Technical paper

Using Power Skiving to Increase the Efficiency and Precision of Internal Gear Cutting

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Power skiving has recently been attracting interest as a highly efficient and precise method of machining internal gears. However, manufacturers are having difficulty establishing power skiving technologies since the technique uses a complex machining mechanism and creates a high cutting load. This study has responded by developing a large machining facility that can handle construction machinery parts, developing machining analysis technology, and enabling mass-production of power skiving technology. This report provides an overview of power skiving technology, and presents the work done for this study.

Key Words*:* *Power skiving, Gear cutting, Machining analysis, Gears, Internal gears*

1. Introduction

To meet the need for lower fuel consumption and reduced noise, users in the automotive and other industries are currently calling for higher levels of machining precision in gears used in epicyclic gear trains. To compensate for labor shortages and increase cost competitiveness, there is also growing demand for more efficient gear machining.

Power skiving (**Fig. 1**) has recently been attracting interest as a highly efficient and precise method of machining internal gears. Power skiving is a machining method in which the swarf is continuously ejected by the tool, making it more efficient than gear shaping and giving it fewer machining restrictions than broaching. Power skiving was devised in 1910 by Julius Wilhelm von Pittler, but it initially had no industrial applications due to the short tool life and rough machining precision of the finished surface. However, starting in 1970, a team led by Masakazu Kojima analytically derived the principle of power skiving,[1][2] while advances and improvements were made in tool coating technologies, machine tool rigidity and rotary shaft synchronization.[3] Power skiving has therefore attracted interest as a feasible new production technology for internal gears, and research has been done on making it an alternative to current machining methods.[4] Research has also been done on tool design[5] and better machining conditions.[6]

For this study, we developed a large machining facility supporting construction machinery parts, developed machining analysis technology, and enabled mass-production of power skiving technology. This report provides an overview of power skiving technology, and presents the work done for this study.

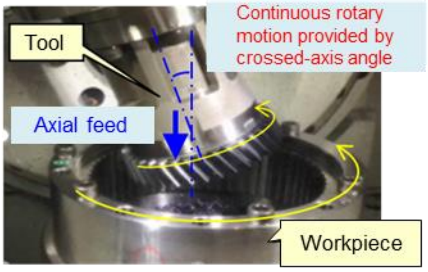

Fig. 1 Power skiving

2. Power Skiving

Gear shaping is a machining method that uses a gear (large gear) engaged in relation with a pinion (small gear). On the pinion side, a component provided with a clearance angle and serving as a cutter (the pinion cutter) is used to machine the workpiece gear by form cutting enabled by the cutter's reciprocating motion (**Fig. 2**). The blades cut in the direction of the workpiece tooth trace, and the cutter axis and workpiece axis are always parallel. This machining method inevitably has low efficiency since non-machining time accounts for half of the reciprocating motion.

Hobbing is a machining method created for external gear machining. It enables highly efficient machining without time wastage by using a cutter's rotary motion. However, since practical hobbing methods for internal gear machining have not been devised, gear shaping has been widely used for internal gears except for some large-diameter/large-module gears enabling the use of tooth milling cutting.

In contrast, power skiving machines the gear by using the rotary motion of a pinion cutter (combining the elements of the pinion cutter used in gear shaping and the rotary motion of hobbing), enabling highly efficient machining of even internal gears using cutter rotary motion. The tool axis and workpiece gear axis are positioned in a skew rather than parallel relationship. The tilt angle creates a sliding component in the direction of the tooth trace when the cutter and workpiece rotate synchronously. This sliding component has a blade cutting action, creating the workpiece gear (**Fig. 3**).

Making highly efficient power skiving possible requires high-rigidity equipment that can withstand the cutting force. It is also important to set the proper cutting conditions using machining analysis since there are a large number of setting parameters used to determine the cutting conditions, and the machining mechanism is complex (with a continuously changing rake angle).

