An improvement in the production flexibility and accuracy of rotor milling process employing Finger Cutters

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Abstract. Finger Cutters (FCs) are the recently SRM-developed rotor cutting technology which can be easily integrated into multi-axis flexible milling machines. Opposite to the traditional disc cutters, FC operates inside the rotor body and as a result of that requires much less torque. This opens a new possibility to utilize multi-axis machines in rotor milling process, bearing in mind that they generally have less torque than specialized milling machines. An introduction to FC technology including mathematical modeling, geometrical definition and cutter body grinding has been presented in ICSM2018 conference in Dortmund [2].

In this work, we will present the recent development in FC technology. In particular, we will focus on an innovative method to increase the production accuracy of the FC-cut rotor bodies. This method incorporates an iterative procedure of milling, measuring and adjusting. First, a theoretical target surface, so-called adjustment cut, is defined with a safety margin from the final finished surface. FC removes the material aiming to match the adjustment cut. Measuring the surface and comparing with the adjustment cut, a set of correction factors are calculated for the next iteration. Employing this iterative procedure, a notable improvement in the rotor manufacturing accuracy is achieved while risk for scrap rotors is reduced significantly.

1. Introduction
Screw machine rotors are traditionally made with disc cutters, where cutter rotates around its axis which is located outside the rotor body, as shown in figure 1. This often requires large diameter of the cutters which induces high vibration and leads to the selection of a larger/stronger milling machine.

Lately the manufactures prefer to use multi-functional machines, to reduce production steps and set-up times. Multi-functional machines have less available torque and lower stability in comparison to traditional milling machines, therefore tools with smaller rotating diameters can be of significant help. In this work we will give an overview of the method, including the tool design, and more specifically we will discuss an innovative iterative method to increase the production accuracy of the final product.
2. Methodology
To reduce the required torque and vibration the cutter diameter needs to be reduced. This condition can be fulfilled with the help of recently developed technique, so-called Finger Cutters (FC). FC rotates around its axis which is located inside the rotor body unlike the traditional disc cutter which has its axis outside the rotor body. This leads to smaller cutter diameters and the possibility to run the cutter with higher rotation speed. Combining a finger cutter with a multi-functional machine, we provide a smooth milling operation where the cutter only needs to be supported from one side due to the lower applied torque and force. The finger cutter in operation is shown in figure 2.

Figure 1. Milling a screw rotor with a traditional milling machine using a rough disc cutter equipped with sectional blades (standard inserts).

Figure 2. A multi-functional machine using a finger cutter to cut a screw compressor rotor. FC rotates around its axis which is located inside the rotor body.

Note that an alternative to the presented method is the method of free formed surface machining [1], which has the advantage of higher flexibility and the possibility to use standard tools, but with the disadvantage of much lower productivity.
3. **The principal of cutter profile design**

The cutter profile is generated when the three-dimensional normal vectors of the rotor profile align with the rotational axis of the cutter as shown in figure 3.

![Figure 3. The three-dimensional normal vectors of the rotor profile align with the rotational axis of the cutter.](image)

To design the FCs, we transform the rotor coordinates from the rotor coordinate system to the tool coordinate system. The mathematical description for this transformation is described in [2].

![Figure 4. Left: Rotor coordinate system, Right: Finger Cutter coordinate system.](image)

3.1. **Cutter design**

The cutter profile is generated from the corresponding rotor profile. Considering that the cutter is rotational symmetric while most of the profiles are asymmetric, a minimum of two cutters is needed for milling an asymmetric profile. The left and right side of the profile generate the corresponding left and right cutter profiles. In practice however, more than two cutter profiles are needed to optimize the milling process of a certain rotor profile. In this case the cutter axis can be tilted in two directions and be moved perpendicular to the center axis of the rotor. The restriction of the setting data (tilting and movement) is governed by the requirement that the mill does not touch the side it will not process.

The female flutes are very open, consequently only three or four cutters are needed to effectively machine the complete female rotor profile. However, the male rotor flute narrows considerably as it gets closer to the root diameter, which results in narrow cutters in that area (These cutters are often made of solid carbide as shown in figure 6). In addition, the small radii at the transition between the root diameter and the sides normally results in milling cutters which are not possible to be produced. Therefore,
small compromises are to be made when producing the cutter which have negligible effects on the final rotor profile. Alternatively, the root diameter can be milled with a disc cutter, if the multi-functional machine allows that, due to geometrical restrictions. For the male rotor approximately seven cutters are needed to machine the complete rotor profile.

![Figure 5. Finger cutters for a female screw compressor rotor.](image)

When designing the cutter there are as usually compromises that need to be considered:
- The profile is normally divided into axial segments, to optimize the position of the blades, to reduce the grinding allowance.
- A higher number of segments might reduce the possible number of effective blades.
- To get as many effective blades as possible the rake angle (see 3.3) will normally become negative. This is not optimal from a cutting perspective especially with rotors of softer steel.

3.2. Grinding the blade
The cutter profile is generated to match the profile of the rotational body and the blades are normally tilted around two axes, shown in figure 7 and 9.

