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AN ALTERNATIVE WAY TO CREATE INTERFERENCE FIT JOINT BETWEEN A HUB AND A SHAFT

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An alternative way of implementation of the transverse method of connecting two cylindrical elements of machines (the so-called shaft-hub connection) with interference fit is proposed. This new way uses the Poisson effect of expansion or contraction of solids transversely to the direction of application of the load. A new coefficient for the materials used in such a connection of machine elements is introduced. This coefficient has been called here coefficient of the maximum permissible relative change in dimensions of solids transversely to the direction of the applied force. Based on investigation and comparison of mechanical properties of materials used in the machine elements, the feasibility of the proposed way of the interference fit is proved. A verification of the proposed method in CAD environment with using FEA is made.

Keywords: interference fit joint, Poisson's ratio, CAD, FEA.

1. Introduction

The interference joints are widely used to connect parts in machines and to transfer torque and forces between parts to be joined [1]. In practice, such connections are made primarily on cylindrical surfaces - for example, connecting a shaft to a hub bore (or bushing bore). In cylindrical joints with interference fit, the functional dimensions of the parts to be connected "interfere" with each other - the diameter of the shaft (the male element) is made slightly larger than the diameter of the hub hole (the female element) [2]. It is well known that due to this "interference" of diameters, after joining on cylindrical surfaces, elastic compression occurs, accompanied by frictional forces, when trying to separate two machine elements [3]. Interference fits between a shaft and its components (such as a hub or bushing) are used primarily to minimize the need for shoulders and keyways [4].

There are two main methods [2] of creating an interference fit between two machine parts - longitudinal (force fit) and transverse (shrink fit or tensile fit [3]). These two methods can be used in combination.

The longitudinal method is implemented by forcing the shaft into the hole of the hub slowly in a press, preferably with oil lubricant applied to the joint [3] or as well as (relatively more seldom) by using a series of impacts [5]. Therefore, the

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interference fit made by means of longitudinal way is called press fit or force fit [2]. This method uses simple and easy technology. However, this way has its drawbacks: crushing and partial cutting (scrapping) of the roughness of the touching surfaces and damage to their ends. These scrapings and crushing of the roughness of the contacting surfaces cause a weakening of the bond strength compared to the joint made by applying the transverse method [6].

The transverse method for creating an interference fit joint between two machine elements utilizes the expansion (when heating) or shrinking (when cooling) of the solid bodies. A shrink fit [2, 3] can be made by heating in advance the hub, to expand its' inside diameter and/or an expansion fit can be made by cooling in advance the shaft to reduce its diameter. The hot and cold parts can be joined together with very little or almost no axial force, and when their temperatures equilibrate to room temperature, the thermal changes in their diameters create the desired interference fit. The disadvantage of this method is that too high a heating temperature can cause structural changes in the material of the hub, which imposes some restrictions on the application of this method.

Currently, as another form of applying the transverse method, the so-called thermo-mechanical joints with "shape memory" of joined elements are gaining ground [1]. This property is inherent in alloys, undergoing reversible martensitic transformation, and is characterized as the ability of a material, deformed in a martensitic state at low temperatures, to restore its shape fully or partially during subsequent heating to ambient temperature.

One interesting combination is the use of the transverse method without using thermal expansion but in combination with the longitudinal method. This combination uses hydraulic expansion (or dilation) of the hub by supplying pressurized oil through passages in the shaft or the hub when they are assembling by pressing [3].

This article proposes a new approach to performing an interference fit between two machine elements using the transverse method. The conditions for its feasibility are analyzed. A comparative study was carried out regarding what materials can be used for machine elements connected by this interference fit.

2. Description of the proposed variant of the transverse method of creating an interference fit

It is known that according to the Poisson effect when a homogeneous solid body is loaded with a tensile force in a certain direction, it elongates in the same direction, combined with contraction in the transverse direction. Conversely, when such a body is loaded with a compressive force in a certain direction, it shortens in the same direction and expands in the transverse direction. If we consider an axisymmetric body (for example, a shaft) loaded along the axis (longitudinal direction) by a tensile (Fig. 1-a) or compressive (Fig. 1-b) force, then in the transverse direction its diameter will correspondingly decrease or increase in accordance with the Poisson effect.

