Design problems of axisymmetric connections in the aspect of machine engineering drawings

A Kołodziej, M Dudziak and K Talaśka
The President Stanisław Wojciechowski State University of Applied Sciences in Kalisz, Nowy Świat 4, 62-800, Kalisz, Poland
E-mail: a.kolodziej@pwsz.kalsiz.pl

Abstract. Axisymmetric connections are often employed in machine building. They can be used as static and movable connections. The final geometric form of elements comprising the axisymmetric connection is heavily dependent on the guidelines provided in the engineering drawing as well as the metrological process carried out as part of manufacturing. The denotation to maintain correct deviation within the framework of selected shape faults appears to be inaccurate. Companies manufacturing such components may control their measuring strategy to avoid a large number of rejected items. In the paper the influence of selected shape faults on coupling parameters within the axisymmetric connection as well as the effect of selected measurement strategy on the results of measurement of specific dimensions are presented. Furthermore, in the paper the guidelines for correct notation in the technical documentation to avoid ambiguity in interpretation have been defined.

1. Introduction
Axisymmetric connections are widely used in machine building. Two main groups of these connections can be defined: stationary connections, an example of which are pin connections, and movable connections, e.g. shaft journal with sleeve. The effective bearing capacity of such connection are primarily affected by the actual outline of the item surface obtained in the manufacturing process. Shape forming errors, both in lateral and longitudinal cross-sections are responsible for the coupling parameters for these types of connections [1–9]. Among such parameters, we can identify: contact stress (direct surface coupling), equivalent stress in the contact area of coupled surfaces, forces and frictional moments resulting from the coupling (in particular during relative motion of coupled surfaces).

It is therefore desirable to perform studies enabling to evaluate the influence of the actual surface condition of axisymmetric coupling components on its load bearing capacity, both under static and dynamic load conditions [1–9].

Determining the unambiguous influence of shape deviation of components comprising the axisymmetric connection obtained in the manufacturing process necessitates the determination of guidelines and planning measurement strategies to be used in the quality control process of these items. The technical documentation usually does not contain detailed information of the correct handling of specific shape deviations. This leads to ambiguity which can be utilized by the controlling entity to qualify a given part as correctly manufactured. It was unambiguously determined that the measuring strategy parameters have a deciding influence on the obtained measurement result [5].

Experimental studies enabling evaluating the actual surface stress condition between the coupled surfaces are problematic. MES simulation examinations are more accessible in comparison. In the paper
the examination methodology enabling to simulate the coupling conditions of the axisymmetric conditions for the purpose of determining the effective load bearing capacity of the connection, assuming the presence of selected shape forming errors of the shaft/axle journal or in the transverse cross-section of the journal is presented. The presented methodology may be adapted to analyzing any connection of this group. For the analysis, the ABAQUS/Standard software was used.

The work demonstrates (using MES analyses), that shape deviations have an unambiguous effect on the coupling parameters of the axisymmetric connection. Furthermore, based on earlier works, it was demonstrated that the parameters of the measuring strategy have a decisive influence on the obtained measurement result. It was therefore proposed that the information presented in the technical documentation contain additional data to specify the performance of measurements during inspection of the manufactured components.

2. Methodology of the research

For the purpose of indicating the influence of shape deviation on the coupling parameters of the axisymmetric connection, the sleeve-journal coupling with nominal diameter 35 mm and length 20 mm was examined. The journal was manufactured with the following cross-section shape errors: ovality, 3-angularity and 5-angularity. The planned shape formation errors were provided in three accuracy classes: IT3, IT6 and IT10 in regards the nominal dimension 35 mm, which results in tolerance values of, respectively: 3 μm, 16 μm and 100 μm.

Figure 1 provides a schematic representation of the analyzed cases of the coupling. The model used for the analysis comprised two components: journal and sleeve.

![Figure 1. Schematic representation of the analyzed connection together with the analyzed connection with considered shape forming errors: ovality, 3-angularity, 5-angularity.](image)

The sleeve is modeled as a rigid component with perfectly round bore, nominal dimension Ø35 mm, whereas the journal was modeled as a deformable component with specified shape deviations implemented within the three assumed tolerance categories. Figure 2 presents the schematic view of the discretized shaft together with an example distribution of equivalent stress in the contact areas with the sleeve. The following characteristics were set for the shaft material: Young’s modulus $E = 210$ GPa, Poisson’s coefficient $\nu = 0.3$, density $\rho = 7850$ kg m$^{-3}$. The shaft with sleeve was coupled with assumed frictional coefficient value $\mu = 0.09$. The performed analyses accounted for three load values at the connection: gravity load, gravity load + 100 N and gravity load + 1000 N. Static analyses were performed for specific angular positions of the journal in relation to the immobile sleeve.
3. Results of the FEM analyses

The obtained results allowed to determine the variability of contact stresses on the shaft journal surface, equivalent stress in the contact area, forces and frictional moments required to dismantle the connection under specific load. Figures 3, 5 and 7 present the distribution of equivalent stress in contact areas of the journal and sleeve as well as reaction forces affecting the journal in the given angular alignment of the sleeve and journal. The results apply to the journal with 5-angular forming error at manufacturing accuracy class IT6. The connection was subject to force value 1000 N. Figures 4, 6 and 8 present the CPRESS stress values for the same cases.

Figure 2. Schematic view of the MES simulation model.

Figure 3. Equivalent stress in the sleeve-journal contact area, journal with 5-angular forming error, load 1000 N, angular position of journal and sleeve – 0°.

Figure 4. CPRESS stress in the journal-sleeve contact area, journal with 5-angular forming error, IT6, load 1000 N, angular position of shaft in relation to the sleeve – 0°.
Figure 5. Equivalent stress in the journal-sleeve contact area, journal with 5-angular forming error, IT6, load 1000 N, angular position of shaft in relation to the sleeve – 18°.

