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ANALYTICAL AND NUMERICAL COMPUTATION OF KNURLED INTERFERENCE FITS IN COMPARISON WITH EXPERIMENTAL STUDIES

M. LÄTZER[1] S. KLEDITZSCH[2]
E. LEIDICH[1] B. AWISZUS[2]

Abstract: *The presented paper is divided into experimental, numerical, and analytical studies and gives an overview of the current computation of knurled interference fits. Experimental joining/push out studies were done to estimate the strength of the connection, to define the forming or cutting joining process, and to validate the numerical model. With the help of the static torque studies we explain the mechanical breakdown of these shaft-hub connections. To save experimental time and improve the connection we validated a numerical model. With the help of the current analytical equations we can compute a forming knurled interference fit up to a geometric interference of 0.55t.*

Key words: *Shaft-hub connection, knurled interference fit, steel/aluminium, experimental and numerical studies*

1. Introduction and state of the science

Shaft-hub connections have had a significant meaning as research objects for drive technology for several decades. The standard connections are, for example, the interference fit (IF), key fit, polygon connection, and gear shaft connection. The increasing pressure to save costs and material resources is obliging the industry and research institutes to find new solutions. One of these is the knurled interference fit (KIF). A comparison between the IF with force closure and the KIF with an additional form closure is shown in Figure 1. The advantages of the KIF are, for example, the ease of production and the low tolerance requirements.

[1] Department of Engineering Design, Institute of Design Engineering and Drive Technology, Chemnitz University of Technology, Germany.
[2] Chair of Virtual Production Engineering, Institute for Machine Tools and Production Processes, Chemnitz University of Technology, Germany.

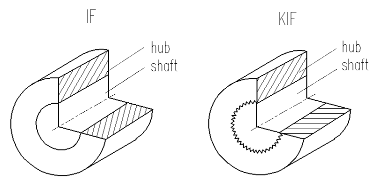

Fig. 1. *Schematic design of the IF and KIF*

At the moment there are no general computation and design fundamentals. Some companies such as INA, BMW, ZF, and Thyssen Krupp Presta are already using the KIF. But for small companies the application of this connection is not reasonable, because many expensive experimental studies are needed. The state of the art for the knurl geometries is *DIN 82* [6] and *DIN 403* [7]. In their PhD theses, *Thomas* [10] and *Bader* [2] investigated the KIF with experimental studies. The result of [4] was an empirical/ analytical computation method for the maximal torque of self-cutting KIF. *Awiszus* and *Kleditzsch* [1] investigated the joining and separating of KIF with regards to a formed joining process, using Finite Element Analysis (FEA), and in [3] and [4] *Coban et al.* show a novel technique for drive train assembly applications using mill-knurling and press-fitting (MKPF).

2. Objectives

The aim of the KIF research project is to create a standard like *DIN 7190* [5] for IF.

For a designer it should be possible to compute and design a KIF by analytic equations and to optimize the geometry of the knurl with the help of the FEA.

3. Material

The knurled shaft is made of 100Cr6, a typical steel for bearings, and the hub is made of the forging alloy EN AW-6082-T6. The difference in hardness between the shaft after tempering and the hub is 6/1. The parameters of the aluminium material are shown in Table 1 below:

Parameters for EN AW-6082-T6 Table 1

Parameter	Value
Young's modulus E [N/mm²]	68434
Yield stress $R_{p0.01}$ [N(mm²]	228
Tensile strength R_m [N/mm²]	321
Poisson's ratio	0.33

The scaling of the knurled shaft, caused by the tempering, was removed by abrasive blast cleaning. After that the coefficient of friction (COF) was determined according to the pressure. It is characteristic of this combination that the sliding COF is higher than the static COF, which is important for an understanding of the experimental studies and for the simulation.

4. Experimental Investigations

With the help of the experimental and numerical studies it was possible to understand the joining process and the mechanical breakdown of the KIF. The experimental investigations are divided into joining, push out, and static/dynamic torque studies.

In the experimental investigations the parameters interference, chamfer angle, and hub diameter ratio were varied (Table 2).

Experimental test parameters Table 2

Parameter	Value
Shaft diameter D_S[mm]	15
Hub diameter ratio Q_H	0.2; 0.5
Pitch t [mm]	0.8
Groove angle α [°]	90
Shaft chamfer angle φ [°]	5; 15
Geometric interference I_{geo} [mm]	0.3t to 0.6t
Joining velocity v [mm/s]	0.5
Period of standing t_S [h]	24

Figure 2 shows the normalized joining force F_j and the push out force F_{po} of a formed KIF with geometric interference of

0.49t.

