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Numerical and analytical investigation of steel–aluminum knurled interference fits: Joining process and load characteristics☆

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ABSTRACT

This paper describes a verified numerical investigation of the joining process and the axial strength of steel/aluminum knurled interference fits (100Cr6/AlMgSi1). Knurled interference fits have huge potential, as demonstrated by their increasing industrial use. However, as is characteristic of state of the art of knurled interference fits, current research lacks generality and makes comparison difficult between results, especially in relation to geometry-, material- and load-specific results. The work in this paper provides detailed investigation results for the influence of shaft-chamfer angle, hub-diameter ratio and geometric interference on knurled interference fits. This includes the type of joining process as well as joining force and axial strength. The joining process is essential for axial strength as well as for the transmission behavior of the connection. Finally, a new approach for the analytical computation of the joining force is presented.

1. Introduction

Shaft-hub connections are commonly used in the powertrain for torque transmission. Therefore, in most cases frictional connections or form-closed connections are used. The knurled interference fit (KIF) is a combination of friction and form closure. During the axial joining process, the knurls on the shaft are formed into the hub. This leads to form closure in the tangential direction. Additionally, a friction closure occurs in the axial direction because of the arising groove pressure. Due to the great potential of this connection, there has been considerable research activity in recent years. However, the fundamental knowledge relating to general design and dimensioning criteria is still limited. This is because industrial research activities are mostly undertaken in relation to specific applications. Meusburger et al. (2003) investigated the Thyssen Krupp Presta joining process for assembled cam-shafts. In that process, the cam is pressed onto the hub in the axial direction. The shaft is realized with knurls in the tangential or in the axial direction. Meusburger (2005) extended this method to the application range of commercial vehicles and the variation of the axially knurled shaft and developed also the numerical simulation of the joining process. However, important knowledge relating to the transmission behavior, including failure criteria is not in the public domain, because of the industrial character and secrecy.

Further industrial research was performed by Coban et al. (2009) They investigated the possible substitution of the weld joint between rear axle differential cases and bevel gears with mill-knurling and press fitting (MKPF). In contrast to conventional KIF, the knurls are not on the shaft but on the hub. In addition to experimental works, Coban et al. (2009) also studied the joining process and the torsional load by using the FEM software ABAQUS Explicit. Based on these studies, they defined a chamfer angle of $\varphi = 90°$ as optimal for their material combination of steel and cast iron. However, they did not derive any analytical approaches or design standards.

Besides the above mentioned industrial research activities, there have also been scientific researches, such as those of Qiao et al. (2008), who investigated camshafts experimentally and numerically. They used the material combinations C45/Q235A and C45/C45. Relating to the identical hardness of shaft and hub for the material combination C45/C45, the knurls are deformed plastically during the joining. Numerically, one tooth of the connections was

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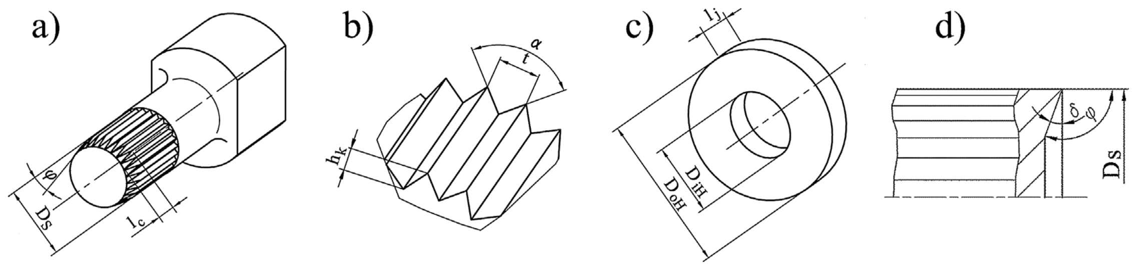

Fig. 1. Design parameter of knurled interference fits: (a) shaft, (b) knurl detail, (c) hub and (d) cutting edge of the shaft.

modeled. However, the variation range in their experimental and numerical investigations is limited. Thus, no generality can be derived. Furthermore, the influence of the shaft chamfer angle was not considered. The influence of the shaft chamfer angle as well as the tooth geometry and the diameter ratio were, however, investigated by Kitamura et al. (2012) and Hirota et al. (2012). Kitamura et al. (2012) investigated KIF of steel/aluminum to determine the influence of the shaft chamfer angle on the joining process and the possible torsional loads. It can be confidently stated that smaller shaft chamfer angles lead to a higher filling ratio and thus to higher strain hardening and higher torsional loads. Compared with a mechanical fitting connection, the KIF of Kitamura et al. (2012), joined by plastic deformation, can transmit a torque 1.5 times higher. Furthermore, they identified a critical hardness ratio between shaft and hub of 3/1 for joining the connection without damage to the knurls.

