Features of calculation of couplings with dowels in manufacture of jointed parts made of steel and cast iron

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Transmission of torque through the coupling connections with dowels must be ensured by interference of a half-coupling with a shaft, while dowels should act as a safety lock in case of overloads. However, an analysis of regulatory documents showed that transitional fits and clearance fits in most cases are recommended in these connections, it is stipulated by simplicity of assembling. Therefore, in order to ensure reliability and durability when designing drives of cylindrical joints with dowels, it is necessary to calculate the maximum and minimum interference, while material of half-coupling and shaft manufacturing is one of the most important factors having the effect on the maximum interference. Therefore, a situation arises when the following combinations of materials are possible in the "shaft – coupling hole" joint: steel – cast iron, cast iron – cast iron, steel – steel and cast iron – steel. In this regard, it is necessary to evaluate the effects of various combinations of materials of the connected parts on formation of maximum and minimum interference and types of fits for the "shaft – coupling hole" joints. Based on the classical theory of strength of materials, the dependencies of the largest and smallest calculated interference were obtained, as well as formulas for correcting these stresses for real assembly conditions. It can be seen from the obtained calculations, that the highest values of the fit tolerances correspond to the joints of a steel shaft with a steel half-coupling, as well as a cast-iron shaft – with a cast-iron half-coupling. The fit tolerance is also affected by the assembly method – when connecting by heating a bush sleeve, and tolerance in upsetting operation is larger. Thus, based on the position of forming rational tolerances and fits, it is recommended to choose a steel coupling if a the shaft is made of steel; it allows expanding expand the fit tolerance and reducing the cost of shaft processing. When making the shaft from cast iron, the coupling should also be chosen from cast iron. Steel shaft joints with a cast-iron coupling are also possible, but at the same time, the requirements for shaft processing accuracy are more strict.
Key words: shaft manufacturing material, half-coupling manufacturing material, dowel connection, fit, interference, fit tolerance.
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Introduction

Various kinds of couplings (elastic and rigid) are widely used in drives of different machines and equipment for connection of two shafts transmitting torque [1]. Elastic couplings are used more widely, because they are able to transmit relatively large torques and to damp out substantial impact loads arising during operation [2]; they are also able to compensate angular, radial and combined displacements of connected shafts within definite limits [3, 4]. From the other side, drives with elastic couplings have several deficiencies such as residual unbalancing (leading to increased vibration at high rotation speed) [5]; high level of stress concentration and sensitivity to corrosion in contact areas [6]. The modern researches [3, 7, 8] propose d new types of elastic elements in order to rise reliability of coupling drives. These elements can transmit large torques and damp out impact loads. These researches, however, didn't examine the problems about the effect of dowel fit in shaft and coupling grooves, as well as coupling fit on a shaft, on service life of a joint.

Initially a dowel should serve as a safety lock in the case of overload of a cylindrical connection with interference "shaft – coupling hole", but at present time, in correspondence with recommendations of the regulatory documents, use a clearance fit or transition fit for the most cases of "shaft – coupling hole" connection [9]. A dowel plays in such connection not only preventive function, but also torque transmitting function.

The regulatory document [10] testifies that shafts can be manufactured of steel (St3, St4, St5, 35, 40, 45, 45, 50, 40Kh, 40KhN, 40KhNMA, 25KhGT) and of cast iron (grey, malleable cast and high-strength cast) of various grades (SCh 18 – SCh 36, KCh 30 – KCh 60, VCh 40 et al). Couplings can be also fabricated of steel, cast iron and other materials [11]. So, we have situation when the following combinations of materials are possible in "shaft – coupling hole" connection: steel – cast iron, steel – steel and cast iron – steel. The effect of various materials on selection of fits in "shaft – coupling hole" connection is not taken into account in regulatory documents in this case.

Thus, it can be seen from the analysis of standards recommendations [10, 11], that a torque transmitting through connection, as well as material of connected parts, are not taken into account during selection of tolerance classes. Thereby it is necessary to assess the effect of various combinations of materials of connected parts on forming ultimate interference values and kinds of fits for a “shaft — coupling hole” connection.

The aim of this research is determination of ultimate interference in a cylindrical connection with a dowel for different combinations of materials of shafts and couplings.

