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The Loop Gripper: A Soft Gripper for Honeycomb Materials

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Abstract

Honeycomb materials are widely used as core layers of sandwich panels in the packaging, furniture, aviation, and space industry. To fulfill the varying requirements of the different applications, a wide range of materials, cell geometries, and cell sizes is used. In combination with comparably low stiffness, fragile cell walls, and large dimensions, the various properties make the automated gripping of honeycomb panels challenging. In this paper, a new concept for a soft gripper, based on adjustable threads, providing the flexibility and sensitivity needed for gripping honeycomb materials, is presented. Based on analysis and preliminary tests, a prototype is designed and built. A series of tests is performed to determine the optimal gripping parameters for different honeycomb materials, as well as to quantify the gripping force. The tests show the suitability of the concept for automated gripping of a wide variety of honeycomb types.

Keywords: flexible automation; soft robotics; automated gripper; honeycomb; sandwich materials

1. Introduction

Sandwich materials provide great mechanical properties, are lightweight, and can be easily adapted to different requirements, e.g. strength, costs, or flammability (1). Therefore, Sandwich materials are an important part of the material range in the transportation industry, where weight is an important economic factor (1), as well as other industries like furniture (2), sporting equipment (3), packaging or construction (4). One of the most common groups of core materials used in sandwich parts are cellular solids with a honeycomb structure. To meet the varying requirements of the different applications and industries, honeycomb cores with a wide range of densities, cell configurations, and cell sizes made from different base materials are used.

The most common base materials are aramid, aluminum and Kraft paper. While aramid and aluminum are most common in the aerospace industry (5; 6; 7; 8), Kraft paper is used for packaging, furniture, or automotive applications (1; 9). The density of honeycomb panels depends on the base material, cell wall thickness, and cell size. Non-metallic cores can be coated with resin to increase their density, stiffness or fire resistance (3; 10). The most common cell configuration are shown in Fig. 1. For applications with high weight and strength requirements, e.g. aerospace applications, mostly the hexagon shape is used (5). Variations of the configuration, e.g. over- and underexpanded, allow easier draping for the layup of curved parts (3). For low-cost applications, mostly corrugated honeycombs of Kraft paper are used (2).

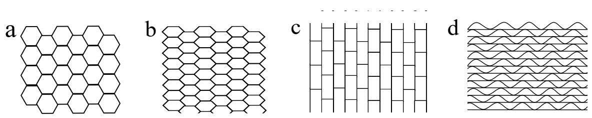

Fig. 1. Geometries of honeycomb cells: hexagonal (a), underexpanded (b), over-expanded (c), corrugated (d)

The basic structure and the variety result in characteristics of honeycomb panels that make automated gripping and handling challenging. Most honeycomb cores show high tolerances in cell size and shape. For example, hexagonal aramid honey-

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combs used in the aerospace industry typically show tolerances of about +/- 10 % of the cell size (11). Different errors, e.g. line errors, cause even larger deviations of the ideal geometry, resulting in tolerances of up to 50 mm in the length and width of large panels. Honeycomb core panels have low, direction-dependent stiffness (5) and show an anticlastic curvature when being bent (3). While honeycomb materials provide high strength to finished sandwich panels, the strength of the material before curing is comparably low. Especially the thin cell walls are fragile and prone to tear (10). However, a fully intact honeycomb structure is crucial for the properties of the finished product, especially in safety relevant applications. To overcome these deficits and to raise the degree of automation, and thereby productivity, of the commonly manual handling and placement processes (12), a gripper is needed that provides the required flexibility to grip a wide range of honeycomb materials and the sensitivity to not damage the material.

2. State of the Art

2.1. Gripping of Honeycomb Materials

In most of the scientific literature, grippers are categorized into the same three categories: grasp by force, grasp by adhesive closure, and grasp by form closure. (13) Classic mechanical jaw grippers can grip the object both by force closure and by form closure, depending on the design of the gripping jaws. Although there are many variations of the jaw gripper (e.g. (14; 15)), this type of gripper is unsuitable for handling of honeycomb panels, since the sole gripping from the outside leads to deflection and possible damage to the honeycomb panels. Other widely used grippers, e.g. vacuum grippers, magnetic grippers or electrostatic grippers can be excluded due to the physical properties and structure of the honeycomb material. Adhesive grippers or cryo grippers (16) that are well suited for handling non-rigid sheet materials can not be used in many honeycomb applications due to the risk of contamination with adhesive, water or other media.

