Formation of Macro Lead Using Plunge Grinding – a Kinematic Approach

Georg Haffner, Matthias Baumann, Frank Bauer

Plunge grinding is considered to produce lead free surfaces for the usage with rotary shaft seals. The term “lead” summarizes all surface structures, which create a rotation dependent pumping effect. Since lead influences the complex tribological system “rotary shaft seal”, it is essential that the process “plunge grinding” manufactures surfaces without lead.

A kinematic simulation model of the manufacturing process “plunge grinding” was developed to understand and visualize the complex interactions between the manufacturing parameters and the macro lead parameters on the surface. Additionally, an approach for the stochastic influence on the surface is also presented to investigate parameters for lead free surfaces. The model has been validated by the measurement of plunge ground parts with the same manufacturing parameters.

1 Introduction

The influence of a sealing counterface in the complex tribological system “rotary shaft seal” plays a major role in many failures of sealing systems [1]. An inappropriate manufactured sealing counterface can increase wear on the rotary lip seal or create a rotation dependent pumping effect.

As a countermeasure, manufacturers and researchers proposed guidelines for the usage of rotary lip seals. Examples are the DIN3760 [2] and DIN3761 [3] where manufacturing parameters for sealing counterfaces and operational limits for sealing rings are proposed. The proposed methods are expensive since they involve the surface finish plunge grinding and a long manufacturing time. This leads to the change of manufacturing process or wrong manufacturing parameters, which both can result in inappropriate surfaces for rotary shaft seals.

A common problem with sealing counterfaces is lead. Lead describes structures capable of moving fluid rotation dependent. There are two different failure mechanisms for lead influenced sealing systems, seen in Figure 1.
In Figure 1, the components of a rotary shaft sealing can be seen. The rotary lip seal is mounted on a surface with lead structures. The structures deviate from the circumference direction of the shaft. Hence, during rotation, the structures can pump fluid in the axial direction. This behavior causes either leakage when the fluid is withdrawn out of the housing or dry run, when the oil is pumped into the housing. Then, the contact between the rotary lip seal and the surface aren’t lubricated sufficiently, the sealing lip wears out which ultimately leads to leakage. Both failure mechanisms are costly and result in downtime of the affected machine and environmental damage.
Lead structures arise during the manufacturing process. They can be subdivided in their structure length and measurement method, Table 1:

**Table 1: Categories of lead [4]**

<table>
<thead>
<tr>
<th>Category</th>
<th>Illustration</th>
<th>Classification</th>
<th>Analysis Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>micro-scop ic</td>
<td>micro lead</td>
<td>stochastically arranged, anisotropic</td>
<td>IMA-Microlead® Analysis</td>
</tr>
<tr>
<td>macroscopic</td>
<td>micro waviness</td>
<td>stochastically arranged, aperiodic, isotropic / anisotropic</td>
<td>/</td>
</tr>
<tr>
<td>macro lead</td>
<td>macro lead</td>
<td>axial periodic, circumferential</td>
<td>Macro lead evaluation acc. to MBN31007-7</td>
</tr>
<tr>
<td>any size</td>
<td>scratches</td>
<td>defects, any size</td>
<td>visual analysis, IMA Scratch Detection Method</td>
</tr>
</tbody>
</table>

The different lead structures were intensively researched over the last years. Micro lead is evaluated using 3D optical measurement systems. The surface is measured on different positions in axial and circumferential direction. The structures on all measured surfaces are evaluated with a structure-based algorithm, which then statistically summarizes the characteristics of the geometry of the structures. A micro lead evaluation method described in [4] is commercially implemented as the IMA-Microlead®Analysis.

Structures, which appear stochastically arranged and aperiodic on a surface, are called “Micro Waviness”, which is a term defined by [4, 7]. Research on this type of lead is currently investigated in [8].

“Macro lead” describes axially periodic structures on a sealing surface, comparable to the thread of a screw. The structures can be oriented obliquely to the circumferential direction. The Daimler AG standardized a measurement pattern and evaluation method in MBN31007-7 [9]. The method returns parameters that are used to determine the suitability of the surface as a sealing counterface for radial shaft seals.

An approach of detecting scratches and defects can be found in [5, 6]. Mostly, they are evaluated with the help of microscopes or surface measurement devices, which can only measure small areas in high resolution for a proper investigation. Both approaches can only consider defects, which were within a measured spot of the surface.