Based on these works, Hirota et al. (2012) investigated the influence of tooth geometry and hub-diameter ratio with the shaft chamfer angle of $\varphi = 30^{\circ}$. They were able to confirm the strain hardening of the hub material by measurements of hardness, which explains the higher torques compared to cutting joining connections. Hirota et al. confirm that for thin walled hubs, expansion occurs, leading to smaller filling ratios compared to thick walled hubs. Based on this, they focus on thick walled hubs to reach a maximum filling ratio and maximum torques. However, thin walled hubs are also of interest, especially, for example, in electric motor applications.

A self-cutting shaft hub connection was researched by Bader (2009). In that study, the shaft is designed with a defined cutting edge. Thus, the knurls are cut into the hub during the axial joining. Based on these experimental studies with the material combinations of soft and hard steel, as well as with aluminum and brass, an empirical approach for the transmittable torque was derived. The necessary correction factors are based on steel/steel experiments. As a result, this approach is not generally applicable, as acknowledged in the works of Lätzer et al. (2012a). It was not possible to use this approach to the calculation of torques for steel/aluminum experiments.

Lätzer et al. (2012a) shows with the help of experimental, numerical, and analytical studies an overview of the current computation of steel–aluminum KIF. 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 Lätzer et al. explain the mechanical breakdown of these shaft-hub connections. To save experimental time and improve the connection Lätzer et al. validated a numerical model. Based on the previous work, Lätzer et al. (2012b) shows the results of the current experimental and numerical investigations of steel–aluminum KIF joined by forming and cutting. It will be demonstrated that in addition to standard parameters such as geometrical interference or the relative hub length ratio, the joining process has a decisive influence on the transmission. The joining process is significantly controlled by the shaft chamfer angle φ and will be explained by joining/push out studies and torque studies. With the help of the torque studies the difference between the design criterion and the mechanical breakdown of the KIF will be shown. In summary of the previous work Lätzer et al. (2014) shows the design and calculation of steel–aluminum KIF in addition to the demand on resource efficiency and lightweight activities requires new material combinations and joining techniques. To prove the reliability research investigations are essential. Lätzer et al. provides detailed explanations of the transmission behavior of steel–aluminum KIF. It becomes clear that KIF formed by joining can transmit about 40% higher static torques than cutting joining KIF due to the material hardening. The analytical calculation, which was validated by the help of experimental and numerical studies, is well suited for predimensioning of steel–aluminum KIF.

Kleditzsch et al. (2014a) shows, that the joining process in particular has an important impact on the join strength of a KIF. A predominantly forming joining process offers some advantages compared to cutting. Forming allows a clearly higher contact pressure over the groove because of the displacement of the hub material, which leads to greater axial reliability. Also, the natural material structure is preserved by the forming, and this, in combination with the hardening of the hub, should allow a higher transmittable torque. The Finite Element Method is used for detailed investigation of the joining process and the transmission behavior in the axial direction. With this method, the local loads, for example the hardening of the hub over the groove due to the formed join, are investigated as well as further parameter variations (e.g., chamfer angle, geometric interference). Hence, an analytical approach for the determination of the necessary joining force was derived. Based on these work, Kleditzsch et al. (2014b) describes numerical investigations of the joining process of knurled interference fits and its influence on the load characteristics of the material combination 100Cr6/AlMgSi1. The described investigations include the influence of the shaft chamfer angle, the hub diameter ratio and the geometric interference. Finally, a new approach for the computation of the joining force was developed.

Junjie et al. (2013) carried out numerical and experimental tests with knurled shaft-hub connections for use in motor shafts. They present a validated simulation model for the computation of the joining force and the torsional load. The accordance between calculated and experimental forces and torques are very good. However, they only investigated the influence of three different interferences on the joining force and the torque. Therefore, their work is also unable to provide general rules.

As is characteristic of the state of research regarding KIF, generality is the missing element because of the hard comparisons regarding geometry-, material- and load-specific results. The work in this paper provides detailed investigation results for the influence of shaft-chamfer angle and geometric interference on KIF. This includes the type of joining process as well as joining force and axial