Proposal of a Fastening Method for Deformable Plastic Parts and Rigid Metal Parts*

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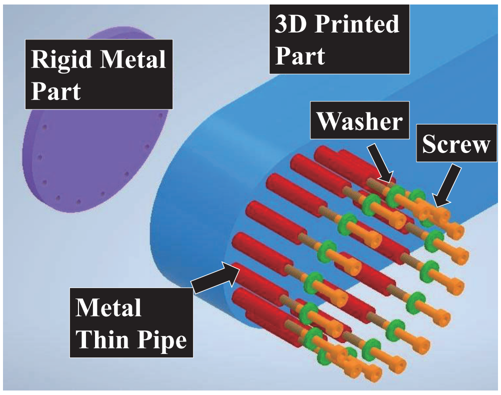
Abstract— **Weight reduction is becoming increasingly important to reduce the power consumption of robots. Our ultimate goal is to fabricate practical industrial robot structures using resin 3D printing technology to reduce the robot's weight. In general, 3D printed parts made of resin are soft and deformable; thus, conventional screw fastening does not work well. This paper proposes a method to reduce the stress on a plastic member by inserting a thin-walled metal pipe into a plastic member and subjecting it to the axial force of a screw. The effectiveness of the proposed method was experimentally verified by measuring the thickness of the plastic test specimen and the tightening torque of screws over one month. The maximum torque load test was also conducted to confirm that the fastening force was sufficient for practical use.**

I. INTRODUCTION

Conventional industrial robots have achieved high positioning accuracy, high-speed operation, and long operating time by combining rigid aluminum alloy structural materials and highly rigid precision reduction gears. With the adoption of the Sustainable Development Goals by the United Nations in 2015, reducing energy consumption has become more important than ever. One of the most straightforward solutions would be to make the industrial robots lighter. If the robot arm is lightweight, it can reduce the energy required to move and thus accomplish its task with less energy. The actuator's output on the arm can also be reduced, resulting in a further reduction of mass that achieves a positive cycle in mechanical design.

To achieve this ultimate goal, the author's research group is conducting fundamental research and development to achieve a 25% weight reduction of conventional industrial robots by applying new lightweight resin materials that can replace conventional light metals to structural materials and, eventually, to reduction gears.

There have been many studies in the past to reduce the weight of industrial robots. In particular, a series of DLR studies pursued improving the power-to-weight ratio to reach the technological limit by reducing the weight and maximizing the actuator power. Those studies developed an extremely lightweight robot with a payload of 10 kg and a body mass of approximately 13-14 kg using a harmonic reduction gear and



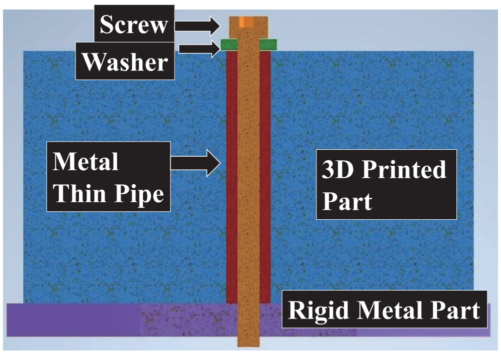


Fig. 1: Proposed fastening method: (top) isometric view, (bottom) cross-sectional view of fastening section.

structural materials made of carbon fiber-reinforced plastic (CFRP)[1]. These results were commercialized by KUKA[2]. However, aluminum alloys instead of CFRP were used for structural materials due to their optimized complex geometry, and high-cost [3].

Eighteen years have passed since the DLR's studies, and the technological environment has changed dramatically. Additive Manufacturing technology, especially 3D printing, has emerged as a major new technology. In 2015, Markforged introduced a 3D printer capable of producing a high-strength composite material with continuous carbon fiber. This method can potentially solve the problem of the high cost of the conventional autoclave forming method using carbon fiber prepreg sheets. Matsuzaki et al. have conducted various basic evaluations of the strength of 3D printed materials containing continuous carbon fibers as a composite material (for example [4]). In contrast, we mainly focus on the possibility of application to industrial robots.