The lead types can occur in superimposition on a sealing counterface. Therefore, the surface should be checked on all four different lead types. A proper manufacturing of the surface is hence recommendable to extend the lifetime of a sealing system.
The measurement of every surface is not applicable for many manufacturers. A greater understanding of the process “plunge grinding” in order to avoid the formation of lead structures is a better option since quality control no longer has to be performed on every part. The focus of this paper will lie on the formation of macro lead.

To understand the influence of different manufacturing parameters of plunge grinding on the formation of macro lead, a kinematic simulation model has been developed. It concerns the dressing process of a grinding wheel as well as the grinding process itself.

2 Materials and Methods

2.1 Research approach

With the development of a kinematics simulation model, which is then used to describe the formation of macro lead, the relationships during dressing a grinding wheel and grinding a part are modelled. Therefore, different simulated surfaces with the focus of changing one specific manufacturing parameter for the investigation of the influence on the resulting surface are generated. Their real counterparts were also ground, measured and equally evaluated as the modelled surfaces. Both, the real part measurement data as well as their “digital twin” are compared to validate the model, Figure 2.

With a validated kinematic simulation model, the extension of the stochastic influence on the surface is also investigated. The distribution and orientation of the grains is extracted from a surface measurement of a grinding wheel and is implemented into the kinematic simulation model. With the stochastic influence applied, the reversal point from macro lead affected to macro lead free surfaces can be evaluated.
2.2 Plunge grinding

The plunge grinding process is used to finish the surface of a rough shaped and – if necessary – hardened part [10, 11]. It uses a grinding wheel which consists of sturdy grains in a cementing matrix, called bond. The shape of the grinding wheel is primarily defined by its as-delivered state. Therefore, a preparation of its shape is needed before it can be used to finish the surface of the part.

2.2.1 Dressing process

Since grinding wheel loses its shape and the grains wear out after several grinded parts, the wheel has to be shaped. This process is called dressing. A tool sturdier than the grains themselves is moved axially with constant speed and a defined depth over a rotating grinding wheel. The surface of the grinding wheel is removed, dull grains are broken so new and sharp edges appear. The resulting grinding wheel surface is shaped properly and uses new grains for the surface finish. When moving the dressing tool over the surface, a helix shaped structure is formed on the grinding wheel. This structure is called dressing spiral, which has a thread count of one. According to [12], the dressing spiral has a major effect on the resulting macro lead structures.

2.2.2 Grinding process

After the dressing process, the part is moved opposite to the grinding wheel. Both, the grinding wheel and the part are accelerated to their speed which is defined by the speed ratio $S$, and the grinding wheel is moved tangentially to the part with a defined velocity to the part’s final diameter. When reaching, both, the part and the grinding wheel rotate with no tangential velocity for a defined period of time $t$, called spark out time. This time defines the final shape of the surface. During the spark out time, the grinding wheel copies its surface in a distorted manner onto the surface of the part, seen in Figure 3.

![Figure 3: Dressing structures applied onto surface](image)

Depending on the speed ratio and the diameter ratio between the grinding wheel and the counterface, the angle $\beta$ changes and therefore the angle of the macro lead structures.
2.3 Mathematical approximation

The procedure above describes the plunge grinding process superficial. All relevant kinematic interactions are considered. The mathematical description has to be split in two parts.

2.3.1 Mathematical description of the dressing process

At first, the dressing process has to be broken down into a representation of its components and its kinematic movement equations, seen in Figure 4. The grinding wheel can be represented as a matrix with \( n \) points – the axial direction - and \( m \) profiles – the circumferential direction, where every point before the dressing process has a height of 1.

![Figure 4: Kinematic description of dressing a grinding wheel](image)

The dressing tool, in this paper a single grain diamond, can be described as an isosceles triangle with the height of \( a_d \) and a width of \( b_d \), which can be calculated when the angle \( \alpha \) of the triangle is known or the value can be derived from literature, where it is located at around 0.5 mm depending on the height \( a_d \).

The dressing tool erases its exact contour out of the grinding wheel surface. It starts at the top left corner of the matrix and passes every profile. The distance of the dressing tool travelled in every profile \( x_i \) can be calculated as:

\[
x_i = \text{round} \left( \frac{i \cdot v_d}{\varphi_{GW} \cdot n_{GW}} \right)
\]

With:

- \( i \) describes the current profile on the circumference


- \( v_d \) corresponds to the dressing velocity
- \( n_{GW} \) corresponds to the velocity in circumferential direction
- \( \phi_{GW} \) corresponds to the diameter of the grinding wheel

When reaching \( i = m + 1, x_i = x_m \), and the dressing tool starts over at the first profile. This scheme repeats until the \( x_i > n \). The result is a dressed grinding wheel surface with only kinematically generated structures.