A few approaches have been made to design a gripper especially addressed to honeycomb material. Existing concepts for honeycomb grippers try to overcome the challenges of the material by inserting rigid gripping elements into the honeycomb cells. After insertion, the gripping elements are spread, either piercing the cell walls for a form fit (13; 17), or deforming the cell walls to apply preload, holding the honeycomb material by friction (18; 19). Piercing the cell walls alters the mechanical performance of the core and is therefore not suited for most applications. Due to the rigid gripping elements, friction based grippers rely entirely on the deformation of the honeycomb. Therefore, the gripper is susceptible to pins directly aligned with cell walls during insertion. Deviations in the cell geometry cause stress peeks in the deformed cells. Both effects pose a high risk of damaging the material.

To overcome these issues of existing concepts for honeycomb grippers, a gripper is needed that provides the flexibility to grip a wide range of honeycomb materials and the sensitivity to not damage the material. To achieve this, the gripper needs to adapt to the material. These are typical properties for so-called soft grippers, which are developed in the field of soft robotics.

2.2. Soft Grippers

Soft grippers are made completely or partly from soft materials. As a result, soft grippers adapt themselves to the gripping object, creating a force or form closure. For this reason, soft grippers are very versatile, with objects of various shapes and surfaces being grasped by one gripper (20). The soft material also enables a sensitive way of gripping (21). The versatility and dexterity of soft grippers are particularly in demand when it comes to automatization in e.g. the food industry (21), the biomechanical field (20), or generally in unstructured or changing environments (22). Due to these characteristics, the soft robot concept is ideally suited for gripping of honeycomb materials.

Most research on soft grippers is guided towards gripping from the outside by friction (21). Due to the large dimensions and low stiffness of typical honeycomb panels only internal gripping is feasible for honeycomb handling. However, only a few designs of internal soft grippers exist. Common internal soft grippers use a size-changing rubber body, which is attached on a pin, that is inserted in a cavity of the object. Two concepts of changing the size of the rubber body exist. In the first option, the body consists of a thin, inflatable membrane (23). In the second concept, the rubber body is squeezed to increase its width (24). However, the gripping pins of existing grippers are too large to be inserted in the small cells of honeycomb material. Additionally, the rigid core of the pins limits the deflection of the gripping pins during insertion.

2.3. Outline

Although soft grippers generally provide the flexibility and sensitivity needed for the gripping of honeycomb, no soft gripper suited for automated handling of large honeycomb panels exists. Therefore, a new internal soft gripper for automated handling of honeycomb panels of different materials, cell sizes, heights and densities, is developed.

First, the requirements for the gripper are examined more closely. Then a basic concept for a new internal soft gripper, based on flexible loops, is presented and tested. Afterwards, the basic concept will be further optimized in order to improve flexibility. Based on preliminary tests a prototype is designed and built. With the prototype a series of tests is performed, to determine the optimal gripping parameters for a wide variety of honeycomb materials, as well as to quantify the gripping force and to validate the concept.

3. A new Concept for a Soft Honeycomb Gripper

3.1. Problem Analysis and Requirements on the Gripper

The new honeycomb gripper needs to fulfill some general requirements. The gripping force should be high enough to grasp the honeycomb panels with a reasonable number of gripping elements. The gripper should be able to grasp honeycomb materials of different materials, cell sizes, heights, and densities. Since so many different honeycomb materials are available, the range considered in this paper is limited to some of the most common materials and cell configurations. These are aramid, aluminium and Kraft paper honeycomb with hexagonal, overexpanded and corrugated cells with a size between 2.5 and 5 mm. Furthermore, the core height is limited to 10-25 mm. The gripping elements, as well as overall mechanical structure should be simple to limit costs and increase reliability. Core panels are often stored in stock, therefore the gripper needs to be able to separate them during gripping. The gripper needs to compensate the high tolerances of honeycomb materials. Lastly, the gripping force should be ensured during a possible power loss.

