Technical paper

Development of ultra high speed, high-accuracy profile grinding machine

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Profile grinding machines used for machining automobile engine cams are required to have performance to shape special contours at a higher accuracy that can meet demands of higher efficiency in engines, as well as a structure to achieve both reduction of installation area and high stiffness.

We would like to introduce our technology development conducted in cooperation with Komatsu NTC. Approaching with vibration analysis technology which is unique to Komatsu, together with thermo-fluid analyses and control technologies, low vibration and high stiffness have been achieved by optimizing the structure of the profile grinding machine bed and its grinding wheel spindle. A new ultrafast, high-accuracy grinding machine capable of predicting machining accuracy while performing grinding has been developed.

***Key Words**: Profile grinding machine, Vibration, Thermic fluid, Control, Cam*

1. Introduction

In recent years, while shift to EV has attracted attention, automobile manufacturers have been continuously working on promotion of engine technology innovation and reduction of CO_2 emission by higher combustion efficiency. To manufacture engines with high-efficiency, it is also essential to improve the performance of machine tools for producing engine parts.

Therefore, we focused on profile grinding machines for high-precision grinding of engine cams, and worked on development of an unconventional machine added with innovative functions making it possible to include ultrafast high-accuracy machining and the following inspection process into the machining process.

The outline of technical development and technical features are introduced below.

2. Profile grinding machine

2.1 Structure and machining method of profile grinding machine

The structure of the cam profile grinding machine and the conceptual diagram of machining are shown in **Fig. 1** and **Fig. 2**. The surface of the egg-shaped cams lined up on the shaft of the workpiece is the target to be machined. High accuracy machining of the cam shape is performed by grinding with an grinding wheel of a diameter around 350 mm moving back and forth on a saddle against a workpiece rotating at a speed of 4,000 to 6,000 rpm.

Each cam is machined from crude to finish by moving the grinding wheel head back and forth several times. Upon completing the machining of a cam, the saddle moves laterally to machine the next cam. The machine is required to process each cam within a short time of about 10 seconds.

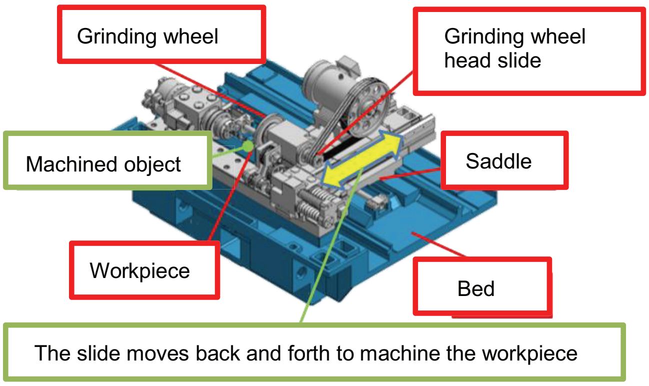


Fig. 1 Structure of cam profile grinding machine

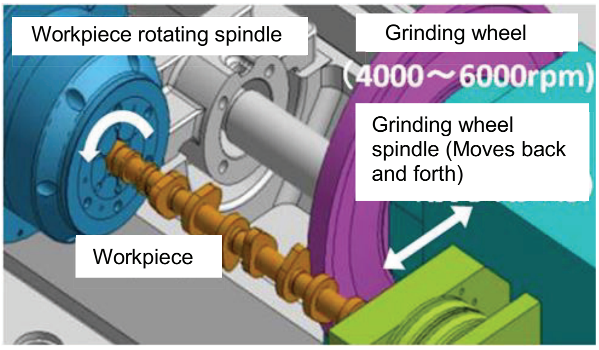


Fig. 2 Conceptual diagram of cam machining

2.2 Problems of profile grinding machine

The cam shape consists of a base circle portion and a nose portion which raises and lowers the engine valve. While machining is performed by synchronizing the back-and-forth movement of the grinding wheel head and the rotation of the workpiece, profile errors are likely to occur at the shape changing points (b, c, and d) as shown in **Fig. 3**, due to the stiffness and control performance of the machine. In addition, whirling vibration of the grinding wheel occurs by a slight imbalance remaining in it. This is transferred to the machining surface of the cam as chatter. Reducing of chatter is the big problem for profile grinding machines for cams. In addition, it has been desired to improve the machining speed and reduce the installation area of the machine for further improvement in productivity.

