

# Development of Automation Technology for Precision Finishing Works Employing a Robot Arm

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There is demand for the automation of finishing processes that require technical skills in the manufacturing of metal parts with a complex shape. Such processes can be categorized into two major types of processes: polishing the surface and chamfering the edges. In this paper, a robot system with model following force control is applied to a polishing process and the method proposed in this paper is applied to a chamfering process. The proposed method consists of two steps: the edge of a part is measured by a tool with model following force control and then the edge is chamfered using position feedback control along the measured path. The validity of these methods has been confirmed by experiments involving actual polishing and chamfering.

## 1. Introduction

The Japanese manufacturing industry is facing such problems as ① tough price competition caused by globalization, ② a shift to high-mix variable-volume production systems which can respond to diversification and rapid changes in market needs, and ③ a decrease of skilled workers caused by an unbalanced population distribution in Japan. One approach to solving these problems is a more advanced level of automation, which enables ① cost reduction, ② streamlining of production, ③ stable quality, ④ enhanced product traceability, and ⑤ quantification of manufacturing know-how. In many processes of parts processing, especially in small-to medium-volume production, automation has already been promoted by the introduction of machining centers and NC processing machines, etc.

On the other hand, in assembling and finishing processes, automation has not been systematically promoted yet because these processes are partly based on skills that are dependent on individual senses of workers and are difficult to quantify. In addition, no machine exists that can reproduce such skillful work except for some tasks that can be automated by developing specialized equipment.

As a solution to automate these skill-dependent processes, we have been developing intelligent robot technology, which means adding feedback from environmental measurements taken by force sensors, image sensors and the like to a conventional robot arm. Since conventional teaching-playback robot arms have no such feedback and just repeat the same motions regardless of environmental

changes or variations, they can only automate simple processes such as welding, spraying and pick-and-place tasks. Adding sensor feedback to the robot may seem rather insignificant when compared to human intelligence, but it enables the robot to find objects and assemble parts by adjusting the contact force. Using these technologies, we have already developed some intelligent robot systems, including the assembly robot system used in cell production for automotive turbochargers. <sup>(1)-(3)</sup>

This paper introduces the technologies and system <sup>(4)</sup> we developed for automating the parts finishing work that relies heavily on manual skilled labor, as is the case with assembly work. In particular, it describes the automation of edge chamfering of parts with complex shapes and polishing of the curved surfaces of precision parts, which is difficult to process with the usual processing machines.

## 2. Finishing processes and their automation

Finishing processes is a general term for processes such as ① deburring, ② chamfering edges, ③ rounding edges, and ④ polishing surfaces. They are performed not only as a final process of producing parts but also during intermediate processes.

A typical piece of equipment for finishing parts is a barrel finishing machine. Parts and abrasives are placed in its barrel and it performs the processing shown from ① to ④ by rotating or vibrating. Methods in which abrasives are applied to parts without using a barrel, and methods using ultrasonic waves, electrolysis, combustion, etc. also exist. The advantages of these methods are that medium to large volumes can be finished simultaneously at relatively low

cost. The disadvantages are the difficulty of finishing large parts because it is not feasible to increase the size of the equipment, and the difficulty of precisely and uniformly finishing parts with complex shapes because the contact between abrasives and parts is affected by their shapes.

In order to solve these problems, application of a robot arm with a wide range of motion capable of complex movements has been proposed.<sup>(5)-(9)</sup> However, the advantage of a wide range of motion causes the disadvantage of low absolute positioning precision (1/10 to 1/100 that of a processing machine). It is difficult to obtain high geometrical precision with robot arms, which consist of rotary joints connected in series, because even a small error in a rotary joint is magnified at the tip and the error of each joint is accumulated by the serial connection of the joints. For this reason, previous applications of finishing robots mainly adopted the following methods in order to achieve highly precise processing comparable to that of machining centers or NC processing machines, but with a robot.