3.2. The Loop Gripper

In this chapter, a new concept for a soft honeycomb gripper is introduced. As existing concepts for honeycomb grippers, the new concept is based on multiple gripping elements mounted to a base plate. The gripping elements are made from flexible threads, which are bent to form loops wider than the cell size of the honeycomb material to be gripped. For gripping, the gripper is pressed onto the honeycomb material, causing the loops to slide into the honeycomb cells. The two dimensional shape of the flat loops results in a much lower 2nd moment of area of the loops around one axis than the other. As a result the soft loops can easily deflect perpendicular to the loop plane and slide of the cell walls into the honeycomb cells without causing damage (Fig. 2a). At the same time compression of the loop within the loop plane results in enough preload to hold the honeycomb material by friction (Fig. 2b). The shape and flexibility allows the loop to adapt to the cell shape and compensate tolerances. The gripping process itself is created passively. However, a wiper mechanism is required to release the grip. Multiple grippers can be combined in a gripper system to minimize deflection of the honeycomb during handling.

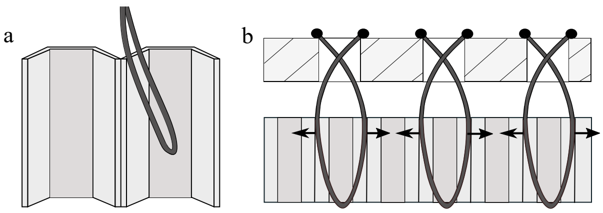

Fig. 2. Basic loop gripper concept

3.3. Validation of the Loop Gripper Concept

To validate this concept, a prototype was built using polyamide thread with a diameter of 0.7 mm. The prototype was tested on two types of aramid honeycomb material with hexagonal cells, further called Aramid 1 and 2. Both types had a cell size of 3.2 mm, but differed in density and therefore in stiffness. The parameters are listed in Tab. 2. The prototype gripper consists of 96 loops with a width of about 5 mm. The gripping force was measured five times for each honeycomb type using the test setup described in Appendix A. The average gripping force of one loop is shown in Fig. 3. With these average forces, 254 loops are needed to hold a 1 m^2 sized honeycomb panel of Aramid 1 with a height of 20 mm, accelerated vertically with 2 $m\,s^{-2}$. 188 loops are needed to hold a panel of Aramid 2 with the same size in this scenario. This equals three gripping heads of the tested size for Aramid 1 and two for Aramid 2 which is considered reasonably low.

The test shows the general feasibility of the loop gripper concept for the gripping of honeycomb material. However, due to the fixed loop size the basic concept is limited to one predefined cell size. In order to meet the flexibility requirement it is necessary to actively change the loop size.

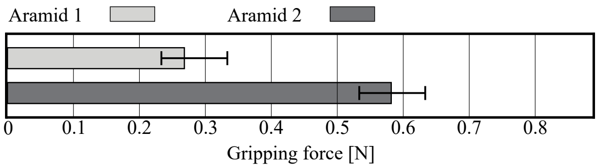

Fig. 3. Forces of one loop of the basic Loop gripper on Aramid 1 and Aramid 2

4. Development of a Loop Gripper with Variable Loop Size

4.1. Requirements on the Loop

To develop a loop gripper with variable loop size, a closer look at the requirements on the loops is needed. The loop undergoes two states, which will be called pre-inserted state and inserted state. Both states have different requirements for length and width of the loop. In the pre-inserted state, the loop needs to be narrow, to glide into the small cells easily. The preliminary tests show that long loops are likely to fold, thereby damaging the material. Therefore, a short loop is generally favorable in the pre-inserted state. The loop in the inserted state needs to be stiff and wide since the gripping force of the loop gripper depends on the stiffness of the loop, as well as the width of the loop compared to the cell size. Additionally, the widest point of the loop needs to be below the gripper plate, within the cell. If this requirement is not met, the angle between cell wall and thread causes a diagonal force on the cell wall, counteracting the gripping force (Fig. 4).

