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MODELLING OF FRICTIONAL TAPERED CONNECTIONS IN MACHINE DESIGN

Стаття присвячена моделюванню фрикційних конічних зв'язків у проектуванні машин. Проектні завдання для пристроїв і механічних елементів потребують підвищення якості на виробництві. Важлива річ – правильне проектування і точне копіювання геометричної форми та структури поверхонь, що з'єднуються. Показано як потрібно отримати об'єктивніші проектні умови для геометричних параметрів конічних з'єднувальних елементів, які задовольняють вищі ступені статичного і динамічного навантаження.

Ключові слова – проектування механізмів, якість виробництва, конічне з'єднання

This paper is devoted to the modelling of frictional tapered connections in machine design. Designing tasks for devices and mechanical units need manufacturing quality increasing. Important thing is correct design and accurate reproduction of geometrical shape and structure of mating surfaces. The article shows how to obtaining more objective design conditions of geometrical features of tapered connection elements, which satisfy in higher degree than before the conditions of state of static and dynamic load.

Keywords - machine design, manufacturing quality, tapered connection

Introduction

Shaped separable and nonseparable axialsymmetrical connections such as: tapered connections, splined connections, fitted bolts are used as one of basic method of connecting mechanical parts. Designer in complex design process determines their nominal form and size limits using his ideas, experience and knowledge about function of considered unit. Reliability and safety features of tapered connections depends fundamentally on accurate reproduction of designed geometry and stereometry of surface. Their real geometrical form is connected with frictional contact of connected elements (journal and seat). Real contact surface of mated pairs is smaller than surface, which is applied during calculations according to current ideal model.

During manufacturing real elements are produced, their geometrical profile is distorted, dimensions are not equal to assumed ones, and surface is rough [3].

Application of modern methods and measuring devices gives the possibility of production process control and metrological estimation of manufacturing errors of connection elements [4]. It allows to precise measurement of form deviations and determination of real mating surface of contact pairs. This is particularly important in direct pressed connections (frictional connections with conical contact surface are ranked among these connections) for the sake of torque moment transmission, seldom for axial forces.

Hence there were conducted the researches of rectilinearity, roundness and angle of cone deviations in order to carry out the objectivization of geometrical profile of mating elements. It will allow to fits modelling in order to form the decision about selection of conception of design solution.

Design of constructional features of tapered connections

During design of mating elements there should be guaranteed their proper cooperation by formulation of specified requirements concerning inter alia: fits, their tolerances and resulting from that clearances or interferences [1].

There are used two methods of tolerancing with reference to conical surfaces [5].

In first method, which is recommended for cones creating fits, tolerancing of cones consists in determining the position of tolerance range and value of tolerance of diameter TD, which is constant along entire length (fig. 1a). Area of tolerance restricts simultaneously the deviations of: diameter, angle and shape. Standard permits to independent tolerancing the roundness of cross section profile, rectilinearity of generating line and angle of cone, but it is not applied in industrial practise.

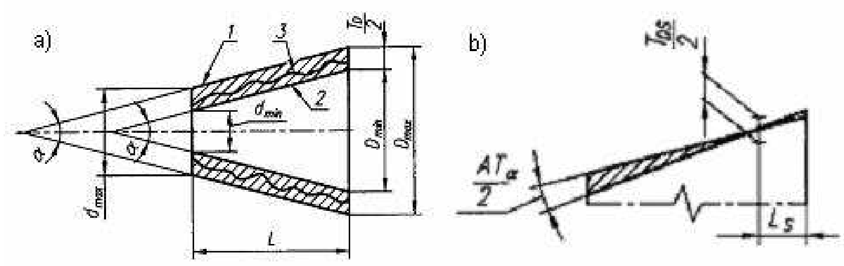

Fig. 1. Cones tolerancing: a) method 1, b) method 2;
1 – generating line, 2 – limiting cone, 3 – real cone

In second method tolerance range of cone dimensions is determined by tolerance diameter TDS and angle AT (fig. 1b). Tolerancing consists in separate determination of tolerances: TDS – diameter of cone in specified plane, AT – angle of cone, TFK – roundness of profile of cross section, and TFL – rectilinearity of generating line. This method is recommended for cones, which are not creating fits.

Fits established by method 1 should be created according to principle of stationary hole. In case of method 2 principle of stationary hole is privileged.

Diameter tolerances of fitted external and internal cones should be manufactured in the same accuracy class. In well-grounded cases there can be permitted different accuracy classes; then it is recommended to take higher tolerance for internal cone, but the difference in accuracy classes of diameters of mated cones should not be grater than 2.

