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ORIGINAL ARTICLE

Design and fabrication of multi-material pneumatic soft gripper using newly developed high-speed multi-material vat photopolymerization 3D printer

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Abstract

This study proposes a versatile, low-cost, shape-conforming soft gripper fabricated using the self-developed high-speed multi-material vat photopolymerization process. This additive manufacturing technology consists of a rotary build plate that moves through 180° along the XY plane and multiple resin vats to accommodate different materials. A cleaning system uses pressurized air and alcohol to prevent contamination between layers and to increase the bond strength. The soft grippers are manufactured using soft (GC3D-ESK) and hard phase (AA-temp) materials to optimize the gripping force and prevent damage of the objects. Experimental results show that the tensile strength of the multi-material fabricated part (GC3D-HSK and AA-temp) is 5 times greater than that of the soft material GC3D-HSK. The multi-material specimen exhibits an elastic modulus of 89.28 MPa, which is much higher than 2.08 MPa of the soft material. The multi-material fabricated specimen exhibits high strength, high elastic modulus, and 65% longer elongation than the hard material. In addition, the specimens that are cleaned with alcohol after successive printing of each layer have 4% higher tensile strength and 30% longer ductility. A shrinkage analysis is carried out to evaluate the material compatibility. The percentage shrinkage for both GC3D-HSK and AA-temp is obtained in the range of 0.1–0.2%. The printed pneumatic soft gripper is used to lift goods of up to 200g using a maximum pressure of 34.3 kPa. The lifting efficiency of the developed gripper is evaluated to be 5.83 g/kPa which is higher than the currently existing grippers. The printed gripper can lift objects of different weights and profiles without damaging the surface. The high-speed multi-material VP 3D printer can be used for additive manufacturing to optimize the design of pneumatic soft grippers.

Keywords Industrial robots · Multi-material additive manufacturing · VAT photopolymerization · Pneumatic soft grippers · High-speed additive manufacturing

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1 Introduction

Industrial robots are a key component in the development of integrated manufacturing systems [1]. With the advent of artificial intelligence in smart manufacturing, the role of robots will grow exponentially in the twenty-first century [2]. The use of industrial robots will greatly reduce the need for human intervention in manufacturing and will minimize errors, thereby increasing precision and productivity [3]. Literature reported that the number of industrial robots in factories had increased to more than two million in 2020 [4].

Robots are used in the manufacturing sector and increasingly in nuclear power plants to handle radioactive substances, for minimally invasive surgery, for repair and overhauling of space stations and in the food industry [5–8]. Automation of industrial robots includes the grasping and manipulation of fragile and complex shapes [9–11].

Without grippers, industrial robots are of no use. Each hybrid manufacturing sector can manufacture more than one component [12] so each robots must be able to grasp and manipulate multiple objects of varying shapes and sizes. The design and development of grippers is the subject of current study.

Grippers that were initially used in industry used hard materials [13]. These hard grippers often damage fragile objects and impose many fabrication constraints [14, 15], so various soft grippers have been developed using advanced materials. Soft grippers have a lower actuation energy than hard grippers [16]. Shintake et al. [17] classified soft robotics into three categories: gripping by actuation, gripping by controlled compliance, and gripping by adhesion. Actuation-based grippers are widely used due to the low cost of fabrication and ease of handling [18].

Soft grippers often encounter stability-related issues [19, 20]. Robotic arms need to accelerate and decelerate rapidly at 10–100 m/s^2 with the operational speed of 2–10 m/s. This agility is crucial for maintaining high productivity. However, soft grippers are often dealt with curling and twisting due to rapid inertial inputs [19]. Moreover, they also lose stability due to disturbances in industrial environments, thus lacking long-term robustness. To overcome the issues with soft grippers, this study proposes gripper made up of multi-material that caters to higher strength and flexibility at the same time. The hard material in the gripper delivers required stability and stiffness to resist curling and twisting at rapid inertial inputs. This provides optimized grasping, manipulation, and excellent stability against disturbances. The combination of these two materials will increase the strength of the gripper and maintain its shape when the gripper receives large pressure. Addressing this issue along with good compatibility between hard and soft resin has resulted in excellent lifting efficiency. (Lifting efficiency is defined as the energy input that is required to lift a unit gram of object.)

Conventional fabrication of a gripper requires the assembly of hard and soft components that are manufactured separately. However, this process is time-consuming and requires an accurate assembly. A manual assembly process lacks accuracy and precision. Multi-material additive manufacturing (MMAM) is used to deliver specific properties without the need of assembly or joints [21, 22]. The composition of materials can also be adjusted to obtain specific properties.

Shaukat et al. classified the multi-material vat photopolymerization techniques into 3 types [21]:

1. Changing the resins during printing
2. Printing one resin formulation while selectively activating photoreactions by changing the light source (layer-by-layer) during 3D printing
3. Printing one resin formulation while selectively activating photoreactions by changing the light source (layer-by-layer) during 3D printing

Of these three categories, our newly built 3D printer comes under the 1st category wherein the resins are changed during the printing process. The first ever multi-material 3D printer using vat photopolymerization technology was built by Maruo et al. in 2001 [23]. This technology utilized two polymer resin-dosing pumps to purge the resin onto the vat where printing process took place. Though this printer successfully fabricated the multi-material samples, the quality of the print was bad due to inaccuracy of printing and contamination. Moreover, the sequential purging, printing, and cleaning was considered very slow and time-consuming [23]. A similar yet simpler technology was developed by Choi et al. in which the vat is intermittently removed and the resin is withdrawn [24]. Followed by the withdrawing of resin A, the vat is cleaned and the predetermined volume of resin B is purged using the syringe. This technology proved efficient in terms of accuracy and quality of print [24]. However, it consumed a lot of time in removing the vat, withdrawing the resin, and purging the new resin after every layer of print.

