscles are designed to mimic the muscles in the human body. Climbing robots have potential applications ranging from building inspection and maintenance to search and rescue missions. A version of the soft climbing robot, like a caterpillar, has a curved design that allows it to climb large structures. Edible robots are biodegradable and can safely deliver drugs to different parts of the body. Because wearable robots can imitate the human body's natural movements, they can be applied to physically rehabilitated patients [4]. Kai et al. [3] pointed out how a soft gripper uses prosthetic robots at the end of the prosthesis to grasp objects more finely and accurately for people with missing limbs. Another example of soft robotic is carried out by Schumacher et al. [1] in which is a heart-shaped pump robot operating at 500 watts and 10000 combustion cycles. Another example of what is meant by Giovanni Rateni, et al. [2] is a gripper design using soft elastomers.

As in the examples given, soft robots' types and usage areas are increasing day by day. In light of these developments, soft robots need to have more complex structures such as, sharp corners, thin structures, cavities, pipelines. These complex structures and the functions they supply can be obtained by using additive manufacturing. An example of a 3D printer made by Gul et al. [6] for soft robotics. The study of Muth et al.[7] is an excellent example of the printing of strain sensors within highly stretchable elastomer. In the work of Dilibal et al. [28] three pneumatic soft actuators are produced with different geometries using TPU and additive manufacturing. Actuators are tested and compared with different finite element methods. Using TPU material Dilibal et al [29] have created soft robotic gripper with embedded sensors using FDM printing method. Detailed examination of Direct 3D printing of silicone elastomer soft robots and their performance comparison with molded counterparts by Yirmibesoglu, et all (2019) [30] showed that soft robots could be manufactured with different methods. Another example of a 3D printer made for soft robotics is the study carried out by Georgopoulou et al. (2021) [31] in which A Sensorized Soft Pneumatic Actuator Fabricated with Extrusion-Based Additive Manufacturing. In this study, two different techniques were used for two different materials. For the conductive material, a filament was produced using carbon powder and printed with the FDM technique. For the insulating material, the silicone material was printed by the extrusion method.

Unique printing materials [8, 9] are needed to produce soft robotic elements with 3D printers. These unique printing materials are classified as smart materials. Smart materials can fulfill the desired functions by responding to the warnings originating from the environment. These external effects can be pH, mechanical, chemical, optical, moisture, thermal and electric fields, or magnetic fields. Because of these features, smart materials make essential contributions to the production of soft robotic elements with 3D printers. 4D printing is the name given to the phenomenon of 3d printing that occurs under certain conditions. This phenomenon occurs when a structure produced with smart materials reacts to ambient conditions and performs functions determined by this reaction [10].

This study aims to design and produce a multi-material 3D printer capable of printing non-conductive and conductive rapidly curing silicone that can be used in soft robotics and medical simulators. The electrical conductivity was achieved by mixing silicone and graphite powder. The parts in the printer are also produced by the additive manufacturing. Test pieces were printed using the produced 3D printer. Specific tests on produced parts produced have been carried out to determine mechanical and electrical properties. Technical data such as strength, elasticity, electrical conductivity have been obtained.

2. 3D PRINTER DESIGN FOR SOFT ROBOTIC ELEMENTS

2.1. Design of the 3D Printer

Proposed 3D printer consists of multiple flow lines of conductive silicone, silicone and silicone agent. They converge in the mixing chamber of the printer as shown in Figure 1. Mixing chamber mix materials homogeneously with each other depending on the type of the material to be printed. The 3D printer has a Cartesian shape with three axes motion. The print bed is heated so that the printed silicone adheres better to the print bed. Technical information of 3D printer is given in Table 2.