Research remedies and methods

The “shaft — coupling with dowel” connections with different combinations of materials of shafts and couplings is the object of this research. Precision parameters for a the “shaft — coupling with dowel” connection, depending on materials of connected parts and assembling method make the subject of this research. The main theses of the theory of precision and mutual substitutability of parts and joints, as well as the elements of the theory of strength of materials were used in calculations.

Results and discussion

Generalized connection scheme with interference, under the effect of an axial load and torque, is presented in the **Fig. 1**. As for our case of a “shaft — coupling hole” connection, only a torque (*T*) will act, while an axial force (*P*) will be small (close to zero).

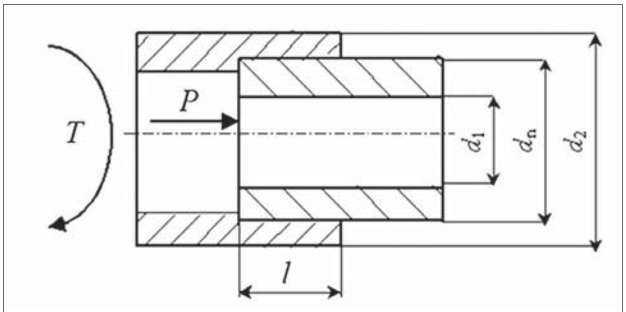

Fig. 1. Generalized connection scheme with interference under the effect of an axial load and torque

Based on this, the minimal interference in a “shaft — coupling hole” connection, which is determined taking into account the condition of torque transmitting and geometry of cylindrical connection with a dowel, is calculated via the following formula [12]:

$$N_{Pmin} = \frac{2^T}{(d_n - b)lf}\left(\frac{C_D}{E_D} + \frac{C_d}{E_d}\right) \quad (1)$$

where T — torque, N·m; C_d and C_D — Lame coefficients for a shaft and hole; E_d and E_D — elasticity modules of shaft and hole material, Pa; f — friction coefficient; d_n — nominal diameter of connection, m; l — connection length, m; b — width of a dowel groove for a hole and shaft, m.

Depending on the assembling method, the friction coefficient is accepted as [12]: pressing-in with lubrication $f = 0.07$; pressing-in without lubrication $f = 0.12$; with bush sleeve heating $f = 0.24$.

Maximal calculated interference depends on maximal pressure, which is determined by the operating conditions of materials of the components in the elastic deformation area, without transition in the plastic deformati on area [12].

When a hole is characterized by the yield strength $[\sigma_{0.2}]_D$, smaller than that for a shaft, and the external diameter size of a coupling is close to the nominal diameter of connection, the maximal interference is calculated via the following formula [12]:

$$N_{PmaxD} = 0.58[\sigma_{0.2}]_D\left(1 - \left(\frac{d_n}{d_2}\right)^2\right)d_n\left(\frac{C_D}{E_D} + \frac{C_d}{E_d}\right) \quad (2)$$

Just this relationship (2) is used most often, because a hole has sufficiently thin wall, while a shaft is usually made of steel and has no internal holes. When a shaft has sufficiently large internal hole and its yield strength $[\sigma_{0.2}]_d$ is comparative with the yield strength $[\sigma_{0.2}]_D$, it is required t determine the maximal interference via the formula [12]:

$$N_{Pmaxd} = 0.58[\sigma_{0.2}]_d\left(1 - \left(\frac{d_1}{d_n}\right)^2\right)d_n\left(\frac{C_D}{E_D} + \frac{C_d}{E_d}\right) \quad (3)$$

where $[\sigma_{0.2}]_d$ and $[\sigma_{0.2}]_D$ — the yield strength values for a shaft and a coupling, Pa; d_1 — internal shaft diameter, m; d_2 — external shaft diameter, m.

Then we take the values of maximal calculated interference, which were determined via the formulas (2) and (3), and select the minimal value corresponding to the most “weak” component.

The values of calculated interference are corrected, taking into account crumbling of surface roughness and temperature expanding of components. The second correction will be equal to zero due to equality of linear expanding coefficients for shaft and coupling materials.