- (1) Teaching-playback method. The exact position is taught to the robot using the tool at the tip of the robot arm and the actual part.
- (2) An automatically generated trajectory based on CAD data, etc. is reproduced for the robot, which is equipped with a passive compliance mechanism. It then pushes the tool against the part and this mechanism compensates for the position error.<sup>(5), (6)</sup>
- (3) An automatically generated trajectory based on CAD data, etc. is reproduced for the robot, which is equipped with a force sensor and force control system and its control system causes the tool to be pushed against the part and compensates for position error.<sup>(7)-(9)</sup>

Method (1) enables high-precision processing because the absolute position is compensated for by teaching the robot using the actual parts. On the other hand, a high level of skill and much time are necessary to teach the robot because teaching precision must be high for precise processing, with the deflection of the tool and the robot while the tool is in contact with the part taken into consideration.

Method (2) reduces the labor and time required to teach the robot by generating the trajectory from CAD data, etc. The problem is that reproduction of the trajectory based on CAD data deviates from the actual surface of the part because of the low absolute positioning precision of the robot and the installation position error between the actual part and CAD data. In order to solve this problem, the passive mechanism compensates for these errors by shifting the tool toward the actual position of the part surface. However, the tool tilts due to gravity because passive mechanisms consist of springs or the like, and this causes the pushing force to change. As a result, the precision is worsened especially in the processing of parts with complex shapes which requires orientation changes of the tool.

Method (3) enables precise control of the contact force

between the tool and the parts because the influence of gravity is removed by measuring the mass and center of gravity of the tool beforehand. Additionally, processing where there is not much space is possible because there is no large mechanism near the tool. On the other hand, processing with a force control robot still faces the following problems:

- The tool tracks the large burrs left by processes such as planing and broaching. As a result, quality standards are not satisfied.
- In order to precisely track parts with complex shapes, it is necessary to reduce the feeding speed because the tracking error of the contact force is dependent on it. As a result, production tact time gets longer.
- The performance of commercial industrial robots is too low to achieve high-speed high-precision tracking. At the same time, the development cost of a high performance robot is too high.
- Setting the conditions to control the dimensions by selecting the right types of tools and their processing conditions (e.g., pushing force, feeding speed, and rotational speed of the tool) is complicated and requires a long time.

In order to solve these problems, we developed a force tracking control system based on the commercial industrial robot, proposed a high-precision and high-speed chamfering method consisting of a measurement step with force tracking control and a cutting step with position control, and improved the proposed method with iterative learning. The proposed method is a combination of method (1) and method (3), and the advantages of both can be expected.

### 3. Force tracking control by an industrial robot

Force tracking control enables industrial robots to precisely track the shape of a target object even if the absolute positioning precision of the robot is low or there is an installation position error of the object. **Figure 1** shows a conceptual diagram of the force tracking control of the robot. It works according to the following steps:

- (1) A preliminary trajectory is generated from CAD

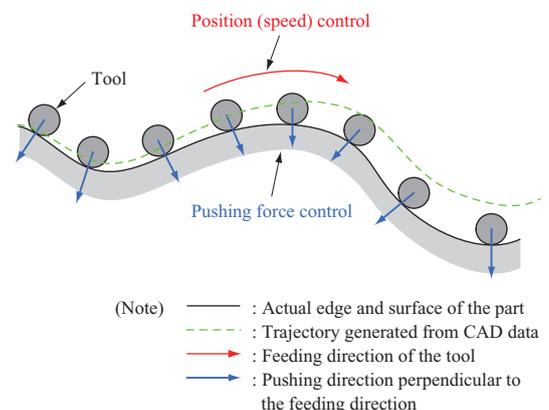


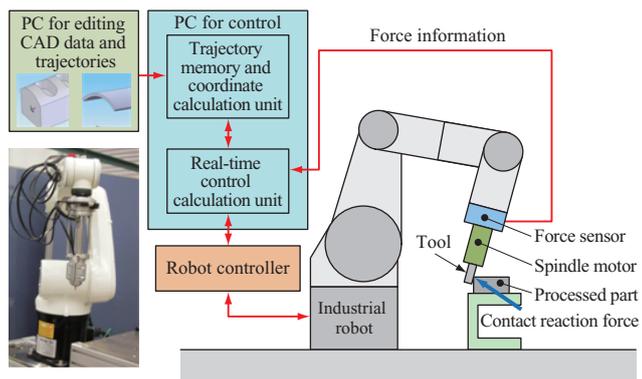
Fig. 1 Model following force control

data of a target object which is sent to the robot. The trajectory has position information and a pushing direction vector perpendicular to the feeding direction at each point on the trajectory curve at regular intervals.