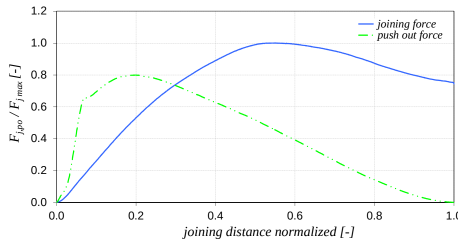

Fig. 2. *Normalized joining and push out force of a formed KIF with geometric interference of 0.49t*

To estimate the KIF based on the joining/push out process the characteristic relative strength S_r was defined. The relative strength, the quotient of push out force and joining force, describes the joint strength.

$$S_r = \frac{F_{po}}{F_j} \qquad (1)$$

Based on the chamfer angle of the knurled shaft (Figure 3) the joining process can be divided into forming or cutting and interacts with the relative strength.

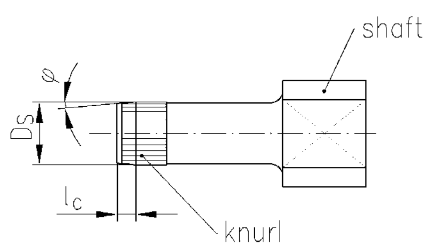

Fig. 3. *Knurled shaft parameters*

According to [1] and [11] a chamfer angel of φ = 5° allows a formed joining. The chamfer angle φ = 45° or 90° leads to a cutting joining. The relative strength as a function of the chamfer angle φ is shown in Figure 4.

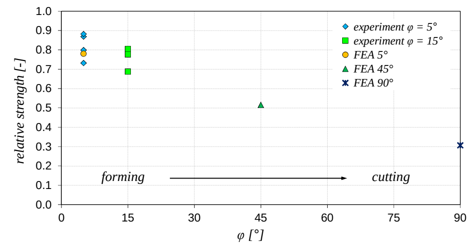

Fig. 4. *Relative strength as a function of the shaft chamfer angel φ*

From the push out photomicrographs of the hubs (Figure 5), we can see the forming zone of the hub according to the joining. The relative strength of this joint was $S_r = 0.8$.

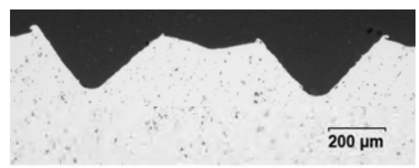

Fig. 5. *Photomicrograph of a hub with geometric interference of 0.49t after push out (φ = 5°)*

In addition to joining and push out, the mechanical breakdown of the joint under static torsional load was analysed. Therefore the universal test bench shown in Figure 6 was used [8].

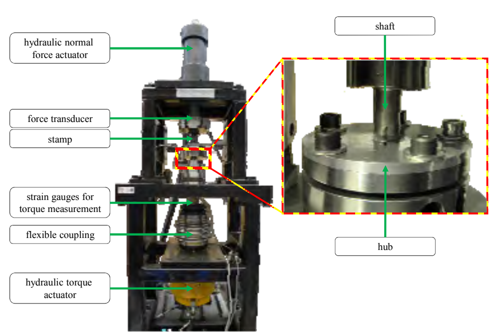

Fig. 6 *Design of the test bench*

Figure 7 shows a typical torque–twist angle graph of two KIFs with different geometrical interferences.

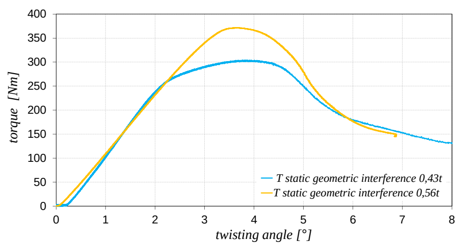

Fig. 7. *Torque–twist angle graph for different interferences*

5. Numerical Simulation of Joining and Push out

Finite Element Analysis, a com mon engineering tool for process investigation and optimization, was used for th e detailed investigation of th e joining and push out process. The simulation of the joining and push out process was realized with the FE-sof tware simufact.forming 10.0. Therefore a symmetric piece (Figure 8) of the whole connection was modelled, to save computation time. The shaft was modelled as a rigid tool with analytical surfaces and is fixed in the axial direction. For join ing and push out the hub is moved by a pusher in the a xial direction.

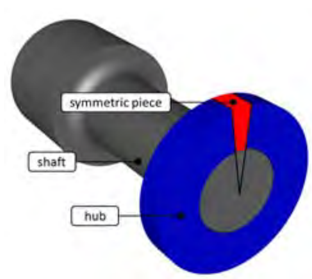

Fig. 8. *Design of the FE-model*

During the experimental test as well as for the simulation the process forces were plotted. Figure 9 shows a comparison between the simulated and the experimental forces of Figure 2.

The joining as well as the push out force is in good accordance. Based on that, it can be stated that the FEA-model is able to represent the KIF well and can be used for the investigation of th e process and in support of t he development of analytical approaches.

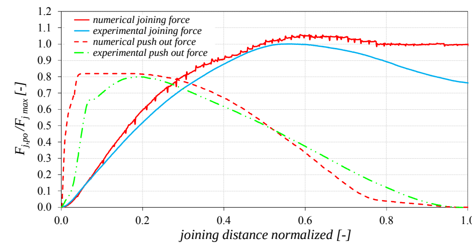

Fig. 9. *Comparison of simulated and experimental forces of a formed KIF with geometric interference of 0.49t*

For the development of an approach for the computation of the possible torsional load it is necessary to consider the joining process, because the surface pressure and strain hardening of the hub material vary depending on the joining process. Thus the simulated radial (Figure 10) and tangential stresses of the hu b were investigated. Also the influe nce of the different process parameters on the inner diameter of the hub was investigated.