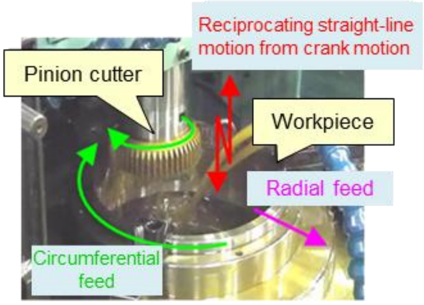

Fig. 2 Gear shaping

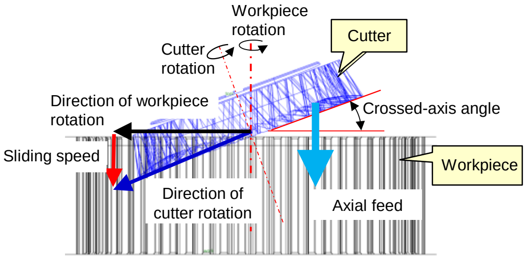

Fig. 3 Machining principle of power skiving

3. Development of Power Skiving Facility

Research has been done on turning power skiving into a feasible new gear production technology, made possible by recent improvements in tool coating, equipment rigidity, and rotary shaft synchronization technologies. Machine tool manufacturers have responded by working on the development and release of power skiving machines since around 2012. However, equipment development has focused on machine tools for small gears used mainly for automotive parts. Very few machine tools have been developed for large gears such as gears for use in construction machinery. Komatsu has developed a machine tool for large gears, after determining from past power skiving tests that equipment rigidity is the most important requirement for these machine tools. The unit was developed in collaboration with equipment provider Karats Precision, Inc. Our primary development concept was to ensure a sturdy equipment rigidity. **Fig. 4** shows the developed power skiving machines (GSV-60N). The unit has a table diameter of 700 mm, and can produce Komatsu's high production-volume internal gear lineup, including gears for medium-sized hydraulic excavators. Its other features are:

- Shaft drive frames are gantry types and have dual support structures, ensuring high rigidity.
- The use of a symmetrical frame reduces body weight and reduces thermal deformation applied to the workpiece.
- Vibration damping structures are used in the guide surfaces of the main shaft and other shafts.
- An automatic tool changer (ATC) is placed inside the body to support a wide range of machining.

Fig. 4 Developed power skiving machine

4. Development of Power Skiving Analysis Technology

4.1 Machining Principle

A complex machining mechanism is needed to make power skiving possible, and this mechanism requires analysis to quantify and adjust the machinability index. **Fig. 5** shows the relative positions of the tool and workpiece during power skiving. The system shown in **Fig. 5** has three Cartesian coordinate system settings. Coordinates unique to the entire system are expressed in the form $S_0(O\text{-}x,\ y,\ z)$. Coordinates fixed to the workpiece are expressed in the form $S_w(O_w\text{-}x_w, y_w, z_w)$. Coordinates fixed to the tool are expressed in the form $S_t(O_t\text{-}x_t,\ y_t,\ z_t)$. The origin of each coordinate systems S_w and S_t are written (0, 0, a) and (0, b, c) respectively in coordinate system S_0. The rotary speed of the workpiece during machining ω_w is given by the formula below.

$$\boldsymbol{\omega_w = \frac{Z_t}{Z_w}\omega_t + \frac{2f\sin\Sigma}{m_t Z_t}}\#(1)$$

where Z_w and Z_t are the number of teeth in the workpiece and tool respectively, ω_t is the angular velocity of the tool, f is the feed amount, Σ is the crossed-axis angle and m_t is the tool's module.

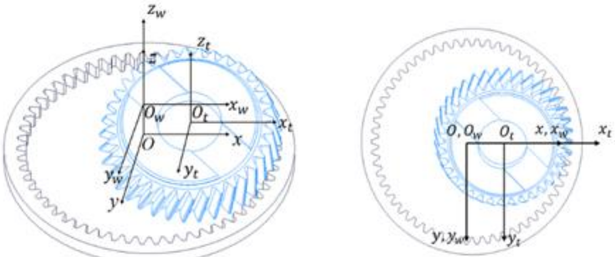

Fig. 5 Tool and workpiece coordinate systems and relative positions

4.2 Tool Path Calculation

We used a simulation to find the power skiving cutter path. The side surfaces of the tool's teeth are involutes. One curve is expressed by:

$$\boldsymbol{edge_{initial}} = \begin{bmatrix} \boldsymbol{r\,(\cos\theta + \theta\sin\theta)} \\ \boldsymbol{r\,(\sin\theta - \theta\cos\theta)} \\ \boldsymbol{0} \\ \boldsymbol{1} \end{bmatrix}\#(\boldsymbol{2})$$

where r is the radius of the base circle, and θ is a parameter determined by the tooth tip diameter r_a. The curve on the opposite side is axially symmetrical, so can be expressed by the same formula. The tip of tool's teeth were approximated by a straight line for the calculation.