- (2) The repulsive force of a tool is measured by a force sensor.
- (3) The position of the tool is measured by a robot controller.
- (4) In a constant control cycle, a position command is calculated from the force and position information using a hybrid position/force control method. This means that the force is controlled in the pushing direction and the position in the other directions.

As a result of these steps, the tool of the robot can track the edge of the target object with a constant repulsive force.

We implemented the experimental system shown in **Fig. 2**. A general-purpose industrial robot with a force sensor installed on its tip was employed because of its low cost and high maintainability. On the other hand, this industrial robot has a constraint condition which does not allow you to freely customize real-time feedback control



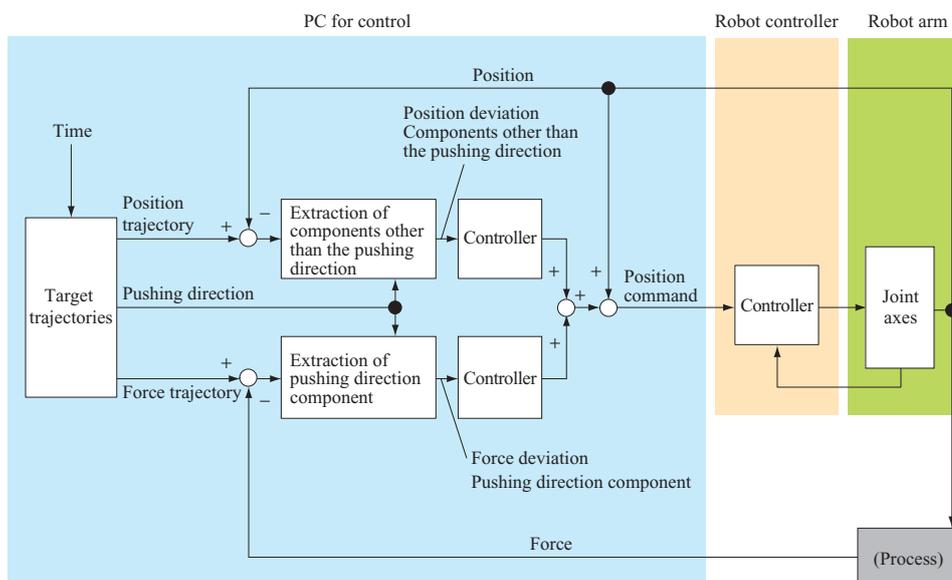
**Fig. 2** Testing system configuration

like research-purpose robots. Therefore, we used a PC for control calculation based on force information, position information, and a preliminary trajectory. The total control cycle is 12 msec because the position information of the robot is sent from the robot controller to the PC according to the cycle specified by the robot controller.

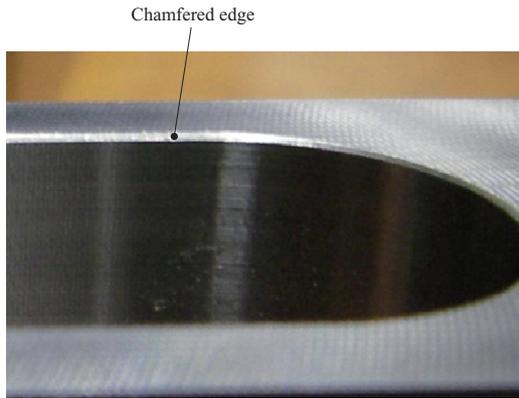
We implemented hybrid position/force control,<sup>(10), (11)</sup> which is commonly adopted for force tracking control, in our experimental system as shown in **Fig. 3**. This control method simultaneously handles force and position. The contact force of the tool is controlled in the pushing direction defined by the target trajectory and the position is controlled in all directions other than the pushing direction. These controls with different goals are used at the same time without interfering with each other by extracting the force deviation and position deviation in perpendicular directions.

