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A Study on the Machining of Compressor Rotors Using Formed Tools

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In this paper it was suggested the machining method that can improve machining accuracy and reduce the machining time applying the formed tools based on the rotor shape feature to finishing machining for efficient machining of asymmetric rotors. For machining the complicated asymmetric rotor profile, machining area is divided and formed tools are manufactured based on the rotor feature., and the efficient machining method of screw motor was proposed using the formed tools and four axis machining devices. With the suggested machining method, machining time could be reduced compared to the general end mill machining method, and the machining errors of the proposed method could be within the allowable tolerance of the product so as to carry out the precise machining.

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NOMENCLATURE

CL = cutter location
BEM = ball end mill
FT = formed tool
CAI = computer aided inspection
CMM = coordinate measurement machine

1. Introduction

Screw compressors – which are used in brake and suspension systems of railroad cars, refrigeration plants, heat pumps that need a high compression ratio, gas compression devices, and air compressors – are representative rotary positive displacement compressors that can be classified largely as one-axis and two-axis screw compressors.

Screw rotors, the key parts of the compressors, have unique shapes. The male and the female rotors go in gear and rotate in opposite directions in a cylindrical airtight container where fluid is admitted, compressed, and discharged by rotation of the rotors using the space between the rotors and the housing. Accordingly, the shape of the rotors is an important factor in the compressor's performance, requiring an accurate manufacturing method for optimum performance. Current rotor machining adopts a method in which a rake is applied to the driving axle of the hob after the formed tools corresponding to the rotor profile are manufactured and attached to the hobbing machines. This method yields a large error at each edge and wide variation in accuracy when the edges are manufactured because 8~20 edges are fixed to the hob. Another disadvantage is that it takes a long time to set up for machining. For optimal machining of the rotors, considering their geometric shapes and the difficulty of machining them, a study of the optimum machining method is needed to reduce the preparation time before rotor machining and to increase productivity by improving the machining accuracy and shortening the cutting time.[1-10]

Some studies on the development of the screw rotor profile and associated performance analysis have been carried out. Studies[11-13] on symmetrical and asymmetrical profiles and limitations of various geometrical properties of screw rotors have been published. In addition, for profile machining, a simple tooth surface equation to describe the rotor's tooth surface through coordinate conversion of the axis right angle section has been published. Variables include setup of the warp angle, lead, and pitch circle radius of the screw rotor, and a machining method that calculates contact lines between the cutter profile and rotor tooth surface. In the study, the pitch circle radius of a cutter was found by comparing the shape of the

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contact lines with a changing pitch circle radius to avoid cutting interference generated during the rotor machining.[14] As one of the solutions to the problems above, this study intends to suggest a new machining method for asymmetric rotors. In other words, this study investigates the machining method to improve the machining accuracy such as machining time and dimension accuracy by utilizing formed tools based on the feature of rotor shape for finishing machining, in order to substitute the method using commercialized tools in the past and to machine efficiently the precise turbo parts such as screw rotor.

To cut a complicated asymmetric profile to achieve this solution, the shape is divided and the corresponding formed tools are manufactured. The machining area is partitioned so that the machining process correlates to each formed tool. An efficient machining path is created to establish a machining method that corresponds to the shape of the tool using multi-axis machining devices that have more than four axes.

2. Shape modeling of rotors

Table 1 shows the shape specifications of a compression rotor used in this study. As a rotor with an asymmetric profile, the modeling of male rotor and female rotor was carried out as a shape that comes from the rotation of the profile along the helix curve perpendicular to the direction of the section.