The tool's teeth are then rotated by an amount corresponding to the tool's rake angle and tilt angle. The tool's teeth are calculated by the formula below, since the calculation is done by applying translation matrices T_{pan1} and T_{pan2} used to make the tooth the center of rotation, and matrices that rotate by an amount corresponding to the rake angle and tilt angle, T_{rake} and T_{inc}.

$$\boldsymbol{edge_{tool} = T_{pan2} \cdot T_{inc} \cdot T_{rake} \cdot T_{pan1} \cdot edge_{initial}}\#(\boldsymbol{3})$$

where the matrices are given by the formulas below.

$$\boldsymbol{T_{pan1}} = \begin{bmatrix} \boldsymbol{1} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{-r_a} \\ \boldsymbol{0} & \boldsymbol{1} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{1} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{1} \end{bmatrix},\quad \boldsymbol{T_{pan2}} = \begin{bmatrix} \boldsymbol{1} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{r_a} \\ \boldsymbol{0} & \boldsymbol{1} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{1} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{1} \end{bmatrix}\#(\boldsymbol{4})$$

$$\boldsymbol{T_{rake}} = \begin{bmatrix} \boldsymbol{\cos\gamma_t} & \boldsymbol{0} & \boldsymbol{-\sin\gamma_t} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{1} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{\sin\gamma_t} & \boldsymbol{0} & \boldsymbol{\cos\gamma_t} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{1} \end{bmatrix}\#(\boldsymbol{5})$$

$$\boldsymbol{T_{inc}} = \begin{bmatrix} \boldsymbol{1} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{\cos\Sigma} & \boldsymbol{-\sin\Sigma} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{\sin\Sigma} & \boldsymbol{\cos\Sigma} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{0} & \boldsymbol{1} \end{bmatrix}\#(\boldsymbol{6})$$

Since the tool rotates at angular velocity ω_t during machining, the T_{rotate} matrix for the conversion is applied, in addition to applying the T_{cross} matrix expressing the tilt of the tool's crossed-axis angle. Then the T_r matrix is applied to correct the tool's position. Accordingly, the tool's path is expressed by:

$$\boldsymbol{edge_{move}(\Delta t) = T_r \cdot T_{cross} \cdot T_{rocate} \cdot edge_{tool}} \#(\mathbf{7})$$

where the matrices are given by the formulas below.

$$\boldsymbol{T_{rotate}} = \begin{bmatrix} \cos \omega_t \Delta t & -\sin \omega_t \Delta t & 0 & 0 \\ \sin \omega_t \Delta t & \cos \omega_t \Delta t & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \#(\mathbf{8})$$

$$\boldsymbol{T_{cross}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & cos(-\Sigma) & -sin(-\Sigma) & 0 \\ 0 & sin(-\Sigma) & cos(-\Sigma) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \#(\mathbf{9})$$

$$\boldsymbol{T_r} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & b \\ 0 & 0 & 1 & c \\ 0 & 0 & 0 & 1 \end{bmatrix} \#(\mathbf{10})$$

4.3 Calculating Cut Shape Using Z-map Model

A Z-map model is a model used when comparing surfaces in three dimensions, and can show regions through which objects pass.[7] Our Z-map model provided grid-based division of workpiece inner diameters, storing the X-coordinate of each grid center in a two-dimensional array on the Y-Z plane. Each new region through which the tool tip passed was then stored in a two-dimensional array by using the calculated tool path to update the X-coordinate in each grid. This method was used to infer the cut shape by comparing the next cutting process to the initial plane or the cut process of the preceding cycle.