In order to confirm the basic performance of the experimental system and the limitation of the conventional method, conventional chamfering and polishing using the hybrid force/position control method were performed as follows:

- (1) Conventional chamfering: the edge of an elongated hole on a test piece which does not have large burrs was chamfered as shown in **Fig. 4**. We employed an electro-deposition grinder for this because it has a relatively small cutting force and is suitable for the limitation on the control precision of the pushing force according to the sensor's precision. The chamfer surface seemed smooth and constant in terms of its dimensions, but there are problems preventing practical usage.
  - (a) Dimension control requires set-up of processing conditions on a trial-and-error basis.
  - (b) The feeding speed is set low for precise chamfering because of the low responsiveness of the force control



**Fig. 3** Control block



(Note) Processing conditions  
 - Tool : Diamond electro-deposition grinder  
 - Grain size : No. 320  
 - Tool diameter :  $\phi$  2 mm  
 - Feeding speed : 0.5 mm/s

Fig. 4 Overview of chamfered edge : slot

associated with the control cycle and delay of the commercially available industrial robot controller. That is, a trade-off relationship was confirmed, wherein an increase in speed causes changes in the pushing force that compromise dimensional precision. In some processes, the work time estimated from the feeding speed of the conventional method by which the finishing process satisfies the dimension tolerances is about two to four times longer than the maximum allowable time or manual work time.

(2) Conventional polishing: a curved surface was polished by force tracking control with a paper flapper. As was the case for chamfering, conditions were defined to satisfy the practical requirements of an actual process and the required roughness was obtained as shown in Fig. 5 (measured roughness: Ra 0.2-0.3).

Since polishing processes are not for precisely shaping a part into the desired dimensions, conditions can be



(Note) Processing conditions  
 - Tool : Flap wheel  
 - Grain size : No. 240-400  
 - Feeding speed : 6 mm/s

Fig. 5 Overview of polished surface : cylinder

defined relatively easily. The feeding speed can be higher than for chamfering. Through conventional chamfering and polishing, the validity of force tracking control for the processing and the limitation that the feeding speed and precision were in a trade-off relationship were confirmed.

#### 4. High-precision edge chamfering method with application of a robot arm

We proposed a high-precision and high-speed chamfering method consisting of a measurement step with hybrid force/position control and a cutting process with position control as shown in Fig. 6. It works as follows:

- (1) Measurement step (performed once in advance)
  - ① Target trajectory for shape measurement is automatically generated from the CAD data of a given part.
  - ② The part (with burrs removed) is installed and the relative position and orientation between the robot and part are calibrated by touch sensing, etc. (Calibration between the CAD data and actual installation position and orientation)
  - ③ The part is tracked by the tool of the robot along the measurement target trajectory so that the desired shape (measurement result trajectory) is obtained. At the same time, the absolute positioning error of the robot is absorbed.
  - ④ The measurement result trajectory is adjusted to generate the target trajectory for processing the part.
  - ⑤ Through iterative learning the target trajectory is corrected in order to improve the accuracy of the target trajectory tracking. (Discussed later)
- (2) Cutting step (performed for each process)  
 The relative position and orientation between the robot and the part are calibrated by touch sensing

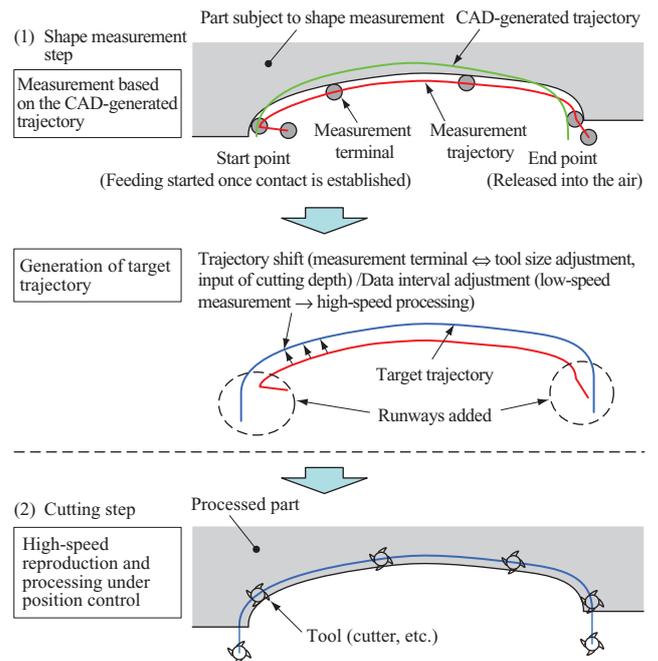


Fig. 6 Chamfering process

(performed only when the repeatability of installation is low). The calibrated target trajectory is reproduced at high speed with position control.

