





Additive Manufacturing of Soft Robots

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Abstract

Soft robotics is an emerging field in science and technology that extends the area of classical robotics to new types of applications. Soft robots uniformly conform to their objects in contact without damaging them, but also without being damaged themselves by these objects. In the field of pneumatic soft robots, the classical production method is silicone injection molding. This method, however, is only economical for relatively large batch sizes. In this context, additive manufacturing (and especially silicone 3D printing) offers a promising alternative for small and medium batch sizes. In this paper, we describe the technology of silicone 3D printing, discuss the way to develop a comprehensive design compendium, and present the application of first design guidelines using an illustrative example.

Keywords

Soft robotics • Additive manufacturing • Silicone 3D printing • Design guidelines

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1 Introduction

Soft robotics is a relatively young emerging field in robotics that deals with the design, fabrication, and control of soft structures [1–3]. Often inspired by skeletonless biological archetypes [4], soft robots have the ability of not damaging their environment [5], but also not being damaged by the environment themselves [6].

The application areas of soft robots typically involve interaction with a soft (living or nonliving) structure. Soft grippers, for example, can be used to grasp unknown or fragile objects [7]. And soft exosystems, for example, can be used to help rehabilitate humans [8]. Other application areas include soft surgical instruments [9], locomotion systems for unknown and unstructured environments [10, 11], and human–machine interfaces [12].

Pneumatically driven soft robots are usually manufactured using silicone injection molding [13]. However, this process requires investments in tooling and fixture construction, which are only profitable for medium and high batch sizes. However, if small quantities, individualized products, or prototypes are required, it is desirable for the soft robotic structure to be manufactured by additive manufacturing (also known as 3D printing) [14–16]. While other additive manufacturing technologies for silicones may become available in the future, extrusion technologies can currently be considered to be the forerunner. For this reason, we focus exclusively on extrusion-based silicone 3D printing in this paper.

The paper is organized as follows. After a brief introduction to (extrusion-based) silicone 3D printing in Sect. 2, a strategy for the development of design guidelines is presented in Sect. 3 in order to strengthen the acceptance of this technology in the industry. A case study in Sect. 4 demonstrates the application of first already developed guidelines and shows the potential of silicone 3D printing in soft robotics. Section 5 concludes this work and gives recommendations for future research.

2 Silicone 3D Printing

Several methods for additive manufacturing of soft robots have been reported in the literature so far, such as fused deposition modeling [17], selective laser sintering [18], stereolithography [19], as well as polyjet technology [20]. However, these methods use materials that do not have the desired elasticity and Shore hardness. For this reason, the authors suggest using (extrusion-based) silicone 3D printing for the production of the pneumatic structure of a soft robot, as it can process real silicones with low Shore hardnesses and high elongations at break.

2.1 Technology Description

Material extrusion processes utilize an extruder assembly and a nozzle to extrude a continuous strand of material onto a build platform. Although the silicone 3D printing process shares many similarities with the popular fused filament fabrication (FFF) process, the feedstock is not a filament but a liquid, which has a much higher viscosity when it is deposited compared to polymers that are typically used in FFF. This has significant implications for the process characteristics as well as the available freedom of design. Therefore, silicone 3D printing has to be viewed separately from the FFF process.

The number of available silicone 3D printing systems is still limited. So far, only three manufacturers offer systems that can be considered as ready for first industrial applications:

- LiQ320 3D printer (InnovatiQ, Germany) [21],
- S600D 3D printer (Lynxter, France) [22],
- Delta Tower Fluid (Deltatower, Switzerland) [23].

While all three systems use the same extruder system from ViscoTech (Germany) [24], the individual processes as well as the offered materials are slightly different. Attached to the extruder is a disposable static mixer (e.g., from Vieweg GmbH, Germany [25]) and a nozzle to deposit the material strand with the desired diameter. Both items are relatively low-cost and have to be regularly replaced. Nozzles are available with diameters ranging from 0.06 to 2 mm.

Like most other additive manufacturing processes, silicone 3D printing is a layer-based process where the same basic steps are repeated for each layer. The process consists of two main steps and some additional pre- and post- processing steps, which may vary between the three systems. Figure 1 illustrates the individual process steps using the LiQ320 system as an example. This system is used to develop the first design guidelines and the case study presented in this paper.