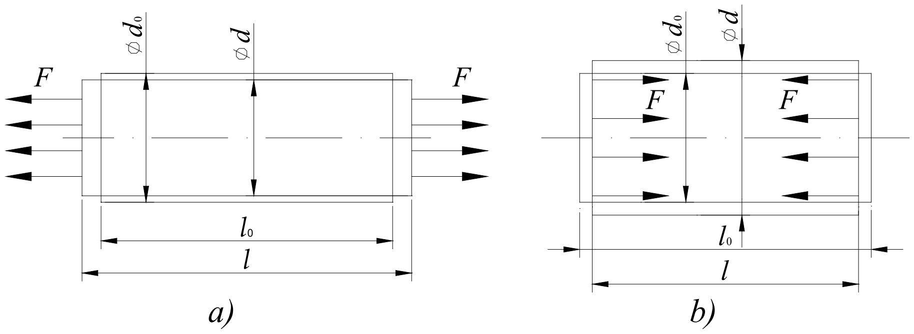


Fig. 1. An axisymmetric body (a shaft) loaded with tensile (a) and compressive (b) force F.

In Fig. 1 the following designations for the dimensions of the shaft are used: l_0 and d_0 are the initial length and the initial diameter respectively, l and d are respectively the length and the diameter after applying the axial force F, which are presented by arrows as uniformly distributed pressure.

Let $\Delta l = l - l_0$ denotes the change in the length in the longitudinal (or axial) direction, $\varepsilon_L = \Delta l / l_0$ - the longitudinal (or axial) strain, $\Delta d = d - d_0$ - the change of diameter (of the transverse size) and $\varepsilon_T = \Delta d / d_0$ - transverse strain.

According to Poisson's effect, the magnitude of the transverse strain ε_T is proportional to the magnitude of the longitudinal strain ε_L (along the axis of the shaft in which the force acts), but with opposite sign. Proportionality is given by the Poisson's ratio ν [15]:

$$\nu = -\frac{\varepsilon_T}{\varepsilon_L} = -\frac{\Delta d / d_0}{\Delta l / l_0}, \tag{1}$$

For small strain values, for which Hooke's law is valid, Poisson's ratio can be considered a constant, and its values for various materials are given in technical reference books.

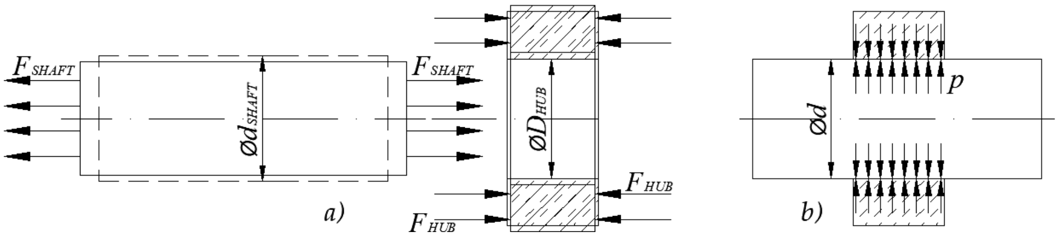


Fig. 2. The proposed method for creating an interference fit joint: a) preloading; b) ready joint.

The proposed way of creating an interference fit consists of preliminary change of the transverse sizes (for example diameters) of parts by applying (Fig. 2-a) a longitudinal (axial) force. After positioning the assembly parts (shaft and hub) in the longitudinal (axial) direction, the force is removed (or the forces are removed), the transverse sizes of the parts are tried to restore their initial values $d_0 = d_{SHAFT}$ and $D_0 = D_{HUB}$. As a result, pressure is exerted on the contact cylindrical surfaces of the parts (Fig. 2-b).

One possible technical implementation of this idea is shown schematically in Fig. 3. The hub is pressed against the base of the machine using the two hydraulic cylinders shown on the left in the diagram. The shaft is stretched using one coaxial (to the shaft) hydraulic cylinder shown on the right in the diagram. The shaft and the hydraulic cylinder (which stretches the shaft) can be axially moved as one piece to position the stretched shaft relative to the axially compressed stationary hub. After correcting axial positioning of the shaft, the shaft and hub are relieved from the loading. Their diametrical sizes are restored to the contact of the cylindrical surfaces (the inner for the hub and the outer for the shaft) for the ready-made connection with an interference fit.

