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Influence of internal hub profile on joining process of shaft-hub-connection by lateral extrusion

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Abstract

Mori et al. (2013) identified the current commercial requirements for higher performance, higher productivity, lower cost and joining of dissimilar materials to lead to a strong demand for new joining and especially joining by forming processes. When joining a shaft-hub-connection by lateral extrusion of the shaft a combination of form- and friction locked joint is established. The internal hub profile which defines the form-closed joint in circumferential direction significantly affects the forming process and hence connection properties. The internal hub profile is mainly characterized by the profile eccentricity $e$, the number of teeth $n$ and type of profile. This study mainly deals with the experimental investigations concerning the influence of the internal hub profile parameters on the forming process and part properties. To identify a suitable internal hub profile characterized by low punch forces, minimal and homogeneous radial deformations and high hub cavity filling numerous joining by forming processes are carried out wherein the mentioned profile parameters are varied. To evaluate the influence of internal hub profile the punch force-stroke curves, the roundness deviation of the hub and the hub cavity filling are used.

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1. Introduction

In the field of power train engineering shaft-hub-connections are standardized connection types, which transmit torque of a shaft to a rotating hub. As a permanent type of connection often a combination of three well-known connection types, positive locking, frictionally engaged and material-closed connections, are established since many years. Using a non-cylindrical internal hub profile for manufacturing a shaft-hub-connection by lateral extrusion, a combination of a positive locking and frictionally engaged connection type occurs. Such a connection type shows significantly higher bond strength compared to the single connection types (Funk et al., 2012). While the tribological conditions in the contact interstice significantly affect the frictionally engaged connection type, the shape of the internal hub profile is decisive for the positive locking connection type and component properties such as radial deformation and hub cavity filling (Dörr et al., 2012).

The scientific task of this study is to identify a suitable internal hub profile, which is characterized by minimal and homogeneous radial deformations of the hub and related residual stresses within the hub, high contact pressure and high cavity filling of the internal hub profile. These requirements are met as best by a cylindrical internal hub profile. At the same time, however, such a profile should transmit high torques what is mainly achieved by a high value of profile eccentricity and number of teeth. Therefore, thin-walled hardened hubs (42CrMo4, 54HRC) showing different internal profiles are joined to a shaft made of 16MnCrS5 by lateral extrusion. These profiles are primarily defined by the parameters profile type, profile eccentricity and teeth number, which each are investigated by separate test series. A suitable lubricant ascertained from previous studies (Dörr et al., 2014) is used here. A schematic illustration of the employed procedure in this study is shown in Fig. 1.

![Fig. 1. Procedure of investigation.](image)

2. Experimental setup

2.1. Tool concept

The forming and joining process of a shaft-hub-connections has been carried out by using a 6,000 kN hydraulic metal forming press at the Institute for Metal Forming Technology. The applied forming method is based on the single-sided lateral extrusion according to classification of Schätzle (1987), whereupon only one acting punch and a static counter punch is used.
The die is represented by the hub within this modified forming method. During the forming and joining process a small axial relative motion of the hub occurs, which is necessary in order to preload the hub radially by a segmented die. Thus, the shaft has an area of free forming space below the hub in the shaft shoulder area. The segmented die is necessary to avoid critical tensile stresses within the hub during the joining process (Fig. 2). Radial movement of the die segments is realized by an inclined plane at the segment’s external surface showing an angle of 9° and an axial force applied to the segments by a hydraulic closing device (Dörr and Liewald, 2012).

![Fig. 2. Tool concept (a) and specimen dimensions (b).](image)

The shaft diameter within the joining area is 22 mm while the hub has a nominal internal diameter of 25 mm and an external diameter of 35 mm (Fig. 2 b). The dimensions of the joining area, such as nominal connection diameter and axial connection length, are defined according to previous investigations conducted by Reinholz (1994).