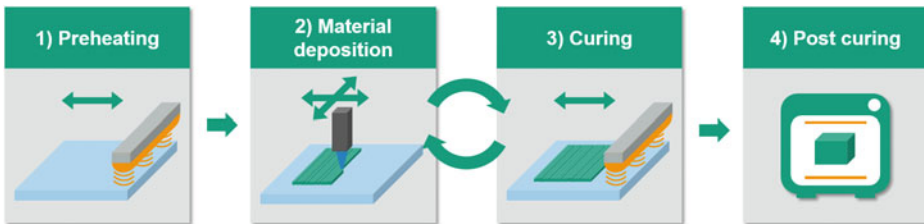


Fig. 1 Process steps of (extrusion-based) silicone 3D printing

- (1) **Preheating:** At the beginning of the process, the ceramic build plate of the printer is preheated. This is done with a curing lamp, which can reach temperatures of up to 2000 °C. The lamp is directly attached to the extruder kinematics. The speed and travel distance of the lamp are usually defined by the settings for Step 3 and can thus be seen as a preliminary curing cycle. Since only InnovatiQ uses a heating lamp to accelerate the curing process, this step is not required for the other two systems.
- (2) **Material deposition:** The kinematics of the printer are used to move the extruder along a predefined path. Along this path, a strand of material is extruded. The first layer is deposited directly onto the build platform, while each following layer is then deposited onto the previous one.
- (3) **Curing:** After placing of each layer, the heating lamp moves across the build platform. The high temperature of the lamp accelerates the curing process of the silicone to a point where it hardens almost instantly.
- (4) **Post curing:** To obtain the best component properties and ensure the silicone to be fully cured, it is advisable to include a final curing step inside an annealing oven as a final process step.

2.2 Processible Materials

In theory, it is possible to process any fluid or paste with extrusion-based 3D printing systems. There are, however, two limiting factors to be considered. The first one is the viscosity of the material after it is deposited onto the build platform, and the second one is the curing speed of the material. A material is only suitable for an extrusion-based 3D printing process if it is liquid enough to be pressed through the nozzle and at the same time solid enough not to lose its shape immediately after it is deposited. In addition, the material must be able to cure immediately so that the individual layers can be quickly placed on top of each other, without flattening due to their own weight.

Regarding silicones, it is possible to process one- or two-component silicones. Both exhibit a hyperelastic and viscoelastic behavior. Here, ‘hyperelastic’ means that the material is nonlinear and can experience high strains and ‘viscoelastic’ means that it exhibits a combination of elastic and viscous properties.

Figure 2a shows the stress-strain diagram of a typical silicone material. We can see the typical S shape, which is why it is not possible to assign a unique Young’s modulus to such a material. Usually, the Young’s modulus is given for a certain strain (such as E_{50} for 50% or E_{200} for 200% strain).

Silicone materials also experience the so-called Mullins effect [26]. During the first loading cycles, polymer chains brake at the micro level, which leads to a permanent change in the elastomeric network [27]. Figure 2b shows the loading–unloading behavior of a typical silicone material illustrating this phenomenon. We can observe that, during

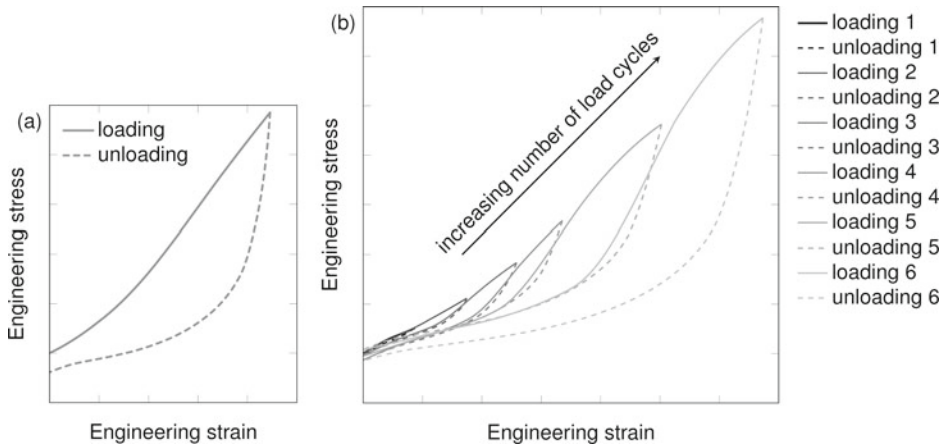


Fig. 2 Characteristic stress–strain behavior of silicone; **a** single deformation, **b** cyclic stepwise-increasing deformation

the first deformation cycles, the stiffness gradually decreases and the material response becomes more and more repeatable.