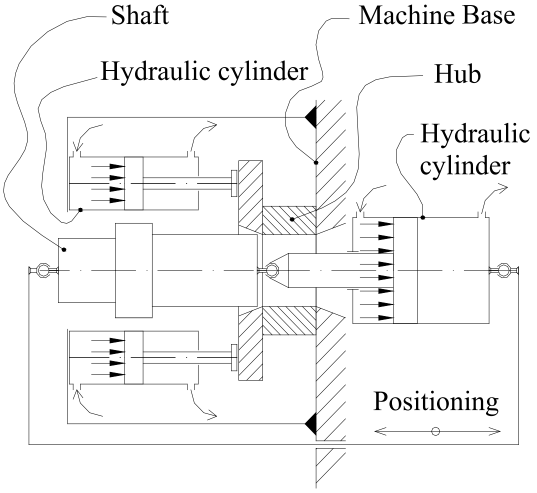


Fig. 3. Scheme of technical implementation of interference fit by the proposed way.

The connections of machine elements with press joints and the methods for their preparation continue to be the subject of research interest. For example, Lou et al. [7] describe a precision assembly method of a kind of small interference fitting parts, Qiu et al. [8] - heating assembly method for interference fit joint for the flywheel. Matej presents an analysis of the interference-fit joints process and their strength by finite element method [9]. Other authors [10, 11] investigate assembling automation of interference fits. There are investigations about the influence of polymer plasticity on the mechanical performance of interference-fit joint [12], about the effect of the coatings of mating parts on the strength of interference fit joints [13], about optimization of interference fit assembly [14].

However, neither both well-established mechanical engineering books [1-4, 6] and thesis [5] nor research papers [7-14] describe the above-proposed way to create an interference fit between machine parts.

3. Limitations concerning the axial force of loading

Preliminary computational studies show that quite large longitudinal (axial) forces F (Fig. 1) are required to achieve the desired preliminary transverse elastic deformations Δd for the proposed assembly method. The large forces are not a problem for modern hydraulic presses, but these forces can generate stresses in the parts to be joined, greater than the limit stress σ_{LIMIT}. Here we accept that limit stress σ_{LIMIT} is equal to the yield stress σ_Y for the ductile materials (as steels, a lot of non-ferrous metals and their alloys) or to the tensile strength σ_{TS} for the brittle materials (as ceramics, glass, cast iron).

Let's consider a thin rod (a shaft) having length l0 and a cross-sectional area A, which is stretched (or is compressed) by an axial force F (Fig. 1). The tensile stress $\sigma = F / A$ for that thin rod is connected, according to the Hooke's law [15], to the relative change of length of the rod (or strain ε_L) and the modulus of elasticity E of the material of this rod by relation $\sigma = E \cdot \varepsilon_L$. From the previous for the load force, the following can be written sequentially:

$$F = \sigma \cdot A = (E \cdot \varepsilon_L) \cdot A = E \cdot \left(-\frac{\varepsilon_T}{\nu} \right) \cdot A = \left(-\frac{(\Delta d / d_0)}{\nu} \right) \cdot A \cdot E = -\frac{\Delta d}{d_0} \cdot \frac{A \cdot E}{\nu} \quad (2)$$

The load force F is limited to be less than the limit force $F_{LIMIT} = \sigma_{LIMIT} . A$:

$$F = -\frac{\Delta d}{d_0} \cdot \frac{A \cdot E}{\nu} \leq \sigma_{LIMIT} \cdot A = F_{LIMIT} \quad (3)$$

The above expression can be represented as follows:

$$-\frac{\Delta d}{d_0} \leq \frac{\sigma_{LIMIT} \cdot \nu}{E} = k_{LIMIT} \quad (4)$$

On the right side of inequality of (4) is introduced a new coefficient k_{LIMIT}, called the coefficient of the maximum permissible relative change in the transverse size. This coefficient k_{LIMIT} depends only on the specific physical characteristics of the material used.

$$k_{LIMIT} = \frac{\sigma_{LIMIT} \cdot \nu}{E} \quad (5)$$

4. Feasibility the proposed way for performing an interference fit and suitable materials for joint parts

The feasibility of the proposed method for performing an interference fit depends on the observance of inequality (3), respectively (4). In (4) Δd presents a sum of two addends: - the first is the size of maximal interference Δd_I of the transverse sizes of the shaft and hub before assembly, and the second Δd_G is the size of the required technological minimal clearance for easy positioning of the shaft with respect to the hub (see "Positioning" in Fig. 3):

$$\Delta d = \Delta d_I + \Delta d_G \qquad (6)$$

For concreteness of examining further, here the implementation of the medium drive fit H7/s6 [4] is analyzed, and it is accepted that only the shaft is stretched along the axis to reduce its diameter d elastically with Δd.