Technological interferences are calculated as follows:

$$N_{\mathrm{Tmax}} = N_{\mathrm{Pmax}}\gamma_{\mathrm{sp}} + \Delta N_R + \Delta N_t + \Delta N_\omega; \quad (3)$$

$$N_{\mathrm{Tmin}} = N_{\mathrm{Pmin}} + \Delta N_R + \Delta N_t + \Delta N_r + \Delta N_\omega, \quad (4)$$

where ΔN_R — correction for crumbling of surface roughness for connected components during connection forming; ΔN_t — correction for temperature deformation of the components during operation; ΔN_r — correction for interference decrease in connection during secondary disassembling and assembling in the process of repair and maintenance works; ΔN_ω — correction for interference decrease caused by centrifugal forces; γ_{sp} — accounting coefficients for specific pressure increase near hole edge, which is determined by the graph [12] depending on relation l/dn (in our case $l/d_n = 1.16$ we accept $\gamma_{\mathrm{sp}} = 0.97$.

If we know the parameters of hole and shaft surface roughness values, then correction for crumbling is calculated via the formula:

$$\Delta N_R = 2 \cdot k_R \cdot (R_{\mathrm{ad}} \cdot \eta_d + R_{\mathrm{a}D} \cdot \eta_D), \quad (5)$$

where $R_{\mathrm{a}D}$, R_{ad} — surface roughness parameters for half-coupling hole and shaft; k_R — transition coefficient from R_a to R_z; η_D and η_d — roughness crumbling coefficient for half-coupling hole and shaft. The value of the roughness crumbling coefficient for half-coupling hole is accepted as follows (depending on assembling point) [12]: pressing-in with lubrication $f = 0.07$; pressing-in without lubrication $f = 0.12$; with bush sleeve heating $f = 0.24$.

Correction for temperature deformation of components is determined vie the equation:

$$\Delta N_t = [\alpha_D \cdot (t_D - t) - \alpha_d \cdot (t_d - t)] \cdot d_n, \qquad (6)$$

where α_D and α_d – the coefficients of material linear expanding for a hole and a shaft; t_D and t_d – operating temperatures for a hole and a shaft (upper and lower values of this range are used in turn); $t = 20\,^\circ C$ – assembling temperature.

Results of the research

Let us present the testing results of the above-described theoretical regulations on the example of universal gear boxes H 909.40.000 with chain couplings manufactured by "Mosselmash" works; such equipment is used in potato combine harvesters KKU and KPK, produced in Russia. We shall consider the effect of different materials for shafts and chain half-couplings on choosing fits "shaft – coupling with dowel". Parameters of the considered connections are presented in the **Table 1**.

Material characteristics for the shaft and the coupling are shown in the **Table 2**.

The results of calculations for different shaft and coupling manufacturing materials, with various assembling methods, are displayed in the **Tables 3–6**.

It can be seen from the tables 3–6 that the value of maximal calculated interference does not depend on the assembling method; however, mechanical properties of connected materials have the effect on this value. So, when assembling a steel shaft with steel half-coupling, the maximal calculated interference makes 127 µm, when assembling a cast iron shaft with cast iron half-coupling, the maximal calculated interference makes 126 µm, while when assembling a steel shaft with cast iron half-coupling and a cast iron shaft with cast iron half-coupling it is equal to 110 and 114 µm respectively. The values of maximal technological interference will exceed the calculated ones and they depend on assembling points of connection, because crumbling of surface roughness for connected components occurs in various ways for different assembling methods.

The values of minimal calculated interference depend not only on mechanical properties of connected materials, but also on assembling methods (friction coefficient). In our case, the minimal values of calculated interference are presented in connection between steel shaft and steel half-coupling, while maximal values – in connection between cast iron shaft and cast iron half-coupling. In this case, the values of minimal calculated interference will be higher for the pressing-in method with lubrication in comparison with the pressing-in method without lubrication. They will also have the minimal value for the bush sleeve heating method. The values of minimal calculated interference will also exceed

Table 1. Parameters of the connection "shaft – coupling with dowel"

Parameters	Units	Designation	Value
Nominal connection diameter	m	d_n	0.05
Connection length	m	l	0.058
Internal shaft diameter	m	d_1	0.01
External coupling diameter	m	D_2	0.095
Dowel width	m	b	0.014
Lame coefficient for a shaft	–	C_d	0.98
Lame coefficient for a coupling	–	C_D	2.38
Shaft surface roughness	µm	Ra_d	1.25
Coupling surface roughness	µm	Ra_D	2.5
Maximal torque	Nm	T	400