Presented methods of tolerance of conical elements allow to define proper selected fits by designer, which determines their function (clearance, interference).

Another important criterion is strength of connection. According to this criterion tapered connection should be calculated for the sake of contact stresses between journal and seat:

$$\delta = \frac{F}{A} \leq \delta_{all} \tag{1}$$

where: F = 2Mo/μDav - normal force, A = πDav L / cos α/2 - pressure surface, δall - allowable stresses, μ- coefficient of friction, Mo - torque, Dav =(D + d)/2, D- diameter of larger basis of journal, d – diameter of smaller basis of journal, L – projection of contact length on axis of connection, α/2 – half-angle of cone.

On the basis of analysis of manufacturing errors of elements of tapered connection it can be concluded that real contact surface of mating couple is smaller than surface taken into account in calculations according current ideal model. Occurrence of these errors causes that functional, strength and operation features are getting worse. In order to improve them the approach to design of tapered connections should be changed.

In new philosophy of design and manufacturing one of essential directions of action is taking into account the real geometrical profile and surface structure of journal and seat in connection:

$$\delta = \frac{F}{A_r} \leq \delta_{all}, \qquad (2)$$

where: *Ar*- real conact surface.

Objectivization of contact surface area of journal and seat

In frictional tapered connections, in accordance with literature record, the theoretical area of total contact surface of mating couple can be determinate as:

$$A_t = \frac{\pi \cdot D_{av \cdot t} \cdot L_t}{\cos\alpha / 2}, \qquad (3)$$

where: At – area of theoretical mating surface of journal and seat, $D_{av\ t}$ – average theoretical cone diameter $D_{av\ t} = (D_t + dt)/2$, D_t – theoretical diameter of bigger journal basis, dt – theoretical diameter of smaller journal basis, L_t – projection of theoretical contact length on axis of connection, α/2 – half-angle of cone.

Presented record does not take into account form errors, which occurs during manufacturing process. There was assumed that mean cone diameter has no roundness deviations and the projection of ideal contact length on axis of connection has no rectilinearity deviations of generating element of cone.

Occurrence of form deviations of journal and seat results in decrease of contact surface, which is not taken into consideration during calculations. Real mating is presented then on a smaller part of surface. Increased and variable contact stresses act on this surface. Hence it was necessary to conduct researches in order to determine real mating surfaces of mated pairs.

Estimation of conical surfaces was performed in plants, where technique state is the highest in Poland. These plants produce axial-symmetrical elements of many responsible products for the sake of safety and reliability criterion. The premise for selection of these plants was high quality of manufacturing, which is obtained with use of modern measuring techniques.

Measurements were performed with coordinate measuring machine UPMC 850 CARAT (measurement of roundness deviation, rectilinearity of generating line and angle of cone). Obtained results were verified with versatile measuring devices - from Taylor Hobson company (Talyrond 265 – measurement of roundness deviations and angle, and Form Talysurf Series 2 – measurement of rectilinearity of generating line).

Obtained results of deviations allowed to determine precisely the real contact surface of journal and seat.

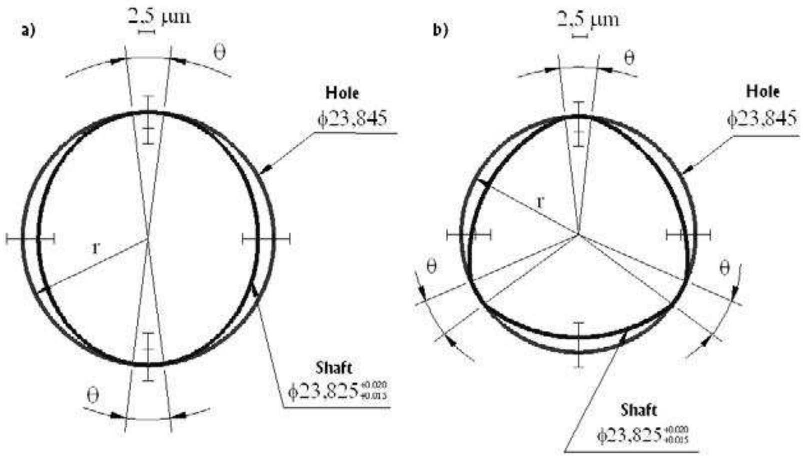

Fig. 2. Special cases of roundness deviations occurring in cross section: a) - ovality, b) – 3-lobbing

There was selected the tapered connection with nominal diameter D = Ø23.825mm and fit H7/n7. The length of connection is l = 80mm. There was measured the diameter of bigger basis of seat, which was manufactured with Ø23,845mm in 36% of produced elements. Rectilinearity and roundness deviations did not exceed 0,5µm. For further considerations there was assumed that seat was manufactured with no errors.