4.4 Machining Analysis and Demonstration Test Results

We used the method above and the conditions shown in **Table 1** to carry out analysis. In power skiving, the workpiece is machined with progressively deeper cuts in the direction of the tool axis x_t. The workpiece was machined five times, numbering each machining pass (Pass1, Pass2, Pass3...). **Table 1** shows the increase in the cut depth made by each pass.

Cut shape is an important parameter linked to explicating machining phenomena. Cut shape data can be used to infer cut force and predict the progress of wear.[8] We used calculations to infer the cut shape of each power skiving pass. **Fig. 6** shows the cut shape of each pass. The images in the top row are 3D views. The middle row are front views. The bottom row are plane views. The two lines in the front view images show both edges of the blade tip in each pass. In other words, the area between the two lines is the blade tip. The area to the left is the area machined by the left cut blade, and the area to the right is the area machined by the right cut blade.

The simulation showed the left cut blade and blade tip doing a large amount of machining in Pass1 and 2, producing a straight cut shape, but as the machining process progressed, machining was done by the right cut blade also, and the cut shape became V-shaped. The plane views also show how machining progressed with each pass.

Fig. 7 shows the swarf produced by each pass during actual machining. Comparing the results to the shapes obtained by calculation shows a match to the machining process described above even after accounting for plastic deformation. The left cut blade and blade tip do most of the machining in Pass1 and 2. The cut shape is also straight in these passes, as is the shape of the swarf. Starting in Pass3, additional machining is also done by the right cut blade. The cut shape and swarf shape both become V-shaped as a result, indicating a match to the simulation result.

Table 1 Cutting parameters

Cutting tool	Teeth number [-]		36
	Module [-]		3
	Helix angle [degree]		20
	Rake angle [degree]		12
Workpiece	Teeth number [-]		58
	Module [-]		3
	Helix angle [degree]		0
Cutting process	Axial feed [mm/rev]		0.8
	Depth of cut [mm]	Pass1	2.18
		Pass2	1.61
		Pass3	1.25
		Pass4	1.00
		Pass5	0.20

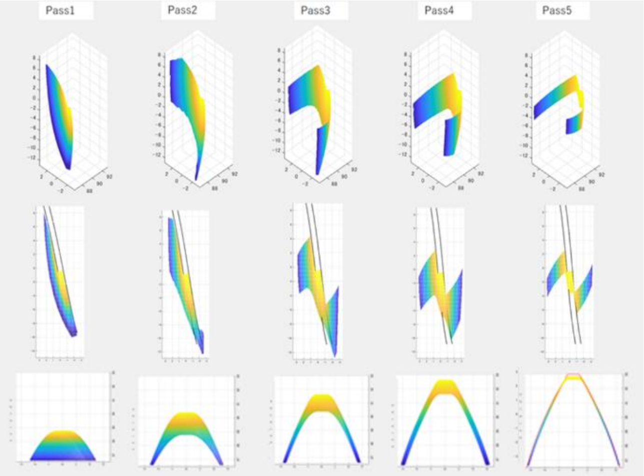

Fig. 6 Cut shape produced by each pass

Fig. 7 Swarf shape produced by each pass in cut test

5. Continuous Machining Test Results

We used the developed machining tool and machining analysis technology to adjust the cutting conditions, and conducted a continuous machining test on an internal gear with a module of 3.25, 95 teeth and a tooth width of 121.5 mm. **Table 2** shows the cutting parameters. **Fig. 8** and **Fig. 9** show the gear precision after machining, which was found to satisfy JIS Class 2 (JIS B1702 1998). However, a tooth tip rise of 25 μm during machining was targeted for the tooth shape. We succeeded in tripling the tooth cutting efficiency of gear shaping (**Fig. 10**), and increasing its tool life by 20% (**Fig. 11**).