Table 2. Material characteristics for the shaft and the coupling

Characteristics	Units	Designation	40Kh steel	SCh20 cast iron
Poisson coefficient	–	µ	0.27	0.25
Elasticity module	Pa	E	2·1011	1.14·1011
Yield strength	Pa	$\sigma_{0.2}$	363·106	206·106

Table 3. The results of calculations of connection parameters in shaft and coupling manufactured of steel 40Kh

Parameters	Units	Designation	Assembling method		
			pressing-in with lubrication	pressing-in without lubrication	bush sleeve heating
			Values		
Minimal pressure	MPa	p_{rmin}	27.559	16.075	8.037
Minimal calculated interference	µm	N_{Pmin}	23.15	13.50	6.75
Maximal pressure	MPa	p_{rmax}	152.218	152.218	152.218
Maximal calculated interference	µm	N_{Pmax}	127.86	127.86	127.86
Correction for crumbling of roughness	µm	ΔN_R	11.59	13.52	17.38
Maximal technological interference	µm	N_{Tmax}	135.62	137.55	141.41
Minimal technological interference	µm	N_{Tmin}	34.74	27.02	24.13
Tolerance fit	µm	T	100.88	110.52	117.28
Standard fit	–	–	Ø50*H*8/*v*8	Ø50*H*8/*u*8 Ø50*H*8/*u*9	Ø50*H*8/*u*9

Table 4. The results of calculations of connection parameters in shaft and coupling manufactured of cast iron SCh20

Parameters	Units	Designation	Assembling method		
			pressing-in with lubrication	pressing-in without lubrication	bush sleeve heating
			Values		
Minimal pressure	MPa	p_{rmin}	27.558	16.075	8.037
Minimal calculated interference	µm	N_{Pmin}	40.44	23.59	11.79
Maximal pressure	MPa	p_{rmax}	86.383	86.383	86.383
Maximal calculated interference	µm	N_{Pmax}	126.75	126.75	126.75
Correction for crumbling of roughness	µm	ΔN_R	11.59	13.52	17.38
Maximal technological interference	µm	N_{Tmax}	134.53	136.46	140.32
Minimal technological interference	µm	N_{Tmin}	52.02	37.11	29.17
Tolerance fit	µm	T	82.51	99.36	111.15
Standard fit	–	–	Ø50*H8*/*x7*	Ø50*H8*/*v8*	Ø50*H8*/*u9*

Table 5. The results of calculations of connection parameters in shaft manufactured of steel 40Kh and coupling manufactured of cast iron SCh20

Parameters	Units	Designation	Assembling method		
			pressing-in with lubrication	pressing-in without lubrication	bush sleeve heating
			Values		
Minimal pressure	MPa	p_{rmin}	27.558	27.558	27.558
Minimal calculated interference	µm	N_{Pmin}	35.39	20.65	10.32
Maximal pressure	MPa	p_{rmax}	86.383	86.383	86.383
Maximal calculated interference	µm	N_{Pmax}	110.94	110.94	110.94
Correction for crumbling of roughness	µm	ΔN_R	11.59	13.52	17.38
Maximal technological interference	µm	N_{Tmax}	119.20	121.13	124.99
Minimal technological interference	µm	N_{Tmin}	46.98	34.17	27.70
Tolerance fit	µm	T	72.22	86.97	97.29
Standard fit	–	–	Ø50*H8*/*x6*	Ø50*H8*/*v8*	Ø50*H8*/*u8*

Table 6. The results of calculations of connection parameters in shaft manufactured of cast iron SCh20 and coupling manufactured of steel 40Kh

Parameters	Units	Designation	Assembling method		
			pressing-in with lubrication	pressing-in without lubrication	bush sleeve heating
			Values		
Minimal pressure	MPa	p_{rmin}	27.558	16.075	8.037
Minimal calculated interference	µm	N_{Pmin}	28.19	16.44	8.22
Maximal pressure	MPa	p_{rmax}	114.7	114.7	114.7
Maximal calculated interference	µm	N_{Pmax}	117.33	117.33	117.33
Correction for crumbling of roughness	µm	ΔN_R	11.59	13.52	17.38
Maximal technological interference	µm	N_{Tmax}	125.40	127.33	131.19
Minimal technological interference	µm	N_{Tmin}	39.78	29.96	25.60
Tolerance fit	µm	T	85.62	97.37	105.59
Standard fit	–	–	Ø50*H8*/*v8*	Ø50*H8*/*u8*	Ø50*H8*/*u8*

the calculated ones and will be also corrected by the value of crumbling of surface roughness for connected components.