Table 1 Specifications of a rotor

Rotor profile	Lead (mm)		Length (mm)	Warp angle of male rotor (deg)	Helix angle (deg)
	Male	Female			
Asymmetric	204	200	62	300	68.681

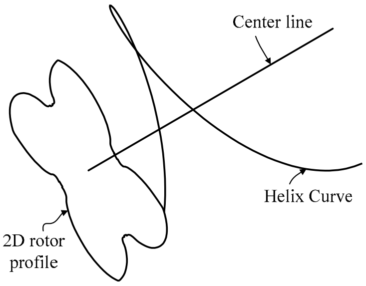


Fig. 1 Modeling method for a rotor

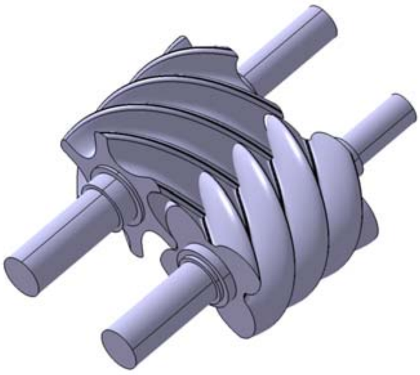


Fig. 2 Screw rotor

Fig. 2 shows the shape of crew rotor created by rotating the helix curve in Fig. 1. The modeling of screw rotor shape was carried out using CATIA, which is a 3D modeler.

3. Formed tools

Formed tools are easy to apply to turnery and milling operations because the final shape can be created with one cutting movement. On the other hand, restrictions on tool size and shape are considerable, limiting their use to the machining of stock with a few of cutting parts. The cutting surface after the machining can result in satisfactory surface roughness because there is no cusp in the end mills.

3.1 The design and manufacturing of tools

To manufacture formed tools, first, the geometric shape of the rotor profile has to be extracted. In the male rotor, because the asymmetric profile rotates around the central axis at the regular helix angle, the section profile of the rotor shape model to the central axis cannot be symmetric as well. The exact tooth profile for a tooth with formed tools can be acquired by generating an intersection of the rotor curved surface and the normal plane perpendicular to the helix curve as shown in Fig. 3. An adequate division of the machining area is needed within a range that can prevent undercuts because the final shape cannot be completed with only one rotation even though the formed tool contains the tooth profile, due to its complicated shape. The final shape can be completed after the formed tools for cutting each divided area are manufactured and machining is performed.

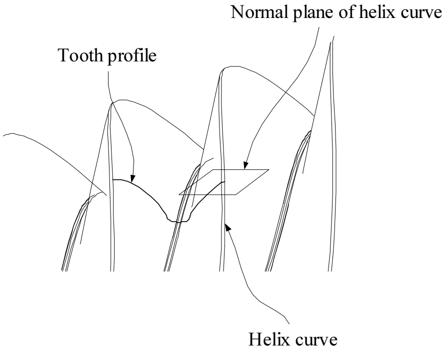


Fig. 3 Tooth profile of screw rotor

The tools are designed to be point symmetric in their shapes to prevent problems with rotation balancing that can occur in high-speed rotation. Fig. 4 shows the manufacturing procedure for formed tools.

The profile of the cutting path was extracted using the modeled rotor, and the extracted profile was divided into machining areas based on their shape. After the formed tools were designed and manufactured to produce the final shape with one rotation of each divided machining area, CAI was conducted.

After the profile, same as the flute of the rotor, was machined from a bar-shaped raw material. The tooth was produced using an electric discharge machine as shown in Fig. 5, with a clearance angle from a tool grinding machine.

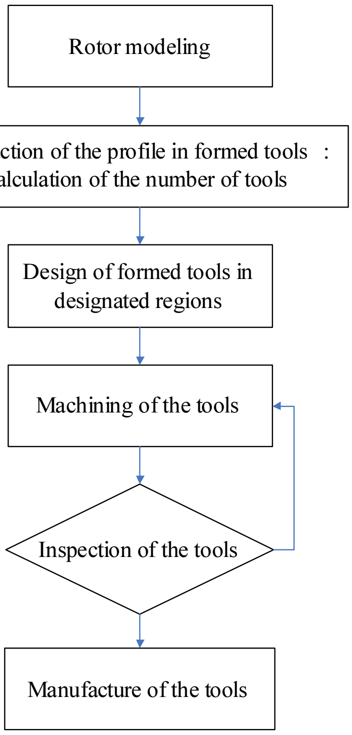


Fig. 4 Manufacturing procedure for formed tools

(a) First formed tool (b) Second formed tool (c) Third formed tool

Fig. 5 Formed tools for screw rotor

3.2 Machining area of formed tools

When dividing the machining area, it is important to minimize the frequency of exchanging the formed tools by considering the extracted tool path and machining issues.