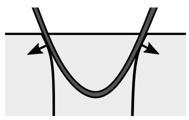

Fig. 4. Diagonal force counteracting the gripping force

4.2. Concepts for Loop Manipulation

Three basic ways to manipulate the geometry of the loop exist: changing the distance between the two ends of the loop (Fig. 5a), changing the angle α at the loop base (Fig. 5b) and changing the length of the thread forming the loop (Fig. 5c). To choose the best concept, all three principles were evaluated based on the requirements on the loop. The result is shown in Table 1. Since changing the loop geometry by manipulating the thread length is the only concept that fulfills all four requirements this concept is used.

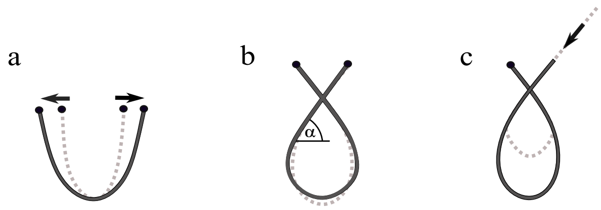

Fig. 5. Ways to manipulate the geometry of the loop: changing the distance of the ends (a), changing the angle (b), changing the length of the thread (c)

Table 1. Evaluation of the concepts for loop manipulation

Requirement	Changing of: distance	angle	length
Narrow pre-inserted loop	●	●	●
Short pre-inserted loop	●	○	●
Wide inserted loop	●	●	●
Broadest part within the cell	○	●	●

Requirement fulfilled ●; not fulfilled ○

4.3. Technical Realization of Loop Manipulation

For changing the loop length the two technical concepts shown in Fig. 6 were developed. In order to validate the basic concept for loop manipulation and to choose the more suitable technical realization, two simple prototypes where built using polyamide thread with a diameter of 0.7 mm. The two grippers were tested on two aramid honeycomb panels with cell sizes of 3.2 mm and 4.8 mm. Both grippers were able to grasp the honeycombs. However, the tests showed a major difference between the two variants, which is mainly caused by the viscoelasticity of polyamide (25). In both concepts the polyamide thread deformed plastically at the tip of the loop in the pre-inserted state. With the first concept, the deformed part of the loop stays at the tip if the thread length is changed, limiting the maximum width of the loop in the inserted state and thereby the gripping force. With the second concept the tip shifts to the side, resulting in a more circular shape and greater maximum width of the loop, as well as higher gripping force, which is generally favorable. A further consequence of the viscoelasticity of the loop material occurs after several gripping cycles. In the first concept, the loop becomes narrower in the inserted state after several gripping cycles, reducing the gripping force. In the second concept, the shape of the loop becomes rounder in the pre-inserted state, preventing damage free insertion of the loops. Since the material polyamide showed great flexibility and provided a great resilience of the loop in all preliminary tests, this material is maintained. To counteract the negative deformations, a combination of the first and second concepts is used as the final concept for loop manipulation. The second concept is supplemented by a third moving plate which restores the original shape of the loop after gripping (Fig. 6c). Since movement of the third plate is only needed at the end of the stroke, the plate can be passively driven to not compromise the simple mechanical concept.

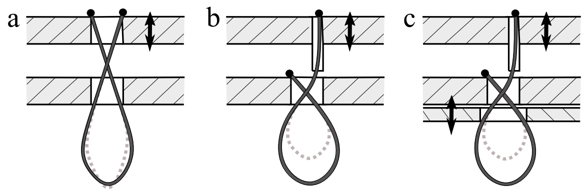

Fig. 6. Technical principles for changing the loop length: symmertical (a), asymmertical (b), combined (c)

5. Experimental Analysis of Gripping Parameters and Gripping Force

5.1. Prototype of the Loop Gripper with Adjustable Thread Length

Based on the concept and the preliminary test a prototype for the loop gripper with adjustable thread length was built. To keep the prototype simple, the restoration of the original shape of the loops was done manually. The prototype gripper is shown in Fig. 9. The gripper consists of six loops. The ends of the loops are fixed to two plates, guided by linear bearings. The width of the loops in the pre-inserted state, as well as the stroke, which determines the width of the loop in the inserted state, are set by adjustable stops. Tubes and a guiding block prevent the thread from buckling.