### 2.3.2 Mathematical description of the grinding process

For the description of the grinding process, a discretization of the part surface is necessary. The distance between the profiles of the grinding wheel discretization and the part surface discretization are chosen equally. The axial velocity of the grinding wheel (or the part) is set to 0, so no movement takes place.

At first, the number of revolutions of the part is calculated with the spark out time times 60 divided by the circumferential velocity. The process can be seen in Figure 5:

![Figure 5: Modelling Process of Grinding a Counterface](image)

The ablation of the part surface is calculated for every profile for every number of revolutions. The interacting profiles are calculated with the following correlation:

\[
i_{GW} = \text{mod}(i_{CF} \times S \times \frac{\phi_{GW}}{\phi_{CF}}, \phi_{GW})
\]  

The modulo function \( \text{mod}(x, m) \) returns the remainder after the division of the continuous index of the grinding wheel with the maximum index of the grinding wheel. This is needed since we defined the grinding wheel surface as a discreet area instead of a continuous surface. Let \( p_{i,CF} \) be a profile on the sealing counterface and \( p_{i,GW} \) a profile on the grinding wheel surface. The new profile for the counterface is then calculated:

\[
p_{i,CF,CF} = \min(p_{i,CF,CF}, p_{i,GW,GW})
\]

The function \( \min(p, q) \) calculates the smallest value of each point of two given profiles \( p \) and \( q \). This number of calculations corresponds to the number of profiles...
times the number of revolutions. The number of revolutions can be calculated by dividing the spark out time by the rotational speed.

The result of this kinematic simulation model is a geometric optimal surface which then can be visualized or used for further calculations like a lead analysis.

### 2.4 Experimental validation

The simulation model needs to be validated, hence, counterfaces with exact same manufacturing parameters were grinded. The counterfaces have a diameter of 80mm and the blanks are made of 100Cr6. All surfaces were grinded with a K60 grinding wheel, which was dressed with a single grain diamond before every grinding process. The counterfaces have to be measured using surface topography measurement devices and are evaluated with an established evaluation method.

#### 2.4.1 Lead Evaluation

The measurement for the lead evaluation according to MBN31007-7 [9] is performed with a tactile or optical measurement device. The surface is measured 72 times with 5 and 0.5 degrees spacing in circumferential direction. Each profile has a length of 2 mm. All profiles are combined to a 360° and a 36° pseudo topography. The term “pseudo topography” means a higher resolution in one direction than in the direction perpendicular to it. The topographies are both recreated with frequency analysis and a least square optimization algorithm [13]. The lead parameters are derived from the resulting surfaces, Figure 6.

![Figure 6: Lead parameters](image)

The parameters are defined as following:

- $D_y$ is the angle between the circumferential direction and the structure angle
- $DF$ is the area enclosed between to peaks
- $DP$ is the length between two peaks or two valleys
- $Dt$ is the height difference between a peak and a valley
• $DG$ is the number of periods a peak passes in one revolution

Except $DF$, all listed parameters are considered. $DF$ is strongly influenced by the contour of the area between the peaks. When using an ideal approximation of the dressing tool, the difference to a real dressing tool may deviate significantly.

### 2.4.2 Surface Measurement of a grinding wheel

Since the kinematic simulation approach doesn’t include stochastic influence of the single grains distributed in the matrix of a grinding wheel, the model can be extended by the information of a grinding wheel surface measurement, Figure 7. Therefore, a grinding wheel has to be measured around its circumference with an appropriate axial and circumferential resolution.

For this task, a measurement device [14] originally used to measure the inner geometry of a rotary sealing ring was adapted to measure the circumference of a grinding wheel. The measurement principle is based on laser line triangulation, which has a high working distance still keeping a suitable axial resolution. The circumferential resolution is only limited to the measuring frequency and the rotation speed of the measurement device.

The grinding wheel surface data is pre-processed – correction of the clamping error, removal of outliers, median filtering and filling of non-measured points - and applied onto the kinematically grinded surface. The height of the combined surface is then normalized to its original height.

This procedure generates a kinematically grinded surface with stochastically distributed grains, creating a more realistic representation of a grinding wheel.

### 2.5 Scope of experiment

The verification of the macro lead model was carried out with over twenty different, defined ground macro lead parts. The parts have a diameter of 80 mm and they are made of 100Cr6. The surface was hardened and precisely ground with a K60 grinding wheel.