In evaluating the applicability of 3D printed parts as robot structural materials, it is extremely important not only to evaluate the material properties but also how to fasten the parts to other parts. This is because the robot is composed

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of many parts and the output from the actuators must be transmitted to the end effectors via fasteners. From the viewpoint of maintainability, replacing parts in a particular unit is essential. Therefore a reversible fastening method for 3D printed parts is necessary.

Screws, keyways, and press-fits have achieved conventional reversible fastening between metal parts. However, these fastening methods are basically achieved by the high Young's modulus of the material. These fastening methods are ineffective for plastic parts, such as 3D printed parts, because they have a low Young's modulus and are easily deformed. Various attempts have been made so far, but most of all are at the know-how level (e.g., [6][7]), and there are very few quantitative discussions on a mechanical design methodology.

We attempted to press-fit a one-way clutch to a 3D-printed part but could not obtain sufficient fastening torque due to the deformation of the 3D-printed part. Thus we developed a new shaft-fastening method that reduces the surface pressure with the polygonal shape by embedding it in a 3D printed part after press-fitting the one-way clutch into a polygonal SUS material with high Young's modulus[5]. This is a clear example of the need for a new robot design method using 3D printing.

This paper proposes a method of fastening metal parts and 3D printed parts using screws, which are most frequently used to fasten parts. More specifically, the proposed method reduces the concentration of stress on the soft 3D printed part by subjecting the axial force of the screw to a metal thin-walled pipe (Fig.1). The effectiveness of the proposed method is experimentally verified in this paper.

II. Proposal of a Fastening Method for Deformable Plastic Part and Rigid Metal Part

In screw fastening, the fastening torque is converted into an axial force by the helical thread, which exerts a compressive force between the fastened parts. Then the screw is subjected to a reaction force, a tensile force. On the other hand, a compressive force applied between the fastened parts generates a frictional force as a vertical reaction force, which restrains the relative shear motion between the parts.

However, if the fastened part is a deformable material such as plastic, it will deform when subjected to high surface pressure. The deformation reduces the compressive force acting on the fastened part, which reduces the frictional force restraining the relative motion of the fastened part and the screw. To solve this problem, this paper proposes the insertion of a thin-walled metallic pipe of high rigidity, which can withstand the compressive force of the screw, into a plastic part. This method is expected to suppress axial deformation caused by a compressive force of the screw and to generate and maintain high fastening force. However, there is a trade-off relationship between the thickness of the thin-walled pipes and the part's mass. In this paper, we experimentally investigate the appropriate wall thickness.

Our ultimate goal is to realize a 6-DOF manipulator with an arm reach length of 1.0 m and a payload capacity

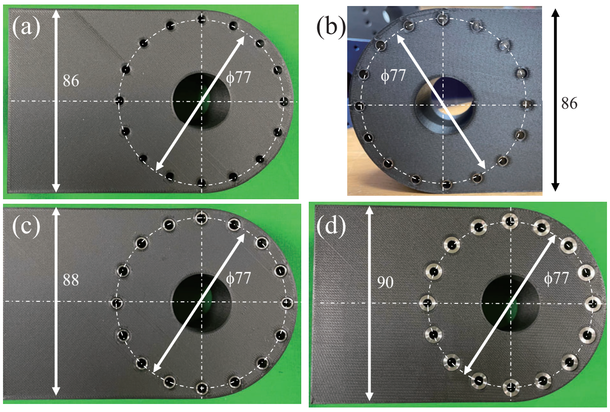

Fig. 2: Test specimen: (a)Nominal, Thin-walled pipe with a thickness of (b) 0.2 mm, (c) 1.0 mm, and (d) 2.0 mm

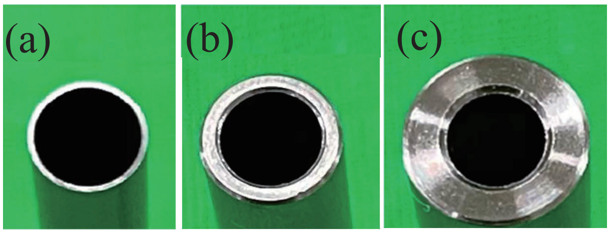

Fig. 3: Inserted thin-walled pipe where inner diameter and thickness of pipe are (a)ϕ4.1 mm, 0.2 mm, (b)ϕ4.0 mm, 1.0 mm, and (c)ϕ4.0 mm, 2.0 mm, respectively.