Fig. 4 presents a graph of the dependence $\gamma(d)$, which represents the ratio $\Delta d(d)/d$, where $\Delta d(d)$ in according to (6) is equal to $\Delta d_I(d) + \Delta d_G(d)$ and depends on the rated diameter d for fit H7/s6. The term $\Delta d_I(d)$ is the maximal interference and the term $\Delta d_G(d)$ is the minimal clearance. The data for maximal interference and minimal clearance for fit H7/g6 are from [16].

The graph of $\gamma(d)$ shows the minimum allowable values of the coefficient k_{LIMIT} for the shaft material so that the interference fit H7/s6 could be made in the way described. So if it is needed to make an interference fit for a rated diameter d =25 mm and only the shaft would be subjected to pre-tensioning in order to reduce its diameter, the shaft material should have a coefficient $k_{LIMIT} \geq 0.002037$; if d = 50 mm → $k_{LIMIT} \geq 0.001511$; if d = 100 mm → $k_{LIMIT} \geq 0.001167$; if d =200 mm → $k_{LIMIT} \geq 0.000874$; if d =300 mm → $k_{LIMIT} \geq 0.000736$ and so on.

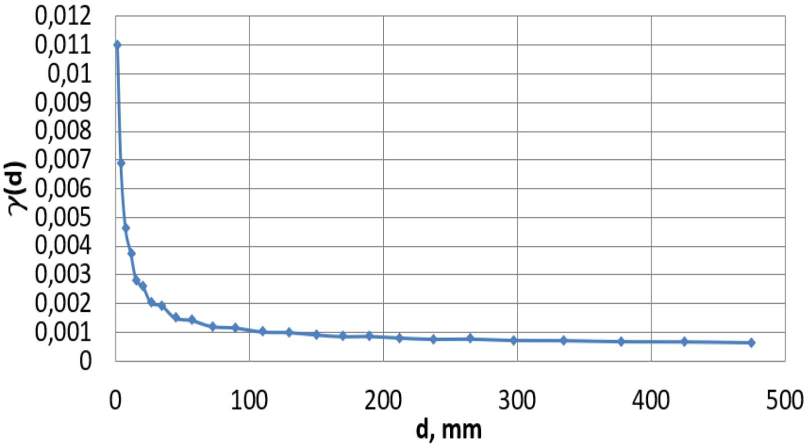


Fig. 4: Graph of dependence $\gamma(d) = \Delta d(d)/d$ with respect to rated diameter d.

Below are shown values [19 - 21] of coefficient k_{LIMIT} for some kinds of materials – steels, cast irons, aluminum alloys, copper alloys, and plastics.