Later, Wicker et al. developed the carousel assembly wherein different vats are made to rotate to print different materials [21]. Compared to previous technologies, this printer provided faster fabrication of samples. However, the rotation of vats created internal turbulence in the resins which posed stability-related issues. Moreover, due to its top-down light scanning technology, the platform is largely immersed into the resin volume and the 3D printing structures are built along the z-axis [21]. Such a printing process greatly enhances the chances of contamination and resin trapping within the confined areas of 3D printed architectures, ultimately making it difficult to wash and perfectly clean the material during the printing steps. In 2013, Zhou et al. proposed multi-material SLA printing using a bottom-up approach [25]. With this setup, the contact between the building platform and liquid resin was minimized and only cleaning of those parts of the structure that are in direct contact with the resin was required. However, their technology of multi-material 3D printing continued to rely on carousal-based vat changeover which created stability-related issues [25]. In the current study, a bottom-up approach of printing technology is adopted wherein the build platform is rotated with ideal vats. This approach adds stability to the printing as large volume vats filled with resins are not moved after every layer. Moreover, this technology also provides an intermediate cleaning vat which helps in preventing contamination after every layer. The currently developed technology is closely resembled to the 3D printer developed by Hu et al. [26]. However, Hu et al. utilized a linear motion of build platform and placed cleaning and drying vats at the last [26]. Due to this placement, the build platform has to travel to the corner of the setup after every layer being printed. In the current study, the rotation motion of build platform is adopted and the cleaning tank is placed in the middle of the resin tanks which minimizes the travelling distance of the build platform after every layer. This saves a lot of printing time and hence the name high-speed 3D printer.

In the current study, the pneumatic soft gripper features alternate layers of soft and hard material to optimize stability, grasping, and manipulation. This pneumatic gripper is fabricated using the novel high-speed 3D printer as explained earlier. The tensile specimens are fabricated using the 3D printer to determine the mechanical properties. The bond strength between the soft and hard materials is determined in terms of the properties of the soft and hard materials. The percentage shrinkage is measured to determine the compatibility of GC3D-HSK and AA-temp materials. The pneumatic soft grippers are fabricated and assembled. The fabricated pneumatic soft gripper is then tested for its grasping and manipulating abilities using objects of various sizes, weights, and profiles. Multi-material pneumatic soft grippers feature less twisting and increased the grasping and manipulation efficiency.

2 Material and methods

2.1 Soft and hard material

The soft and hard materials are selected to produce the specified mechanical properties for the printed component. The hard material renders the printed parts stable against fast motion, acceleration, and deceleration and the soft material features high elastic deformation, low stiffness, and good adhesion and ductility [27]. The materials are also reasonably priced and are easy to obtain. The hard material is light-curing resin AA-Temp (Yang Ming Digital Dental Co., Ltd., Taipei, Taiwan) and the soft material is light-curing resin GC3D-ESK (Gold Chain International Co., Ltd., Taoyuan, Taiwan).

AA-Temp is a biomedical light-curing resin with a high bending strength and minimal shrinkage and allows good biocompatibility after light curing. The mechanical performance is better than that for typical acrylic PMMA and it can be used in VP-type 3D printers.

GC3D-ESK is an acrylic light-curing resin. The mechanical properties of this resin are very similar to that of polyurethane. The material exhibits excellent toughness and resilience properties when it is cured using light.

2.2 Design for soft pneumatic grippers

The dimensional details of the gripper for this study are shown in Fig. 1. The d gripper consists of three clamping jaws with an angular separation of 120°. All three clamping jaws are connected to the upper bracket, as shown in Fig. 1c. Each clamping jaw consists of 12 GC3D-ESK hollow air chambers. The jaw support structure is printed using a 1-mm-thick AA-Temp, which can be bent without suffering excessive elongation or deformation.

The cross-section of the outer air chamber is printed using GC3D-ESK to produce an elastic mask, which allows elastic deformation when air pressure is applied. When the pressure in the air chamber increases, the structure is stretched so the clamping jaws bend in the opposite direction to that of the upper air chamber and fit the shape of the object.

2.3 Multi-material additive manufacturing

Figure 2a shows a schematic diagram of the high-speed multi-material VP 3D printer. The 3D printer consists of a platform, a rotating screw system, and a power source. As shown in Fig. 2a, the platform consists of multiple resin vats and a cleaning vat. The rotating system holds the build plate that can be raised and lowered along the Z-axis using a rotating screw mechanism. The light source is also attached to this rotating screw system to align the build plate and the rotating screw along the same vertical axis.

Figure 2b shows the working principle of the developed machine. This study uses two resin materials (AA-temp and GC3D-HSK). Figure 2b shows two resin vats (vat A and vat B). Vat A is filled with AA-temp resin and Vat B is filled with GC3D-HSK soft resin. A cleaning vat between the two resin vats is used to clean the printed sample when each layer is added. Figure 2c shows the construction and operation of the cleaning vat, which consists of 9 nozzles that