A major disadvantage of silicone materials, however, is their tendency to age, which leads to an increase in stiffness and thus embrittlement of the material. Environmental influences, such as temperature or various chemicals, can also accelerate aging [28].

3 Development of Design Guidelines

One of the most important arguments for using additive manufacturing (AM) is the great design freedom it has to offer. At the same time, this freedom is also the main reason why industrial applications have been rare so far. Just like any other manufacturing technology, AM technologies possess process-related restrictions that must be taken into account when designing a part. Considering these restrictions poses a particular challenge. Some design limits are common to all technologies, but others are unique for each single one.

To develop a comprehensive design compendium, there are many different design guidelines to be considered. To structure the development of design guidelines, they will be divided into two categories and two subcategories. The first category is *general design guidelines* that are relevant specifically for material extrusion technologies. They are independent from the manufacturing system or the material used. The second category is *specific design guidelines* that encompass all guidelines specifically relevant to the silicone 3D printing process.

Each category has the same two subcategories. The first one is *design for manufacturing*, which contains all guidelines describing the limitations of the manufacturing process.

In the case of general design guidelines, this subcategory describes rules regarding the staircase effect or the extrusion width, for example. In the case of specific design guidelines, it describes the characteristic values for process-related questions like “What is the minimum wall thickness?” and others. The second subcategory is *design for function*. Within this subcategory, coming from the intended application, design recommendations are given for realizing a specific function.

4 Case Study

The silicone gripper considered in this case study is a pneumatically actuated gripper with three fingers, as shown in Fig. 3 (see Fig. 7 for the actuated gripper). Each finger is approx. 50 mm long and consists of several air-filled chambers. Each chamber is 15 mm high, 15 mm wide, 5.2 mm deep, and has a wall thickness of 1 mm. The fingers are used simultaneously for gripping and can only be actuated together. They are arranged at 120° angles to each other and run together in a central connection, which can be directly plugged into a pressure source. Upon actuation, the air is distributed equally between all fingers. The gripper was originally designed for a multi-stage casting process [13] and is now to be redesigned in terms of silicone 3D printing. Since the functionality of the original component is already given, only design for manufacturing guidelines are relevant for the redesign.

4.1 Selection of Design Guidelines

The limitations of the casting process differ significantly from those of silicone 3D printing. Undercuts and cavities in particular are special challenges in the casting process. However, they are a basic requirement for producing a functional pneumatic actuator. The main challenges of pneumatic components suited for the silicone 3D printing process are the two following questions:

Fig. 3 Pneumatically actuated universal soft gripper

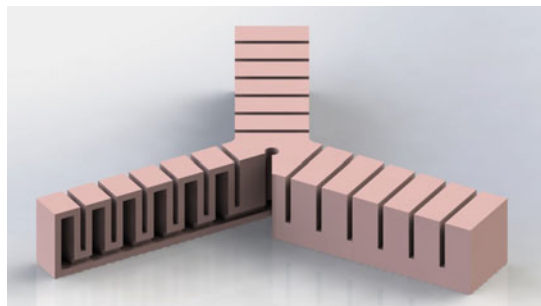
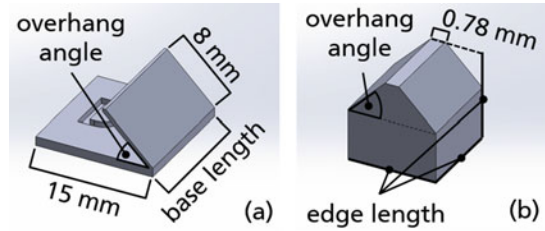


Fig. 4 Benchmark components for **a** identifying the minimum overhang angle and **b** determining the best configuration for a hermetically sealed cavity [29]



1. What is the minimum overhang angle for inclined surfaces?
2. Which wall thickness should be chosen to create airtight cavities?