2.3 Contribution to shape error of each portion and countermeasure policy

As shown in **Fig. 4**, there are three portions that mainly contribute to shape error on the machined surface of the cam. The most influential part is the grinding wheel spindle, and the coupled stiffness of the shaft and the bearing is involved. The second is the grinding wheel head, in which the stiffness of the static pressure guide legs and the clearance variation caused by the stiffness are involved. The third is the structural system consisting of the bed and saddle in which the reduction in dynamic stiffness caused by the torsional vibration and bending vibration is involved.

To improve the machining accuracy, one of the solutions is to increase the stiffness of the three portions by changing the structure. However, conflicting issues such as significant increase in mass and spindle diameter are anticipated in order to achieve the target machining accuracy.

Therefore, we have adopted a countermeasure policy to achieve a targeted machining accuracy by taking three approaches in parallel, i.e., structural measures, vibratory source measures, and control measures.

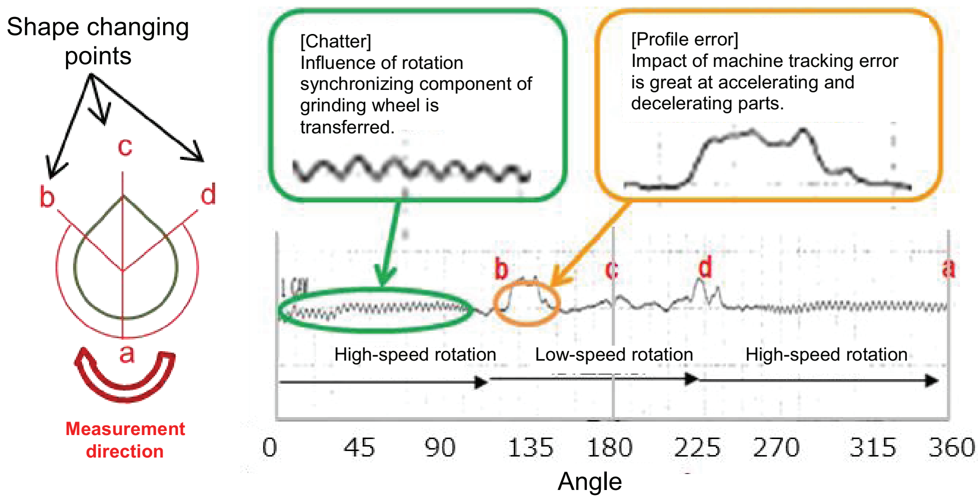


Fig. 3 Shape error of machined surface

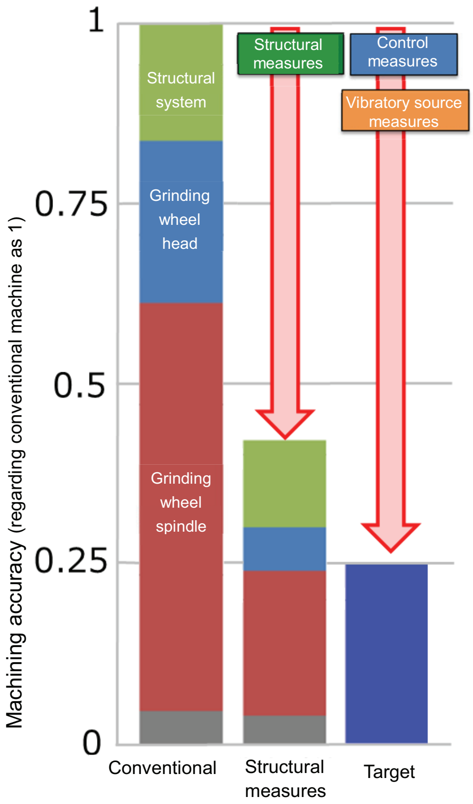


Fig. 4 Contribution to machining accuracy by each portion and countermeasure policy

3. Structural measures

3.1 High-stiffness design of grinding wheel head static pressure guide

From the static analysis results as shown in **Fig. 5**, it has been revealed that the leg stiffness of a static pressure guide of a conventional grinding wheel head is insufficient since leg opening deformation is caused by static pressure.