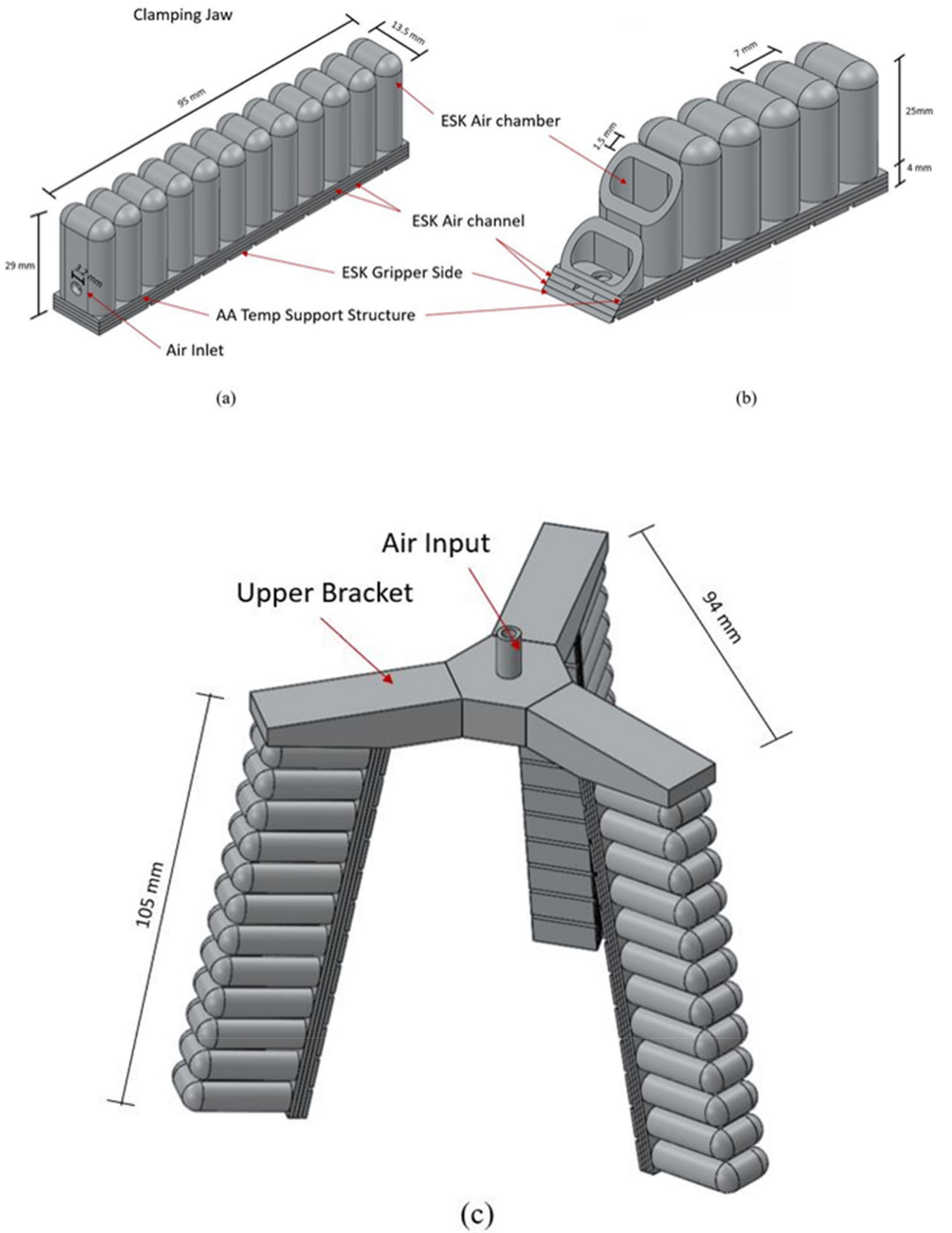


Fig. 1 The proposed pneumatic soft gripper: **a** clamping jaw, **b** cross-section of clamping jaw, and **c** complete pneumatic soft gripper

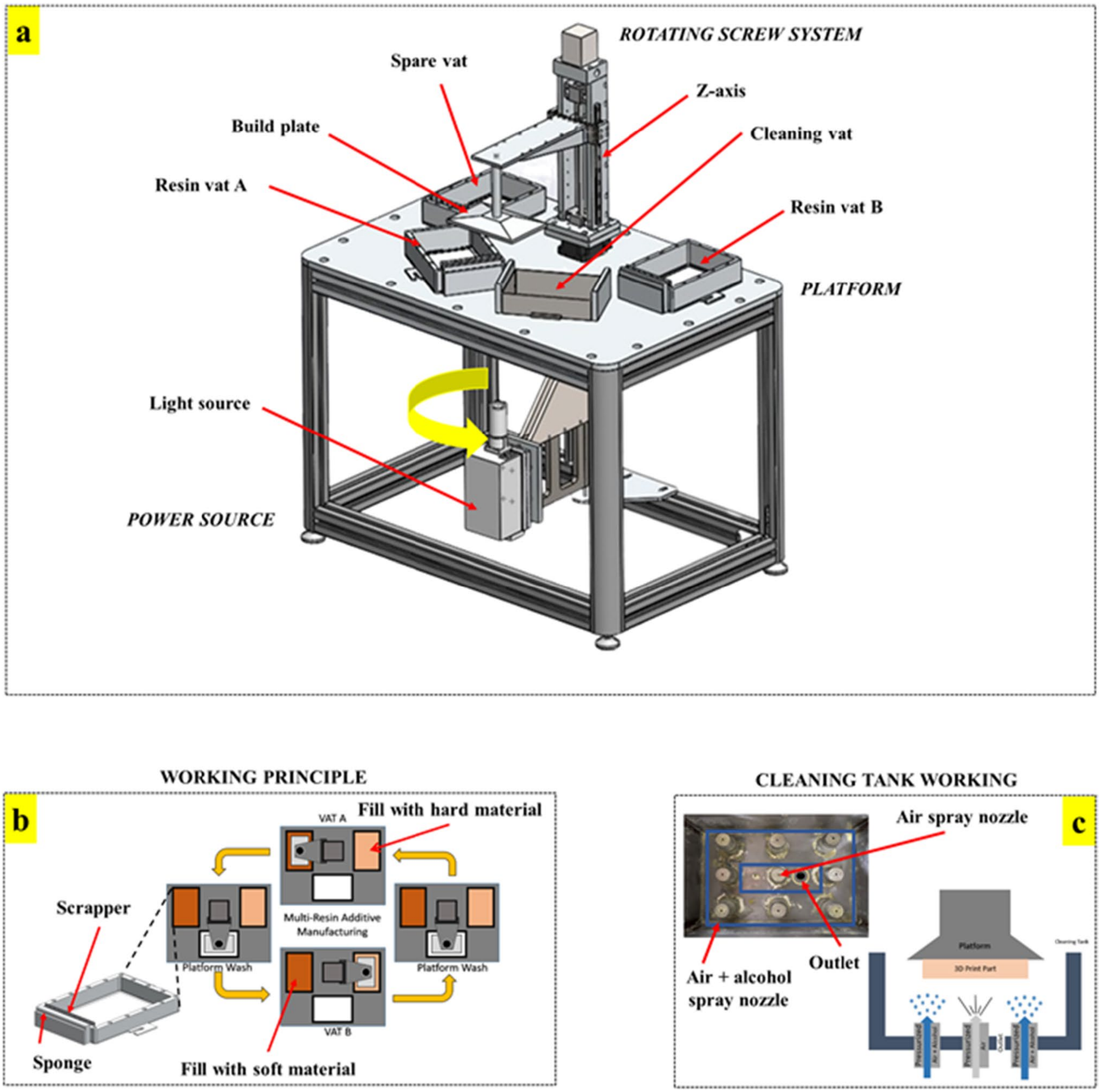


Fig. 2 A schematic diagram of the high-speed multi-material VP 3D printing: **a** operating principle of the printer and **b** construction and working principle of the cleaning vat

spray air and alcohol. The pressure of the air is maintained to clean the sample after each layer is printed, without damaging it. The cleaning vat also features an outlet to flush the residual alcohol, as shown in Fig. 2c.

Figure 2b shows that the build plate is initially washed in the cleaning vat to avoid contamination. The plate then rotates towards Vat A to print a single layer of hard material and then the build plate rotates to wash the built layer. The plate then rotates towards Vat B to print the soft material. This process continues until the sample is completely printed.

Figure 3a shows the high-speed multi-material VP 3D printer, which was developed at the National Taipei University of Technology. The operation of the 3D printer is demonstrated in Fig. 3b. State "1" corresponds to Fig. 3b and is the position from which the build plate moves down towards Vat-A, which is filled with AA-temp resin. When a single layer of AA-temp is cured, the build plate rises to state "2."