In an experimental study conducted by the authors, two benchmark parts were developed and manufactured to determine the answers to these questions [29]. The first benchmark part is a solid base with an inclined wall, see Fig. 4a. This part is used to identify the minimum overhang angle and is thus printed in different configurations. The parameters varied are the overhang angle and the length of the wall. The second benchmark part consists of a cuboid with a prism on top that resulted in a test geometry of a house-like shape, see Fig. 4b. The geometry is hollow and is used to determine the best configuration for a hermetically sealed cavity. The wall thickness, the edge length of the cuboid, and the overhang angle are the relevant parameters that were varied for each of the printed benchmark parts.

The two developed design guidelines state [29]:

1. *Minimum overhang angle:* In general, overhang angles should be at least 50° . For continuous extrusion paths longer than 15 mm, angles between 40° and 50° are also feasible.
2. *Minimum wall thickness for hermetically sealed cavities:* For a 0.4 mm nozzle, the wall thickness should be at least 1.17 mm. This corresponds to at least three shells for an extrusion width of 0.39 mm (at an overhang angle of 45°).

Note that these two guidelines are only valid for InnovatiQ's LiQ320 3D printing system and Silastic 3D 3335 liquid silicone rubber from Dow Chemical (USA) and the minimum wall thickness for hermetically sealed cavities is angle-dependent (not analyzed here).

In addition to the specific design guidelines stated above, two general guidelines were also considered for the redesign of the gripper. The first guideline states that the wall thickness of thin walls should always be a multiple of the extrusion width. This avoids hollow areas (when the shells from the outside and the inside of the chamber wall are creating a gap that is too small for additional material) or material accumulation (when the shells from the outside and the inside of the chamber wall are overlapping) inside the chamber walls of the gripper.

The second general guideline states that very short extrusion paths should be avoided. This guideline is another design for manufacturing guideline to be considered for all material extrusion processes. Each time the print head stops to extrude material and moves to a new location, material has to be retracted inside the extruder to prevent excess material to leave the nozzle. This creates large pressure changes inside the extruder. Restarting the extrusion process creates a short time period where material is extruded unevenly. This can be minimized but is hard or even impossible to avoid completely. Therefore, the number of pressure changes should be kept minimal. Considering that, shells (also called perimeters) and infill structures should ideally consist of a single continuous path. This can be achieved by choosing a design with a consistent wall thickness and certain infill structures.

4.2 Application of Design Guidelines

To adapt the gripper to the requirements of silicone 3D printing, the critical areas of the original design have to be identified. For this purpose, the design features of a single actuator are analyzed. It consists of multiple hollow chambers connected to each other at their base. An air duct runs along the base, which guides the compressed air from the central connection into the individual chambers. The areas of the design to be adjusted are the horizontal overhangs and the wall thickness of the chambers (cf. Fig. 3).

In a first design iteration, the chambers were chamfered at the top to avoid horizontal overhangs. From the first specific design guideline described above, it is known that it is possible to manufacture an overhang angle of 45° successfully for continuous extrusion paths longer than 15 mm. All inclined surfaces of the gripper thus have an overhang angle of at least 45° , see Fig. 5 (blue). The second specific guideline states that at least three shells are required to create an airtight wall around the chamber. For the used extrusion width of 0.39 mm, this results in a wall thickness of 1.17 mm, which was used for the first iteration of the redesign, see Fig. 5 (red).

The first redesign was printed and tested. While the gripper was manufactured successfully and came out of the printer without any visible defects, the tests showed that the actuators were not completely sealed. Submerging the gripper in water while pressurizing it revealed that the air was escaping at the top of the chambers and from the duct. The reason for this is most likely the problem discussed in the second general design guideline (avoidance of very short extrusion paths) discussed above. The first redesign (Fig. 5, top) created a very small cross sectional area at the top of the chambers, which leads to many short extrusion paths (Fig. 5, bottom; red dotted line). To avoid this problem, for the second iteration of the redesign (Fig. 6, top), the inclined surfaces were rotated by 90° to create a surface with longer extrusion paths (Fig. 6, bottom; red dotted line). The minimum overhang angle was also increased from 45° to 50° (Fig. 6, top; blue), and an