The proposed method has the following advantages in comparison to conventional methods:

- ① Cutting with position control can remove burrs and chamfer to the desired dimensions at the same time.
- ② Feeding speed can be set higher because the responsiveness of position control is higher than force control.
- ③ Cutting depth, etc. can be easily adjusted by editing the target trajectory.
- ④ Skilled labor is not required because the robot measures the precise shape of the parts by force tracking.

This method does not increase the production tact time when it is applied to parts that have small variability in dimensions and small installation error.

## 5. Improvement of the proposed method with iterative learning control

We applied iterative learning control and improved the proposed method for chamfering at higher feeding speeds without deteriorating its roughness.

In the proposed method, the feeding speed is set low for the measurement step for precision while the speed is set high for the cutting step to reduce tact time.

The higher feeding speed worsens the tracking errors (e.g., overshooting and vibration) from the target trajectory and makes the surface rougher at the cutting step. This deterioration of tracking precision is mainly caused by the delay of a filter within the signal processing of the robot controller to enable stable and smooth motion.

In order to improve the tracking precision, we added an iterative learning (P-type)<sup>(12)</sup> step before the cutting step.

As shown in Fig. 7-(a), the resultant trajectory is obtained as the result of the robot motion generated by sending a command with the present target trajectory to the robot controller. As shown in Fig. 7-(b), the next target trajectory

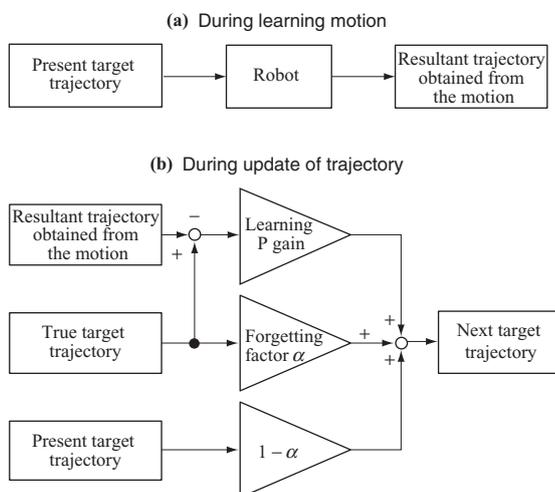


Fig. 7 Iterative learning control block

is updated from the present target trajectory by comparing the present target trajectory, the resultant trajectory, and true trajectory obtained in the measurement step.

Repeating the processes in Figs. 7-(a) and -(b) converges the target trajectory and the resultant trajectory comes close to the true target trajectory within a certain range of error. In order to adjust the learning speed, a forgetting factor of value 0-1 is applied. In general, a smaller forgetting factor accelerates learning but makes it easier to diverge.

The effect of the iterative learning control was confirmed as shown in Fig. 8. After less than 10 rounds of learning, the tracking errors such as overshooting and vibrations were reduced.

## 6. Experiments

### 6.1 Performance of chamfering

We verified the performance of the proposed method through chamfering a circular edge of a test piece. As shown in Fig. 9, a chamfered surface with an inclination of 30 degrees was made along a hole with a diameter of