Using the obtained data of technological interference, we determined tolerance fits for analyzed connection of the components. From the point of view of mutual replacement, increase of a tolerance fit of a connection has a positive effect and provides possibility of using less precise technological equipment and, respectively, lowering of production cost. It can be seen from the obtained data that the maximal values of tolerance fits correspond to connection between a steel shaft and steel half-coupling (**Fig. 2**) as well as connection between a cast iron shaft and cast iron half-coupling (**Fig. 3**). The assembling method has also the effect on the tolerance fit: when bush sleeve heating method is used for connection, the tolerance fit in upsetting is larger. Based on this, and taking into account the position of forming rational tolerances and fits during construction of a "shaft – coupling with dowel" connection, it is recommended:

– to choose a steel coupling for a steel shaft, to provide expanding of a tolerance fit and lowering of shaft processing cost;

– to choose a cast iron coupling for a cast iron shaft.

Connection between a steel shaft and a cast iron coupling is also possible, but with more strict requirements for precision of shaft processing.

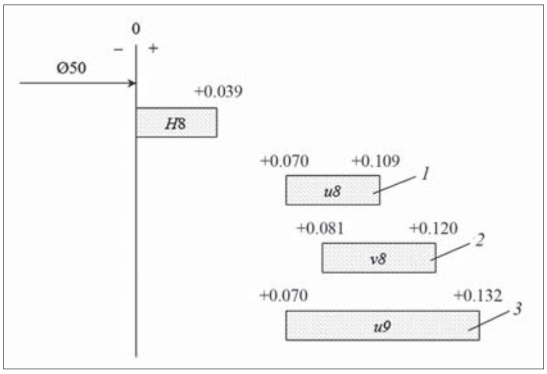

Fig. 2. The location scheme for tolerance fields of half-coupling hole and shaft, manufactured of 40Kh steel:
1 – pressing-in with lubrication; *2* – pressing-in without lubrication; *3* – bush sleeve heating

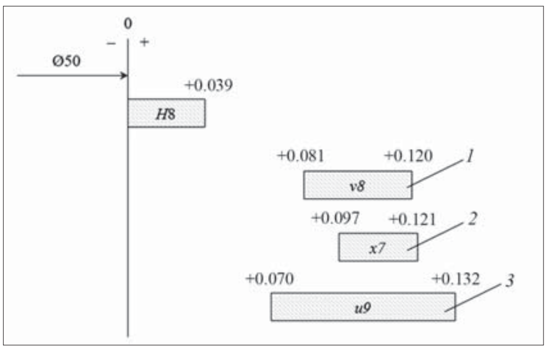

Fig. 3. The location scheme for tolerance fields of half-coupling hole and shaft, manufactured of SCh 20 cast iron:
1 – pressing-in with lubrication; *2* – pressing-in without lubrication; *3* – bush sleeve heating

Conclusion

Thus, based on regulations of the theory of precision and mutual replacement of components and the classic theory of strength of materials, the relationships for maximal and minimal calculated interference were obtained; they take into account geometric features of connection as well as material characteristics of a shaft and a coupling. Based on the result of calculation and choosing connection fits for shafts with 50 mm diameter in universal gear boxes H 909.40.000 with chain couplings manufactured by "Mosselmash" works, which are used in potato combine harvesters KKU and KPK, it was established that the values of calculated interference depend not only on mechanical properties of connected materials, but also on assembling methods (the tolerance fit is larger when connecting via the bush sleeve heating method). Smaller values of minimal calculated interference are noted for connection between a steel shaft with a steel half-coupling and larger values - for connection between a cast iron shaft with a cast iron coupling. The obtained data also testify that the maximal values of tolerance fits correspond to connection between a steel shaft with a steel half-coupling as well as between a cast iron shaft with a cast iron coupling. In general, use of obtained fits increases service life of connections and decreases intensity of rejects.

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