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# Approach for the Development of Forming Tools for Radial Rotation Profile-Forming

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**Abstract.** The incremental forming process Radial Rotation Profile-Forming (RRPF) has been developed to enable the production of profiled hollow parts with low sheet thinning and high geometrical accuracy. As a result of low thinning, a smaller initial sheet thickness can be used, while material and weight can be saved.
The two principal forming steps are the production of the preform by Rotational Swing-Folding (RSB) and the subsequent radial profile forming of the hollow part in one clamping position. The special feature are the purposed wrinkles in the first process step, which formed in the indentation of the profiled mandrel. This is an advantage, because of the additional thickening. Due to the radial profiled forming in the second process step, the axial profile can be formed with less thinning.
The focus of the article is on the development of the forming tools for the second process step of RRPF. Based on the general law of gearing, the forming tools for the production of a component are developed. First, a forming simulation of an example component validates the approach. For this purpose, some simplifications have been made in order to consider the profile forming process separately. Afterwards, the experimental results of the incremental sheet metal forming process for the production of the profiled hollow parts are presented.

## 1. Introduction

For the production of novel and lighter components, different approaches can be used. In addition to optimizing the stiffness and strength from components (for example, through material or topology optimization), a lightweight design is taken into account in the production process. Given the availability of numerical methods, improved sensor and measurement technology and the development of new materials or composite materials, weight reduction, based on forming technology, can be operated (e.g., composite forging [1, 2] or press hardening [3]).

For the production of profiled hollow components by sheet metal forming, there are established forming processes such as the GROB-forming [4], rolling [5] or deep drawing [6]. For the production of lightweight components with additional functions (gearing, profiling), Sheet-bulk metal forming is investigated. The aim is to achieve a three dimensional material flow during sheet metal forming, an overview for different approaches is presented in [7]. Usually, in the first process step a thickening occurs (for example by upsetting) and in a second process step, the additional functional elements are formed. Similar on this approach, a novel incremental forming process known as Radial Rotation Profile-Forming (RRPF) has recently been developed. An additionally aim of the forming process is to reduce the relative movement between the tool and the workpiece, which results a low process-induced sheet thinning. Thereby allowing a smaller initial sheet thickness. In addition to the requirement of minimized relative movement between the workpiece and the tool, wrinkling is a challenge.

## 2. Process Principle: Radial Rotation Profile-Forming

The objective of the Radial Rotation Profile-Forming incremental forming process is the production of profiled hollow components. The principle of the process chain is shown in **Figure 1**. The two principal tasks are the production of the preform by Radial Swing-Folding (RSB) and the profiling of the hollow part. For the preform production, the round blank is fixed on a profiled mandrel. Due to the swinging of a cylindrical forming tool, the blank is placed on the contour of the mandrel and formed into a cup. In turn, a minimum relative movement in the axial and radial directions between the tool and the workpiece exists, due to the special position of the swinging axis. As a result, a low sheet thinning occurs in the flange of the workpiece. In addition, tangential compressive stresses occur because of a reduction in the diameter, which initially leads to a thickening of the edge. Furthermore, wrinkling occurs when the buckling stability is exceeded and a wrinkle-free preform is not possible. However, the most disadvantageous wrinkling can be used positively, because the wrinkles are formed in the indentation of the profiled mandrel (**Figure 1**: see Z).

In the second process step, the material distribution at the edge and the wrinkles are used to produce a profiled hollow part with low sheet thinning by radial forming. During the process, the cylindrical swinging tool works as a counter holder. Due to the rotation and continuous radial feed of the forming tool into the profiled mandrel, the axial profile is formed. Due to the minor relative movement in the axial direction, the elongation of the component and, as a result, the sheet thinning of the workpiece are minimized.