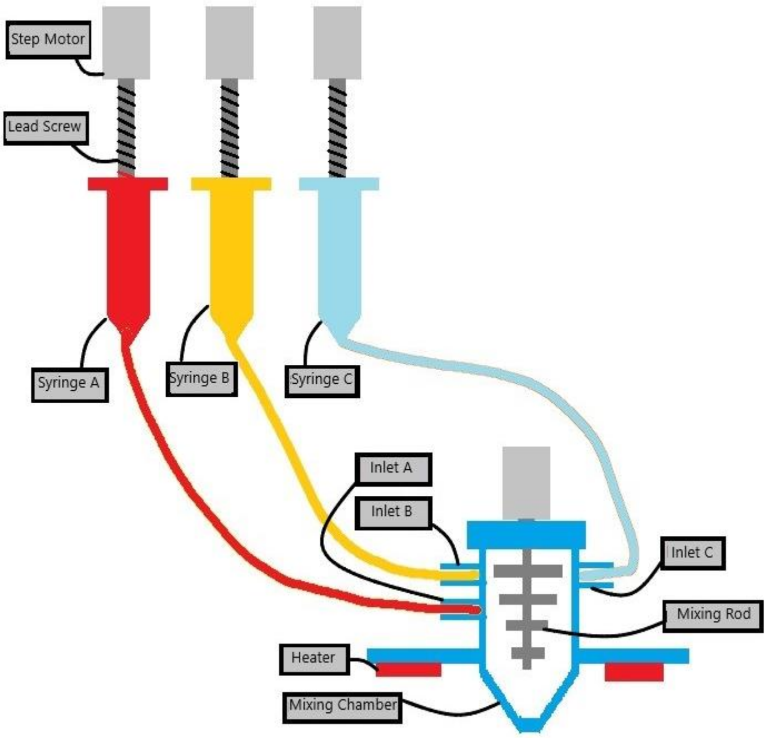

Figure 1. General system schematic

Table 2. General information of 3D printer

General Dimension	580x490x560 mm
Printer Bed Dimension	300x200 mm
Printing Area Dimension	300x200x200mm
Motor Type and Quantity	Nema 17 Step Motor, 6 Pieces
Vertical Movement	Threaded Rods
Horizontal Movement	Pulley System
Motherboard	Re-ARM with RAMPS 1.4 Motherboard
Software	Repetier Host

Extrusion system consists of two modules parts such as syringe pump and the mixer. The syringe pump is shown in Figure 2. The syringe system is located on the top of the 3D printer. The syringe system consists of three separate syringe tubes with pistons attached to threaded rods that are controlled by Nema 17 motors. The transformed linear motion is transferred to the pistons in the tube, and the movement of the silicone is provided. Silicone is transmitted to the mixing chamber through the pipes. In addition, the tubes in the syringe part serve as a reservoir for the silicone and other materials used in the 3D printer. Each syringe has an equal volume and a storage capacity of 78 ml. It provides insulation against moisture, air, and heat to silicone. The storage conditions of the syringe prevent the stored silicone from curing. In this way, the printing and storage life of the used silicone increases significantly. Previously prepared materials can be easily refilled into the tubes by the easy assembly provided by the syringe mechanisms. The assembled image of the mixing chamber mechanism is given in Figure 3.

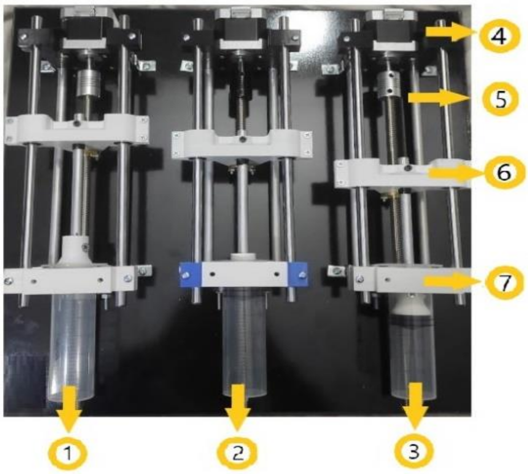

Figure 2. Syringe System, The numbers 1, 2 and 3 in the picture are syringes. It is where the mixture to be printed from the 3D printer is stored. Number 4 in the image is the Nema17 motor that will move the material from the syringe. The number 5 in the picture is the threaded rod that converts the rotational motion obtained from the motor into linear motion. Numbers 6 and 7 in the picture are the parts that restrict the movement of the syringe.

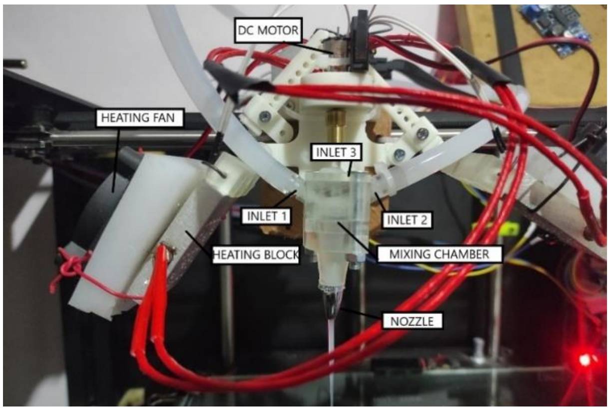

Figure 3. Extruder mechanism picture

Three inlets on the mixing chamber connected to a separate syringe with different material. Materials entering the mixer through separate inlets are dynamically mixed with the blade mechanism. Rotational motion is transmitted by dc motor. The characteristics of the blade mechanism, such as the speed, the number of teeth, and the dimensions, are adjusted so that the materials are mixed homogeneously. In addition, gear blades are placed at an angle of 45 degrees. Due to the design and movement of the blade mechanism, pressure builds up on the mixture. The resulting pressure and the rotational movement of the mixer enable the mixed material to move in both radial and axial directions, and the mixer mechanism transmits the extrusion motion of the syringe pumps. Two heating blocks at the outlet of the mixer mechanism are used to cure the silicone. Heating blocks are located at the bottom of the mixer on the right and left sides to shorten the production time. The image of the printer while printing is given in figure 4.