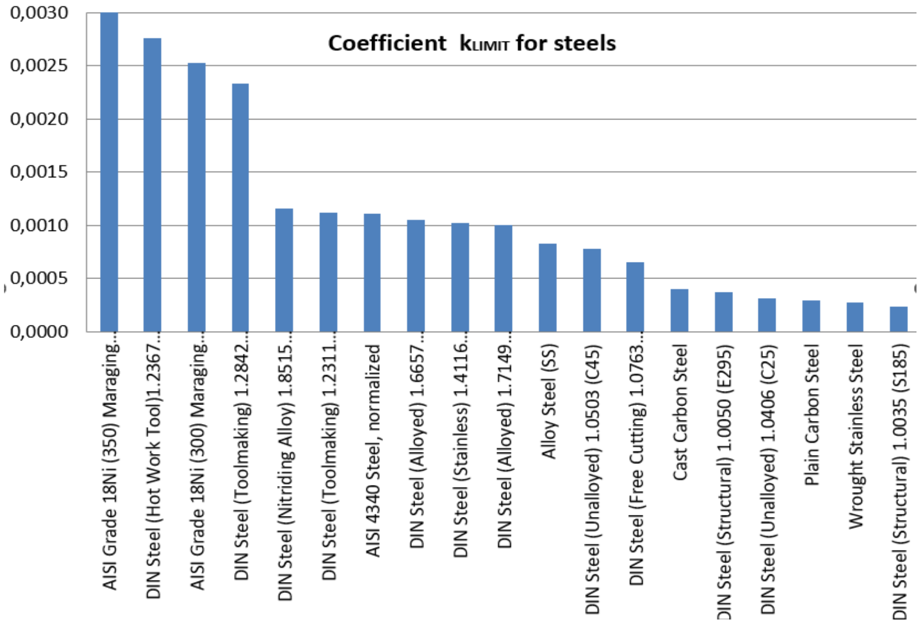


Fig. 5: Coefficient k_{LIMIT} for steels.

Data from Fig. 5 and Fig. 4 show that for fit H7/s6 only the first four steel brands in Fig. 5 - AISI Grade 18Ni (350) Maraging Steel [18]; DIN Steel (Hot Work Tool)1.2367; AISI Grade 18Ni (300) Maraging Steel [19]; DIN Steel (Toolmaking) 1.2842 could be used for diameters below 100 mm, the steels as DIN Steel (Nitriding Alloy) 1.8515 or AISI 4340 Steel, normalized could be used for diameters above 100 mm, while steels as Plain Carbon Steel or Wrought Stainless Steel are unusable for described way of making interference fit H7/s6.

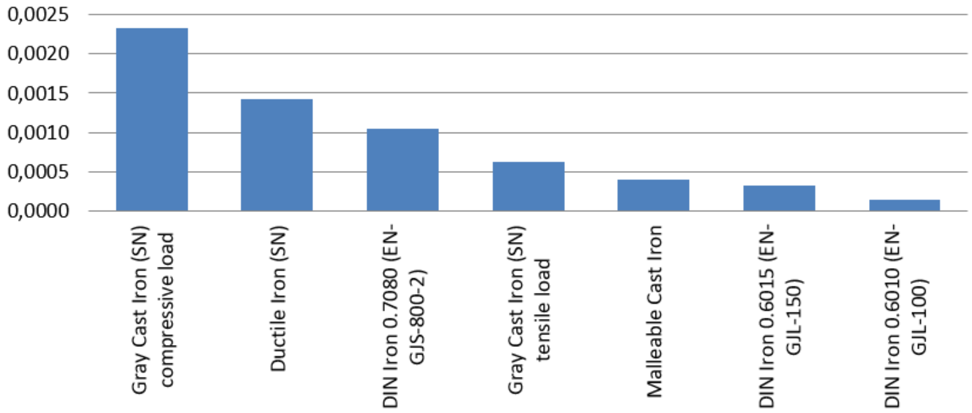


Fig. 6: Coefficient k_{LIMIT} for some cast irons.

Data from Fig. 6 and Fig. 4 demonstrate that only the ductile iron (SN) and the DIN Iron 0.7080 have suitable coefficient k_{LIMIT} for making the H7/s6 type interference fit for sizes below 100 mm, made by means of the discussed way. In Fig. 6 the high value of k_{LIMIT} for the first brand is for compressive load.

Fig. 7, Fig. 8 and Fig. 9 show the values of coefficient k_{LIMIT} for some suitable aluminum alloys, copper alloys and engineering plastics respectively. Using Fig. 4 it can be seen that in the considered case the aluminum alloys and the engineering plastics offer much more possibilities to make the interference fit H7/s6 by means of the proposed way, than the copper alloys (only the DIN Copper Alloy 2.0966 (CuAl10Ni5Fe4) could be used for diameters > 100 mm).