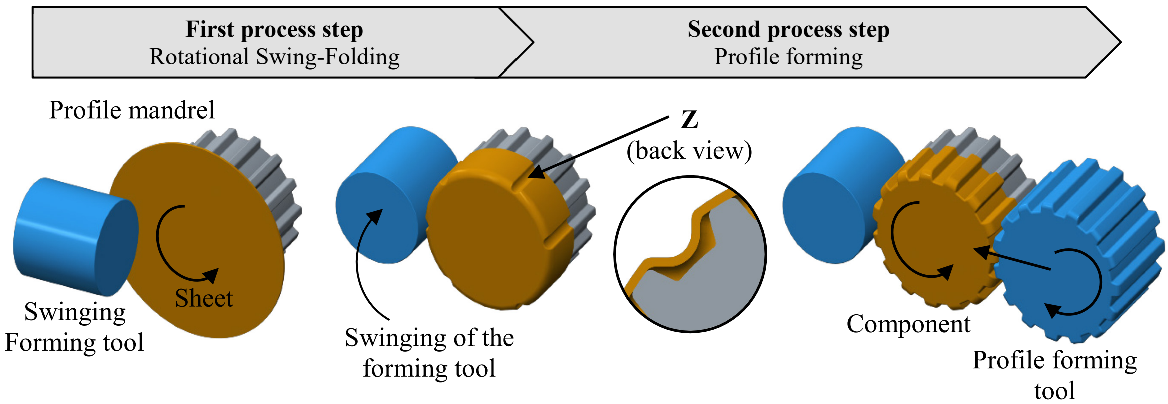


Figure 1: Process principle

## 3. Development of the Forming Tools

The focus of the paper is on the approach to developing the forming tools for the second process step of Radial Rotation Profile-Forming. In the following, the fundamental differences in the kinematics of profile forming will be discussed, after which the methodological approach for the development of the forming tools is presented. The approach will be shown for an example component. Numerical and experimental investigations for the production of profiled hollow components are then presented. The aim is to obtain a calibrated simulation model for rotatory forming. In combination with a validated simulation (sheet thickness, form and wrinkling) of the Rotational Swing-Folding [8], numerical investigations for the process chain are possible.

### 3.1 Introduction: radial forming

For a general comparison between translational and rotatory forming, a simulation under the same conditions is done. **Figure 2** shows the orange-colored workpiece, the blue forming tool and the gray die. The radial movement of both forming processes are equal.

Based on the comparison of the simplified 2D simulation of the profile forming process, a few basic findings can be identified. Thinning in the translational forming takes place mainly between the top circle and the flank (see A). For the rotary forming process, thinning takes place between the flank and the foot circle (see C), while lower sheet thinning occurs as well as an asymmetrical profile formation (compare C and E). The reason is in the rotatory movement, which always takes place from the same side. The first contact between the workpiece and the forming tool consistently occurs on the right edge, so that tensile stresses are generated in the tangential direction. A further finding is the shaping in the radial direction (profile depth); see the comparison between B and D at the end of the forming process. The forming tools are in the same position, but the workpiece is only in contact with the die for translational forming. Consequently, in the rotary forming, a deeper radial feed is necessary.

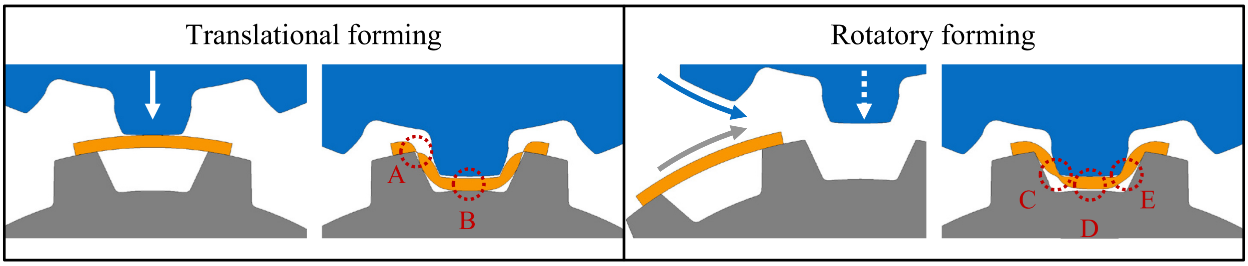


Figure 2: Comparison between translational and rotatory profile forming

The RRPF process should have minimum process-included sheet thinning; therefore, only rotatory forming is suitable.