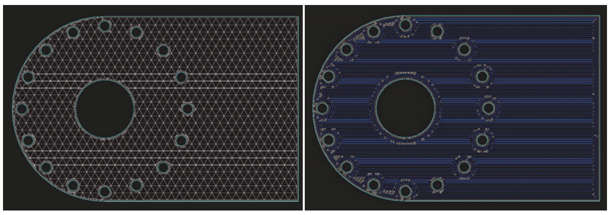

Fig. 4: Modeling path: (left) layer only with a short carbon fiber filament (Onyx) , (right) layber with Onyx and a continuous long fiber indicated by blue lines

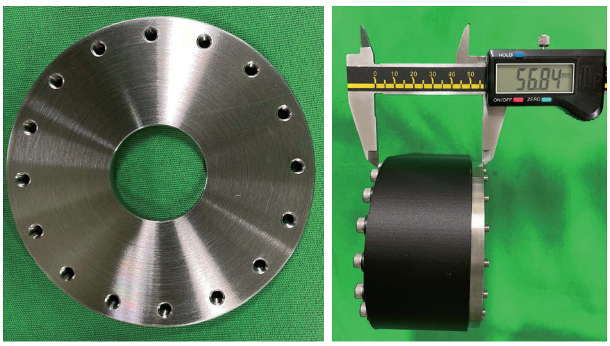

Fig. 5: Output frange (left) and measurement of the thickness (right)