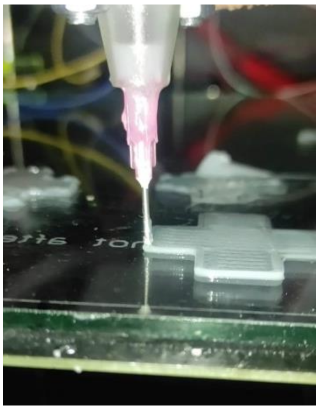

Figure 4. 3D printer while operating

2.2 Methodology

Three different materials used are Dragon Skin ™ 10 VERY FAST make-up silicone, thixotropic agent, and graphite powder. Dragon Skin ™ silicones are fast-curing liquid silicone compound often used in film sets to create skin effects and other special effects. Dragon Skin ™ is in the form of two components A and B. These are used by forming mixtures in appropriate proportions. Dragon Skin ™ silicone mixture can be used between -53 ° C and + 232 ° C. The shore value of silicone is 10A in ASTM D-412 [11] test standards. Aa thixotropic agent was used to densify the silicone. Silicone has been more suitable for a 3D printer with the thixotropic agent. After obtaining printable silicone, graphite powder was used to obtain conductivity. The mixing ratios of the materials to obtain two types of silicon, conductive and non-conductive are shown in Table 3.

Table 3. Mixture percentage

	Dragon Skin A	Dragon Skin B	Grafite Powder
Non-Conductive Silicone	50%	50%	0%
Conductive Silicone	48.7%	48.7%	2.6%

At the beginning of the printing process, the 3D Repeiter software with slicer separates the designed part into layers. The software determines the conductive and non-conductive parts of each layer according to the color of the drawn parts. According to these determined regions, the 3D printer sets which syringes will work. At each print just two materials come to the mixer section of the 3D printer using hoses and mixed homogeneously in the mixer and get out due to the pressure supply from the syringe pumps. When switching materials, a certain amount of material left in the mixer from the previous operation is disrupting the design. Therefore, the material transition is applied. Between the material passes, extruder is sent to an empty corner to clean the material remaining in the mixer and discharges the unwanted material inside. This operation is repeated for each material pass.

Curing is the phenomenon of silicone in liquid form reaching its final hardness upon exposure to specific environmental conditions. The curing process of the silicone used in the project starts at room temperature (73 ° F / 23 ° C). Curing time in room temperature exceeds 30 minutes. Heating blocks, one on the right and one on the left of the mixer are placed for the curing process in the 3D printer.

Heating blocks reach a temperature of 80°C. With the curing technique used, the curing of a single layer was shortened to 30 seconds. In addition to the heater blocks, the printing bed of the 3D printer is heated, contributing to the curing of the silicone.

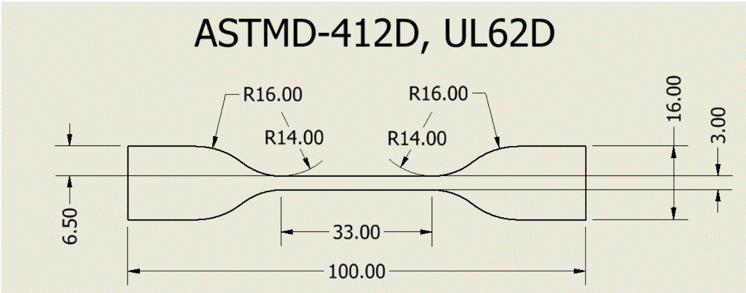

Figure 1. Specimen dimensions ASTMD

For the tensile test, a dumbbell test piece in accordance with ASTM D412 standard (Figure 5) was designed. The tensile test has been done using a printed test specimen. As a result of this test, the strength values of the piece were calculated. One of the test specimens is shown in Figure 6. The test piece is 100mm long and 16mm wide. The throat of the test piece is 3 mm wide and 33 mm long. There is fillet in 16mm and 14mm diameter corners to prevent stress concentration. Also, the test piece is printed with 3mm thickness.

Figure 2. Printed part

3. TESTS AND RESULTS

3.1. Tensile Test

3D printed parts has a shore value of 10A and were subjected to a tensile test according to ASTM D412 standards. The tensile has been done with several steps. These steps are, reaching the specified elongation within 15 sec, holding the specimen for 10 min with desired elongation, release test specimen quickly without any snap back, and rest the test specimen for 10 min. The same test was repeated 5 times to find a mean results. Results are given in Table 4.