As shown in Fig. 6 through Fig. 8 below, the slope of the left tooth is gentler than the slope of the right one, which sets the rotor valley as a baseline among the generated intersection lines. An interference (A-A') occurs on the right side when the cutting path is generated. Accordingly, the left side was divided and defined into two machined areas. The machining leap that may occur during the tool exchange is to be eliminated by slightly piling up the machined areas (0.5 mm towards the tool radius). The right part of the profile was determined to be one part due to its lack of interference with the left part.

Measurement system uses toolmaker's microscope (Mitutoyo, 505B, resolution: 0.5 ㎛, maximum magnification: ×100) to evaluate the error of formed tools in terms of two criteria, which are error between design value of formed tools and measurement value of manufactured tools (error of shape accuracy) and deviation of both edges of formed tools (balancing error).

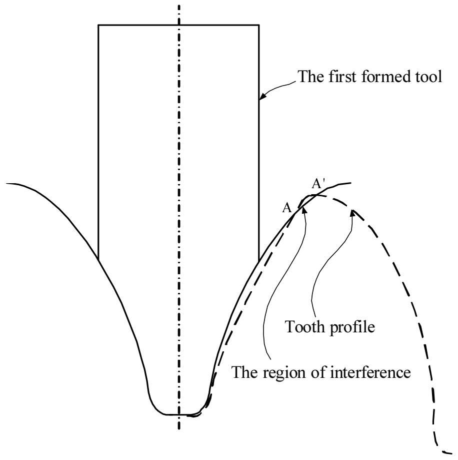


Fig. 6 Profile of the first formed tool

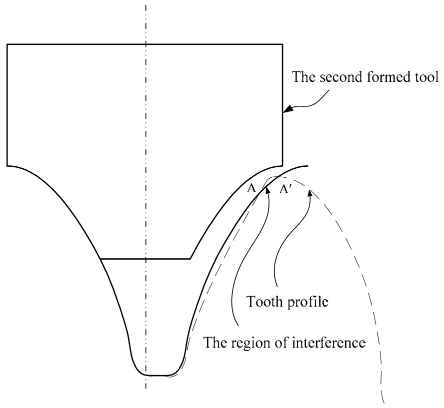


Fig. 7 Profile of the second formed tool

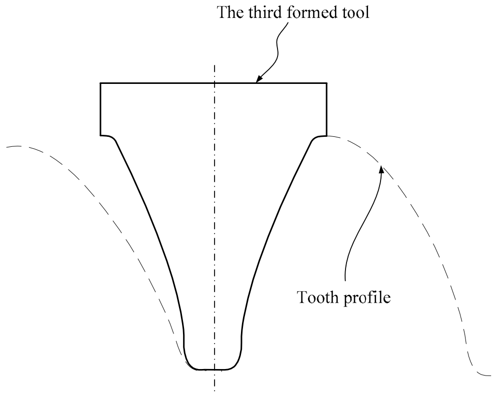


Fig. 8 Profile of the third formed tool

Though it is desirable for a test method to consider the measurement of all points because the tool’s profile has freeform curves, two-dimensional coordinate values were measured at points that represent 1 mm intervals from the edge of the tool toward the perpendicular direction of the tool’s axis, as shown in Fig. 9. Because the formed tool has two teeth, size accuracy tests were performed.