![Figure 7. Helix angle.](image)
The helix angle is defined as shown in figure 7, a normal value for FC tool is about 20°. The reason for having a helix angle is to get a smoother cut as a result of entering the blades successively. The rake angle is defined as shown in figure 8 and it describes the angle of the cutting face relative to the work piece.

![Figure 7](image7.png)

Figure 7. Definition of helix angle.

![Figure 8](image8.png)

Figure 8. Definition of rake angle. Left figure positive, right figure negative rake angle.

![Figure 9](image9.png)

Figure 9. Negative rake angle tends to be used for these FC.

Figure 9 shows a negative rake angle, which tends to be used for these FC, due to geometrical limitations. Normally a positive rake angle is preferable, more positive for softer materials.

To grind the blades to the rotational profile a built-in probe in the grinding machine will measure the plane of the blades and the plane will be defined mathematically, see figure 10. During the grinding cycle the cutter will be rotated to ground each point of the profile at the horizontal center plane.

![Figure 10](image10.png)

Figure 10. Measuring the plane of the insert.
To grind an FC from new rectangular inserts takes about two hours. To regrind or to grind from pre-profiled inserts takes about 30 minutes. Finally, we note that a coated carbide blade has an expected life of 10 cutting meters.

By providing the inserts with chip breaker grooves as shown in figure 11, for breaking the chips to shorter width and ease of disposal. This will also give the rotor better surface, due to less vibration and thus longer tool life. The grooves are displaced for each cutting insert so that they do not affect the profile.

![Image of an insert with chip breaking grooves](image)

**Figure 11.** An insert with chip breaking grooves

4. Compensation method

Even though the inserts can be sharpened within an accuracy of ±0.002 mm, the rotor profile will come out with the accuracy around ±0.050 mm due to tool/workpiece deflections and machine deviations, if no compensations are made. The principal of the compensation method is described below.

![Image of the actual profile section and associated cutter](image)

**Figure 12.** The actual profile section and associated cutter

Here we first compute the tool for the actual profile section, see figure 12. The tool can be moved translationally and/or rotationally. With these new setting data we calculate the adjustment cut by using the same mathematics as when calculating the tool, but reversed. The stock allowance to the final profile should be as constant as possible, see figure 13.

When calculating the adjustment cut, the tool is getting closer to the opposite side of the rotor profile, consequently the possible collision has to be checked. A reasonable clearance for this should have been included during the tool design.
In the next step we machine the profile up to the adjustment cut and then measure the rotor segment while mounted on a multi-functional milling machine.

Employing a mathematical description of the motion of the tool, in two translational and two rotational directions, the compensation values will be obtained. Those values are then used in the next cutting step for minimizing the deviation.

The next step is to make a new adjustment cut or directly aim to the final profile. It is important to have the same stock allowance between each cut to get correct adjustment values. In addition, we note that to manufacture a rotor with minimum risk of scrap, it is preferable that rotor stays clamped during the entire machining process, not to be removed for the measurements in intermediate steps. This leads to both higher accuracy and productivity in the machining process of the rotor.

With this method a reasonable accuracy of the rotor profile is ±0.015 mm. The level of accuracy is an estimation based on the result of rotors made with finger cutters without this compensation method and our experience of accuracies when measuring rotors. The accuracy is almost independent of the rotor size, since the cutters are grounded with a given accuracy independent of the cutter size. In addition, the deviation from the theoretical profile is mainly caused by deflection which is related to movement along and around the machine axis, which will mainly be compensated by this method. The method does not have any set-up time directly related to the profile milling, since the profile is machined in the same clamping during many other production steps. A 500 mm female rotor have a cycle time of 5 hours and the male have about 6 hours. Note that this is very dependent of the rotor design and the machine.

In addition to what we discussed so far, the productivity must be evaluated with respect to the complete machining process and available machines. The method is most beneficial for small batches of large rotors while for larger batches the traditional milling machines are competitive.
advantage of using flexible multi-functional machines is that one can manufacture components in single setup, which significantly affects both productivity and accuracy. The FC is optimized for machining the final profile but can be used for roughing as well. Due to the cost of the FC the rotor should preferably be rough machined with standard cutters of various sizes. Considering the accuracy, size of the cutters and machining time, the presented method is most advantageous for larger rotors (diameter >400 mm).

5. Conclusion
In this work we discuss the recent development in Finger Cutter (FC) technology which is an innovative method for rotor milling. A compensation method is introduced to increase the accuracy of the production while reducing the risk of rotor scrap. This method is based on an iterative procedure of milling, measuring and adjusting. The method gives the highest accuracy if the rotor remains clamped throughout the entire machining process.

References
[1] Zabel A 2014 Modern machining processes for the manufacturing of screw machine components Inter. Confrenece on Screw Machines 2228 267–278
[2] Bergström A 2018 An innovative rotor milling method for flexible multi-functional machines ICSM2018 conference doi:10.1088/1757-899X/425/1/012007.