2.2. Specimen types

The internal hub profile is mainly characterized by the profile eccentricity, the teeth number and the type of profile. To investigate the influence of the profile eccentricity e, polygon profiles according to DIN 32711-1 (2009) showing four different values of eccentricity (Fig. 3 a) are used. Also epitrochoid, hypotrochoid and a complex trochoid are used to examine the effect of different types of profile. The basic equations of such profiles are given by Fig. 3 b). Based on a complex trochoid having an eccentricity of $e = 0.8$ mm, the teeth number $n$ is varied from $n = 3$ to $n = 7$.

$$\begin{align*}
a) & \text{epitrochoid:} \\
& x(\alpha) = R_m \cdot \cos(\alpha) + e \cdot \cos((n + 1) \cdot \alpha) \\
& y(\alpha) = R_m \cdot \sin(\alpha) + e \cdot \sin((n + 1) \cdot \alpha) \\

b) & \text{hypotrochoid:} \\
& x(\alpha) = R_m \cdot \cos(\alpha) + e \cdot \cos((n - 1) \cdot \alpha) \\
& y(\alpha) = R_m \cdot \sin(\alpha) + e \cdot \sin((n - 1) \cdot \alpha) \\

& \text{complex trochoid:} \\
& x(\alpha) = R_m \cdot \cos(\alpha) + 0.5 \cdot e \cdot \cos((n + 1) \cdot \alpha) + 0.5 \cdot e \cdot \cos((n - 1) \cdot \alpha) \\
& y(\alpha) = R_m - \sin(\alpha) - 0.5 \cdot e \cdot \sin((n + 1) \cdot \alpha) + 0.5 \cdot e \cdot \sin((n - 1) \cdot \alpha) \\
\end{align*}$$

![Fig. 3. a) Investigated internal hub profile parameters and b) basic equation of trochoids.](image)

3. Results

3.1. Punch forces

The influence of the profile parameters on the process is given by the punch force - stroke diagrams depicted in Fig. 4. Each curve represents the average of at least 10 experiments.
The punch force-stroke diagrams essentially consist of three sections. In the first section which ranges from 0 mm to about 0.4 mm an elastic compression of the shaft occurs. The second section identifies the free deformation of the shaft without contacting the hub. This section ends at about 1.4 mm to 1.8 mm whereupon a larger profile eccentricity leads to a shortening of this section range. The force path within the third section is significantly influenced by the profile parameters and the tribological conditions. The tribological conditions, however, have not been varied in this study and are neglected.

Fig. 4 a) shows the influence of the profile eccentricity to the punch force during the joining of a shaft-hub-connection by lateral extrusion. It can be seen that a larger profile eccentricity leads to an increase of punch force. However, it should be noted that the amount of force differences for profile eccentricities of 0.8 mm, 0.9 mm and 1.0 mm decrease at the process end and are very low. Merely the punch force of the joining of a polygonal hub having a profile eccentricity of 1.12 mm shows higher values for the entire third section.

The use of different numbers of teeth of the internal hub profile shows that an increase of teeth number leads to a rise of punch force. Also within this test series a convergence of punch forces for teeth numbers below 7 at the process end is detected.

Regarding three different profile types, examined in this study, the lowest punch force is determined when using an epitrochoid internal hub profile. The punch force measured while forming and joining process of such an epitrochoid internal hub profile is approximately 613 kN (stroke 7.0 mm) and hence is nearly 17 % lower than when using a hypotrochoid internal hub profile, where a punch force of almost 735 kN is measured. Using an internal hub profile based on a complex trochoid leads to a medium punch force of about 649 kN. Main reason for these differences is the differing hub cavity volume. Compared to a cylindrical internal hub profile with an internal diameter of 25 mm an epitrochoid profile shows an increase of the hub cavity volume of 12.7 % and a decrease of the maximum punch force of 4.5 %. In contrast to that, a hypotrochoid internal profile shows a 9 % smaller hub cavity volume and an increase of the maximum punch force of 13 %. The complex cycloid shows a slight increase for both values of almost 1 %. Within the test series, dealing with the influence of the teeth number, no such significant change of internal hub cavity volume occurs. The difference of the punch force thus results solely from the influence of the teeth number. An increase of the profile eccentricity however leads to a reduction of the internal hub volume. So an eccentricity of 0.8 mm of a polygon profile shows a 7 % smaller internal hub volume compared to a cylindrical hub (e = 0 mm). Within this test series the differences of punch forces are caused by both the difference of the internal hub volume and the influence of profile eccentricity.