Moreover, it is also found that the actual guide stiffness is greatly reduced compared to the designed value when this deformation causes a change in the clearance at the static pressure guide as shown in **Fig. 6.**

To improve these problems, the thickness of the legs was increased and a structure to add static pressure from both sides on each leg has been adopted to the development machine.

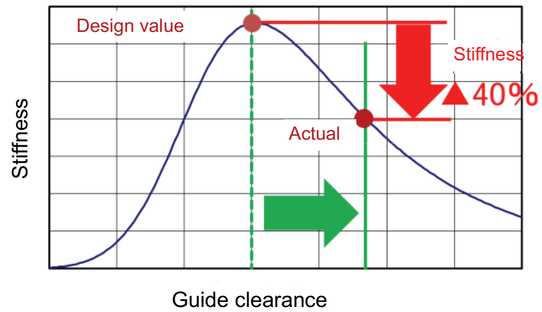


Fig. 6 Stiffness variation caused by clearance at static pressure guide

3.2 Optimal bed design

Fig. 7 shows a comparison of analysis results of bed dynamic stiffness between conventional and development machines. Any elasticity natural frequency of structure system in addition to rotation frequency of the grinding wheel spindle may cause reduction in the dynamic stiffness leading to deterioration of shape accuracy.

Therefore, in the development machine, a structure in which the natural frequency of the lowest order elastic mode is outside the range of the grinding wheel spindle operating speed frequency is studied and adopted by the optimization method by FEM.

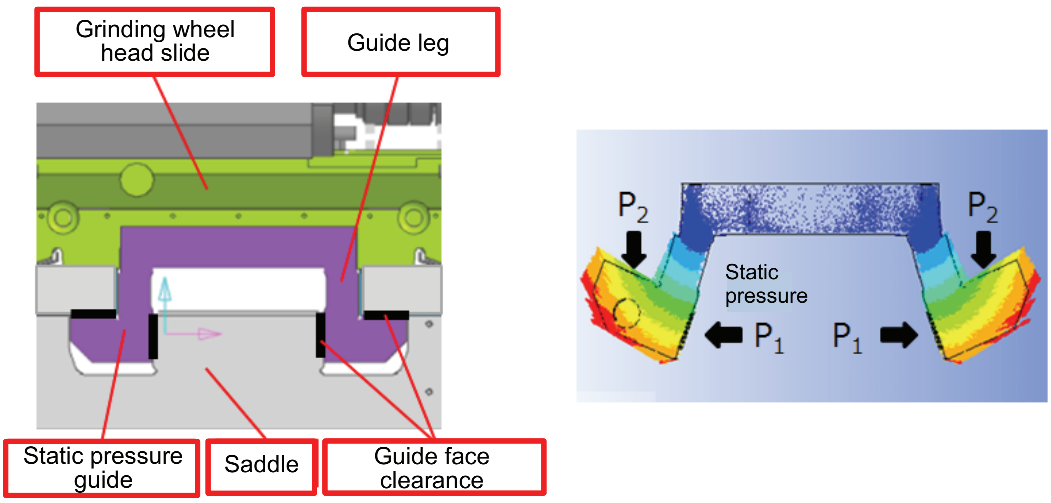


Fig. 5 Static pressure guide structure and leg part static analysis

Fig. 8 shows the flow of design optimization. A solid shape as shown in **Fig. 8 (a)** was used for eigenvalue analysis and the obtained element density indexes are shown in **Fig. 8 (b)**. In this Figure, parts in red and blue indicate higher and lower contribution to stiffness, respectively. Therefore, it is possible to achieve weight saving while keeping stiffness as well as to design the lowest order natural frequency to be increased by shaving off the portions indicated in blue. As a result, a V-shaped front surface supported at 3 points as shown in **Fig. 8 (c)** has been obtained, and this structure has been adopted for the development machine.