5.2. Design of Experiment

To validate the concept and to find the optimal gripping parameters for different materials, the correlation between gripping force and gripping parameters was examined experimentally for a wide selection of common honeycomb materials, using the prototype gripper and the test setup described in Appendix A. An example for each kind of tested material is shown in Fig. 7. All tested honeycomb materials and their parameters are listed in Tab. 2.

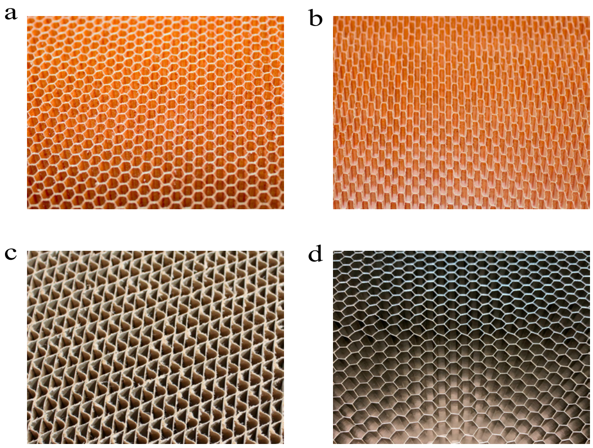

Fig. 7. Examples of the tested honeycomb materials: hexagonal aramid (a), overexpanded aramid (b), corrugated paper (c), hexagonal aluminium (d)

Table 2. Parameters of the tested honeycomb materials

Material	#	Cell config.	Cell size [mm]	Density [kg mm^{-2}]
Aramid	1	hexagonal	3.2	29
	2		3.2	48
	3		4.8	96
	4	overexpanded	2.5 (x 7)	53
Paper	1	corrugated	4 - 5.3	57
	2		4 - 5.3	65
	3		4 - 5.3	93
Aluminum	1	hexagonal	3.2	72
	2		5	87
	3		5	49

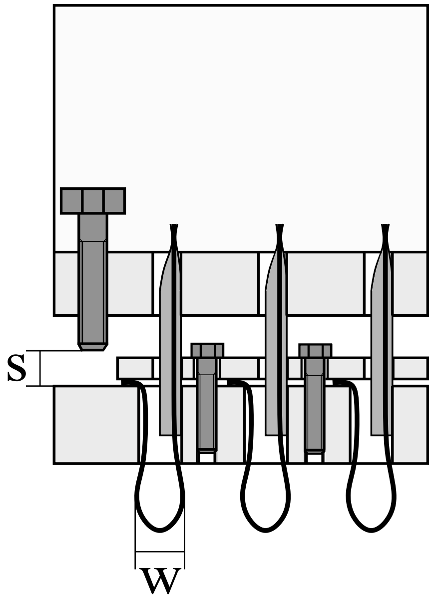

Fig. 8. Loop gripper with the parameters Stroke (s) and Width (w)

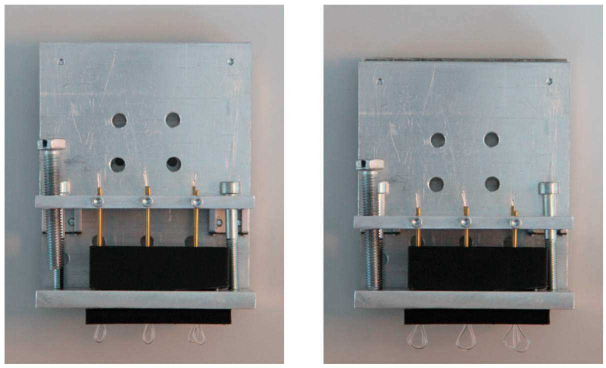

Fig. 9. Prototype gripper with loops in pre-inserted state (left) and inserted state (right)

The gripping parameters are: the diameter of the thread and the thread length in both, the pre-inserted and the inserted state. Thread length depends on the stroke and is adjusted by the stops as shown in Fig. 8 and 9. The diameter of the thread controls the stiffness of the thread and the thread length controls the length and width of the loop in the pre-inserted and the inserted state.

Polyamide threads with diameters of 0.3 mm, 0.7 mm, 1 mm and 1.3 mm were taken into consideration. Preliminary tests showed that the 0.3 mm thread is not stiff enough to apply a noticeable gripping force and that the minimal loop width achievable with 1.3 mm thread is significantly bigger than the addressed cell sizes. 0.7 mm and 1 mm thread diameters lie between these limits and were selected for the tests.