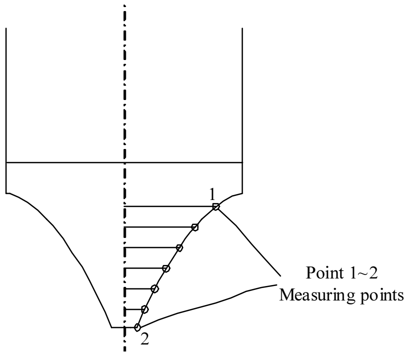


Fig. 9 Measuring points on formed tool

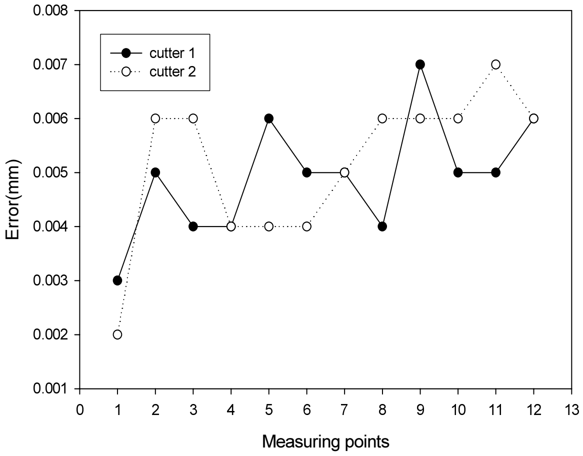


Fig. 10 Errors on the third formed tool

Fig. 10 shows the test result of the third formed tool. The maximum error is 0.007 mm. Given the machining error of typical screw machines (0.1 mm), the accuracy of the formed tools is quite good.

4. Rotor machining

4.1 Machining planning and path

Rough machining of the rotor is generally carried out through the perform work such as casting or the rough machining of stock material. The finishing machining investigated in this paper using formed tools can be applied regardless of the rough machining types. In this paper, the experiment selected the method of rough machining from stock material. For rough machining, tapered end mill machines were selected at maximum sizes that do not interfere with the divided machining areas to increase productivity. Then the paths were calculated by an iso-parametric method for each area and four-axis machining was performed.

After rough machining, each one time machining was done using the three manufactured formed tools for the finishing machining. This method generates a CL point, follows the tools' trace along the helix angle, leaves no machining marks, and performs the cutting that is not part of the finish operation.

The smooth finishing machining path was generated by considering cutting depth, path intervals, tool path based on the machining area division, and undercut to secure the position of the machining tools of rough machining and constant cutting power. Fig. 11 shows the result of pre-simulation for rough machining, where the rough machining path was predicted using Vericut program.

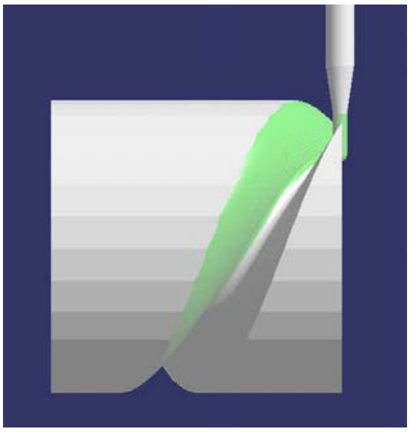


Fig. 11 Roughing the toolpath of the rotor

Although four axis machining is impossible when the rotor shape is very complicated, the rotors machined in this study and most rotors are the shapes suitable for four axis machining. Cutting machining of the formed tools of rotor directly requires two moving axis of X and Z, and one rotating axis. When cutting, Y axis must be used at start and end points for machining in view of the formed tools and end mill which cannot be easily cut in the direction of –Z. Four axis machining can be done by making the formed tools move straight along the axis of the rotor as shown in Fig. 12, and by fixing the screw rotor to the rotary table and rotating at a constant angular speed. The ratio of straight movement speed of the formed tools to revolution speed of the rotor is reflected in the cutting conditions because it determines the pitch of the screw rotor.