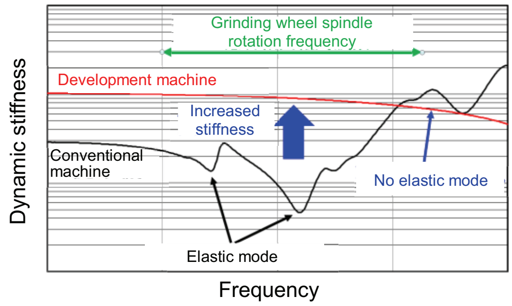


Fig. 7 Analysis results of bed dynamic stiffness

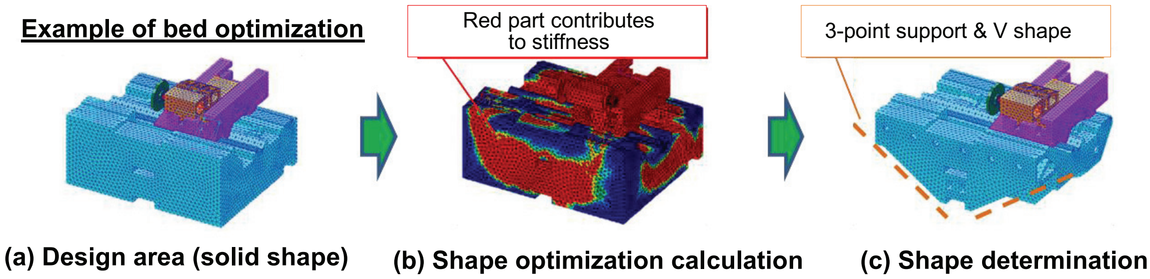


Fig. 8 Result of cross sectional

3.3 Achievement of higher stiffness of grinding wheel spindle (shaft and bearing)

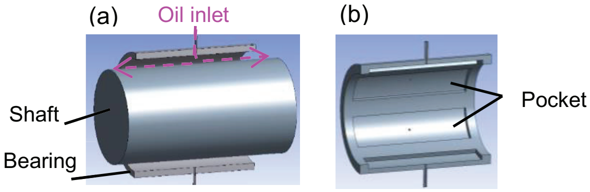
As the contribution degree analysis in **Fig. 4** shows, the grinding wheel spindle, which significantly contributes to machining accuracy, is an indispensable important part requiring further enhancement in stiffness. Since the dynamic stiffness of the grinding wheel spindle is affected by the stiffness of both the bearing and shaft itself, we have established a prediction method for grinding wheel shaft dynamic stiffness and tried to achieve a higher dynamic stiffness aiming at 2 times as high as that of conventional ones.

3.3.1 Bearing analysis

A hybrid hydrodynamic bearing which allows oil to be pressure fed in the narrow gap between the shaft and bearing as shown in **Fig. 9 (a)** is used on the grinding wheel spindle. The static pressure generated in the gap and the dynamic pressure supports the bearing. Though an approximate expression called the Reynolds equation is used from the old times for designing hydrodynamic bearings, this can be used only for analyzing simple shapes. Therefore, in this research, a three-dimensional thermal fluid analysis model has been established by using computational fluid dynamics (CFD) to design the bearing. Advantages of using CFD are as follows.

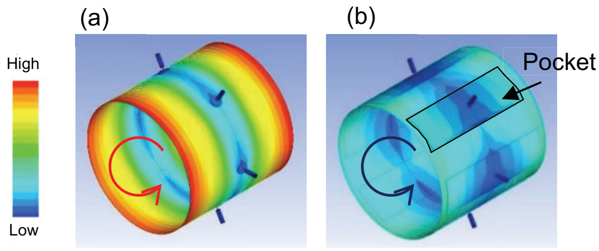
- It is possible to realize a pocket with a complicated shape as well as arrange bearing oil feeding nozzles at irregular intervals in consideration of grinding machine characteristics.
- It is possible to check occurrences of local negative pressure which may be a factor of bearing stiffness deterioration.
- It is possible to take into consideration the oil viscosity reduction caused by viscous heat generation associated with high-speed rotation.