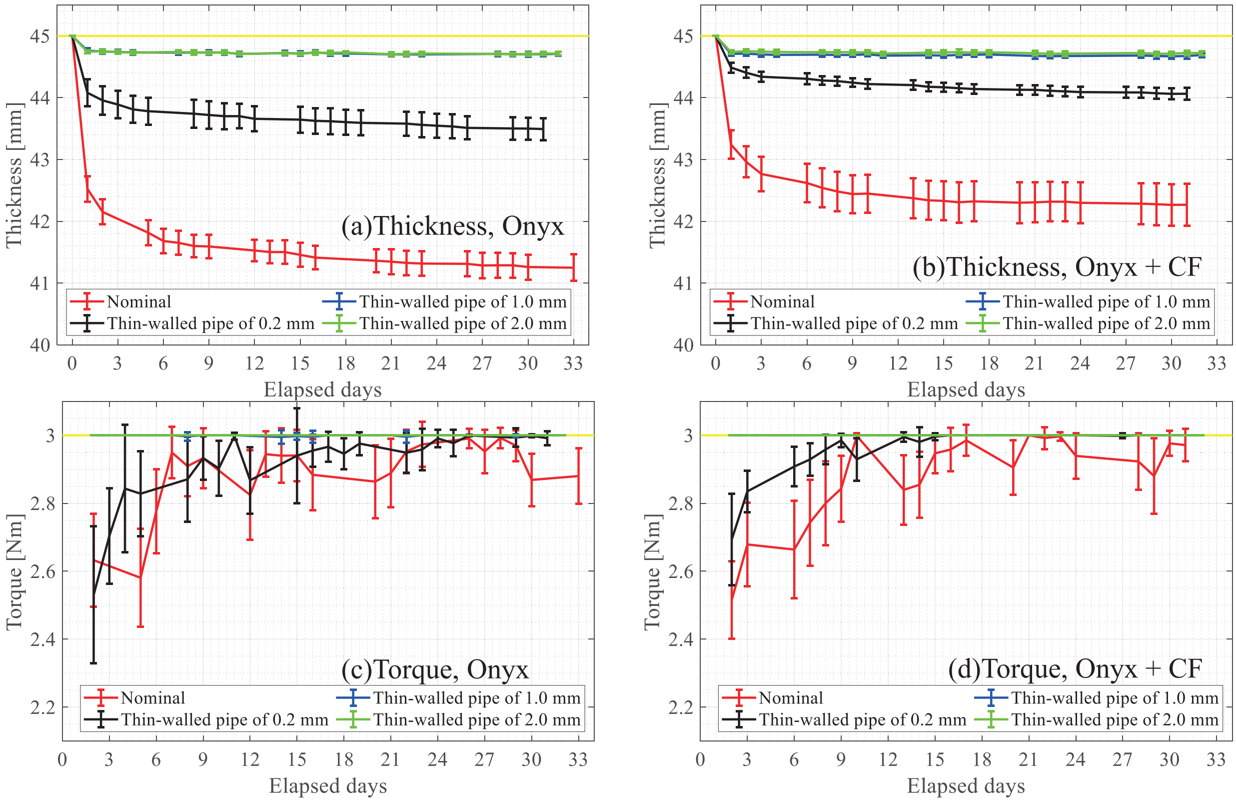

Fig. 6: Time series change of the thickness of the specimen and residual torque: (top) averaged thickness of the specimen, (bottom) averaged residual torque. The yellow lines on the top graphs show designed thickness of the specimen. CF means continuous fiber.

of 15 kg, which utilizes a new lightweight material. The SHA25M101SG (Harmonic Drive Systems, Inc.), which has a rated output of 200 W, was selected as the actuator for this manipulator. This actuator is a unit product consisting of an AC servo motor and a hollow shaft Harmonic reduction gear with a reduction ratio of 1:101, and a flange provides its output. This paper assumes a case in which a plastic structural part is directly fastened to the flange by 16 screws.

III. Evaluation of the Proposed Method by Time-series Change

A. Test Specimen

This section describes test specimens to be attached to the output flange of the actuator. The specimens are fabricated by a 3D printer using Fused Filament Fabrication. The 3D printers used were either Onyx One, Mark Two, or X7 from Markforged.

The shapes of the specimens are shown in Fig.2. A total of four types of specimens are considered: (a) a nominal specimen made of plastic material only, and three types with thin-walled pipes of different thicknesses inserted ((b) 0.2 mm, (c) 1.0 mm, and (d) 2.0 mm). Both the thickness of the specimen and the length of the thin-walled pipes are 45 mm. The material of the thin-walled pipe subjected to axial force is SUS304, and its appearance is shown in Fig.3.

The filament used for modeling is Onyx (Markforged), a nylon plastic-based filament reinforced with short carbon fibers. The strength of the filament can be further increased by simultaneously molding continuous carbon fibers into the filament. This study investigates two modeling methods: one using only Onyx filaments and the other using additional continuous carbon fibers. We used the slicer software Eiger provided by Markforged, and the modeling conditions were as follows: filling rate of 37%, eight solid layers, and two walls. The generated modeling path is shown in Fig.4.

Experiments will be conducted in the next section on a total of eight different specimens, each with four different geometries and two different material combinations.

B. Measurement Procedure

A disk of the same shape as the output flange of the actuator (Fig.5(left)) is fastened to the test specimen with 16 screws. We measured the time series change of the amount of sinkage of the screws into the part and the fastening torque of the screws. Sixteen M4 female threads are concentrically arranged on the flange. The measurement method is as follows.

1) Gradually increase the fastening torque up to 3.0 Nm while ensuring that all screws are evenly tightened using a torque wrench.
2) Measure the distance between the screw head and the

disk using a digital caliper(Fig.5(right)).[1]

3) Leave it for a day (or three days on the weekend,.)
4) Gradually increase the fastening torque using a torque wrench, and measure the torque when it starts to move. If the movement does not start when the torque reaches 3.0 Nm, the measured value is set to 3.0 Nm.
5) If all measurements are less than 3.0 Nm, return to 1).
6) If the measured value is 3.0 Nm at any location, loosen all screws by about 30 deg and return to 1).

The above measurements were conducted over one month to investigate the time-series changes in specimen thickness and fastening torque.

C. Results

The upper row of Fig.6 shows the number of elapsed days on the horizontal axis and the average specimen thickness on the vertical axis. The lower row shows the number of days elapsed on the horizontal axis and the average value of fastening torque on the vertical axis. The left column shows specimens with Onyx only, and the right column shows specimens with Onyx and continuous carbon fiber (CF).

The thickness of the specimen was obtained by subtracting the thicknesses of the screw head, washer, and the disk to be fastened from the 15 measurements shown in Fig.5(right) and taking the average. Error bars indicate the standard deviation. The values at day 0, indicated by the yellow lines in Fig6., are the design thickness of 45 mm, and the target fastening torque of 3.0 Nm.

The specimen with no embedded metal thin-walled pipe (red line in Fig. 6) was considerably deformed, and the deformation continued for one month, gradually decreasing in deformation but not reaching a steady state. In the specimen with a 0.2 mm-thick thin-walled pipe inserted (black line in the figure), the deformation was suppressed compared to the red line, but the gradual decreasing trend continued. In contrast, the specimens with 1.0 mm and 2.0 mm thicknesses inserted (blue and green lines in Fig.6) deformed approximately 0.3 mm at the first fastening, but after that, the deformation was found to be almost constant and did not continue. The deformation of its first time was the same as in the experiment in which the axial force of fastening a screw was applied only to a thin-walled cylinder. Therefore, this deformation is caused by the fastening system and not by the part to be fastened. Comparing the 1.0 mm and 2.0 mm thicknesses in Fig.6(a) shows that the thicker wall of the pipe has slightly less deformation, but the deformation is almost the same. Comparing Fig. 6(a) and (b), Fig.6(b) shows that the deformation is reduced. The less deformation seems to be due to the increased rigidity of the specimen caused by the continuous carbon fibers. Fig. 7 shows the specimen conditions with the red line and green line in Fig. 6(a) after one month. In the most deformed specimen, the washer sinks significantly, and at the same time, the surrounding area rises and is significantly deformed. On the other hand, less deformation is observed in the specimen with a 2.0 mm-thick pipe inserted.

[1]However, due to the limitation of the caliper length, the point farthest from the outer edge could not be measured. Therefore, there are 15 measurement points.

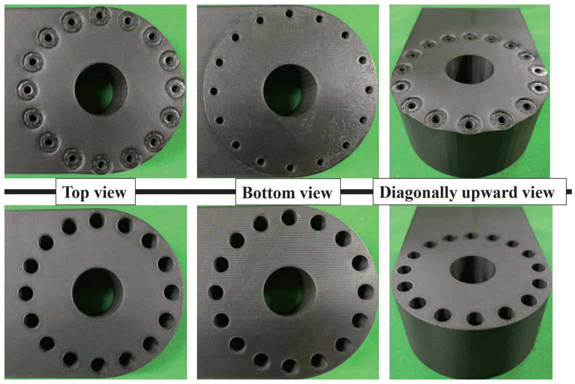

Fig. 7: Deformation of specimens after one month measurement: (top) nominal, (bottom) proposed method with thin-walled pipe of 2.0 mm

Fig. 8: Buckling of the pipe ends where wall-thickness is 0.2 mm

In the case of 0.2 mm thickness, when the screw and thin-walled pipe were removed and observed after the test, it was found that the wall thickness of the pipe was not sufficient to withstand the compressive force, and the terminal parts were buckled (Fig. 8). On the other hand, the deformation of pipes with thicknesses of 1.0 mm and 2.0 mm remained constant, and there was almost no difference in the deformation values. Thus it is suggested that the optimum wall-thickness of the pipe exists between 0.2 mm and 1.0 mm, simultaneously achieving sufficient strength and lightweight.

The fastening torque decreased significantly at the beginning of the measurement when no pipe was inserted or when the wall thickness was 0.2 mm, and gradually approached the target value of 3.0 Nm as the days passed. In both cases, the error bars were large. In contrast, the fastening torque did not decrease for the 1.0 mm and 2.0 mm thicknesses, and the target value of 3.0 Nm could be maintained at all times.

These results indicate that the proposed method is effective in maintaining the fastening force of the screw by inserting a thin-walled pipe with a wall thickness of 1.0 mm or more to suppress the deformation of the specimen under the conditions of this experiment.

IV. Evaluation of the Maximum Fastening Torque

In order to verify the maximum moments that the proposed fastening method can withstand, we carried out the experiments in which one end of the specimen was fixed by the proposed method, and a vertical load was applied to the other end of the specimen.

A. Experimental Method

We fabricated the three specimens that have the terminal shape shown in Fig.2(a), (c), and (d). Only Onyx was used as the material, and no continuous fibers were included. A total of three specimens were prepared: Nominal without pipes, with a pipe wall thickness of 1.0 mm, and a pipe wall thickness of 2.0 mm.

The specimen was fixed to the jig in Fig.9(right) with the fastening torque of 3.0 Nm, and the force was applied vertically downward at a distance of 200 mm from the center of the fixed part by a precise universal testing machine (Shimadzu AG-I, maximum test force 100 kN). An aluminum part protected the specimen from preventing localized fracture due to the soft surface of the specimen caused by the indenter with a tip diameter of 10 mm. The indenter was gradually pushed down at a rate of 3.0 mm/min, and the resulting pushing force and specimen displacement were measured.

B. Results

Fig.10 shows the test result, where the horizontal axis is the displacement of the indenter pushed down from the point where it contacted the specimen, and the vertical axis is the upward reaction force. It is clear that the proposed method (yellow and orange lines) has a steeper slope than the case without pipes (blue line), indicating that the stiffness is improved. Yield is not caused by the failure of the screwed part of the specimen but by the fracture of the upper or lower edge of the specimen due to tensile or compressive loading, respectively.

The maximum load was achieved at the pipe thickness of 1.0 mm instead of 2.0 mm. The result is presumably due to the difference in hole diameters in the specimen. The difference in hole diameter resulted in different modeling paths inside the specimen. This result also suggests that the internal structure of the specimen is dominant for the maximum allowable moment.

The allowable continuous torque of the assumed 200 W actuator is 81 Nm, and the maximum torque is 204 Nm (Fig.10 dotted lines.) It is confirmed that the proposed fastening method can sufficiently withstand the maximum allowable torque.

V. CONCLUSIONS

This paper proposed a new fastening method for a soft and deformable 3D-printed part to fix a rigid metal part and experimentally verify the effectiveness of the method. Specifically, by inserting a thin-walled pipe around the screw, the axial force acting on the screw is received by the thin-walled pipe, thereby reducing the stress on the 3D printed part. The measurements over one month showed that the proposed method could prevent screws from sinking into the 3D printed part, decreasing the fastening torque. Experiments to measure the maximum fastening torque by applying a

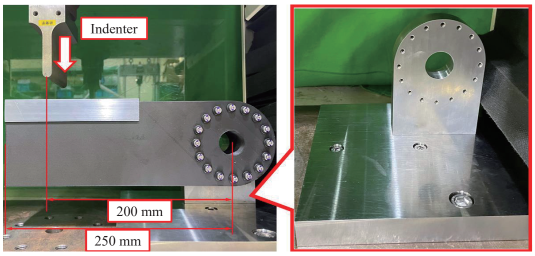

Fig. 9: Experimental setup for the maximum fastening torque measurement: (left) overview of the setup and pushing position, (right) rigid base fixed on the testing machine

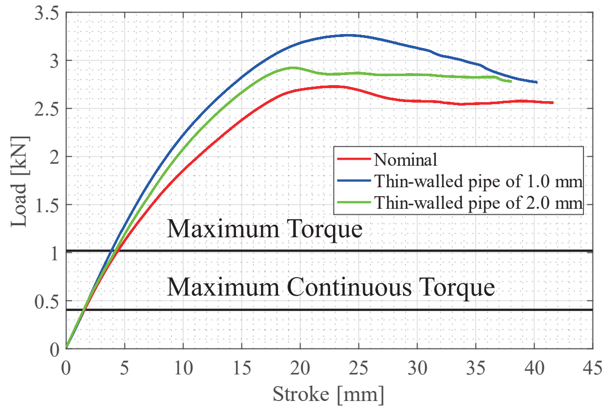

Fig. 10: Relationship between tester displacement and measured vertical reaction force. The two lines, Maximum Torque and Maximum Continuous Torque, are the calculated values of the assumed 200 W actuator values, respectively.

moment to the fastening part experimentally confirmed that the proposed method achieved sufficient fastening force.

In this paper, the maximum torque of the fastening part was measured. However, forces and moments in various directions act on the robot arm. Therefore, it is necessary to measure the strength against shear forces and bending moments in the future. All the studies described in this paper were conducted within the scope of statics, but it is necessary to consider dynamic loads such as vibration and durability against repetitive loads. Furthermore, the application of other 3D printing materials and the relationship between the 3D printing path and strength are important issues to address in the future.

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