Figure 6. CPRESS stress in the journal-sleeve contact area, journal with 5-angular forming error, IT6, load 1000 N, angular position of shaft in relation to the sleeve – 18°.

Figure 7. Equivalent stress in the journal-sleeve contact area, journal with 5-angular forming error, IT6, load 1000 N, angular position of shaft in relation to the sleeve – 36°.
Figure 8. CPRESS stress in the journal-sleeve contact area, journal with 5-angular forming error, it6, load 1000 N, angular position of shaft in relation to the sleeve – 36°.

Figure 9 presents the juxtaposition of graphs describing the variability of equivalent stress in the sleeve-journal contact area as a function of the journal rotation angle in relation to the sleeve for all the cases of shape forming error, forming accuracy categories and loads. Figure 10 presents a juxtaposition of functions describing the change of FT frictional force resulting from the journal – sleeve coupling. The defined frictional force is generated when the examined connection is to be decoupled. Similarly, it is possible to determine the moment of friction MT, which changes value as a function of the rotation angle equivalent to the change of value of the frictional force FT. The graphs do not show the changes in CPRESS pressure values as a function of the connection angle of the journal in relation to the sleeve. Regardless, they exhibit a type of variability that is identical to the equivalent stress during the angular change of alignment of the shaft in relation to the sleeve. All the results provided at figures 9 and 10 apply to the contact area of one selected “angle” of the surface irregularity in relation to a given shape forming error.

Analyzing the study results, it is concluded (confirming the conjecture), that the most disadvantageous forming error case is the ovality of the transverse cross-section both in regards to the changed accuracy class of component manufacturing and the coupling load. Such a shape, both in regards to the equivalent stress and CPRESS pressure and frictional force and moment exhibits the most disadvantageous angular position at around 90°. The manufacturing accuracy class is critical in this regard. Increasing the load from 100 N to 1000 N causes a major increase in the equivalent stress by at least three times. The increase in angularity does not cause a significant reduction in value of both the equivalent stress and CPRESS pressure; however, it affects the decrease in the angular range of load of the selected irregularities due to specific forming error. For 3-angularity, the given angle” has a load at 240°, whereas for 5-angularity, it is only at 144°. The increase in angularity in relation to the forming error in the transverse cross-section has a decisive effect on the force value and frictional moment. At the highest load at the 5-angular cross-section, the frictional force decreases in comparison to the 3-angular cross section by the factor of three. The same relation is observed for the frictional moment value.
Figure 9. Equivalent stress in the journal-sleeve contact area as a function of the journal rotation angle in relation to the sleeve: a) ovality – gravity load, b) 3-angularity – gravity load, c) 5-angularity – gravity load, d) ovality – gravity load + 100 N, e) 3-angularity – gravity load + 100 N, f) 5-angularity – gravity load + 100 N, g) ovality – gravity load + 1000 N, h) 3-angularity – gravity load + 1000 N, i) 5-angularity – gravity load + 1000 N.
Figure 10. Frictional force caused by the coupling of the journal and the sleeve as a function of the rotation angle of the journal in relation to the sleeve: a) ovality – gravity load, b) 3-angularity – gravity load, c) 5-angularity – gravity load, d) ovality – gravity load + 100 N, e) 3-angularity – gravity load + 100 N, f) 5-angularity – gravity load + 100 N, g) ovality – gravity load + 1000 N, h) 3-angularity – gravity load + 1000 N, i) 5-angularity – gravity load + 1000 N.
During quality inspection, the measure-taking strategy is defined by a number of parameters. These include: number of measuring points, type of reference component, spacing between measures taken from the component side, selected frequency filter, diameter of the measuring tips, pressure of the measuring tip. In the paper [5] a detailed analysis of the influence of the selected parameters of the measuring process on the obtained value of roundness deviation have been provided. Figures 11 and 12 present the selected results [5].

**Figure 11.** Values of roundness deviations obtained by pulse method for a variable number of measuring points: 4p – 3.89 µm, 8p – 7.12 µm, 16p – 13.23 µm, 32p – 13.49 µm, 64p – 14.71 µm, 3203p – 15.03 µm [5].

**Figure 12.** Values of roundness deviation obtained using different radii of measuring tips: r = 1.75091 mm – 19.61 µm, r = 3.50025 mm – 15.03 µm, r = 4.00012 mm – 12.93 µm [5].

4. Conclusion
The presented study methodology is helpful for accurate design of the technological process together with the guidelines necessary to obtain the assumed surface form of the finished component. Furthermore, it is necessary for estimating the actual load of the designed axisymmetric coupling. The analysis of the presented study results may be successfully employed for planning the measure taking strategy in the quality control processes during the manufacturing of components. The knowledge of effective load bearing capacity of a coupling in the aspect of identified forming errors allows to plan the measure taking strategy to detect the most disadvantageous configurations of the negative aspects. The description of shape deviation in the technical documentation should be supplemented with information to answer as many of the questions posited below [8]:

- what measuring strategy should be employed (frame based, point based, examination of generating lines, or examination of roundness outlines),
- the number of measuring points required,
• the number of examined generating lines and/or number of roundness outlines,
• the required spacing of observed generating lines and/or roundness outlines,
• what is the required distance between the first and last roundness outline from the edge of examined area,
• what are the metrological characteristics of the measuring tip (geometry and radius of the measuring tip with mechanical filtering of the examined profile, length of the sensing pin affecting its bending, measurement pressure, measuring speed,…),
• what filter and what filter conditions are to be used,
• what reference component is to be used for result evaluation.

5. References

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