Fig. 10 shows a typical example of CFD analysis on the shape of a hydrodynamic bearing. **Fig. 10 (a)** and **Fig. 10 (b)** show temperature distribution in a cylindrical bearing and a bearing with a pocket (see **Fig. 9 (b)**), respectively. It is observed that the temperature rise inside the bearing is suppressed by the pocket. For the same bearing diameter and length, the narrower the bearing gap and smaller the pocket area the higher becomes the bearing stiffness, however, the bearing internal temperature rise becomes larger too. Therefore, we used CFD to find the optimum bearing gap and pocket shape to keep the bearing internal temperature rise low while increasing the bearing stiffness.



Examples of (a) shaft and cylindrical bearing, (b) bearing with pocket

Fig. 9 Hydrodynamic bearing structure



(a) Cylindrical bearing, (b) Bearing with pocket

Fig. 10 Analysisexample: Bearing temperature distribution

3.3.2 Analytical method of grinding wheel spindle dynamic stiffness

Then, we like to introduce our method to predict the dynamic stiffness of the grinding wheel spindle during rotation which affects vibration of the shaft associated with imbalance of the grinding wheel resulting in a factor of machining accuracy deterioration. The dynamic stiffness of the grinding wheel spindle in a combination of shaft and bearing was predicted by the following two steps.

(1) Derivation of bearing characteristics: We analyzed the fluid reaction force *f* caused by micro vibration *e* associated with imbalance of grinding wheel by using CFD, and used this result and the following equilibrium equation for fluid reaction force to predict the bearing damping *c* and spring constant *k*. (*x*, *y*: Plane perpendicular to the rotating axis)

$$\begin{bmatrix} c_{xx} & c_{xy} \\ c_{yx} & c_{yy} \end{bmatrix} \begin{bmatrix} \dot{e}_x \\ \dot{e}_y \end{bmatrix} + \begin{bmatrix} k_{xx} & k_{xy} \\ k_{yx} & k_{yy} \end{bmatrix} \begin{bmatrix} e_x \\ e_y \end{bmatrix} = \begin{bmatrix} f_x \\ f_y \end{bmatrix}$$

(2) Dynamic stiffness during rotation: Using the bearing characteristics derived by (1) above, we analyzed the rotor dynamics for imbalance force and predicted the dynamic stiffness of the combination of shaft and bearing for the main spindle rotating speed (**Fig. 11**).

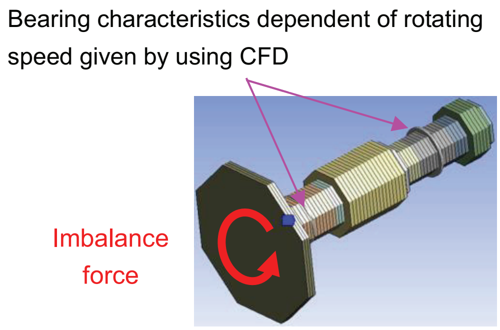


Fig. 11 Rotor dynamics analysis

3.3.3 Comparison between predicted grinding wheel spindle dynamic stiffness and actual measurement on machine

Using the above analysis method, we examined and optimized the grinding wheel spindle and bearing structure of the development machine and verified the actual machine. **Fig. 12** shows the grinding wheel spindle dynamic stiffness ratio based on the conventional rated rotational speed, and **Fig. 13** shows the oil temperature rise ratio. Solid lines are analysis predictions, symbols are actual machine measurement results. From this, analytical predictions and measured results almost agree, and the validity of this prediction method can be confirmed. And, compared with the conventional machine, the development machine's grinding wheel spindle stiffness has been increased by about 2 times while the oil temperature rise was kept equivalent. The target dynamic stiffness has been achieved.