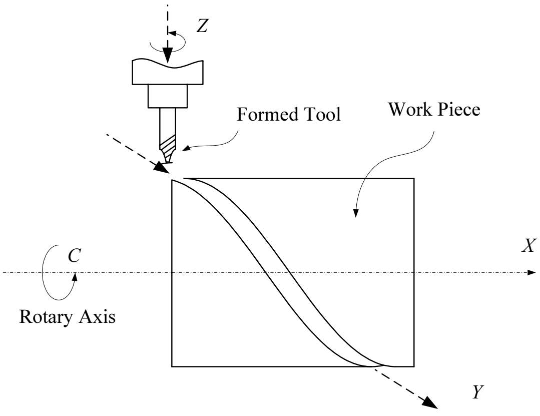


Fig. 12 Screw for 4-axis machining

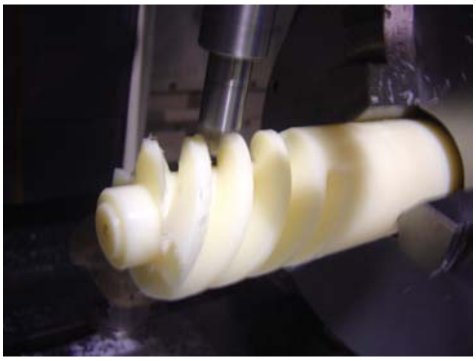
4.2 Machined rotor

The machining conditions are as shown on Table 2. A ball end mill was used for roughing machining, and the manufactured formed tools corresponding to each divided area were used for finishing machining. In finishing, the clearance was 0.001 mm, and the cutting conditions were 1,200 mm/min at feed rate and 3,000 rpm at spindle rate.

Table 2 Cutting conditions of rotor machining

Process	Tool	Feed rate (mm/min)	Spindle rate (rpm)	Clearance (mm)
Roughing	BEM $\phi3$	2,000	3,000	0.2
Finishing	FT 1	1,200	3,000	0.001
	FT 2	1,200	3,000	0.001
	FT 3	1,200	3,000	0.001

Fig. 13(a) shows four axis machining of a screw rotor using each formed tool, and displays the final finishing machining by the third formed tool. Fig. 13(b) is a machined, manufactured screw rotor. The machining material is polyurethane. This is because the study was conducted under the limitation to the shape machining of the screw rotor rather than physical cutting such as cutting conditions.



(a) Rotor machining using formed tools

(b) Male rotor by 4 axis machining

Fig. 13 Machined male rotor

4.3 Machining error and trend of rotors

To measure the accuracy of the compressor screw rotor that had finished the machining, the machined rotor was measured using a touch trigger three dimensional measurement machine (CMM) and the measured data were compared to the CAD data used in the machining. Accurate inspection can be carried out using three dimensional measurement machine, CMM (Dukin, Sigma785N) with major specifications of Resolution (㎛) 0.1 and Maximum Permissible Error (㎛, L : ㎜) 2.0+L/300 per ISO 10360-2.

The machined rotor presented as a machined sample is asymmetric and male, and the outer diameters are 60.2 and 62 mm. After generating a plane perpendicular to the central axis of the rotor as shown on Fig. 14 from the machined rotor shape, the section curve extracted by intersecting this plane with the rotor curved surface was measured. Although it is desirable to consider all the points because the section curve is also a freeform curve, the two-dimensional coordinate values were measured at points corresponding to each 1 mm interval in the perpendicular direction from the axis of the rotor. Inspection was carried out under the definition that the distance between the section curve and the sampling point is the error.