Table 2 Cutting parameters

Cutting tool	Teeth number [-]		52
	Module [-]		3.25
	Helix angle [degree]		20
	Rake angle [degree]		5
Workpiece	Teeth number [-]		95
	Module [-]		3.25
	Helix angle [degree]		0
	Tooth width [mm]		121.5
Cutting process	Axial feed [mm/rev]	Pass1 to 4	0.5
		Pass5	0.3
	Depth of cut [mm]	Pass1	2.00
		Pass2	2.00
		Pass3	2.00
		Pass4	1.10
		Pass5	0.31

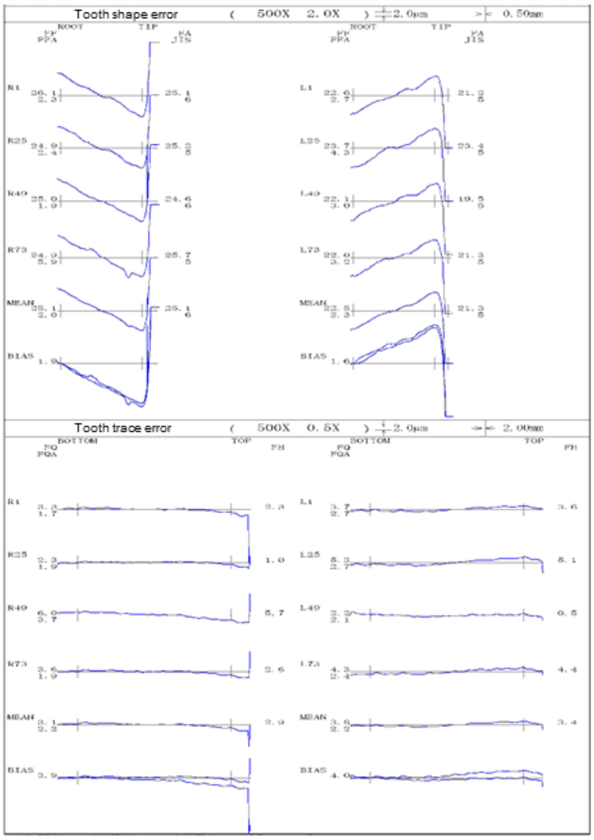

Fig. 8 Gear precision (tooth shape/tooth trace)

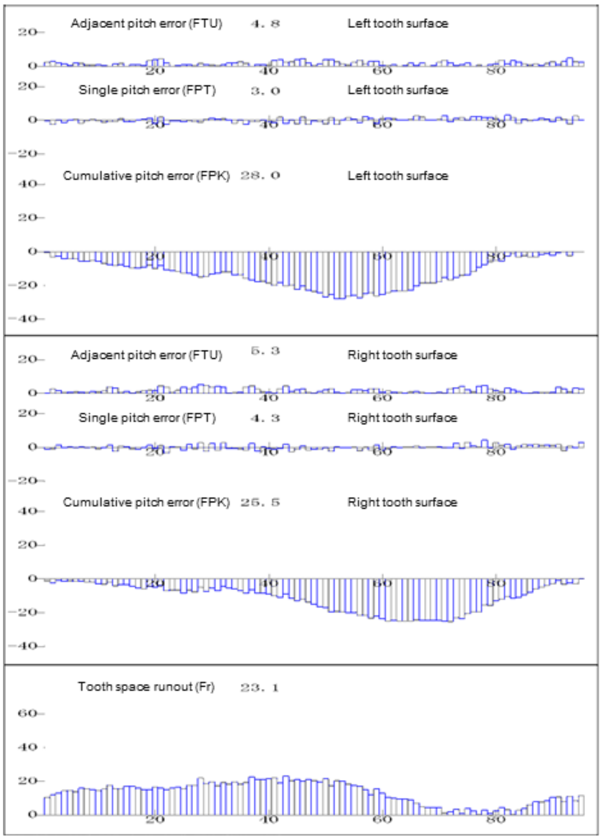

Fig. 9 Gear precision (pitch, tooth space runout)