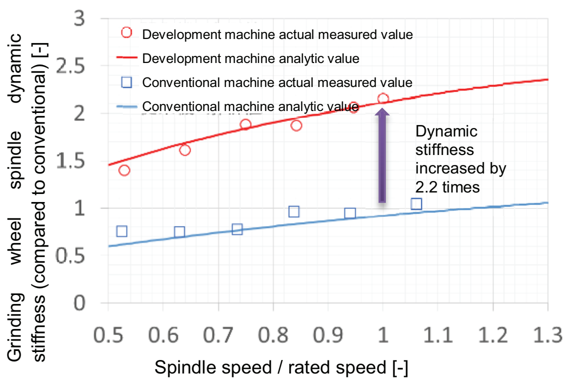


Fig. 12 Grinding wheel spindle dynamic stiffness ratio

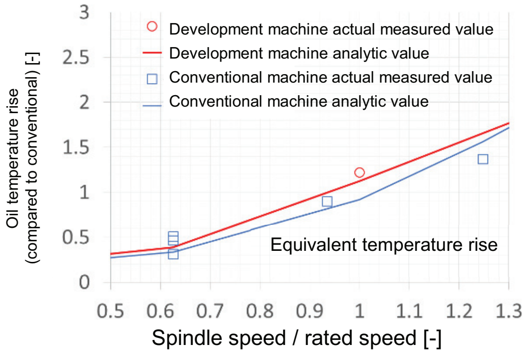


Fig. 13 Bearing oil temperature rise ratio

4. Measures against vibratory force

4.1 Optimization of grinding wheel head motion

In a profile grinding machine, in addition to the elastic mode of the structural system, there is a rigid body mode due to installation stiffness, and its natural frequency is approximately 20 to 30 Hz. Since a cam shape is created by moving the grinding wheel head back and forth during machining, rigid body vibration mode is excited in response to inertial force of the grinding wheel head.

In the development machine, as shown in **Fig. 14**, an algorithm that reduces acceleration high-frequency components by smoothly changing the grinding wheel head acceleration is adopted, and generation of rigid body vibration mode can be suppressed to 1/4 or less.

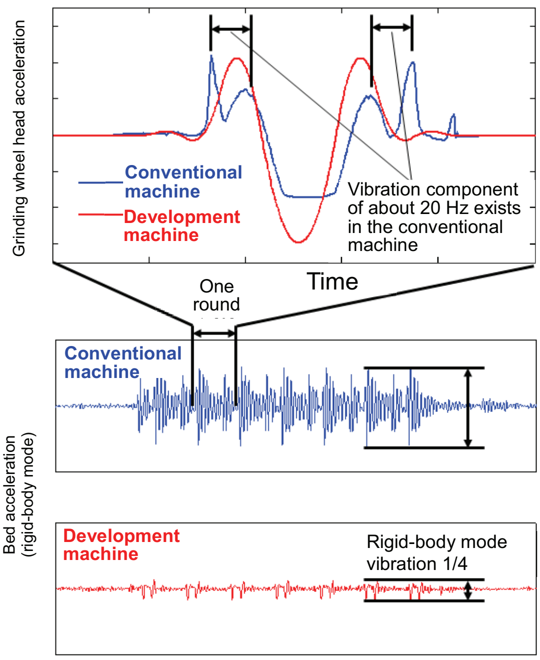


Fig. 14 Grinding wheel head acceleration and rigid body vibration

5. Development of innovative servo technology

In this chapter, we like to explain the control technology "RT-VISYON (trademark) Real Time - Virtual Quality Control System on Machining", which automatically predicts and compensates the machining accuracy. **Fig. 15** shows a developed grinding machine equipped with RT-VISYON.

Fig. 15 Grinding machine equipped with "RT-VISYON"

5.1 New servo

Fig. 16 shows a "PC Networking Servo System based on High-speed Versatile Communication EtherCAT" configured with a Komatsu NTC's controller. This controller enables real-time feedback of all information during machining and large-scale high-speed calculation (RT-VISYON described later) using all the information.

It is intended to improve control performance (speed improvement and shape error reduction) by installing a unique and advanced control method which is robust and optimal for a machine in the controller. **Fig. 17** shows a comparison of the control performance (deviation) between a conventional commercially available servo and the new servo. The new servo has high performance, in particular, in the high speed region of crude machining. Also, in actual machining, the machining time is reduced by 30% while shape error is reduced at the same time.