### 3.2 Methodical approach

The development of the forming tools must be specially considered, because using the negative of the component, such as in deep drawing, is not possible. Due to the rotary forming process with the usage of the negative of the component, a penetration (**Figure 3**: left, red area) between the tool and the workpiece will occur, which will damage the component. To prevent this, a pure rolling rotation between the component and the tool is desired. For this purpose, the general law of gearing is used for the development of the forming tools (**Figure 3**: right). This law describes how the teeth of interlocking gears must be shaped to ensure the best-possible transmission of a uniform rotary motion.

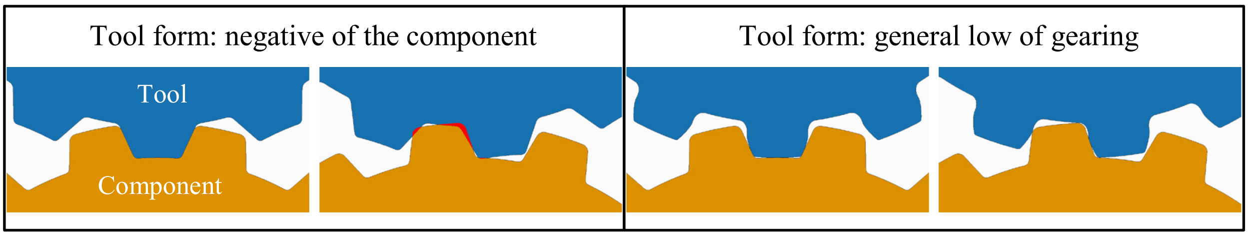


Figure 3: Comparison between different approaches for tool geometries

The aim is to obtain, at the point of contact with the teeth (pitch point), a pure rolling motion. According to the law of gearing, the normal (**Figure 4**: left) of the two contact surfaces (on the tooth flanks) must always pass through the pitch point, while the angular velocity in the contact area during the interaction must be equal.

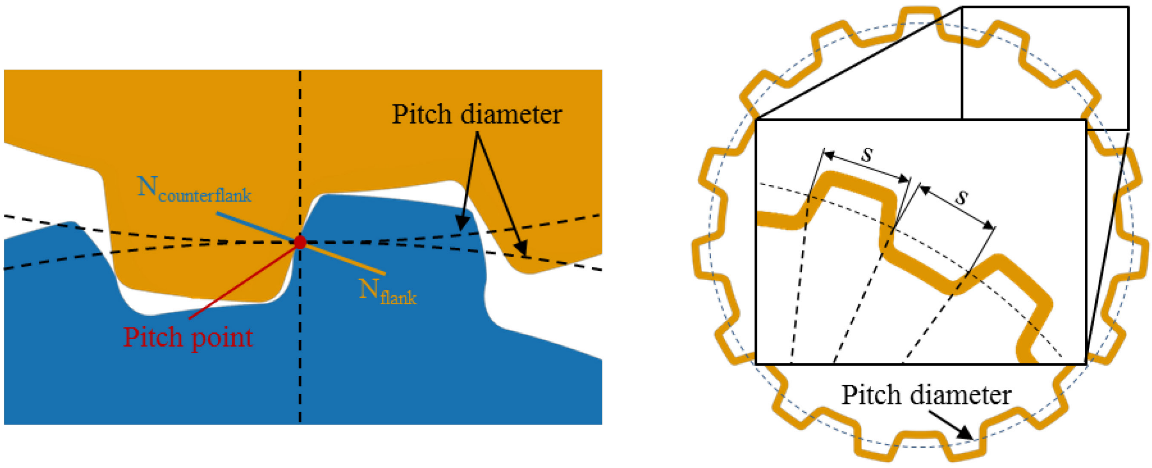


Figure 4: Law of gearing (left) and determination of the pitch circle (right)

In compliance with the general law of gearing, a counterflank can be constructed for each given flank, which meets the requirements for uniform transmission of the angular velocity.