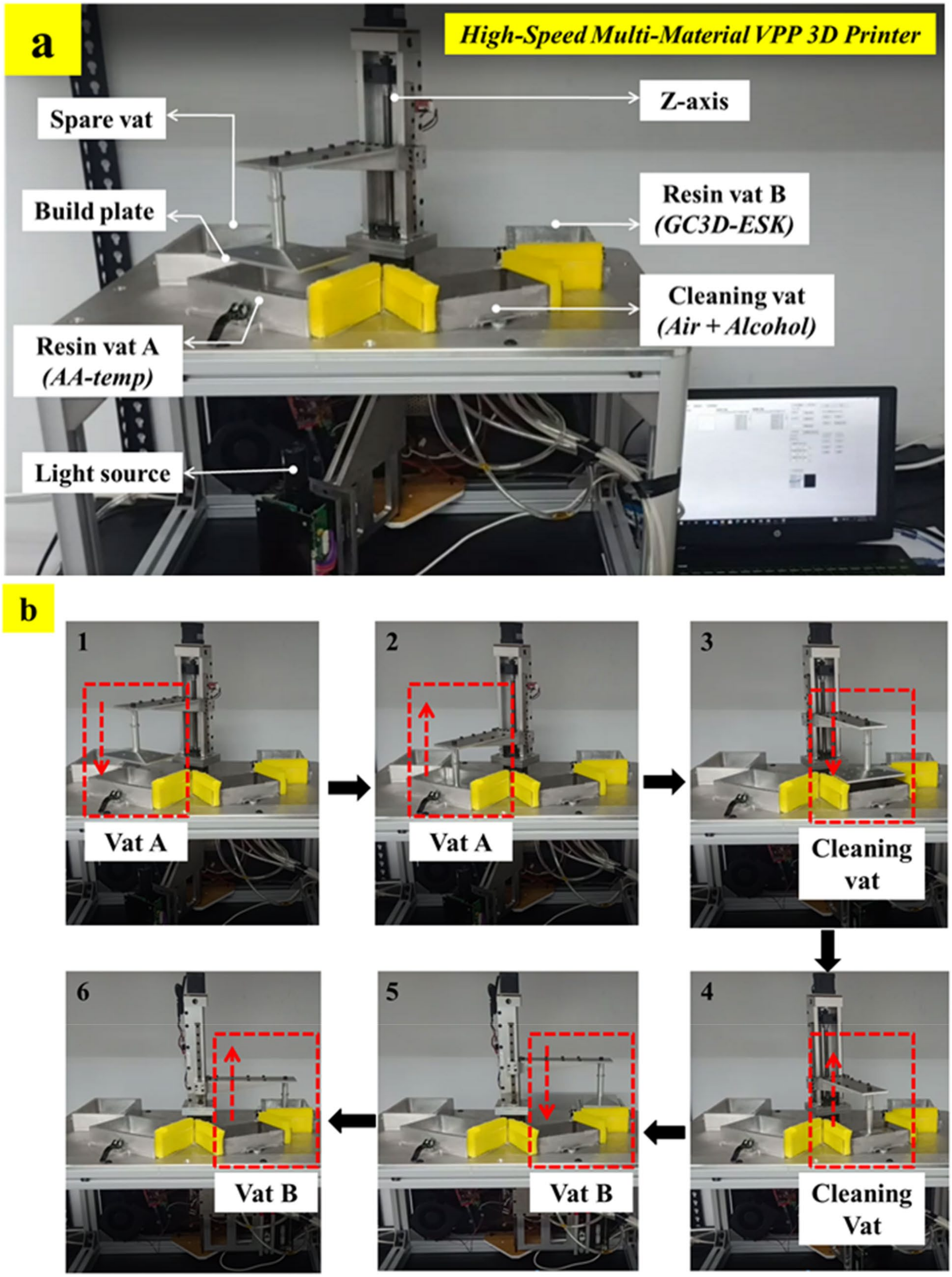


Fig. 3 High-speed multi-material VP 3D printer: **a** construction and **b** 3D printer operating

Table 1 Printing parameters for soft GC3D-HSK and hard AA-Temp materials

Parameter	Soft material (GC3D-ESK)	Hard material (AA-Temp)
Base layer (pcs)	10	10
Base exposure time (s)	45	30
Exposure time (s)	11	4
Layer thickness (μm)	100	100

The rotating system rotates by 45° to clean the built layer. State "3" involves the build plate descending towards the cleaning vat and state "4" corresponds to the build plate rising after cleaning. When the AA-temp layer is cleaned, the rotating system rotates by another 45° to print the GC3D-HSK material. States "5" and "6" involve the printing of the soft material (i.e., GC3D-HSK resin). The process is continued until the entire sample is completely printed.

2.4 Additive manufacturing and measuring the mechanical properties of hard and soft materials

All specimens were fabricated using the printing parameters that are shown in Table 1. The hard and soft materials were printed using a layer thickness of 100 µm. The translucence of the two materials affects the exposure time for each material. AA-temp has a brighter color than GC3D-ESK so it requires a shorter exposure time.

The mechanical properties of the additive-manufactured AA-temp and GC3D-ESK materials were measured using a tensile test machine (Universal Testing Machine CY-20, Chun-Yen Co., Taichung, Taiwan). The tensile specimens comply with ASTM D638 Type IV standards. Dual material specimens were also prepared to determine the bonding strength between the two materials, as shown in Fig. 4. The tensile data for each material is for five specimens and is sued to determine various mechanical properties. Young's modulus (E) for each material is calculated using Eq. (1):

$$E = \left(\frac{\Delta_p}{A_0}\right) / \left(\frac{\Delta_c}{L_0}\right) \tag{1}$$

where Δ_p is the increase in load, A_0 is the cross-sectional area, Δ_c is the increase in the extension, and L_0 is the original length of the specimen. The tensile test compares the mechanical properties of the multi-material 3D printed sample with those for the individual soft and hard materials. This study also determines the effect of various cleaning treatments at joints between the two materials on their mechanical behavior.