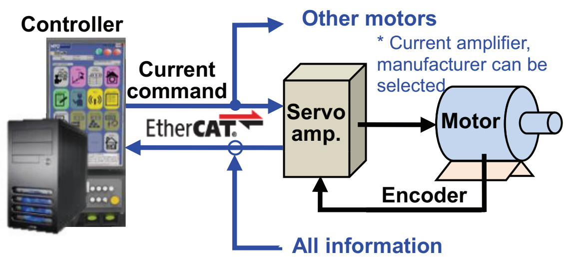


Fig. 16 PC networking support system based on high-speed general purpose communication system EtherCAT

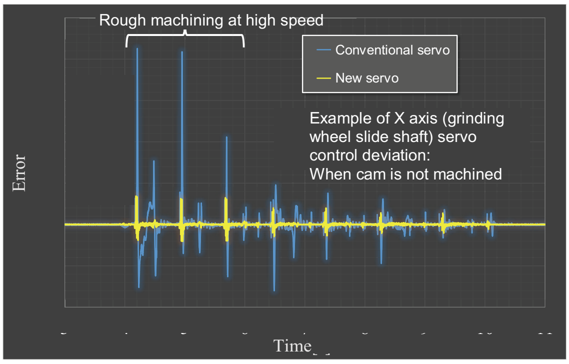


Fig. 17 Control performance of new servo

5.2 RT-VISYON

Fig. 18 shows the concept of RT-VISYON. A conventional, commercially available servo controls the position and speed of a motor with high accuracy. In contrast, RT-VISYON automatically compensates for machining accuracy of a workpiece during the process while predicting the finished product accuracy of the workpiece in real time. In case of cam grinding where the grinding wheel contacts the workpiece, the machining accuracy of the product may deteriorate by deflection of the workpiece, grinding wheel imbalance, cam shape and machining conditions, etc. The accuracy of the machined product which cannot be measured in real time is predictable by "Virtual Metrology" (hereinafter VM), whose accuracy and robustness is improved by such as applying Kalman filter, by sampling of 1 [ms] or less. **Fig. 19** shows a NC screen with VM, which can visualize important machining state quantities, in addition to shape error and chatter as indexes of accuracy of the product machined by the cam grinding machine. As **Fig. 20** shows a comparison between the shape error measured by a measuring instrument in the post-process and the shape error predicted by VM, it is understood they are well-matched with each other. **Fig. 21** shows a comparison of chatter on the machined surface predicted by VM when grinding wheel imbalance (main factor of chatter generation during grinding) is exists or not. From these figures, it is proved that the structured VM is predicting the machining accuracy of the product with high accuracy.

Then, the results of automatic compensation of the accuracy of the machined product after cam grinding derived by using VM real time prediction values are shown. **Fig. 22** shows the results of chatter and shape error improved by automatic compensation performed by combined operation of VM and servo. Chattering control (automatic compensation) automatically eliminates chatters being transferred to the uppermost surface during machining while controlling the contour of cam with 1 [µm] accuracy. From the above figures, it can be seen that the grinding machine equipped with the RT-VISYON VM and automatic compensation is capable of quality control during machining.

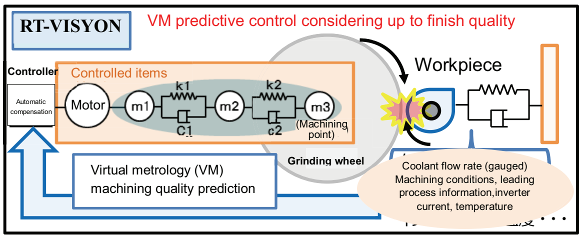


Fig. 18 Concept of RT-VISYON

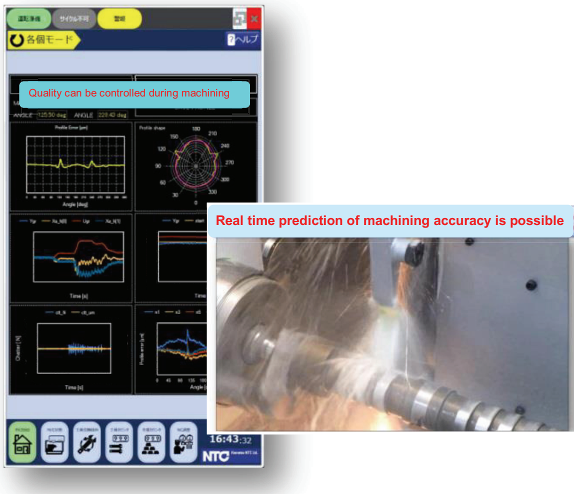


Fig. 19 NC screen with VM (machining accuracy of product visualized)