The given flank represents the outer contour of the component. First, the rolling diameter must be determined. This is located at the point where the distance between valley and mountain is equal (see **Figure 4:** right, distance s).

For the development of the counterflank (see **Figure 5**), the flank rotates to the pitch point. Afterwards, a normal from an arbitrary point ($P_1$) of the flank $F_1$ is built, up to the point of intersection ($W_1$) with the pitch circle (1). On the opposite side of the pitch circle of the forming tool is where a point ($W_2$) is generated. The component and the forming tool rotate until points $W_1$ and $W_2$ meet at the pitch point (2). The normal is also rotated and point $P_1$* is created. According to the law of gearing, the point of the flank must overlap with a corresponding point of the counterflank, while the normal of the counterflank, must pass through the pitch point. In order to obtain the point of the counterflank, the flanks must be rotated back to their initial position (3). By repeating the construction for other points on the flank, the profile of the counterflank ($F_2$) is created.

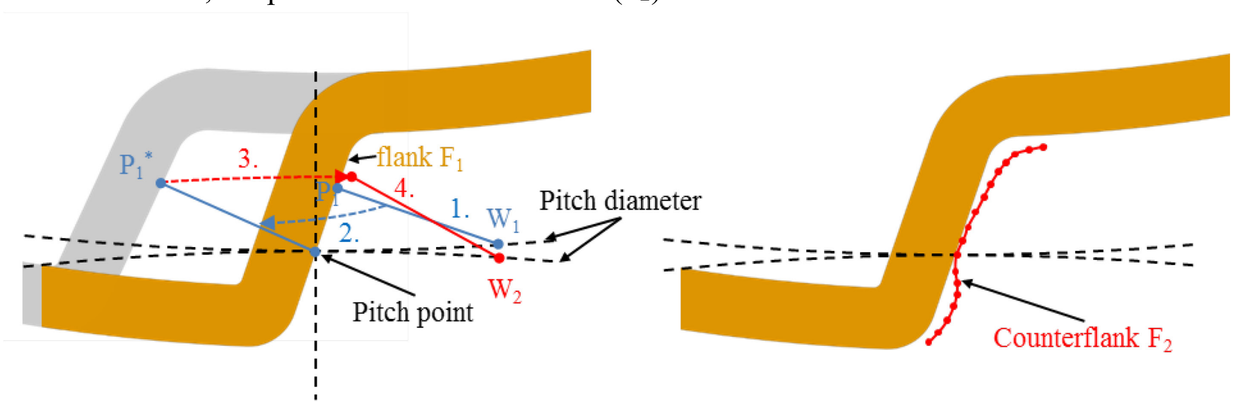


Figure 5: Construction of the counterflank

The connection of every point of contact (for example, in Figure 5, point P1* and the pitch point) is the contact path; this is the path of all successive points of contact of the two profiled flanks.

### 3.3 Analytical construction of the forming tools

The development of the forming tools will be shown for an example component. The workpiece is a synchronous pulley, based on DIN 7721-2 (15xT20 profile) with straight flanks and an opening angle of 50°, as shown in **Figure 6**. The initial sheet thickness of the profiled hollow component is 1.5 mm.