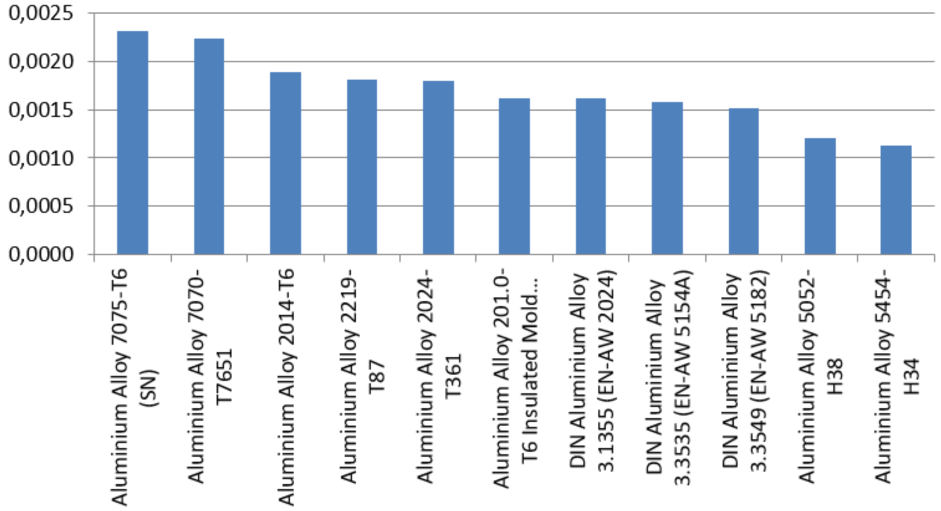


Fig. 7: Coefficient k_{LIMIT} for aluminum alloys.

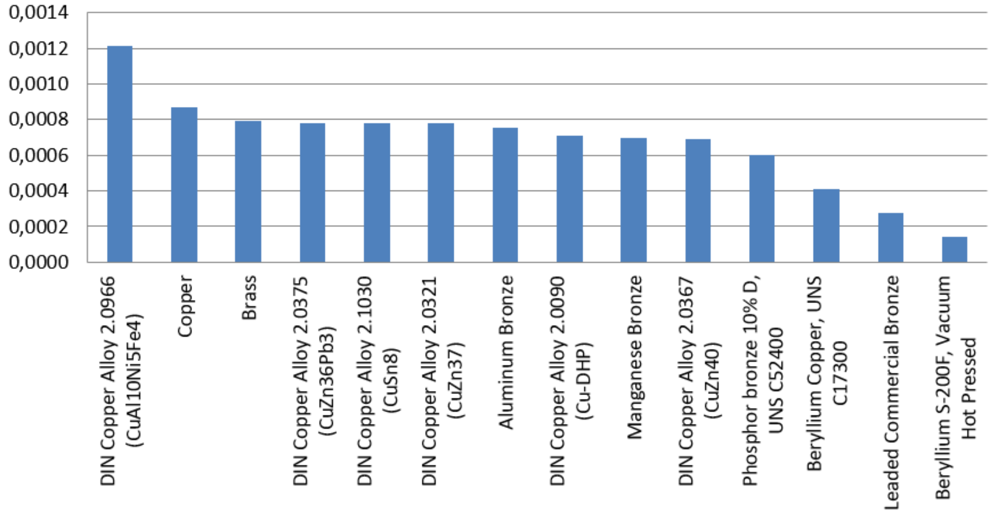


Fig. 8: Coefficient k_{LIMIT} for some copper alloys.