The spark out time $t$ is replaced with $R$, which corresponds to the time needed for one revolution. Since the time is dependent on the rotational speed of the part, it was replaced with a more general parameter.
As seen in the table, different aspects of manufacturing parameters are investigated. The experimental data is used to show the influence of varying the manufacturing parameters as well as validating the simulation data.

3 Experimental results

The experimental results were focussing on different interrelationships between the manufacturing parameters and the resulting lead parameters. The interactions were split into their respective manufacturing parameters to display the influence of every parameter on the resulting surface.

3.1 Influence of the radial feed and speed ratio

At first, the influence of the speed ratio on the lead depth was investigated. Therefore, five different ratios were analysed. The other manufacturing parameters were kept constant, Figure 8.

The lead depth in the simulation model shows the highest lead depth at a speed ratio of 10, the lead depth at 10.5 halves. At the speed ratio between 10.1 – 10.4, the lead depth stays at around 1/10 of the height at speed ratio 10.
The manufactured surfaces show a similar course. The lead depth differs at specific points which may arise through stochastic effects of the grinding wheel. When increasing the radial feed, the height of the resulting structures also increases. The effect is undefinedly applicable in the simulation, however, in a real grinding process, this behavior should not apply.

### 3.2 Influence of the spark out time

The same behavior appears when keeping the radial feed and the dressing velocity constant, only changing the spark out time, seen in Figure 9.
Three different spark out times, which represent 1-3 revolution, were investigated. The higher the number of revolutions, the lower the lead depth gets, when using non-integer speed ratios. At integer speed ratios, the lead depth remains unchanged. The model cannot represent the initial, mostly stochastic changes of the counterface properly and therefor differs more.

### 3.3 Influence of the dressing velocity

The dressing velocity greatly impacts the resulting lead structures. In Figure 10, the influence on the lead angle is shown, when keeping the speed ratio and the spark out time constant.

---

**Figure 10: Influence of dressing velocity on period length**

<table>
<thead>
<tr>
<th>Dressing velocity [mm/min]</th>
<th>Period length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>0.05</td>
</tr>
<tr>
<td>100</td>
<td>0.1</td>
</tr>
<tr>
<td>125</td>
<td>0.15</td>
</tr>
<tr>
<td>150</td>
<td>0.2</td>
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<tr>
<td>175</td>
<td>0.25</td>
</tr>
<tr>
<td>200</td>
<td>0.3</td>
</tr>
<tr>
<td>225</td>
<td>0.35</td>
</tr>
<tr>
<td>250</td>
<td>0.4</td>
</tr>
<tr>
<td>275</td>
<td>0.45</td>
</tr>
<tr>
<td>300</td>
<td>0.5</td>
</tr>
</tbody>
</table>

\[ a_d = 20 \mu m \]
\[ S = 10.0 \]

---

**Figure 11: Influence of dressing velocity on lead angle**

<table>
<thead>
<tr>
<th>Dressing velocity [mm/min]</th>
<th>Lead angle [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>0.1</td>
</tr>
<tr>
<td>100</td>
<td>0.2</td>
</tr>
<tr>
<td>125</td>
<td>0.3</td>
</tr>
<tr>
<td>150</td>
<td>0.4</td>
</tr>
<tr>
<td>175</td>
<td>0.5</td>
</tr>
<tr>
<td>200</td>
<td>0.6</td>
</tr>
<tr>
<td>225</td>
<td>0.7</td>
</tr>
<tr>
<td>250</td>
<td>0.8</td>
</tr>
<tr>
<td>275</td>
<td>0.9</td>
</tr>
<tr>
<td>300</td>
<td>1.0</td>
</tr>
</tbody>
</table>

\[ a_d = 20 \mu m \]
\[ S = 10.0 \]
The lead angle and the period length rise linear when increasing the dressing velocity, Figure 11. Therefore, a smaller dressing velocity leads to a smoother surface with lower structure angles but higher frequent structures. Increasing the dressing velocity, the structures become less frequent, but the lead angle rises as well as the lead depth.

### 3.4 Reversal point lead/lead-free surface

The kinematic simulation model can only produce macro lead afflicted surfaces since the resulting surface is geometrically optimal and the surface can be discretized arbitrarily fine. Therefore, a frequency analysis as used in MBN31007-7 will always find a frequency in circumferential direction and therefore detects lead. However, with specific manufacturing parameters, macro lead free surfaces can be grinded. This behavior is not representable with only kinematic influences.