The thread length, controlled by the stroke, changes both, length and width of the loop, but only the width is expected to increase the gripping force. Therefore the loop width was measured as a function of the stroke for both thread diameters in steps of 1.25 mm.

The thread length in the pre-inserted state was determined in preliminary tests to achieve optimal insertion characteristics of the loops. For 0.7 mm thread the optimal thread length for insertion results in 3.5 mm loop width and for 1 mm thread in 4.2 mm loop width.

The thread length in the inserted state was varied by increasing the stroke in eleven steps of 1.25 mm up to a maximum of 12.5 mm. The gripping force was measured five times on different honeycomb panels of the material type for each set of parameters.

5.3. Experimental Results

The results of the measurements of loop width depending on stroke are shown in Fig. 11. It is noticeable that the width of

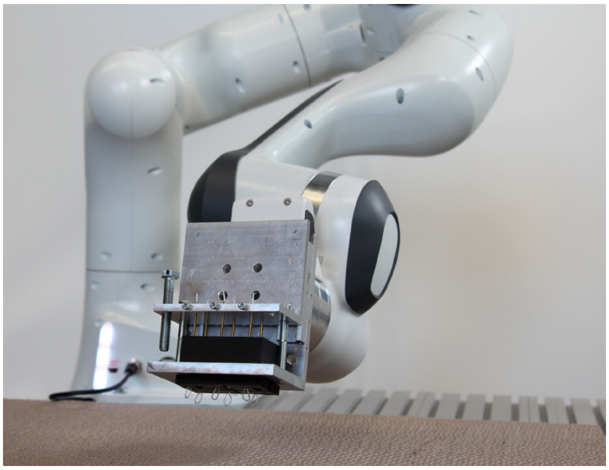

Fig. 10. Prototype of the loop gripper mounted on a robot

the loop initially increases almost linearly, subsequently reaching a plateau. From this point on only the length of the loop changes. Based on this result, it is expected that the maximum gripping force does not occur at maximum stroke, but at an optimal stroke smaller than maximum stroke.

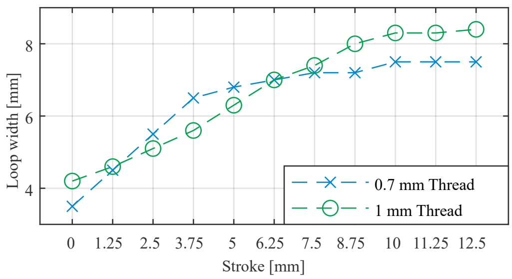

Fig. 11. Width of the loop during the measurements

During the measurement of the gripping force it became apparent, that the thin aluminum cell walls deformed plastically even with the 0.7mm threads. Therefore, the prototype gripper is not suited for handling of aluminum honeycomb without damage and this material was excluded from the tests.
The gripping forces for the remaining materials are shown in Fig. 12 to 15. For both, the 0.7 mm and the 1 mm threads, the gripping force increases to a maximum and then decreases again, confirming the hypothesis suggested by the correlation between loop length and stroke. The location of the maximum varies, depending on the honeycomb material. An exception is the overexpanded honeycomb with the 0.7 mm thread. With this combination the force rises continuously, which indicates that due to the high elasticity of over expanded cells, the maximum force occurs above the tested stroke.

While the 0.7 mm thread did not damage any of the honeycombs, the 1 mm thread did. As the loops of the 1 mm thread are not as flexible, they deformed the cell walls of most materials during inserting. Further damage was caused by the 1 mm thread during gripping. For Aramid 1 and 2 the force on the cell walls caused the cell walls to separate. All measurements that damaged the material are grayed out in Fig. 14 an 15. However, neither Aramid 3 and 4, nor the corrugated Kraft paper materials were damaged. The optimal gripping parameters for each material are listed in Tab. 3.