3.2. Roundness deviation

To evaluate the radial deformation of the external hub surface, the roundness deviation of the hub in the initial state and in the joined state was determined by using a 3D coordinate measuring machine. The measurement was performed starting at the three horizontal planes at intervals of 2, 6 and 11 mm measured from the upper end face of the hub. The determination of the reference circle was carried out using the Least Square Circle method. The roundness deviation in general describes the difference between the maximum and minimum distance of the
measured points to the reference circle. The maximum or minimum values have been calculated as the mean of the three largest respectively smallest values to exclude measurement failures (Fig. 5).

As a result of the forming and joining process an increase of the roundness deviation within all test series occurs. The results regarding the influence of the profile eccentricity show the largest values of roundness deviation. Within this test series an increase of the profile eccentricity causes an increase of roundness deviation. Smallest roundness deviation of all tests is detected when using a complex trochoid having 4 teeth. The test series dealing with different teeth numbers does not show a clear trend of roundness deviation depending on the teeth number. It should be noted that the segment die provide a fix number of 6 segments. This might causes an inhomogeneous elastic deformation of hub if the teeth number differs to the number of segments. Therefore, when using a 6 teethed internal profile the supposedly smallest roundness deviations should occur. This optimum was not observed throughout the experimental results. Within the other test series the teeth number was kept as constant, so that the determined difference only was caused by varying profile parameters. Regarding the profile type an epitrochoid profile leads to the smallest deviations. The complex trochoid shows the lowest dispersion along hub height thus the smallest cylindricity deviation.

3.3. Hub cavity filling

In order to assess the hub cavity filling the joined parts were sawed within the mid-plane of the joining area. The radial gap between shaft and hub at the tip of each tooth was measured and an arithmetic mean value was calculated (Fig. 6). The determination of the gap was carried out for two different stroke values, 7.0 mm and 7.5 mm.

The results of radial gap measurement are depicted in Fig. 7. An increase of punch stroke leads to a decrease of the gap respectively to an increase of hub cavity filling. The highest hub cavity filling (the smallest gap) was achieved during test series "teeth number" for $n = 3$. In this case an increase of punch stroke causes no significant decrease of the radial gap. Whereas an epitrochoid profile leads to the smallest gap within this test series, a reduction of the profile eccentricity or a decrease of the teeth number causes a reduction of the radial gap.
4. Conclusions

Form- and force-closed shaft-hub-connections showing different profile parameters were joined by lateral extrusion and punch force, roundness deviation and cavity filling were determined to find a suitable internal hub profile. Table 1 shows the identified optimal profile parameters and performance requirements.

Table 1. Identified optimal profile parameters related to appraisal criterions.

<table>
<thead>
<tr>
<th>appraisal criterion</th>
<th>profile eccentricity</th>
<th>teeth number</th>
<th>profile type</th>
</tr>
</thead>
<tbody>
<tr>
<td>punch force</td>
<td>0.8 mm</td>
<td>3</td>
<td>epitrochoid</td>
</tr>
<tr>
<td>roundness deviation</td>
<td>0.8 mm</td>
<td>4</td>
<td>epitrochoid</td>
</tr>
<tr>
<td>hub cavity filling</td>
<td>0.8 mm</td>
<td>3</td>
<td>epitrochoid</td>
</tr>
<tr>
<td>performance requirements</td>
<td>high (1.12 mm)</td>
<td>high (6)</td>
<td>low notch effect (complex trochoid)</td>
</tr>
<tr>
<td>selected profile parameters</td>
<td>0.8 mm</td>
<td>6</td>
<td>complex trochoid</td>
</tr>
</tbody>
</table>

(1) The smaller the profile eccentricity, the lower the punch force, the roundness deviation, and the radial gap.
(2) From process point of view, low teeth numbers are desirable.
(3) Based on the performed studies from process point of view epitrochoid profiles are preferable. However, this profile type leads to a strong notch effect within the shaft and therefore it is to be replaced by complex trochoid.

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