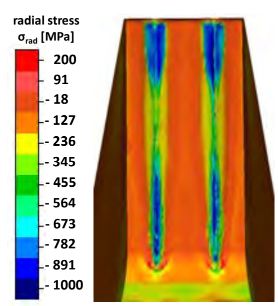

Fig. 10. *Simulated radial stresses of hub*

6. Analytical Studies

The current analytical equations for the computation of the steel/aluminium KIF are based on the allowable surface pressure criterion

$$p = \frac{F}{A}. \tag{2}$$

Due to the linear elastic slope, which is shown in Figure 7, at the beginning of the torsional load the allowable surface pressure can be used as a criterion.

Based on the knowledge of previous studies and research projects at the Institute of Design Engineering and Drive Technology, the allowable surface pressure is much higher than *90%* of the yield stress. The allowable surface pressure varies according to whether forming or cutting joining is used. For forming joining the strain hardening of the material has to be considered.

The current allowable surface pressure p_ε of a forming joining KIF up to a geometrical interference of *0.55t* can be computed with Equation (3):

$$p_\varepsilon = k_f\left(\varepsilon\right). \tag{3}$$

The current yield stress $k_f(\varepsilon)$ of the hub material, which is shown in Figure 11, can be calculated according to *Ludwig* [11] with the following equations:

$$k_f\left(\varepsilon\right) = C \cdot \varepsilon_V^n \tag{4}$$

with

$$C = R_m \cdot \left(\frac{e}{n}\right)^n. \tag{5}$$

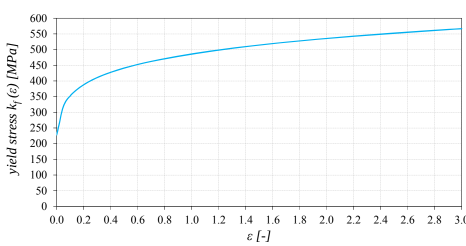

Fig. 11. *Yield stress graph of the aluminium material EN AW-6082-T6*

The absolute term C consists of tensile strength R_m, the Euler number *e*, and the strain hardening exponent *n*.

According to whether a forming or a cutting joining process is used, the current yield stress $k_f(\varepsilon)$ varies.

During a forming joining process, strain hardening occurs due to the plastic strain ε of the hub material that is reached, and the yield stress, which is necessary for an additional plastic deformation, increases. With larger geometrical interferences of up to *0.55t* or chamfer angles, chip formation occurs, which leads to a cutting joining process. During cutting joining the strain hardening is marginal.

The geometry of the knurled section for the computation of KIF is shown in Figure 12.

The allowable torsional load at the current yield stress can be computed with the following equation:

$$T = h_e \cdot l_j \cdot z \cdot r_e \cdot p_\varepsilon. \tag{6}$$

where h_e is the height of the contact area, *z* is the number of knurls, and r_e is the effective radius of the circumference force at the contact area.

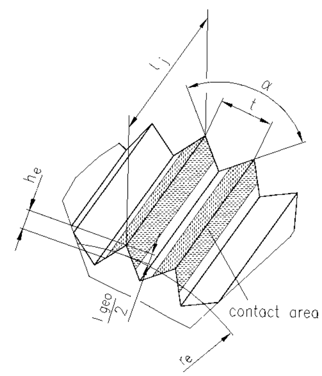

Fig. 12. *Knurl parameters*

In Figure 13 a comparison between the experimental torque and the computed torques according to Equation (6) is shown for several cases.

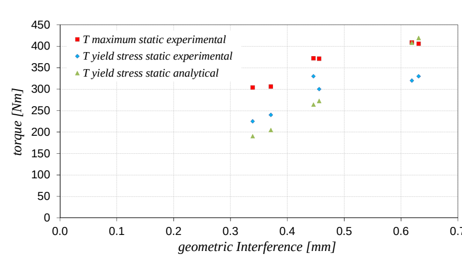

Fig. 13. *Comparison of experimental and analytical torque*

Up to a geometric interference of *0.55t* the analytical computation shows acceptable results. For connections with higher interferences the chip formation leads to a lower current yield stress. To consider the forming and cutting joining more generally, Equation (3) needs to be optimized further.

7. Conclusion

Through experimental investigations of the forming joining and the torsional load of KIF, the basis for a detailed analysis of the connection and the validation of the numerical simulation was generated. Based on the experimental and simulated results the analysis of the process was realized in order to develop adequate dimensioning fundamentals for KIF. The presented works show that the methods used are adequate. The derived equations for the computation of the surface pressure and the torque need to be optimized further in prospective works, especially with regards to a possible chip formation by larger chamfer angles and geometrical interferences of *0.55t*.

Acknowledgements

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