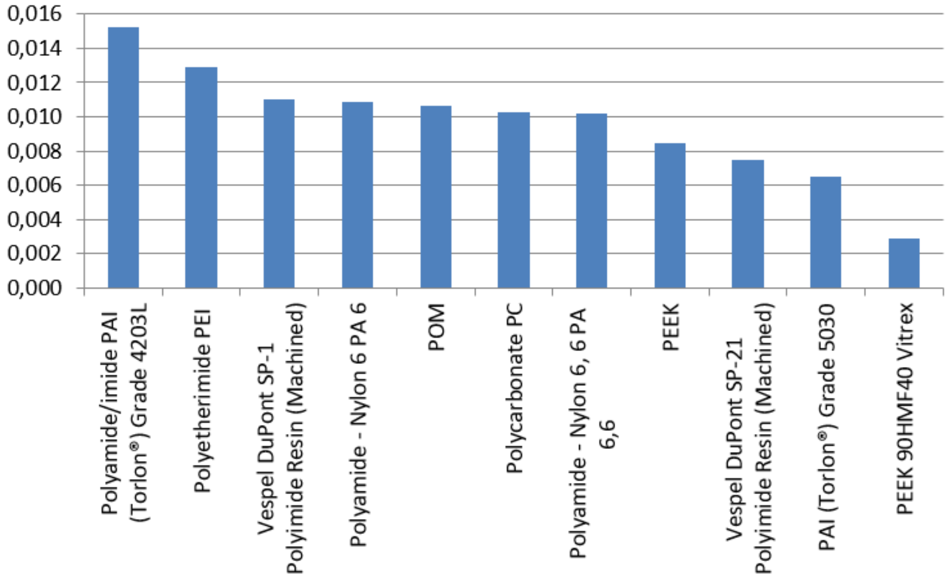


Fig. 9: Coefficient k_{LIMIT} for some engineering plastics

However, most engineering plastics exhibit so-called cold creep [20]. It limits the ability to create a durable interference fit with constant performance. Creep-resistant plastics are proposed in [21], which can be used for the discussed way of the interference fit creation (Fig. 9) - Polyamide/imide PAI (Torlon®) Grade 4203L [22] ($k_{LIMIT} = 0.015$), Vespel DuPont SP-1 Polyimide Resin (Machined) [23] ($k_{LIMIT} = 0.011$) or PEEK 90HMF40 Vitrex [24] ($k_{LIMIT} = 0.003$).

It should be noted that due to the lower values of the modulus of elasticity E in cast irons, in aluminum and copper alloys and plastics compared to steels, with the same value of the interference fit, the functional load-carrying capacity of the joint will be correspondingly lower.

5. Verifications of the proposed method by CAD using FEA

To test the applicability of the proposed interference fit creation method, a series of tensile load simulations were performed on various 3D shaft models in the CAD environment of the SolidWorks'2021 software by means of the "Simulation" module which uses the FEA (finite element analysis) methods.

The example below shows some results for a ∅64 mm DIN 1.2842 (90MnCrV8) steel shaft tensioned to create an interference fit H7/s6. That steel has the following properties that are of interest here: Elastic modulus - 210 GPa, Poisson's ratio - 0.28, yield (here limit) strength - 1750 MPa. The shaft (Fig. 10) has an axial bore of ∅38 mm to be reduced the required tensile force.

The maximum permissible force F_{LIMIT} for this shaft with axial bore was calculated, according to (3), to be 3.645 MN and the required tensile force F - to 2.002 MN. To achieve the required change of the transverse shaft dimension with respect to that of the hub, the simulation showed that a tensile force F equal to 2.280 MN is required.

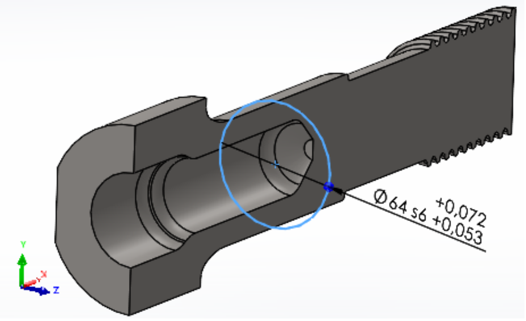
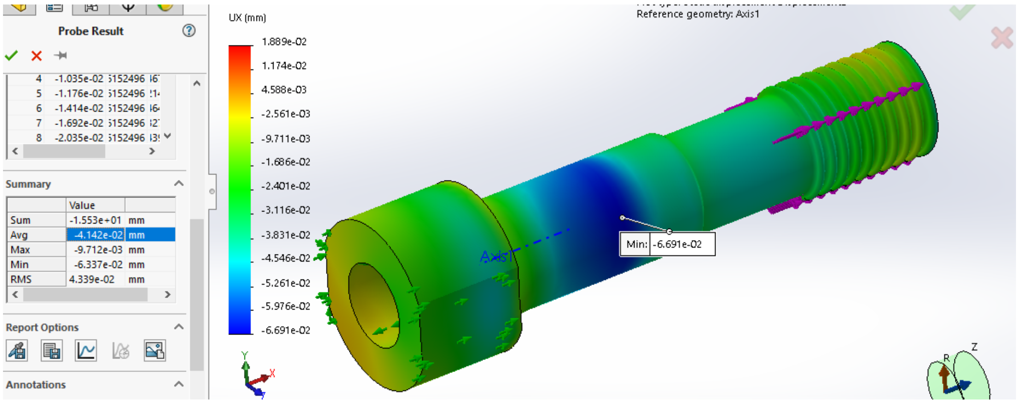


Fig. 10: Shaft with an axial bore.