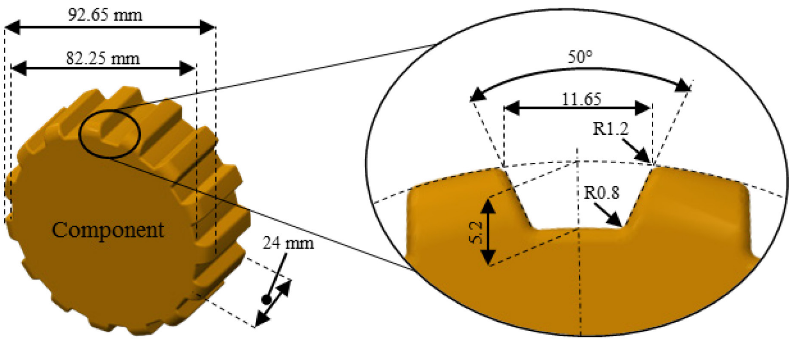


Figure 6: Component dimensions

The profiled die is a negative form of the component with reduced constant sheet thickness. For the development of the profiled roller, the general law of gearing is used. The pitch circle of the profiled component is $d_W$=86.883 mm and the distance between two pitch points is s=9.082 mm. Given that there are 15 profiles, the pitch is 24°. **Figure 7** shows the forming tool and the component for different angles of rotation with the path of contact (red). It can be seen that there is only a point contact between the tool and the component during the rotation. The developed tools have a pure rolling motion with the idealized component.

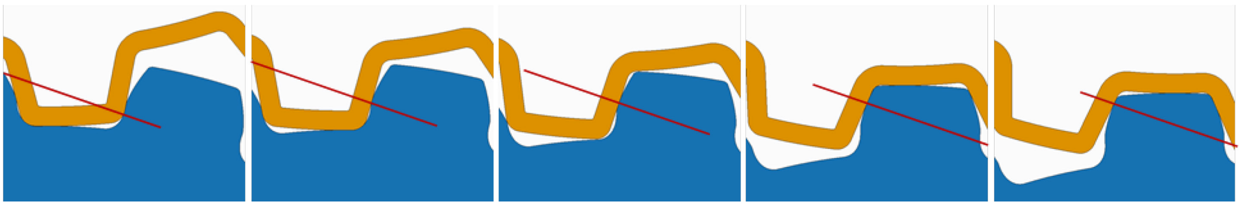

Figure 7: Rolling movement between workpiece and forming tool

## 4. Numerical Investigations

Due to the production of the preform by Rotational Swing-Folding, the sheet thickness in the radial direction is uneven and additionally receives influences due to wrinkling [8]. As a result, the forming process has complex influences. In order to obtain basic knowledge, development is first carried out with a rotationally symmetrical preform in order to reduce influences and disturbances. As such, conventional spinning is used for the production of a wrinkle-free preform. As a result, the forming of the profile in the second process step can be considered separately.

A simulation of the process chain is performed to examine the approach of the development of the forming tools. The tools are rigid bodies and the blank is meshed with hex elements. The material of the ideal preform is DC04 (1.0338) and the sheet thickness is 1.5 mm. The profile forming process with the developed forming tools is shown in **Figure 8**. The form of the profiles of the component are uniform and the tip circle and root circle show a good rational form.

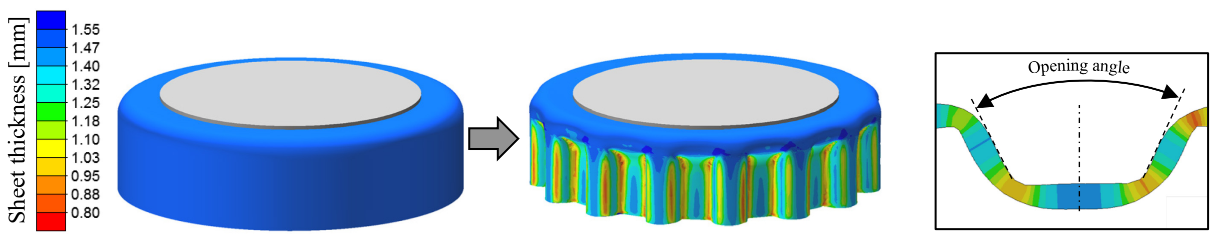


Figure 8: Simulation of the process chain

The geometric dimensions of the simulated workpiece were measured and compared with the required dimensions in **Table 1**. The tip circle and the root circle were determined by the minimum zone circle method (MZCI) and in turn the profile depth was calculated.