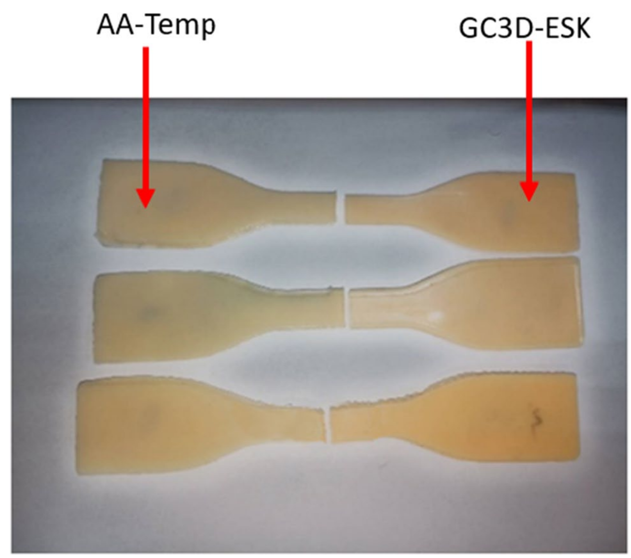


Fig. 4 Tensile specimen using soft and hard materials that is printed using high-speed multi-material VP 3D printer

The rigidity of each material was measured using a shore hardness machine (LX-D, Wenzhou Measuring, Wenzhou, China). Five specimen pieces with dimensions of 12 mm × 10 mm × 5 mm were produced and the average hardness was measured by indenting at least five points on each specimen.

2.5 Post-curing and shrinkage test

After printing, the green part was exposed to ultraviolet light in a chamber (Phrozen Cure, Phrozen Technology, Hsinchu, Taiwan) for 1 min. This chamber has UV light installed around the chamber with a total of 60 W output power. To ensure that all sides of the part are equally exposed, the green part was placed on a rotating plate that rotates through 360° during the post-curing process. Five specimens with dimensions of 12 mm × 10 mm × 5 mm were used to determine the shrinkage to ensure that the printed multi-material parts comply with industrial standards. Any error in the printing, such as improper layers or contamination, produces excessive porosity, which causes excessive shrinkage post-curing so this test ensures that the gripper is properly printed.

2.6 Grip angle and gripping test

For this study, the grasping strength of the multi-material gripper that was fabricated using the 3D printer was measured as a pressure using a manual pneumatic gauge. The clamping jaw bends and increases the pressure to grasp the object. The bending angle for the gripper was measured using an angle gauge. This bending angle is used to determine the ability of the printed soft gripper to clamp.

3 Results and discussion

3.1 Mechanical properties of the 3D printed parts

The mechanical properties of the multi-material 3D printed parts are compared with those for the 3D printed hard (AA-Temp) and soft materials (GC3D-HSK). Table 2 shows the various properties of the soft, hard, and multi-material parts. The hard material (i.e., AA-Temp) features greater load-bearing properties, such as tensile strength, Young's modulus, and hardness. The soft material (GC3D-HSK) exhibits greater elongation. The load-bearing and elongation properties of the multi-material parts are between those of AA-Temp and GC3D-HSK. This study also shows that the tensile strength values for the multi-materials parts increase if alcohol and pressurized air are used because contamination is reduced after printing each layer. This absence of contamination increases the bond strength between the different materials and prevents delamination between the layers [28].

The tensile strength of AA-Temp (hard material) is the greatest, at 24.6 MPa as shown in Fig. 5a. The tensile strength of the soft material (GC3D-HSK) is only1 MPa. The multi-material printed part (without alcohol cleaning) has a 5-times greater tensile strength, with a value of 5 MPa. Figure 5a shows that the tensile strength of the multi-material that is subject to alcohol cleaning is 4% greater. Young's modulus varies similarly to tensile strength (Fig. 5b).

Figure 5c shows the percentage elongation, which represents the ductility (flexibility) of the 3D printed parts. The soft material (GC3D-HSK) is elongated by 48.4% and the hard material (AA-Temp) is elongated least, at 3.4%. The elongation percentage for the multi-material with alternating soft material layers is 65% greater than the value for AA-Temp and the use of alcohol increases ductility by 30%. The tensile test results indicate that using multiple materials can enhance the strength of a single soft material. Compared to the previous research [16], this result provides concrete evidence that a multi-material approach effectively enhances performance compared to using a single soft material.

3.2 Post curing—shrinkage test

Ultraviolet radiation is used to cure the materials and causes shrinkage. Excessive shrinkage negates the use of newly developed 3D printer for industrial applications so a shrinkage analysis of the printed samples is used to determine the feasibility of the printer. Alternating soft and hard layers are printed together so different shrinkage ratios generate residual stresses in the samples. Excessive residual stress distorts the printed components. Determining the shrinkage for each sample also shows the printing consistency for the machine. To measure the shrinkage along the X, Y, and Z axes, five specimens of soft GC3D-HSK and hard AA-Temp materials were printed using the printer.

Tables 3 and 4, respectively, show the printed, post-curing, and shrinkage results for GC3D-ESK and AA-Temp. The respective average shrinkage ratios for GC3D-ESK and AA-Temp materials along the X, Y, and Z directions are 0.17%, 0.18%, and 0.16% and 0.10%, 0.08%, and 0.08, respectively. Tables 3 and 4 show that the shrinkage ratio for these materials is very similar so there is less distortion and warping.

The printing direction affects the degree of shrinkage after curing and can cause non-uniform shrinkage [29–31]. This necessitates a design tolerance. However, the experimental results for this study show uniform shrinkage in all directions so the resins are sufficiently cured during the printing process and no design tolerance is necessary. Even though it is not directly related to shrinkage, post-curing can increase the maximum tensile strength of the material [29, 32] .