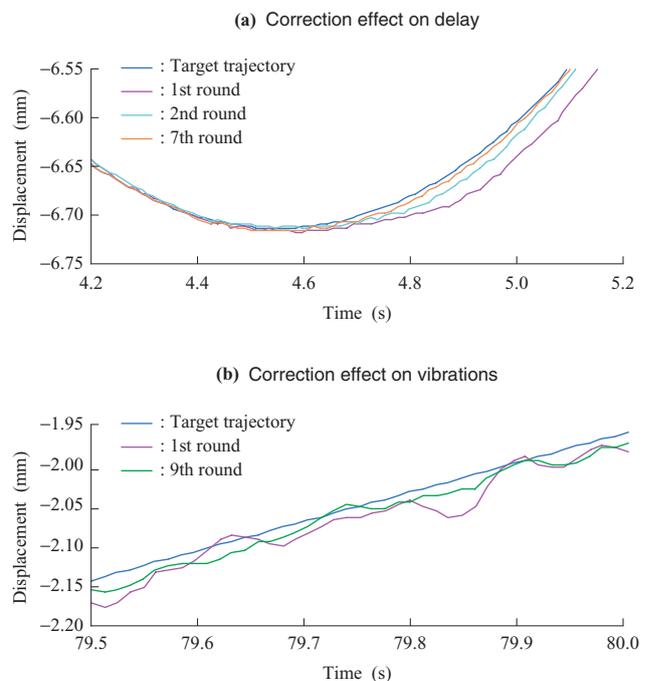


Fig. 8 Effects of iterative learning control

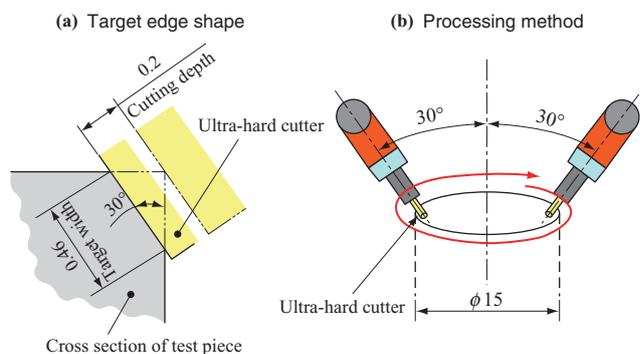


Fig. 9 Target shape of edge and chamfering method : Hole on a flat surface (unit : mm)

15 mm in a plane. The target width of the chamfer was set to 0.46 mm and the target roughness to Ra 3.2  $\mu\text{m}$  or less, which are values taken from actual requirements.

A cylindrical cutter ( $\phi 3$  mm) was employed in order to verify the performance of the three-dimensional motion of the robot. (A conical cutter achieves this chamfering with planar movement without changing the orientation of the robot.)

First, we simply compared two variations of the same process in which one had the measurement step before the cutting step and the other did not have the measurement step. As shown in **Fig. 10-(b)**, the chamfer without the measurement step — the target trajectory of which was generated directly from the CAD data of the test piece — was impractically rough. On the other hand, the width of the chamfer with the measurement step was stable as shown in **Fig. 10-(a)** and we confirmed the validity of the measurement step.

Next, we compared another two situations; one with iterative learning in the measurement step and one without the learning. As shown in **Table 1**, the width variability of the case with the iterative learning was smaller than the case without learning and the roughness of the case with the iterative learning was also smaller. In addition, the width variability is sufficiently small compared with the general requirement of manual finishing. Therefore, we confirmed the validity of the proposed method consisting of the measurement step with iterative learning and the cutting step.

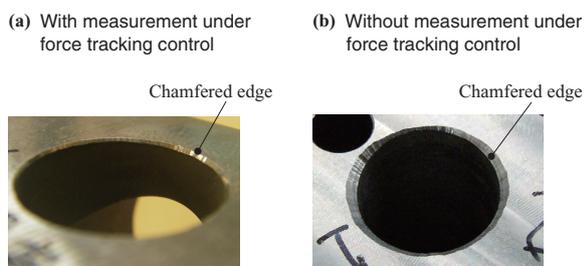
Examining the result in detail for the further improvement, the processing widths in both cases were smaller than the target value by about 0.1 mm on average, which corresponds to a cutting depth of about 0.04 mm. The possible causes are

accumulation of repeated position error of the robot, elastic deformation of the tool and robot, backlash of the joints of the robot, etc.

## 6.2 Applicability to various shapes

We verified the applicability of the proposed method to the edges of various shapes.

The first case is the 3-dimensional edge of an elongated hole on a cylindrical surface as shown in **Fig. 11**. The appearance of the chamfered edge of the test piece after processing is shown in **Fig. 12** whereas the resulting width and roughness are presented in **Table 2**. Since the variability of the chamfer width is rather small and the roughness satisfied the target value, we confirmed the applicability of the proposed method.