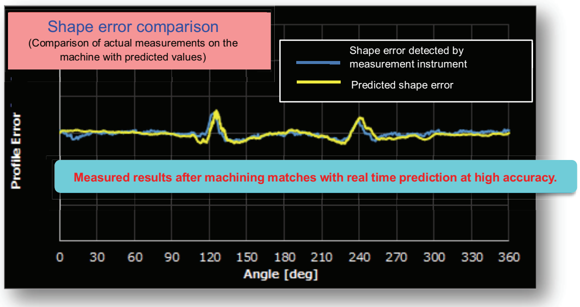
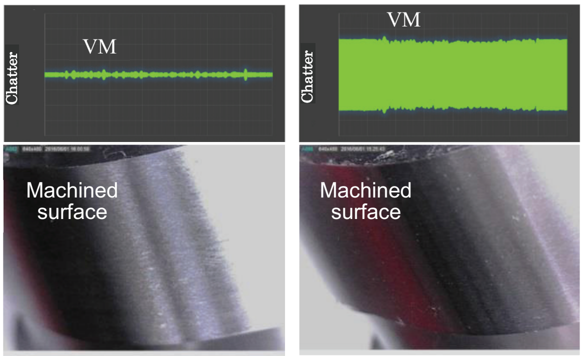


Fig. 20 Predicted accuracy of shape error by VM



(a) No imbalance of grinding wheel (b) Imbalance of grinding wheel exists

Fig. 21 Accuracy of chatter predicted by VM

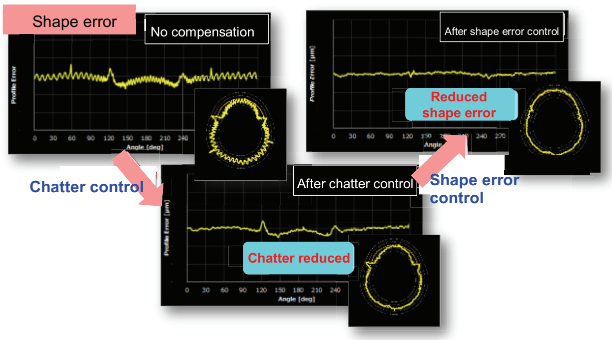


Fig. 22 Improvement of machining accuracy by VM and automatic compensation

6. Conclusion

Table 1 shows the improved performance items achieved by this technology development.

Table 1 Improved performance items

Item	Improvement performance (compared to conventional)
Grinding wheel spindle dynamic stiffness	2 times
Machining accuracy (shape error)	Improved by 70%
Machining accuracy (chatter)	Improved by 40%
Machining time	Reduced by 30%

We introduced the outline and technical features of the newly developed ultra high speed and high accuracy profile grinding machine.

We believe we have developed a machine that may not only meet market needs but also differentiate our products from competitors by integrating the world's first innovative control technology while fully taking advantage of unique technologies of Komatsu Development Division Technology Innovation Center, i.e. vibration analysis, thermal fluid analysis, and control technologies. In the future, we plan to continue development not only for horizontal deployment of the Komatsu NTC profile grinding machine lineup but also development of other models.

References

[1] Komatsu NTC Ltd. Product Catalog "Profile Grinding Machine PX3560"

Introduction of the authors

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[A comment from the authors]

We have introduced the achievements of the "Komatsu NTC Project" for which the Komatsu Development Division Technology Innovation Center and the Komatsu NTC Development Division worked together from the second half of 2014 to 2016. In this project, a video conference involving all staff members was held weekly until the completion of development, and the number of times was over 100 in total. Looking back on the project, we believe discussions in the conferences were important opportunities for us to share mutual progress, problems and policies as well as to align the vectors of development. Now that the project has been completed, a cooperative development is under way on a derived theme of the grinding machine. Of course, the weekly regular video conferences are still held (and the record of conferences is updated).