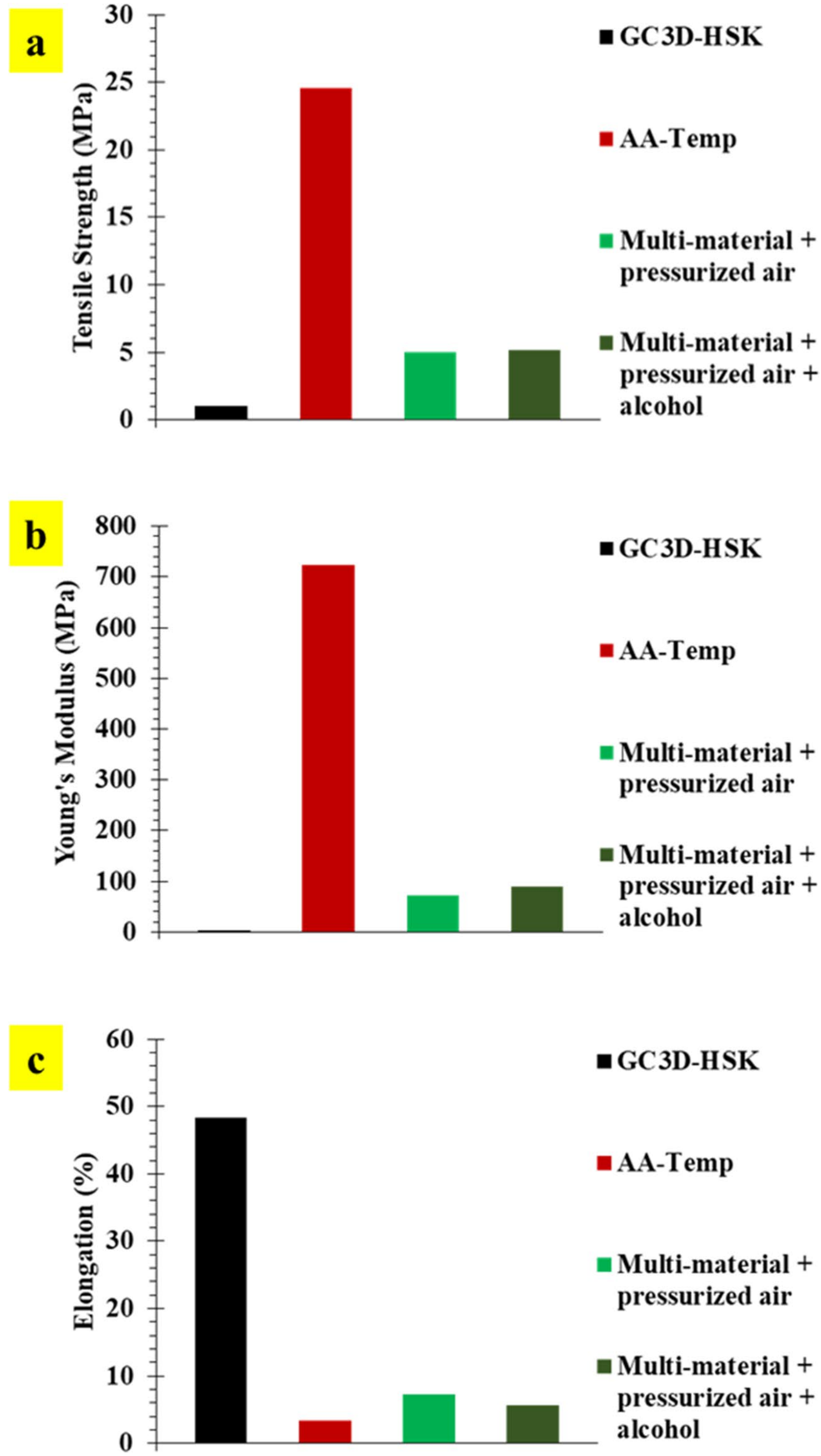
3.3 Grip angle and gripping analysis

A pneumatic soft gripper was fabricated using a high-speed multi-material VP 3D printer that produces alternating layers of soft and hard materials. The outer layer consists of soft material so it can grasp and manipulate fragile objects. The inner hard layers increase the stability of the gripper by preventing excessive twisting. This gripper resolution is relatively high compared to the other 3D printing fabrication methods such as FDM [33–35] and SLS [19]. The gripper consists of three clamping jaws with

Table 2 Mechanical properties of parts that are printed using the high-speed multi-material VP 3D printer

	Single material (GC3D-ESK)	Single material (AA-Temp)	Multi-material (pressurized air + alcohol)	Multi-material (pressurized air)
Tensile strength (MPa)	1.0	24.6	5.2	5
Elongation (%)	48.4	3.4	7.3	5.6
Young modulus (MPa)	2.08	723.6	71.23	89.28
Hardness (Shore D)	16	80	-	-

Fig. 5 Mechanical properties of parts that are printed using the high-speed multi-material VP 3D printer: **a** tensile strength, **b** % elongation, **c** Young's modulus



an angular separation of 120°. Figure 6 shows the deformation of the clamping jaw for a pressure of 0 kPa, 9.8 kPa, 19.6 kPa, and 34.3 kPa. The maximum angle of 50° is achieved using a pressure of 34.3 kPa, but for this study, a pressure of 19.6 kPa is sufficient for gripping.

This study uses cherry tomatoes as a model of soft material. As shown in Fig. 7, the gripper lifts the cherry tomato without damaging the surface. Various other materials/objects were also used to test the gripping strength of the grippers. Figure 8 shows the grippers lifting several materials with

Table 3 Shrinkage for the soft material (GC3D-ESK)

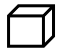
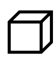
	Dimension (wxdxh): 12x10x5 (unit:mm)	Soft Material (GC3D-ESK)					
		1	2	3	4	5	Average
Printed Part	X (mm)	12.01	11.99	11.98	12.02	12.00	12.00
	Y (mm)	10.06	10.04	10.05	10.03	10.07	10.05
	Z(mm)	5.03	4.99	5.01	5.01	4.99	5.01
Post Curing	X (mm)	11.99	11.97	11.96	12.00	11.98	11.98
	Y (mm)	10.04	10.03	10.03	10.01	10.05	10.03
	Z(mm)	5.03	4.98	5.00	5.00	4.98	5.00
Shrinkage	X (%)	0.17%	0.17%	0.17%	0.17%	0.17%	0.17%
	Y (%)	0.20%	0.10%	0.20%	0.20%	0.20%	0.18%
	Z(%)	0.00%	0.20%	0.20%	0.20%	0.20%	0.16%

Table 4 Shrinkage for the hard material (AA-Temp)

	Dimension (wxdxh): 12x10x5 (unit:mm)	Hard Material (AA-Temp)					
		1	2	3	4	5	Average
Printed Part	X (mm)	12.00	11.98	12.00	12.01	11.99	12.00
	Y (mm)	10.01	10.03	9.98	9.98	10.00	10.00
	Z(mm)	5.01	4.98	5.00	5.00	4.99	5.00
Post Curing	X (mm)	12.00	11.97	11.98	11.99	11.98	11.98
	Y (mm)	10.00	10.02	9.98	9.97	9.99	9.99
	Z(mm)	5.00	4.97	5.00	5.00	4.99	4.99
Shrinkage	X (%)	0.00%	0.08%	0.17%	0.17%	0.08%	0.10%
	Y (%)	0.10%	0.10%	0.00%	0.10%	0.10%	0.08%
	Z(%)	0.20%	0.20%	0.00%	0.00%	0.00%	0.08%

different shapes and weights. The maximum weight that the pneumatic soft gripper can lift is 200 g. The pressure that is applied to the clamping jaws increases linearly with the weight that is lifted by the gripper. The maximum pressure that is produced by the air chamber is 34.3 kPa.