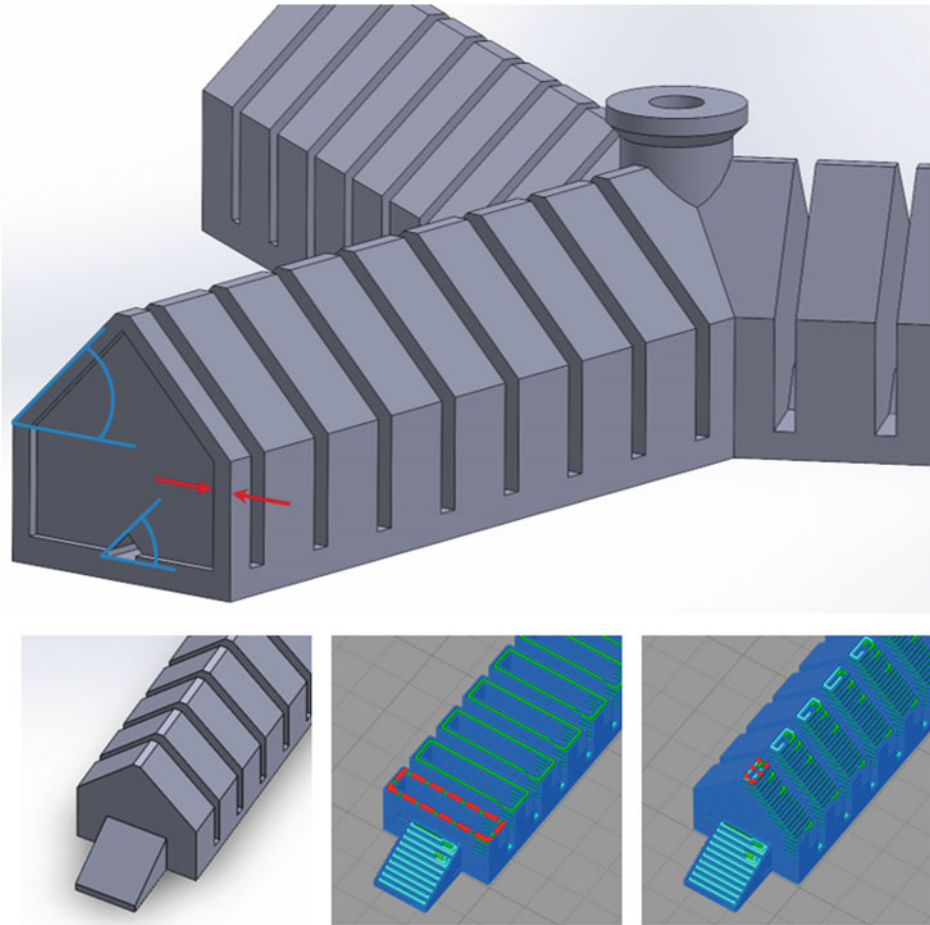


Fig. 5 First redesign iteration of the universal gripper with many short extrusion paths

additional shell was added (resulting in a wall thickness of 1.56 mm) to make sure that the air chambers and the duct are fully sealed (Fig. 6, top; red).

The second version of the gripper was successfully printed and tested in a water bath just like the first version. No rising air bubbles could be observed. The gripper was then mounted on a robot arm (DOBOT Magician from Variobotic GmbH, Germany) and activated using an electric pump. It was reliably used to handle fruits and vegetables, see Fig. 7. The desired motion of the fingers could be achieved and is comparable to the motion of the casted version of the gripper.