As shown in Fig. 11, the shaft model is supported in the axial direction on the left, and on the right by means of the threaded part is loaded with tensile force. According to the obtained results regarding the radial dimensional change shown in Fig. 11, applying a tensile force of 2280 kN, the required, according to (3), reduction of the diameter Δd by 0.082 mm is obtained.



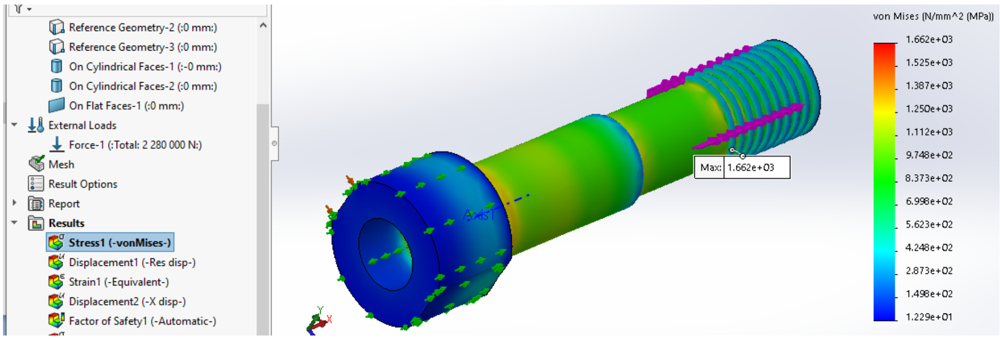
Probe Result

4	-1.035e-02	5152496	
5	-1.176e-02	5152496	
6	-1.414e-02	5152496	
7	-1.692e-02	5152496	
8	-2.035e-02	5152496	

Summary

	Value	
Sum	-1.553e+01	mm
Avg	-4.142e-02	mm
Max	-9.712e-03	mm
Min	-6.337e-02	mm
RMS	4.339e-02	mm

Fig. 11: Radial change of the transverse sizes of the shaft in tension.



Reference Geometry-2 (:0 mm:)
Reference Geometry-3 (:0 mm:)
On Cylindrical Faces-1 (:-0 mm:)
On Cylindrical Faces-2 (:0 mm:)
On Flat Faces-1 (:0 mm:)
External Loads
Force-1 (:Total: 2 280 000 N:)
Mesh
Result Options
Report
Results
Stress1 (-vonMises-)
Displacement1 (-Res disp-)
Strain1 (-Equivalent-)
Displacement2 (-X disp-)
Factor of Safety1 (-Automatic-)

Fig. 12: Resulting von Mises equivalent stresses in the tensioned shaft.

The resulting von Mises equivalent stresses (Fig. 12) of the shaft are lower than the yield strength of the material, but these results are obtained after careful prevention of abrupt changes in the shape of the shaft. There are areas with stress concentration. Consequently, the shape of the shaft must be carefully thought out to ensure smooth transitions between different transverse dimensions.

6. Conclusions

The proposed way of performing an interference fit between two machine elements, which consists in preliminary elastic change of the nominal size of the connection in the transverse to the applied longitudinal force (or forces) direction, is quite feasible. That is possible if the materials and the value of the rated size of the interference fit are selected appropriately.

Here a coefficient k_{LIMIT} called a coefficient of the maximum allowable relative change of the size transverse to the direction of the applied force is introduced. This coefficient depends only on the specific physical characteristics of the material used - limit (yield or ultimate tensile) stress, a Poisson's coefficient, and a modulus of elasticity. The higher the limit stress and the Poisson's coefficient, and the smaller the modulus of elasticity of the material, the greater relative change can be achieved in the transverse size for a given machine element by applying longitudinal force, but that change must be smaller than the coefficient k_{LIMIT} of the material.

Appropriate materials (steels, irons, aluminum alloys, copper alloys, and engineering plastics) for the discussed variant of the transverse way for making an interference fit joint between two machine elements are proposed.

Nevertheless, in conclusion, it should be said that to confirm the applicability of the proposed way for creating cylindrical shaft-hub connections with an interference fit, it is necessary to conduct experimental and field studies.

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