Table 1: Comparison of required and simulated dimensions (in mm)

| | Outer diameter (MZCI) | Profile depth | Pitch | Opening angle |
|---|---|---|---|---|
| **Required dimension** | 92.65 | 5.20 | 20.00 | 50.00° |
| **Simulated dimension** | 92.88 | 5.17 | 20.00 | 50.30° |
| **Deviation** | 0.25% | -0.58% | 0.00% | -0.60% |

The results show good agreement, especially with respect to the outer diameter and the opening angle. The standard deviation in the pitch and the opening angle is a result of the discretization of the simulation model and the shaping of the radii and the flank profile. However, the results show that the approach for the development of forming tools is usable.

## 5. Experimental Investigation

For the experimental investigations, a universal spinning machine was extended with a device for a profiled forming tool (**Figure 9**), which is contra-rotating but in angular synchrony with the machine main spindle. Even in the case of the radial feed of the forming tool, angular synchrony is ensured by a joint rod.

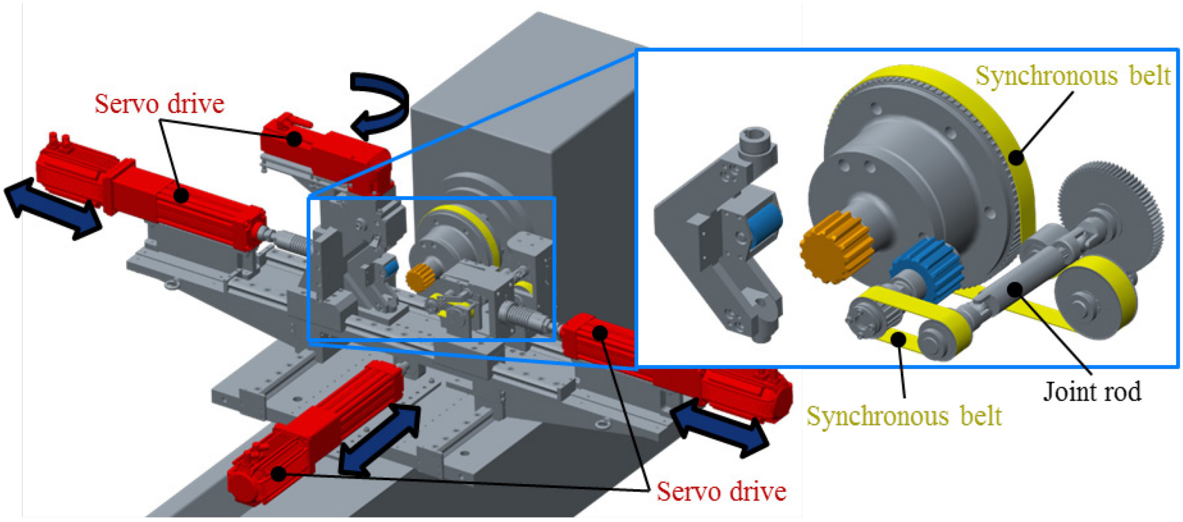


Figure 9: Forming machine

For the experimental investigations, the developed forming tools were used. The material of the blank is DC04 (1.0338) with an initial diameter of 130 mm and a sheet thickness of 1.5 mm.

In the first process step, a rotationally symmetrical preform (Figure 10: left) is produced with three straight spinning paths and a feed of 0.5 mm/U. Due to the production, a tailstock is used to increase the machine stiffness. The preform is wrinkle-free and has a good rationally symmetrical form. The radial feed of the profiling tool is 0.3 mm/U and the forming is done in one clamping. **Figure 10** (right) shows the profiled component, which is depicted with uniform profiles and without cracks.