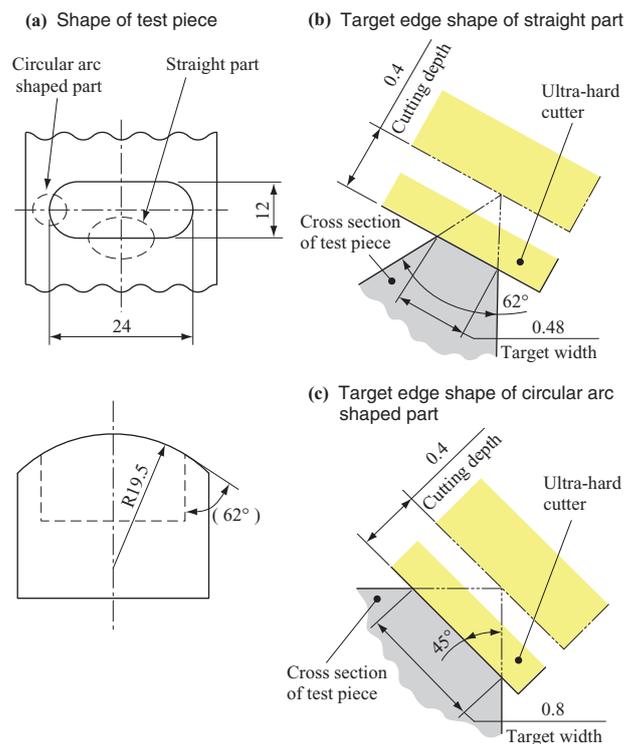


**Fig. 10** Overview of chamfered edge : Hole on a flat surface

**Table 1** Results of chamfering : Hole on a flat surface

Item	Unit	With learning	Without learning
Maximum processing width	mm	0.430	0.461
Minimum processing width	mm	0.296	0.259
Average processing width	mm	0.358	0.348
Standard deviation	-	0.049 6	0.074 6
Variance	-	0.002 46	0.005 56
Arithmetic average roughness Ra	$\mu\text{m}$	1.82	2.51
Maximum roughness in 10-point mean roughness Rz	$\mu\text{m}$	7.95	11.5

(Note) The value corresponding to each processing width shows the measurement results at 12 points on the circumference.



**Fig. 11** Target shape of edge : Slot on a cylinder (unit : mm)



**Fig. 12** Overview of chamfered edge : Slot on a cylinder

**Table 2** Results of chamfering : Slot on a cylinder

Item	Unit	Circular arc shaped part	Straight part
Maximum processing width	mm	0.335	0.571
Minimum processing width	mm	0.284	0.517
Average processing width	mm	0.310	0.546
Arithmetic average roughness Ra	$\mu\text{m}$	1.2 - 1.8	

(Note) The value corresponding to each processing width shows the measurement results at 7 points on the circumference and 9 points on the straight section.

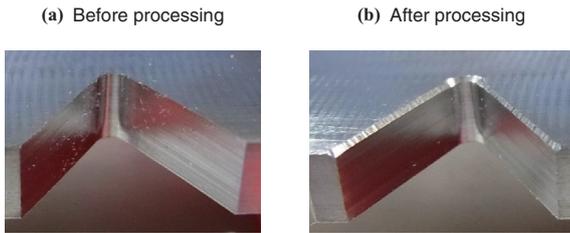


Fig. 13 Overview of chamfered edge : V-shaped groove

Showing further improvement, the dimension became slightly smaller than the target value seen in the chamfering of the circular edge.

Another case is the edge of a V-shaped groove as seen in gears and splines. The appearance of the chamfered edge of the test piece is shown in Fig. 13. The results indicate the same trend as mentioned before, which verified the applicability of the proposed method.

## 7. Conclusion

In order to automate finishing processes that normally require skilled labor, we established an intelligent robot system with force tracking control, proposed a chamfering method consisting of a measurement step with hybrid force/position control and a cutting step with position control, and improved chamfering precision by adding iterative learning to the measurement step. Through experiments, we confirmed the validity of the proposed method in terms of dimensional stability and roughness and its applicability to the various shapes of edges.

As the next step, we will apply this technology to actual finishing processes. At the same time we will also develop technologies to control the dimensions to shape various edges and to improve robustness so that diverse conditions can be handled uniformly.

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