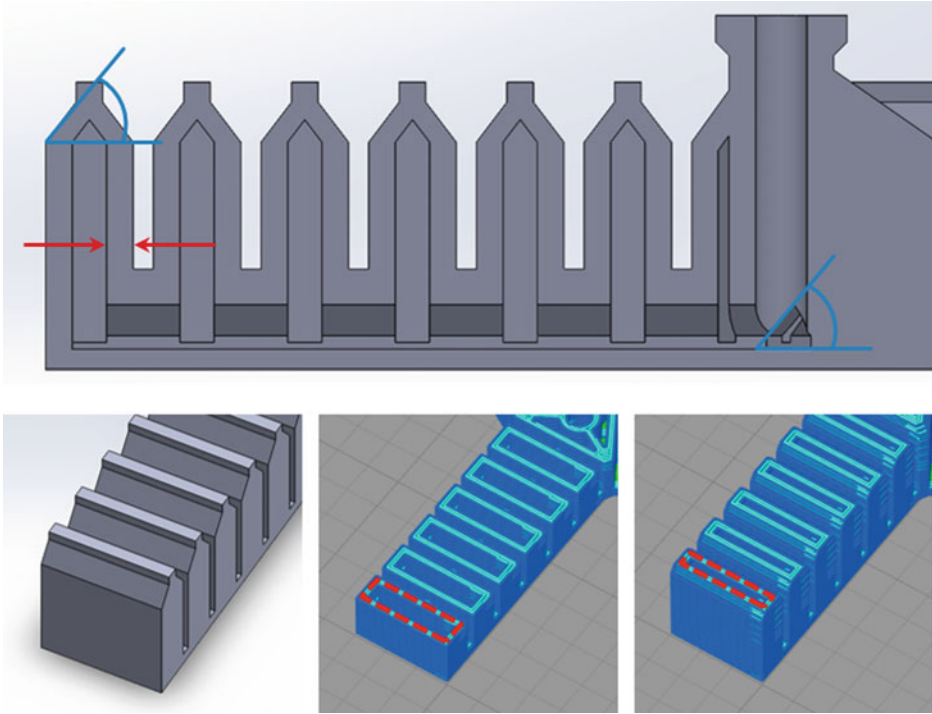


Fig. 6 Second redesign iteration of the universal gripper with longer extrusion paths

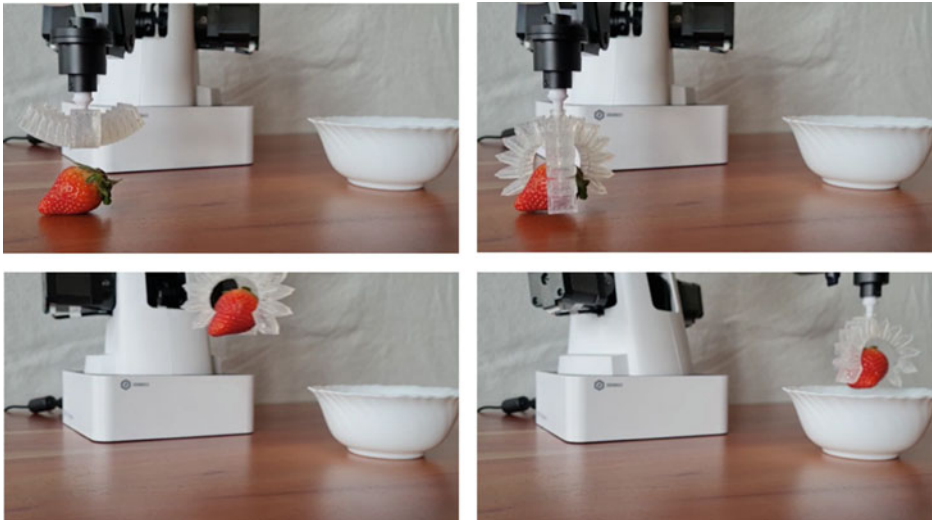


Fig. 7 3D printed universal gripper mounted on a robot arm when grasping a strawberry

5 Conclusions and Outlook

Soft robots can interact safely with humans as well as their environment, adapt well to differently shaped objects, and they are also inexpensive. Silicone 3D printing makes it possible to produce pneumatically driven soft robots with the desired properties in individualized form from a single piece. The presented case study shows that a deeper understanding of the capabilities and limitations of the process is necessary to redesign an existing part or to design a new one. Design guidelines can be an important tool to assist in the design process. The first guidelines developed by the authors and presented in this paper were successfully applied to redesign an existing universal gripper that was previously created for casting. The design guidelines also facilitated troubleshooting following the testing of the first design iteration. Since the minimum overhang angle and the minimum wall thickness for airtight cavities are scientifically validated values, other factors such as the length of the extrusion paths could quickly be identified as the main cause for leakage.

Silicone 3D printing is a relatively new technology, nearing its introduction to industrial usage. Therefore, the authors intend to further develop the presented guidelines and investigate additional ones. An additional topic to be considered in future research will be the durability of printed silicone parts as well as the aging of the material. Both should be investigated to ensure a successful introduction into industrial applications.

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