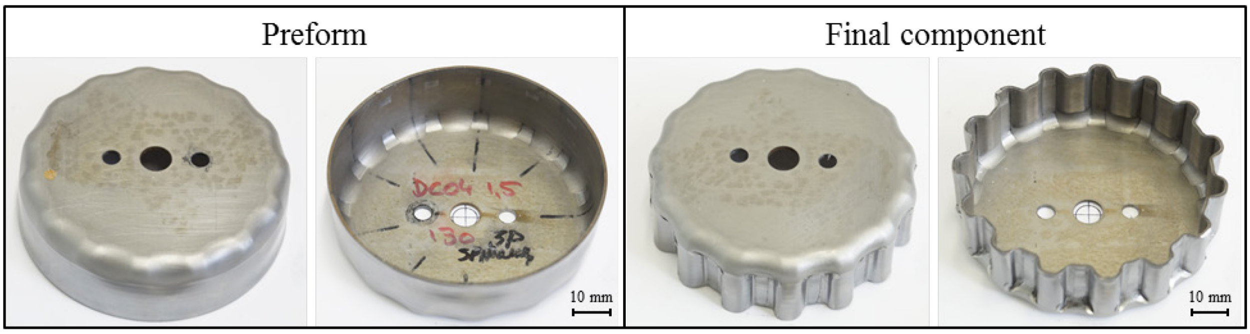


Figure 10: Experimental results

For the comparison between the simulation and the experiment, the outer diameter, the profile depth and the sheet thickness are investigated. Therefore the component is subdivided (**Figure 11**: left) in the transition zone and the cylindrical zone. The transition zone is between the front surface and the profiled cylindrical zone and will not considered for the further investigations. The determination of the diameter is carried out by the coordinates of the individual points in one measuring plane (**Figure 11**: left), after which the diameter is calculated using the minimum zone circle method (MZCI). The sheet thickness is measured on the same plane. **Figure 11** (right) presents a section of the calculated diameter and the measuring points from the coordinate measuring machine. There is a very short distance from the measuring points for the calculation of the preform diameter, as well as the profiled component, to the calculated diameter (average deviation of 0.067 mm). As a result, the roundness of the components is very good.

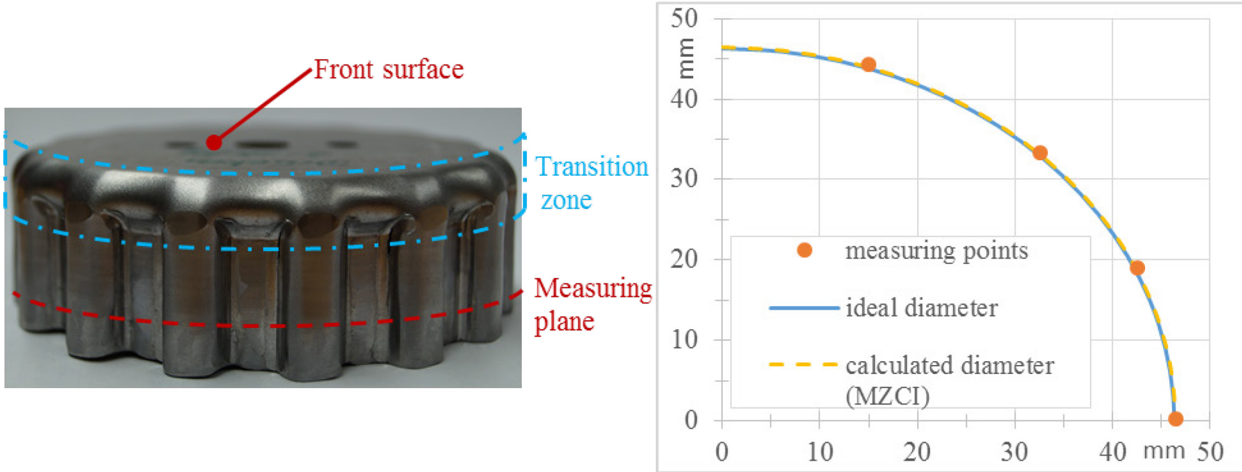


Figure 11: Measuring plane on the component (left) and diameter measurement (right)

For the comparison between the simulation and the experiment, the three-path spinning process for the production of the preform was also simulated, so that the influence of the first process step is considered. **Table 2** presents the results, the outer diameter and especially the sheet thickness of the simulation and the experiment show good agreement.

