The Characteristics and Causes of Push-off During Screw Rotor Manufacture, and its Compensation by Multi-axis Machine Path Calculations

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Abstract. When grinding helical components, errors occur at the beginning and end of the contact path between the component and grinding wheel. This is due to the forces on the component changing as the grinding wheel comes into and out-of full contact with the component. In addition, shaft bending may add depth changes which vary along the length. This may result in an interrupted contact line and increased noise from the rotors. Using on-board scanning, software has been developed to calculate a compensated grinding path, which includes the adjustments of head angle, work rotation and infeed. This grinding path compensates not only lead errors, but also reduces the profile errors as well. The program has been tested in rotor production and the results are shown.

1. Introduction

Screw rotor pairs are designed to have a continuous line of contact along the entire length of their flanks, at or near the pitch line. Cutting or grinding tools exert forces on the rotor which might cause varying amounts of deflection along the length, thereby affecting the contact line.

This occurs when the grinding wheel comes into, and out of full contact with the component, as occurs at the beginning and end of each flute. In addition, bending of the rotor shafts can occur, resulting in depth changes which vary along the length. These behaviours are commonly known as “push-off”, and their effect is to cause intermittent contact along the rotor length as the rotors rotate, with undesirable consequences.

Davey [1] has described one effect of having positive metal at one end of the rotor body. As the rotors rotate, the raised section comes into and out of mesh with the mating rotor, creating gaps on the driving flank where contact should occur, and a consequent reduction in clearances on the non-driving flank. To allow for this effect, profiles may need to be modified to keep the non-driving side clearances within tolerance, but the overall effect is increased leakage and reduced compressor efficiency.

Holmes [2] has presented evidence that intermittent contact results in transmission errors which are a direct cause of increased levels of rotor noise during operation.

Fortunately, push-off behaviour is usually consistent from part to part, and Davey described a method of applying local accelerations and decelerations to the work rotation as the cutting tool enters and leaves the flute. This has the effect of offsetting profile errors at each end of the rotor body.

This paper presents a method of compensation which includes the continuous adjustment of head angle, work rotation and infeed, and using measurements from on-board scanning in a Holroyd Zenith machine. The on-board scans are in good agreement with CMM scans after calibration with a master rotor. Software has been developed to calculate a compensated grinding path. By measuring the lead at the pitch diameter of all flutes and root radius along the body length together with the 360° profile scans at 3 transverse sections (middle and each end), a networked computer can generate the compensated grinding path from this scan data. This grinding path compensates not only lead errors, but also reduces the profile errors.
2. Calculation of compensation path

The software is developed based on Holroyd’s Zenith machine [3], whose axis designations are shown in Figure 1.

The push-off causes lead and profile errors which can be compensated by multi-axis adjustments as a function of work rotation, infeed, and head angle

\[ \Delta w = \frac{\partial w}{\partial C} \Delta C + \frac{\partial w}{\partial X} \Delta X + \frac{\partial w}{\partial A} \Delta A \]  

(1)

Where

- \( W \) = Change in rotor contact position, mm
- \( C \) = Work rotation, radians
- \( X \) = Infeed, mm
- \( A \) = Head angle, radians

\( \frac{\partial w}{\partial C} \), \( \frac{\partial w}{\partial X} \), and \( \frac{\partial w}{\partial A} \) are calculated by Holroyd’s HPMS program.

Formula (1) is used for both profile and lead.

The root scan is used to calculate \( \Delta X \) within the rotor body. \( \Delta X \) on the overrun section is calculated based on tests on rotor deflection (vertical and horizontal movements) under grinding force.

Three 360° profiles were scanned at the middle and 10 mm from each end of the body. The mean measured profile was calculated using the on-board software. The least squares method was used to calculate the head angle adjustments \( \Delta A \) and infeed adjustments \( \Delta X \) based on profile differences between the middle and end sections.

The lead scan results are used to calculate \( \Delta W \). As for the lead scan, \( \frac{\partial w}{\partial C} \), \( \frac{\partial w}{\partial X} \), and \( \frac{\partial w}{\partial A} \) are constant coefficients at the pitch line. The head angle adjustment is applied linearly from the location where the push-off starts. \( \Delta C \) is calculated along the grinding path from Formula (1). Further modification of the path may be needed if the first attempt does not achieve an acceptable result.
3. Grinding test results

For the purpose of testing, a male rotor was manufactured with the following geometry:

- Flutes: 4
- Nominal outside diameter: 221.385 mm
- Nominal lead: 521.000 mm
- Rotor body length: 452.5 mm

A flute of the rotor was ground, then lead and profile were measured. A compensation path was created from the scan data, and applied to the full rotor grinding.

3.1 Profile scans

Figure 2 shows the profile differences between the middle and end sections before compensation. Figure 3(a) shows the predicted results of compensation calculated using the least squares method. It can be seen that the differences were mainly caused by depth change from the calculated result. Figure 3(b) shows the measured profile differences after compensation.

![Figure 2. Profile differences between middle and end sections](image-url)
Figure 3. Profile after adjustment applied
3.2 Root depth

A typical root measurement scan is shown in Figure 4 (root depth versus traverse position). It can be seen that the rotor depth variation is 0.025 mm, and deepest at the end of the body.

![Figure 4. Root scan before compensation (vertical scale: 1 division = 0.01mm)](image)

Figure 4 shows the root scan after the compensation. Note the change in vertical scale. It can be seen that the root variation has been reduced significantly to 0.006mm.

![Figure 5. Root scan after compensation (vertical scale: 1 division = 0.001mm)](image)
3.3 Lead results

The single flute lead of the rotor was scanned on Zenith and CMM for comparison. It appears that the scan results have good agreement as shown in Figure 6. The single flute lead scan results of the rotor ground with a compensation path are shown in Figure 7.

![Figure 6. Lead errors of a rotor ground without a compensation path](image)

(a) Machine Lead Scan Results.

(b) CMM Lead Scan

Figure 6. Lead errors of a rotor ground without a compensation path
Figure 7. Lead errors of a rotor ground with a compensation path.

(a) Machine Lead Scan

(b) CMM Lead Scan
Figures 8 and 9 show full lead inspection of the rotor inspected on a customer’s CMM. It can be seen that the leads have been improved significantly.

**Figure 8.** CMM inspection of a rotor ground without a compensation path
4. Conclusions

Using on-board scanning in the grinding machine, software has been developed to calculate a compensated grinding path, which includes the adjustments of head angle, work rotation and infeed. The on-board scans are in good agreement with CMM scans after calibration with a master rotor. By measuring the lead at the pitch diameter of all flutes and root radius along the body length together with the 360° profile scans at 3 sections, which are middle section plus two end sections, a networked computer can generate the compensated grinding path from this scan data. This grinding path compensates not only lead errors, but also reduces the profile errors as well. The program can also take into account the required lead modification in additional to push-off compensation.

The program has been tested in rotor production. The rotors produced using this method showed expected improvements on CMM lead scan at the pitch diameter. The profile errors at the beginning and end of the rotor body are also reduced. The quality of manufactured rotors is significantly improved.

Figure 9. CMM inspection of a rotor ground with a compensation path
References

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