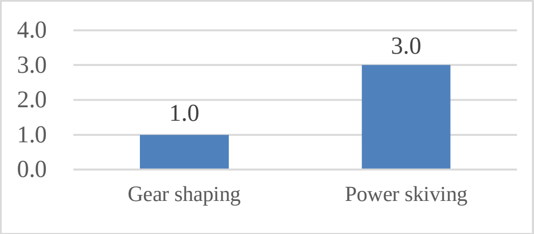

Fig. 10 Tooth cutting efficiency

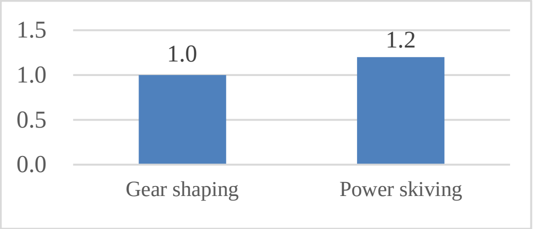

Fig. 11 Tool life

6. Using Power Skiving to Reduce Equipment Size

Power skiving has other benefits besides improving machining efficiency. It can also reduce part size such as by shortening gear cut end portions, and increase precision by enabling hard machining after heat treatment. Komatsu has used power skiving to reduce the size of a reduction gear unit. **Fig. 12** shows a final reduction gear unit for a hydraulic excavator. Since internal gears have conventionally been machined by gear shaping, the limitations of the machining method have resulted in uniform gear specifications for the speed-reducing first stage and the second stage of the internal gears used in two-stage planetary reduction gear units. Changes in gear specifications between the speed-reducing first stage and second stage were not made when using gear shaping due to considerations such as guaranteeing the first and second stage alignment and the machining cost. This issue resulted because machining from the same direction requires a large relief groove to be provided between both gears due to interference between the tool and workpiece, while machining from another direction requires the workpiece to be reversed. In contrast, power skiving from the same direction enables a relatively small relief groove between both gears by optimizing the crossed-axis angle and tool shape. Mounting an ATC unit in the power skiving machine also enables two-stage workpiece machining with different specifications for the first stage and second stage within a single process. The example in **Fig. 12** enables an optimum design by using different specifications for each stage. Ring gear inner diameter (tooth bottom diameter) has been reduced by 9%, resulting in an 8% weight reduction along with the size reduction of the built-in parts (planetary gear, sun gear and carrier). Maintaining the ring gear wall thickness within the constraint of the overall unit size also enables a ring gear/hub split structure and as such the use of lower-grade material for the hub since it does not require strength as a gear part. The use of power skiving and other new technologies enables the unit to achieve a production cost reduction of 10% relative to conventional units.

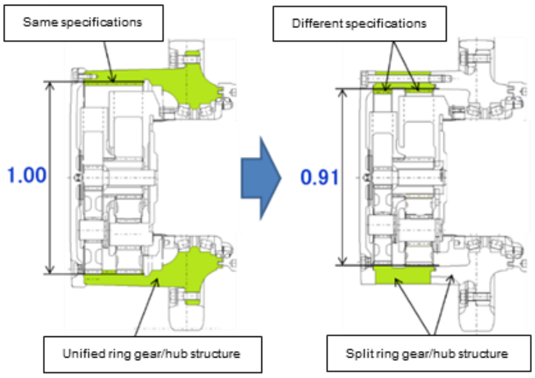

Fig. 12 Example of size reduction in final reduction gear unit

7. Conclusion

For this study, we developed a large machining facility supporting construction machinery parts, developed machining analysis technology, and achieved mass-production of power skiving technology. We demonstrated that power skiving can triple the machining efficiency of gear shaping, and increase its tool life by 20%. By drawing on the benefits of power skiving, we also succeeded in reducing the size of a final reduction gear unit, reducing its weight by 8% and production cost by 10%.

Moving forward, our aim is to help increase the market competitiveness of Komatsu's construction machinery by working on stably mass-producing the developed technologies and increasing the size of the parts they support.

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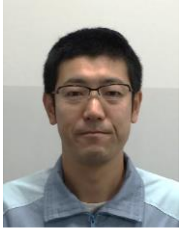
[A comment from the authors]

Power skiving can do more than just improve machining efficiency. The quality improvements and other benefits made possible by power skiving can be used to create part shapes and structures that can give components a competitive edge. We will continue to work on developing technologies designed to enable the use of power skiving for producing a wide range of parts not limited to the examples presented here.

We would like to express our heartfelt appreciation to Professor Sugita of the University of Tokyo and his students, who took part in this study through a collaborative project between industry and academia.

Introduction of the authors



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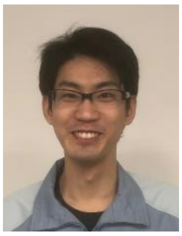

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