Table 3. Optimal stroke for the tested honeycomb materials in mm

Material	**#**	**Stroke in [mm]**	
		0.7 mm thread	1.0 mm thread
Aramid	1	8.75	5.00
	2	5.00	5.00
	3	6.25	5.00
	4	12.5	7.50
Paper	1	6.25	6.25
	2	10.0	7.50
	3	6.25	3.75

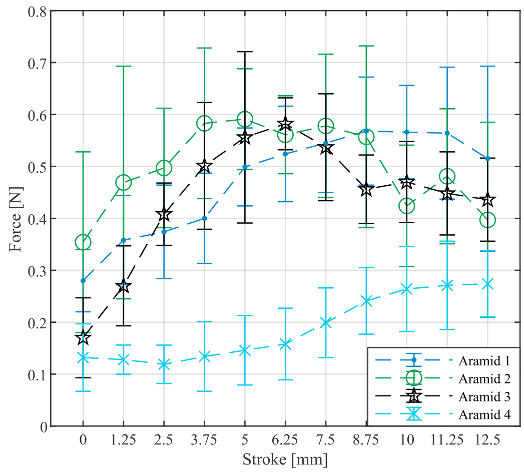

Fig. 12. Average gripping force of the loops with with 0.7 mm thread on aramid

6. Discussion

The 1 mm thread shows overall higher gripping forces than the 0.7 mm thread. However, as the 1 mm threads damaged some of the honeycombs during insertion, this thread is only valid for honeycomb materials with comparably large cells or high strength, e.g. Aramid 3. Since 0.7 mm threads did not damage any of the materials except aluminum, they provide overall greater flexibility.

Tab. 3 shows, that for materials with the same cell size and different densities, the maximal gripping force occurs at different stroke. It can be concluded that the optimal loop size

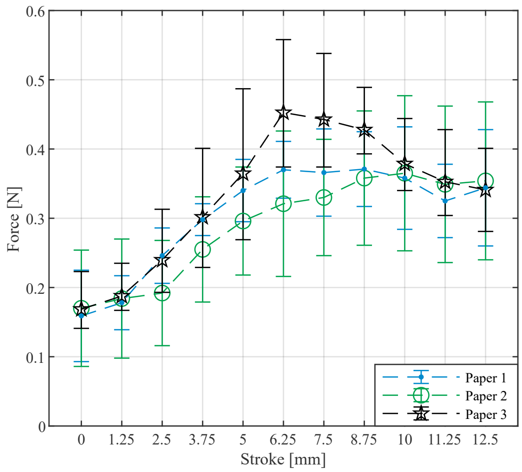

Fig. 13. Average gripping force of the loops with with 0.7 mm thread on paper

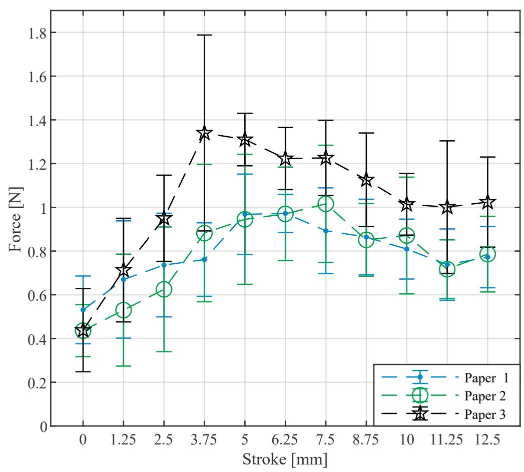

Fig. 15. Average gripping force of the loops with 1 mm thread on paper

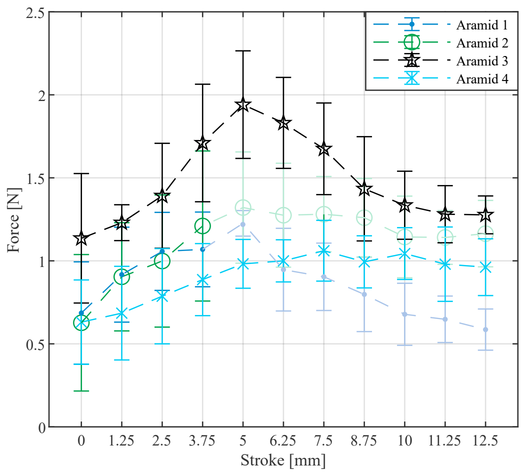

Fig. 14. Average gripping force of the loops with with 1 mm thread on aramid

depends largely on the stiffness of the material to be gripped. Therefore the optimal loop size cannot be derived from the size of the honeycomb cell alone and the materials density has to be considered. In a manufacturing process in which various honeycombs panels are used, a loop gripper is needed that can vary the stroke between gripping cycles.