Table 4. Tensile test results for 3DIW parts

3D Printed Part	Test #1	Test #2	Test #3	Test #4	Test #5
Tensile Strength (KPa)	3200	3182	3238	3220	316
%100 Modulus (KPa)	151	148	155	152	147
Maximum Elongation (mm)	498	494	496	502	480
Elongation @ Break (%)	498	494	496	502	480

Finite element analysis has been done to support the calculations. The material properties for finite element analysis are set manually. The hardness of the material is set to 10 according to the Shore A value, tensile strength 32.75 bar, 100% modulus 1.51 bar. Detailed material properties are given in Table 5 and results of the finite element analysis is shown in Table 6.

Table 5. Material properties

Property	Value
Specific weight	1.07 g/cc
Specific Volume	1.63 m3/kg
Shore A Hardness	10
Tensile Modulus	32.75 Bar
100% Modulus	1.51 Bar
Viscosity	23000 cps

The test piece was subjected to a tensile force of 100 N by being fixed at one end in the analysis. The results are given in Table 6.

Table 6. Finite element analysis results

Results	Minimum	Maximum	Unit	Time(s)
Total Deformation	0	2.9015e-006	m	1
Maximum Shear Stress	3.724e+005	6.235e+006	Pa	1
Maximum Shear Elastic Strain	4.8411e-006	8.1055e-005	m/m	1

According to the test results, the printed test piece can stretch 4.94 times its own length. At the same time, due to the high strength values, it has been observed that the printed soft robotic elements can maintain their form during motion.

3.2. Conductivity Test

One of the qualities required for sensor production is electrical conductivity. For this reason, the electrical conductivity of the parts produced by 3D printer were tested in the second stage of the tests. In order to perform the electrical conductivity test, the printed geometry with the conductive material was determined. Using this geometry, the test specimens were printed. The required coefficients to obtain the resistance of the conductive material were calculated over the determined geometry. Our test specimen has a length of 80mm, width of 1mm and thickness of 3 mm electrically conductive zone. According to these dimension, A/L value of conductive zone is $(3.10^{-5}\ (1/m))$. After the necessary calculations, the produced part was accepted as a resistor added to the system. A voltage difference of certain magnitudes was applied to the system using a calibrated voltage source. While the circuit is under load, the amount of current passing through the conductive region was measured with the help of an ampere meter. The resistance value was calculated using the current values obtained. By using the calculated resistance and geometric values, the resistivity value of the conductive material was found. Detailed results are given in table 6.

Table 4. Conductivity results of 3DIW parts

3D Printed Part	Test #1	Test #2	Test #3	Test #4	Test #5
Voltage	5 V	7 V	6 V	8 V	4 V
Ampere	0.8 A	1.14 A	0.95 A	1.33 A	0.62A
Resistance	6.25 Ω	6.14 Ω	6.32 Ω	6.02 Ω	6.45 Ω
Resistivity $\left(\frac{A}{L}\rho\right)$	1.88×10^{-4} Ωm	1.84×10^{-4} Ωm	1.89×10^{-4} Ωm	1.8×10^{-4} Ωm	1.94×10^{-4} Ωm

As a result of the tests and calculations, the average electrical resistivity value was obtained as 1.87×10^{-4} Ωm at room temperature. The average values of the conductors are between 10^{-2} Ωm and 10^{-8} Ωm. The electirical resistivity value of graphite at room temperature is 1×10^{-5} Ωm. By looking at these values, it is seen that the conductive silicone mixture can easily transmit the given current.

4. DISCUSSION

The findings of the use of silicone type material for 3d printing of soft robotic elements are consistent with those of Yirmibesoglu, et al. [30], The main difference of this study is that it can print conductive silicon simultaneously with non-conductive silicon. These findings further support the idea of 3d printing of silicon materials as in the study of Georgopoulou et al. [31] main difference in our study is that it is conductive material is embedded by extrusion of conductive silicon instead of printing with FDM. The results of the study shows similar results for the test of dumbbells using ASTM D-412 standard as carried by Miriyev et al [32]. When the two studies are compared, ıt can see that, values are found to be a match with each other. As a result of the two studies, it has been seen that the silicone materials printed with 3D printers have high strength. In addition to these properties, they were able to preserve their elastic properties. Because the 3 DIE materials preserve these properties, it has been seen that 3D printers can be used in soft robotic applications.

5. CONCLUSION

At the end of this study, a 3D printer and extrusion system is designed and produced to be used for production of soft robotic elements with conductive and non-conductive silicon. The part production time has been improved by more than 40%, with a reduction in curing time. The properties of the test piece taken by our 3D printer have been found to be close to the specified material properties. Another result of the study showed that silicone in the syringes of the 3D printer did not cure over time, and curing started at the exit of the syringe. These results showed that the designed 3D printer and extrusion system is capable of printing soft robotic elements.

ACKNOWLEDGEMENT

This project is funded by Tubitak 2209-b with application I.D. 1139B412001047.

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