Next there was measured the diameter of bigger basis of journal, which dimension was from D = Ø23,840 to D = Ø23,845 in 42% of produced elements. Rectilinearity and roundness deviations did not exceed 5µm.

On the basis of performed measurements there was made the quality analysis of connection. There were analysed the possible changes of contact surface caused by form deviations of journal, while seat Ø23,845mm was treated as ideal one.

Surface contact O_t occurring on theoretical circumference of mating elements can be described [2]:

$$O_t = \frac{\pi \cdot r \cdot \theta}{180^\circ}, \tag{4}$$

where: r – radius of ideal circle, θ – angle of contact arc of journal and seat.

Because there are different models of roundness deviations in cross section (fig. 2 a, b) than real circumference of contact can be described as:

$$O_r = x\frac{\pi \cdot r \cdot \theta}{180^\circ}, \tag{5}$$

where: x = 2, 3,..., n (model of two, three,..., n-angular).

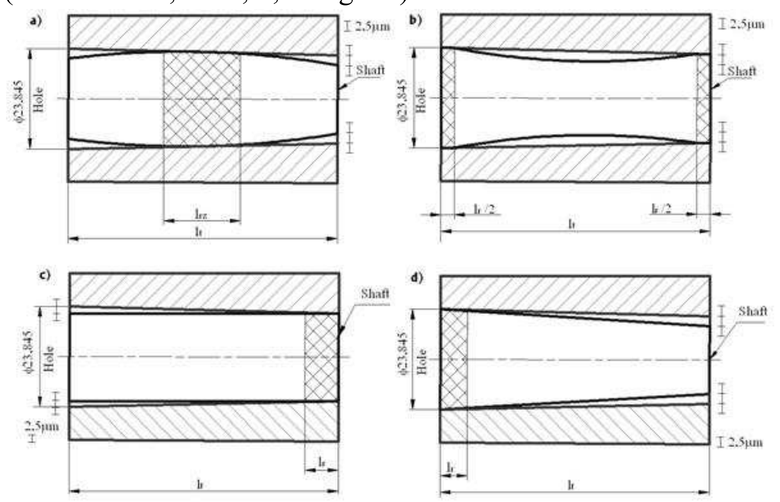

Fig. 3. Examples of connections of ideal seat Ø23,845mm and real journal $\text{Ø}23{,}825^{+0{,}020}_{+0{,}015}$ *of tapered connection H7/n7 in longitudinal section: a) concavity of generating line, b) convexity of generating line, c) and d) journals with deviations of angle*

The relation between real circumference of contact and theoretical circumference in cross section can be described by coefficient of change of contact circumference of mating elements β:

$$\frac{O_r}{O_t} = \beta, \tag{6}$$

where: O_r- real circumference of contact, O_t- theoretical circumference of contact.

In result of performed calculations for examples presented in figure 2 there were obtained the real values of circumferential contact of mating elements. These are the following: (fig. 2a) - 11% and (fig. 2b) – 13% of theoretical value.

Rectilinearity deviations of generating line and angle of journal have also the influence on the size of faying surface. The relation between real length of contact surface and theoretical one (fig. 3 a÷d) can be described by coefficient of change of length of contact surface γ:

$$\frac{L_r}{L_t} = \gamma \quad , \tag{7}$$

where: Lr – real length of contact surface, Lt – theoretical length of contact surface.

In result of performed calculations for examples (fig. 3) there were determinate real values of length of contact surface of mating elements. These are the following: (fig. 3a) – 19%, (fig. 3b) – 10%, (fig. 3c) and (fig. 3d) – 10% of theoretical value.