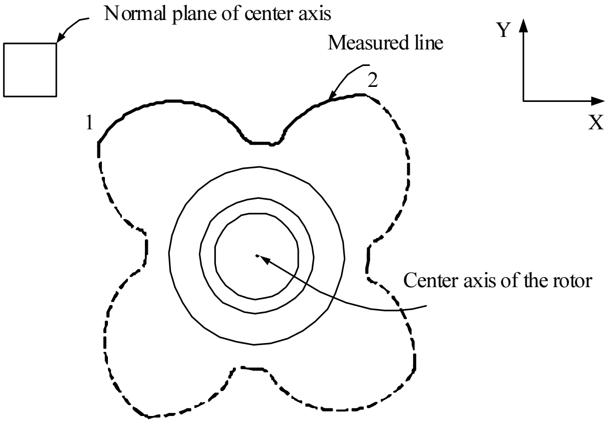


Fig. 14 Measuring points of the shaped rotor

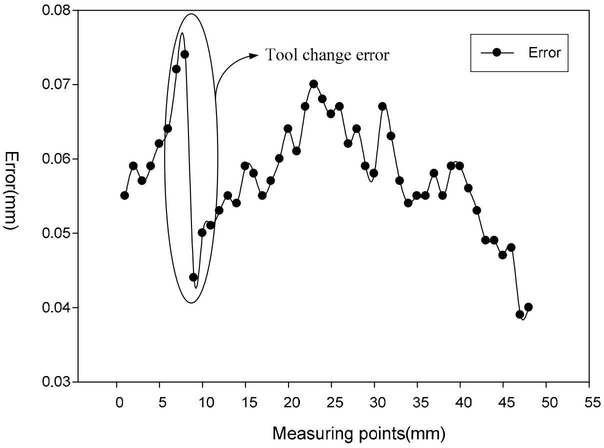


Fig. 15 Errors on machined rotor profile

From the measurement results in Fig. 15, it is shown that machining errors are higher at the tool exchange points (measuring point 5~10). The phenomenon that machining errors become higher at the time of tool exchange occurs because the machining errors are generated relatively higher even within the final tolerance limit as shown in the data of Fig. 15. It is believed that this is caused by complicated reasons such as chatters including the change of tool exchange points due to the formed tools change. It can be understood that machining errors are generated, because the difference in the machining coordinates occurs due to the change in tools position (CL) at the time of tools exchange. In order to avoid this phenomenon, the dimension accuracy and balancing error of the formed tools were inspected using toolmaker’s microscope, and the formed tools with the machining error less than that of final product. To reduce the machining error at the time of tools exchange, it is necessary to improve the accuracy of formed tools further. Furthermore, the error tends to increase at the points where the cutting depth along the axis starts to deepen (measuring point 20~35). It can be understood that the machining error becomes higher due to the increase in cutting force and chatters, which are generated because of the feature of formed tools that cannot be easily cut in the direction of -Z and of the feature of the shape that the sectional area of end edge is small. It can be found that the suggested rotor machining method using formed tools is an efficient machining method because the machining errors generally satisfy the product final tolerance within 0.07 mm.

4.4 Cutting time

To verify the efficiency of the area division and machining method using formed tools suggested in this study, the two different machining methods were compared as shown in Table 3. The method using formed tools was compared with the method using the general ball end mill. However, with the path of the general ball end mill tool, only the results numerically calculated through the CL data computation were used for the comparison. While the cutting time with the general ball end mill was 24.67 min, the time of the method suggested in this study was 7.2 min, a 70.8 % reduction.

Table 3 Comparison of conventional method and proposed method

Process	Tool type	Cutting conditions			Lead time (min)
		Feed rate (mm/min)	Depth of cut (mm)	Spindle rate (rpm)	
Proposed method	FT 1	1,200	0.2	3,000	7.2
	FT 2	1,200	0.2	3,000	
	FT 3	1,200	0.2	3,000	
Conventional method	Ball end mill	1,200	0.2	3,000	24.67

5. Conclusions

In this paper it was suggested the machining method that can improve the machining accuracy and reduce the machining time using the formed tools based on the rotor shape feature for finishing machining to carry out the efficient machining of precise turbo components such as screw rotors. The cutting area was divided and the formed tools corresponding to each divided area were manufactured to machine an asymmetric rotor used in the screw compressor, and an efficient machining method for the screw rotor using a four axis machining device was suggested. The machining time for the suggested formed tools method turned out to reduce the machining time by 70.8 % compared with the method using a general end mill. The machining path generation time was simplified in comparison with the end mill tool method resulting in more efficient machining. Finishing machining within 0.07 mm can be conducted to meet product tolerances and a reduction in machining error. This method is an efficient machining process, with better use of multi-edge tools and lower setup time than previous methods using multi-edge tools and hobbing machines.

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