In the current study, the concept of lifting efficiency is proposed which can be defined as the energy requirement by the gripper to lift an object of unit weight. Table 5 evaluates the lifting efficiency of the newly developed multi-material pneumatic gripper with the previously reported ones. It can be observed from Table 5 that the currently designed gripper delivers the highest lifting efficiency of 5.83 g/kPa. Such a high value is obtained due to good compatibility between hard and soft materials. Moreover, the efficient cleaning phase after successive layer printing reduces the contamination to a great extent. Furthermore, the presence of hard

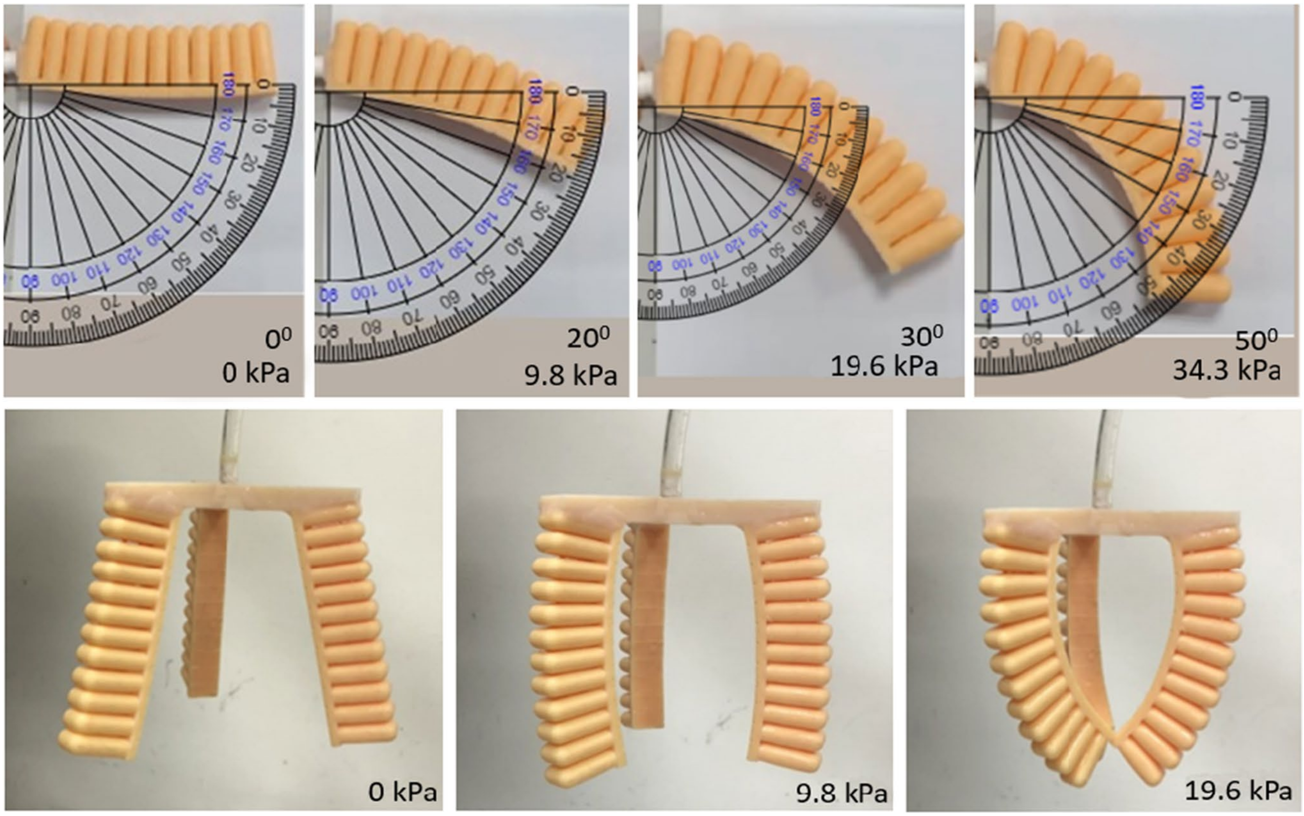


Fig. 6 Bending test for the multi-material gripper using different pneumatic pressure

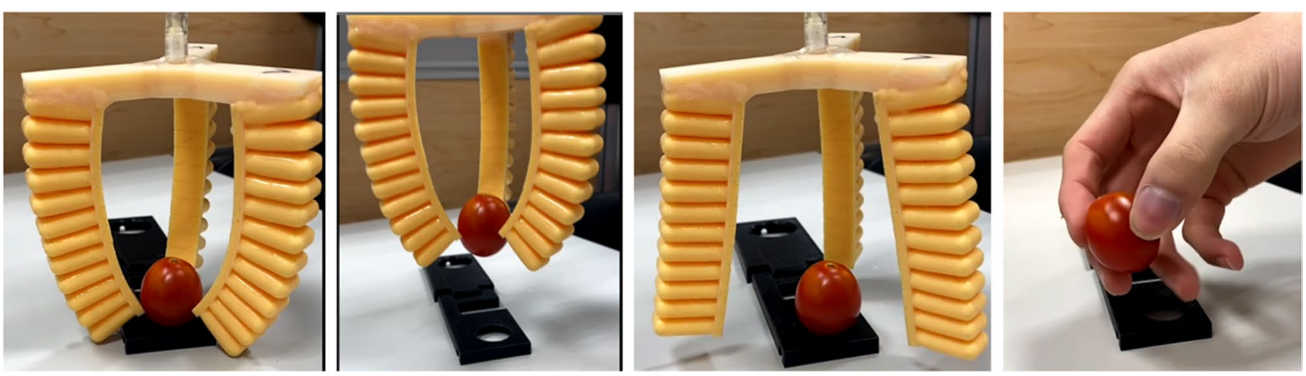


Fig. 7 Demonstration of grasping and manipulation for the multi-material pneumatic soft gripper, which results in no damage to the surface of a cherry tomato

material also adds enhanced stability to the gripper. All these factors lead to the higher lifting efficiency.

The use of soft materials in the gripper design enables flexibility in the handling process. The soft material enables the gripper to conform more efficiently to the contour of the object, maximizing surface contact and minimizing the risk of damage or deformation to the object being held.

In addition, gripper designs equipped with segments can offer additional benefits. These components play a crucial role in preventing slippage during the lifting process. With a flexible structure, the gripper becomes more effective at maintaining stability and balance when interacting with objects of various shapes. This enhances the safety and reliability during the gripping process.