Applying stochastic influences like the distribution and the contour of grains enables the model to create macro lead-free surfaces, seen in Figure 12. The figure shows the speed ratios from 10.0 to 10.5 in 0.1 steps over revolution beginning at 1 to 15 with the step size of 2. The considered parameter is the lead angle. The lead angle switches from its positive value to 0, when the dominant structures of the surface are in circumferential direction.

![Figure 12: Reversal point macro lead](image)

At one to three revolutions, every speed ratio produces macro lead afflicted surfaces. As seen for speed ratios 10 and 10.5, the angle of the structures doesn’t turn over to 0, therefore, the surfaces keep their macro lead angle. The speed ratios between 10.1 and 10.4 show the transition between macro lead afflicted and macro lead-free surfaces appears at different revolutions. The term “transition” means, that the most dominant reoccurring structures on the surface detected by the frequency analysis used in MBN31007-7 is directed in circumferential direction. Before that, the dominant structures are detected rotated by 0.3° relative to the circumference. The transition mostly appears between 5 to 9 revolutions so according to this simulation
model, the number of revolutions needed to produce macro lead free surfaces has to be higher than 5, at least.

4 Discussion and conclusion

The paper presented a kinematic simulation model of the manufacturing process ‘plunge grinding’ with the extension of a stochastic distribution of grains on the grinding wheel. The model has been explained in detail and verified by grinding exact counterparts of the counterfaces and comparing them with the help of the MBN31007-7 macro lead evaluation method.

The kinematic influence of the concerned manufacturing parameters on the resulting counterpart surface have been investigated. The speed ratio showed a great influence on the lead depth and the period length and a minor influence on the lead angle. The spark out time has a great influence on the lead parameters when working with speed ratios between 10.1 and 10.4, but has nearly no influence with speed ratio 10 and 10.5. The dressing velocity influences all lead parameters. The radial feed, however, just influences the lead depth.

The stochastic influence on the transition between macro lead afflicted and macro lead free surfaces has also been investigated and speed ratio specific transition times have been discovered. But the method implies using a surface topography measuring device to extract the information of the grain distribution as well as their size distribution. This approach limits the usability of the tool to owner of these devices. An improvement would be the mathematical recreation of a grinding wheel surface using a parametric function, which describes the grain size and the local distribution.

5 Nomenclature

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( i )</td>
<td>Current Index</td>
<td>[-]</td>
</tr>
<tr>
<td>( \phi_{GW} )</td>
<td>Diameter grinding wheel</td>
<td>[mm]</td>
</tr>
<tr>
<td>( \phi_{CF} )</td>
<td>Diameter counterface</td>
<td>[mm]</td>
</tr>
<tr>
<td>( a_d )</td>
<td>Radial feed</td>
<td>[\mu m]</td>
</tr>
<tr>
<td>( v_d )</td>
<td>Dressing velocity</td>
<td>[mm/min]</td>
</tr>
<tr>
<td>( b_d )</td>
<td>Width dressing tool</td>
<td>[mm]</td>
</tr>
<tr>
<td>( t )</td>
<td>Spark out time</td>
<td>[s]</td>
</tr>
<tr>
<td>( R )</td>
<td>Revolution (of the counterface)</td>
<td>[-]</td>
</tr>
<tr>
<td>( n_{GW} )</td>
<td>Circumferential velocity grinding wheel</td>
<td>[1/min]</td>
</tr>
<tr>
<td>( n_{CF} )</td>
<td>Circumferential velocity counterface</td>
<td>[1/min]</td>
</tr>
<tr>
<td>( S )</td>
<td>Speed ratio</td>
<td>[-]</td>
</tr>
</tbody>
</table>
\( D_y \)  Lead angle  \([°]\)  
\( D_P \)  Period length  \([\text{mm}]\)  
\( D_G \)  Number of threads  \([-]\)  
\( D_t \)  Lead depth  \([\mu\text{m}]\)  
\( D_F \)  Feed cross section  \([\mu\text{m}^2]\)
6 Authors

University of Stuttgart, Institute of Machine Components (IMA)
Pfaffenwaldring 9, 70569 Stuttgart, Germany:
Georg Haffner, M. Sc., ORCID 0000-0002-6484-235X, georg.haffner@ima.uni-stuttgart.de
Dr.-Ing. Matthias Baumann, ORCID 0000-0002-1962-5153, matthias.baumann@ima.uni-stuttgart.de
PD. Dr.-Ing. Frank Bauer, ORCID 0000-0001-7799-7628, frank.bauer@ima.uni-stuttgart.de

7 Literaturverzeichnis:


