Study on improvement in the quality of drilled holes using a robot manipulator

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Abstract

Drilling is the major process in aircraft parts production. However, in order to increase the assembly efficiency of aircrafts, the parts tend to be larger, and sometimes they are made of one body. Therefore, in the aerospace industry, there is a tendency to use robot manipulators that are more flexible than conventional gantry machines in drilling. Many studies have been conducted on robot drilling since they have advantages in terms of flexibility. However, the insufficient machining accuracy of the robot is still a problem to be solved. The quality manufacturing requirement specifications for aircraft parts are very high, and the main materials used in the aircrafts, such as carbon fiber reinforced plastic (CFRP), are difficult materials. This paper introduces a study on drilling of CFRP materials using six degrees of freedom (6-DOF) industrial robots.

1 Introduction

Carbon-Fiber-Reinforced Plastic (CFRP) materials are widely used in the aerospace industry due to their high strength-to-weight ratio. In the past, the production cost of CFRP was so high that it was used only in specific fields such as military aircrafts and spaceships. However, recently, as the unit price of CFRP production has been lowered, it has been applied not only to civil aircrafts but also to commercial vehicles. In particular, aircraft parts are often made large to improve assembly efficiency. As the use of CFRP parts in the aerospace industry has increased, many studies have been conducted to automate the production of CFRP parts using robot manipulators [1,2,3]. Aircraft parts are often large to improve assembly efficiency. A robot manipulator can be considered the most suitable for the manufacturing process of aircraft parts because it has the advantage of excellent work flexibility and space utilization. However, in spite of the advantages of such robot manufacturing processes, the improvement of the machining accuracy and machining quality of the robot is still a challenging research area. Therefore, in this paper, we introduce a study on the CFRP drilling process using industrial robots. In the process of manufacturing aircraft parts, CFRP material is generally machined through processes such as drilling, routing, and cutting after molding. Among these processes, the drilling process occupies a large portion of the CFRP aircraft part manufacturing process. The drilling characteristics of the thin plate-type aircraft parts are different from the general drilling characteristics. Furthermore, the characteristics of CFRP drilling with a robot become more complex. To study the characteristics of robot drilling, the machining force was monitored using a tool dynamometer. In addition, the control method considering the machining force was applied to improve the quality of the drilling holes

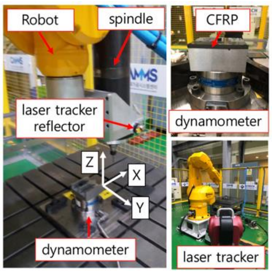

Fig. 1. Experimental setup.

2 Robot drilling experiment analysis

A 6-axis industrial robot manipulator (TX200, Staubli) used in the experiment is able to carry a 150-kg load and has a repeatability within ± 60 μm. Figure 1 shows the experimental equipment. A tool dynamometer was installed on the workpiece to measure the machining force during drilling and a laser tracker was used to measure the position of the robot end effector. The quality of the drilled hole is closely related to the machining path accuracy. In general, industrial robots are often used for pick-and-place applications; hence, the path accuracy of the robot end is not shown. That is, it does not guarantee that the end of the robot will perform a linear motion exactly. Furthermore, in the case of a machining robot, the path accuracy deteriorates when the machining force is continuously applied to the end. Therefore, some researchers have solved this disadvantage by installing a separate linear motion mechanism at the end of the robot. However, when the linear device is attached to the end of the robot, the flexibility, which is the maximum advantage of the robot, deteriorates. Therefore, it is ideal to attach only the spindle to the end of the robot. Thus, it is necessary to analyze the machining force and position error in the drilling by the robot. For comparative experiments, drilling was repeated under the same machining conditions in the machining center. The workpiece was a T1000 grade CFRP with a thickness of 5.7 mm. The tool was a ∅ 6.375 mm diamond coating tool. Machining conditions were: 9000 rpm, 0.1 mm/rev. Figure 2 is a graph showing the 3-axis (X, Y, Z) machining force when the workpiece is machined on a general CNC machine and when using a robot under the same conditions. Comparing the machining force of the CNC machine for drilling with that of the robot, it can be confirmed that an abnormal machining force is generated along the x-axis when drilling using the robot. Upon comparing the machining forces along the X-axis and Y-axis, it can be seen that CNC machines have small and symmetrical forces, while the robot drilling is large and deflected. Figure 2(c) shows that the hole quality is degraded by the machining force biased along the X axis.