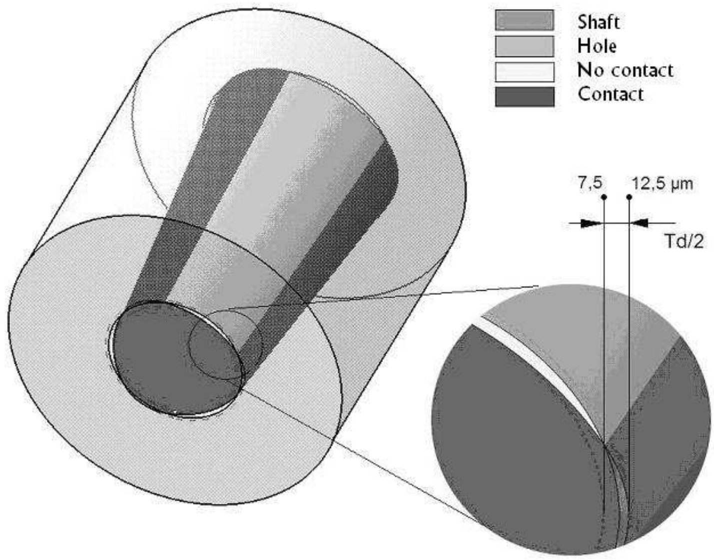

Fig. 4. Isometric view of tapered connection; seat manufactured as ideal one with diameter Ø 23,845, journal $\phi 23{,}825^{+0{,}025}_{+0{,}015}$ *with roundness deviation – three-angular*

On the basis of real models obtained in result of conducted measurements there was taken an attempt of spatial visualization of form deviations, which are occurring in tapered connections. There were presented examples of possible form deviations of journal in connection, while seat was treated as ideal one (nominal geometrical profile with smooth surface). Figure 4 illustrates a connection of three-angular journal with ideal seat in 3D system. Whereas systems of mating elements in longitudinal section with journal deviations were presented in figure 5.

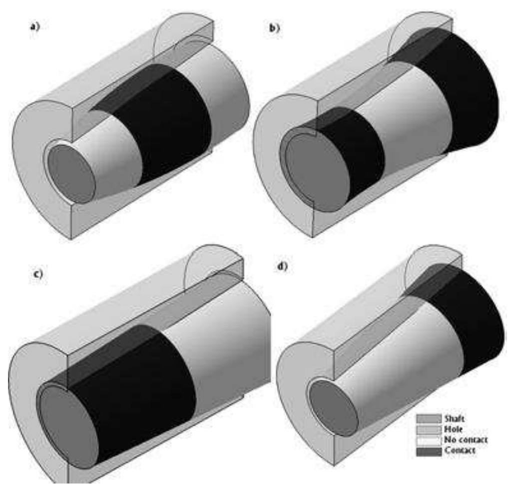

Fig. 5. Isometric view of tapered connection; seat is manufactured as ideal one Ø 23,845 with roundness deviation; a) concavity journal $\phi 23{,}825^{+0{,}025}_{+0{,}015}$*, b) convexity journal* $\phi 23{,}825^{+0{,}025}_{+0{,}015}$*, c), d) journal* $\phi 23{,}825^{+0{,}025}_{+0{,}015}$ *with angle deviation in left and right side*

In connections of journal and seat (fig. 2, 3, 4 and 5) there can be distinguished the zones: surface contact and lack of contact. Occurring roundness deviations in cross section and rectilinearity deviations of generating line and angle of journal conditions the value of outline surface contact, which area is not more than a dozen or so percent. While possible compilations of this deviations decrease its value to a few percent of nominal surface.

Similar analysis and estimation of influence of constructional features on magnitude of faying surface should be done also for seats of tapered connections. Only compilation of form deviations of journal and seat allow to determine the real mating surface of connected elements.

Summary

Designing tasks for devices and mechanical units need manufacturing quality increasing. Important thing is correct design and accurate reproduction of geometrical shape and structure of mating surfaces.

Load capacity of connection elements is determined by taken assumption of nominal mating surfaces, which are dependent on assumed type of fitting (running fit, slide fit, close fit).

Variable outline profile obtained in manufacturing process causes the decrease of contact area between mating surfaces, and out of that mating conditions worsening. As a result of that there are variable values of friction coefficient in main directions of equilibrium, and also movement in plane of X, Y, Z axes, which cause the occurrence of different friction forces in these axes.

The occurring manufacturing errors of connection elements take effect in: decrease of outline surface of contact, function modification (interference, clearance), decrease of strength and load capacity, alignment worsening, decrease of smooth control of interference, assembly stresses, stress concentration, variable value of coefficient of friction.

From that reasons it should be conducted the modelling of spatial fits which contain form deviations of mating elements. It will allow to determine the change of contact surface and value of friction coefficient in three dimensional space in plane of load action in X, Y, Z axes.

Spatial description of surface contact of mating elements and determination of real load in cross and longitudinal section of connection will allow for objectivization of contact surface, and also to form a decision about selection of design solution. Hence it is necessary to possess a knowledge about modern methods and measuring devices based on sets of points and software and application of advanced computer techniques.

Connection of these fields leads to obtaining more objective design conditions of geometrical features of tapered connection elements, which satisfy in higher degree than before the conditions of state of static and dynamic load. It allows to define the real functional and operating features. It is also possible to estimate the reliability and safety of designed connection.

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