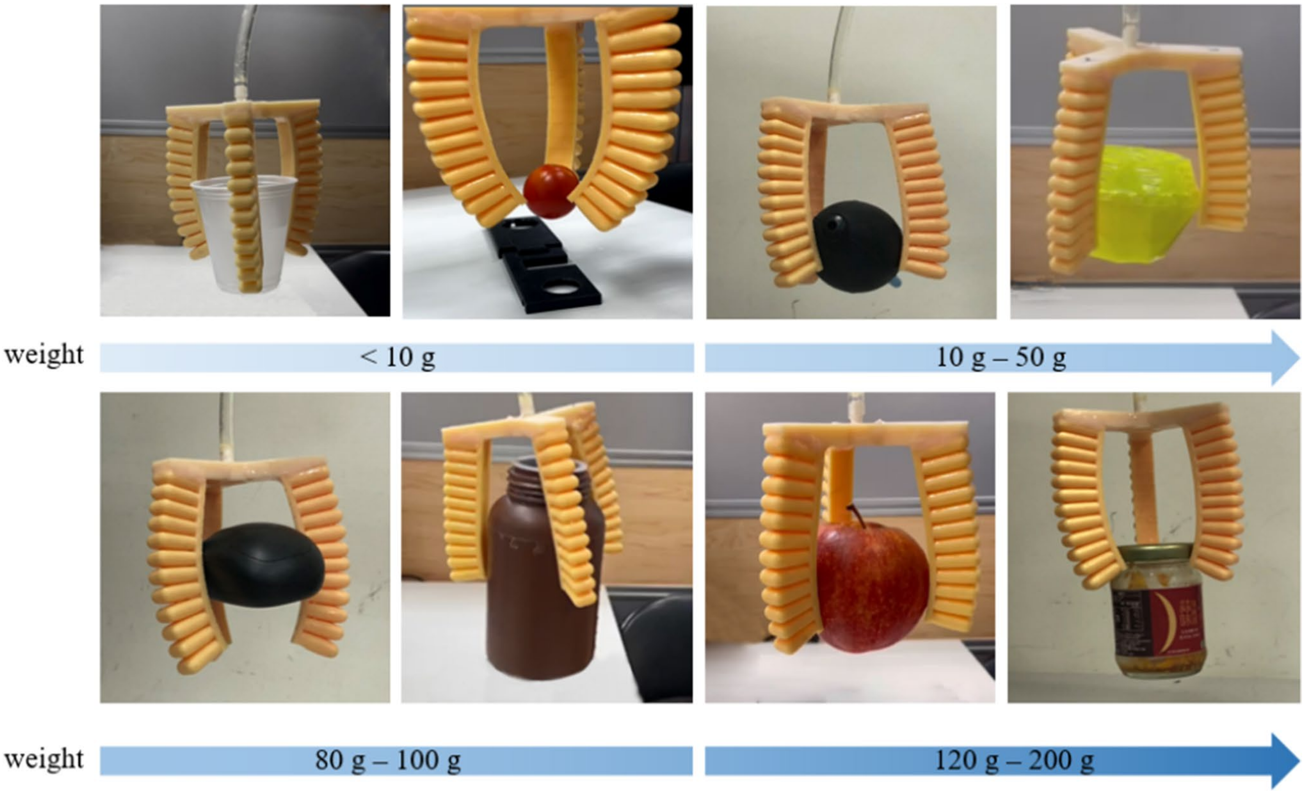


Fig. 8 Grasping and manipulation of different objects with different sizes, weights and profiles

Table 5 Lifting efficiency comparison of this gripper with other developed grippers

Authors	Materials	Additive manufacturing process	Maximum pressure (kPa)	Lifted weight (g)	Lifting efficiency (g/kPa)
Zhong kui Wang and Shinichi Hirai [36]	Soft—TangoBlack+ Hard—VeroWhite	Material jetting	40	50	1.25
Tawk et al. [15]	TPU	Material extrusion	150	198	1.32
Ding et al. [37]	Soft—RTV-2 silicone rubber Hard—PA-12 nylon	Selective laser sintering	150	10.2	0.068
			100	90.5	0.905
			40	73.4	1.835
			110	105.3	0.957
			110	580	5.272
Wang et al. [38]	0.6% NaOH + 3% Carbomber ETD 2020	Direct ink writing	25	8.4	0.336
			60	23.1	0.385
			70	46.5	0.664
			80	50	0.625
			30	20	0.666
This study	Soft—GC3D-HSK Hard—AA-Temp	Vat photopolymerization	34.3	200	5.83

4 Conclusions

This study develops a multi-material vat photopolymerization-based 3D printer for high-speed fabrication. A cleaning system is developed to prevent contamination between each layer and to increase the bond strength. The properties of multi-material parts can be tuned for specific requirements. The fabricated multi-materials feature optimized mechanical properties and flexibility. The tensile strength and flexibility of the multi-materials, respectively, increase by 4% and 30% after cleaning with alcohol. The shrinkage shows that the shrinkage for both materials is only 0.1–0.2%. The hard AA-temp and soft GC3D-HSK materials are compatible with each other because they feature a similar shrinkage percentage. Negligible shrinkage during post-curing also shows that the developed printer cures correctly (the percentage of residual resin requiring further curing is extremely low).

The developed printer is used to fabricate a pneumatic soft gripper using hard AA-temp and soft GC3D-HSK soft resin materials. The printed gripper addresses the problems of grippers that are constructed using soft materials, such as excessive twisting and instability due to acceleration and deceleration. The multi-material gripper grasps and manipulates objects of varying weights, shapes, and sizes and the pressure that is applied prevents damage to the surface of delicate and fragile objects. The gripper lifts a 200-g object using a pressure of 34.3 kPa which accounts for a lifting efficiency of 5.83 g/kPa.

The clamping jaws of the gripper bend to a maximum angle of 50° using a pressure of 34.3 kPa. The gripper grasps and manipulates various profiles of different sizes. These grippers have extensive applications in smart manufacturing using autonomous robotics to achieve the goals of Industry 4.0.

This study is limited to demonstrating the working principle of the novel 3D printer and fabricating a pneumatic soft gripper but future studies might fabricate tunable lattice structures. The infinite design and fabrication freedom that is delivered by this printer and the high consistency and speed will allow the development of a multi-tessellated, multi-material lattice structure for structural and flow applications.

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Declarations

Competing interests The authors declare no competing interests.

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