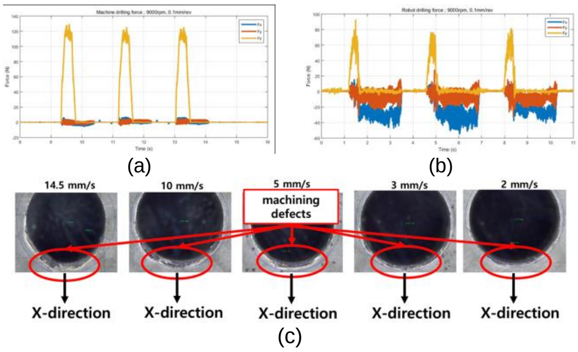

Fig. 2. (a) Machining load of the machining center, (b) Machining load of the robot manipulator, and (c) Robot drilling defects in various conditions.

Figure 3 shows the error values of the position data of the laser tracker. These error values deteriorate the drilled hole quality. It was confirmed from the data of the laser tracker that the position error of the x-axis increases due to the abnormal machining force along the x-axis. Furthermore, through repeated experiments, it was found that the larger the machining force, the larger the position error. These results are due to the weakness of the robot along the X-axis direction when drilling along the Z-axis direction. The rotational stiffness of each joint remains unchanged; however, the stiffness of the tool coordinate system depends on the posture of the manipulator.

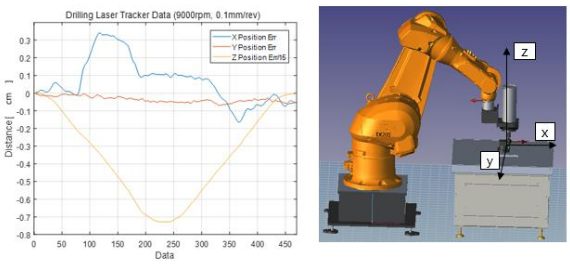

Fig. 3. Position error data of laser tracker during robot drilling.

The joint rotational stiffness and the stiffness of the tool tip are interrelated by the Jacobian matrix. That is, if the rotational stiffness of each joint is known, the stiffness of the tool tip can be obtained. When the rigidity of the tool tip is calculated, the displacement with respect to an arbitrary machining force can be predicted, and the position error of the robot can be corrected in real time. Figure 4 is a photograph of the inlet of the hole during actual CFRP drilling. In Fig. 4(a), before the algorithm is applied, it can be considered that a moment between the force generated along the x-axis and the center of the robot is generated, thereby causing a defect in the entrance portion in the direction of the negative x-axis. Figure 4(b) shows that the defects in the drilled-hole entrance part are significantly reduced after the algorithm is applied.

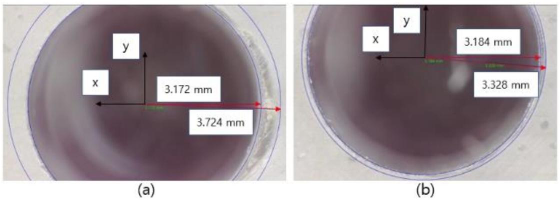

Fig. 4. Comparison of defects in the hole entrance before and after applying the algorithm

3 Conclusions

Robot drilling has great advantages in terms of work flexibility. However, there is a disadvantage that the structural stiffness is poor and the quality of the hole processing deteriorates. Especially, the biggest problem in robot drilling is a path error during drilling compared to general machining centers. To solve these problems, the relationship between the machining force and the position error of the robot end-effector was analyzed. Simultaneously, the quality of CFRP drilling holes was also analyzed. The joint rigidity of the robot was experimentally determined and the quality of the CFRP machining hole was improved by applying an algorithm that compensates for the position error.

References

[1] A. Frommknecht et al., “Multi-sensor measurement system for robotic drilling,” Robot. Comput. Integr. Manuf., 2017; 47: 4–10.

[2] T. Olsson et al., “Cost-efficient drilling using industrial robots with high-bandwidth force feedback,” Robot. Comput. Integr. Manuf., 2010; 26, 24–38.

[3] L. Cen et al, “Effect of robot dynamics on the machining forces in robotic milling,” Procedia Manuf., 2017; 10, 486–496.

[4] R. Hartenberg, J. Denavit, “Kinematic synthesis of linkages,” New York: McGraw-Hill Book Company; 1964.

[5] J.K. Salisbury, “Active stiffness Control of a Manipulator in Cartesian Coordinates,” 19th IEEE Conf. Decis. Control, December 1980.

[6] C. Dumas, S. Caro, C. Mehdi, S. Garnier, B. Furet, “Joint Stiffness Identification of Industrial Serial Robots,” Robotica, Cambridge University Press, 2011, pp. 1–20.