Table 2: Comparison of simulated and measured dimensions (in mm)

| | | | | |
|---|---|---|---|---|
| **Preform** | outer diameter (MZCI) | simulation | 93.59 | |
| | | experiment (deviation) | 95.45 | (2.0%) |
| | sheet thickness | simulation | 1.64 | |
| | | experiment (deviation) | 1.65 | (0.3%) |
| **Profiled component** | outer diameter (MZCI) | simulation | 92.88 | |
| | | experiment (deviation) | 92.91 | (0.0%) |
| | profiled depth | simulation | 5.08 | |
| | | experiment without cracks (deviation) | 4.73 | (-6.9%) |
| | | experiment with cracks (deviation) | 5.06 | (-0.5%) |
| | sheet thickness (root circle) | simulation | 1.36 | |
| | | experiment (deviation) | 1.37 | (0.7%) |
| | sheet thickness (tip circle) | simulation | 1.34 | |
| | | experiment (deviation) | 1.34 | (0.0%) |

The highest deviation indicates the profile depth. The reason is due to the sharp edge of the forming tool. In contrast to the rounded edge of the ideal forming tool, shown in the **Figure 12** (left), the roundness of the manufactured tool is too small. Therefore, cracks occur at this point (**Figure 12**: right) in the transition zone when the tool is moved in the radial direction until the required profile depth is reached. Based on the simulation, the roundness of the edge of the tool can be investigated, so that no cracks occur.

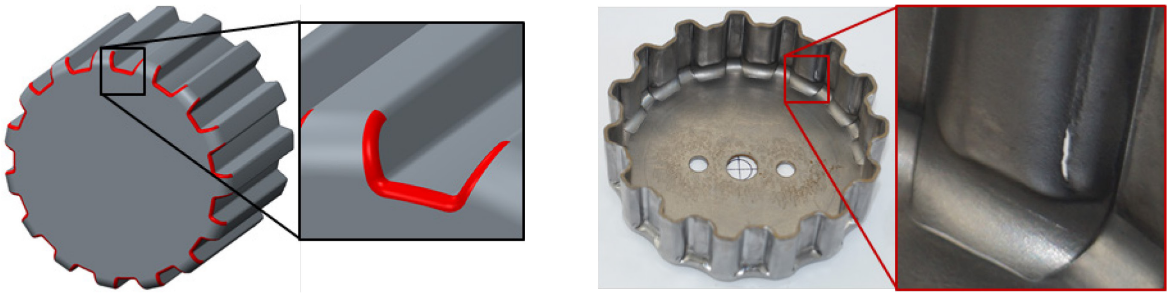

Figure 12: Ideal forming tool (left) and profiled component with a crack (right)

In principle, the approach for the development of the forming tools, especially the counterflank, can be validate to in terms of the outer diameter and the profile depth.

## 6. Summary and Conclusion

This paper presents the newly developed incremental forming process, Radial-Rotation Profile Forming, which was invented at the professorship Virtual Production Engineering at the TU Chemnitz. The two principal tasks are the production of the preform by RSB and the profiling of the hollow part. The aim is to produce a profiled component with less sheet thinning.

At the beginning, rotatory profiling and translational profiling were compared. The result was that rotatory profiling had a bigger springback and, due to the production, sheet thinning was asymmetrical. However, because of the pure rolling motion, sheet thinning was less than that by translational profiling. Subsequently, the approach for the development of forming tools with a pure rolling motion was presented and the construction of the counterflank of an exemplary component was shown. For the experimental investigations, a universal spinning machine was extended with a device for a profiled forming tool, which is contra-rotating but in angular synchrony with the machine main spindle. To investigate profile forming in more detail, a wrinkle-free preform was produced by spinning. The produced profiled components were measured on a plane to determine the outer diameter and the profile depth. The comparison between the simulation and the experiment showed good agreement. Consequently, the simulation model can be used for the development of forming tools for RRPF with the produced preforms by RSB.

The comparison between the ideal and the produced dimension showed a small deviation. Therefore, in further investigations, the maximum sheet thickness of the preform should be used for the development of the forming tools. In addition, the investigations showed that a larger rounding in the transition area is necessary for a reduction in the risk of cracks.

## Acknowledgements

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