Comparison of the results of the loop gripper with adjustable thread length 0.7 mm thread (Fig. 12) with the results of the static loop gripper with 0.7 mm thread (Fig. 3), shows that for Aramid 1 the average gripping force of one loop of the dynamic gripper is much higher than the average gripping force of one loop of the static loop gripper. However, for Aramid 2, the gripping force differs only slightly. This comparison proves that the gripping force can be increased with the loop gripper with adjustable thread length, by choosing optimal gripping parameters.

The standard deviation of all measurements in Fig.12 to 15 is rather high. The high scattering of gripping force is probably caused by the small number of loops of the prototype gripper. Therefore, the gripping force is strongly depending on the exact position of each loop in the cell. With a higher number of loops, the standard deviation is likely to reduce. This is also indicated by the results of the tests of the basic loop gripper with 96 loops (Fig. 3), where standard deviation was reasonably low.

The tests prove, that the loop gripper with adjustable loop size fulfills the flexibility and sensitivity requirements and is able to grip a wide range of honeycomb materials, making the automated manufacturing of sandwich materials more reasonable. Additionally the optimal gripping parameters determined, allow to design individual grippers for specific material ranges.

7. Conclusion and Outlook

In this paper, the loop gripper was introduced as a new gripper concept for automated handling of honeycomb materials. It was shown, that manipulation of the loop geometry is needed in order to meet the flexibility requirements. Based on evaluation of different requirements, variation of the thread length was chosen for the manipulation of the loop geometry. Measurement of the correlation between gripping force and gripping parameters on a wide range of common honeycomb materials, showed that the loop gripper concept fulfills the flexibility, as well as the sensitivity requirements needed to grip many common honeycomb materials without damage. The optimal gripping parameters and achievable gripping forces determined for the tested materials allow to design loop grippers for specific applications.

However the tests also showed limitations of the concept. Aluminum honeycomb was damaged during gripping and the polyamide threads showed to be not optimal due to their viscoelasticity. In future work other materials with small bending diameter and large linear elastic range should be evaluated to eliminate the need to restore the loop shape after gripping. Loops preformed to a designed shape made from e.g. thin metallic wire, would greatly increase design freedom and could further improve the flexibility of the gripper. Finally, dividing the base plate of the gripper into several parts or using semi-soft plates could enable the loop gripper to deposit honeycomb cores in curved forms and thereby enlarge the field of application of this new gripper concept.

CRediT author statement

Franziska Roth: Methodology, Investigation, Validation, Writing - Original Draft, Visualization. Henrik Eschen: Conceptualization, Methodology, Resources, Supervision, Writing - Review Editing. Thorsten Schüppstuhl: Project administration, Funding acquisition

Appendix A. Test Setup

The test setup for the measurement of gripping force is shown in Figure A.16. The setup consists of two tables guided by a linear bearing mounted to a frame. The first table holds the honeycomb material and is connected to the frame with a force sensor S2M by the company HBM with a range of 0 N to 100 N. The second table holds the gripper and is connected to a lever to apply force. The the setup is adjusted so that the gripper and the honeycomb are oriented perpendicular to the linear bearing and in line with the force sensor. A measuring amplifier Quantum X by HBM and software CatmanEasy was used for capturing and evaluation.

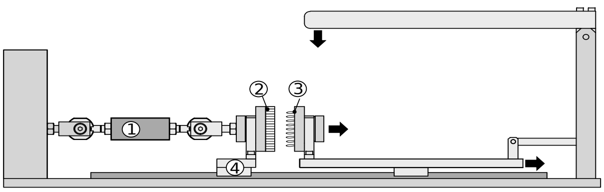

Fig. A.16. Test set up for measuring the gripping force of the loop gripper: (1) force sensor, (2) guided table with honeycomb panel, (3) guided table with loop gripper, (4) linear bearing

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