FE-simulation of the Presta joining process for assembled camshafts – local widening of shafts through rolling

R Scherzer, C B Silbermann and J Ihlemann
Professorship of Solid Mechanics, Technische Universität Chemnitz, Reichenhainer Straße 70, 09126 Chemnitz, Germany
robert.scherzer@mb.tu-chemnitz.de

Abstract. Considerable weight benefits and the option to combine various steel alloys of the single parts are the major advantages of assembled over conventional camshafts. The Presta joining process is the leading manufacturing method of assembled camshafts in the global market. The process is divided into two substeps. At first, the outer diameter of the shaft is widened with a profile oriented orthogonal to the shaft axis at the intended cam seat. At this position the shaft is subsequently joined with a cam with an internal profile oriented parallel to the shaft axis. As a result, these perpendicular profiles form a tight fit due to plastic deformations. Consequently the simulation of the manufacturing process has to start with the simulation of the rolling of the shaft. The resulting profile requested in this step is axisymmetric, but the arrangement of tools is not. Thus a three-dimensional model is required, which is presented in this work. Furthermore, the infeed of the rolling tool is unknown and controlled by the stiffness of the holders of the rolling tool. This work shows the modeling of this behavior. To predict realistic results for the underlying process, the use of precise material models is essential in order to take several hardening mechanisms into account. However, the use of complex material models implies additional effort, which is shown in this work.

1. Introduction
To this day many manufacturing processes are primarily based on in-house experiences and large experimental efforts. But this approach becomes unsustainable when today’s requirements of lightweight and highest efficiency should be met. Hence, the use of computer simulations and more precise numerical methods in development processes is almost inevitable. Consequently, there is a big potential of saving costs and time by reducing the production of expensive prototypes. However, the quality of numerical simulations is based on the quality of the employed boundary conditions, among others. Hence, a deep understanding of the underlying production process is required to obtain reliable predictions. This work discusses the Presta joining process, which is explained in detail below.

The Presta joining process is a shaft-hub-connection creating a combination of press fit and form fit. It is primarily used as the world’s leading manufacturing method for assembled camshafts and allows up to 30% weight reduction compared to conventional cast or forged camshafts. This in turn implies a significant inertia reduction of the rotating camshafts [1, 2].

The manufacturing process is divided into two substeps. First, the shaft is formed by rolling the intended cam seat to create a local widening at this position. This diameter enlargement is enabled by rollers with an approximately sinusoidal cross sectional surface and results in a profile oriented orthogonal to the shaft axis (figure 1a).
Figure 1. Schematic representation of the Presta joining process: (a) rolling of the shaft, (b) forcing the cam onto the previously rolled cam seat of the shaft

Subsequently, the rolling step is followed by the actual joining of the cam with the shaft. Contrary to the rolled profile of the shaft the cam’s inner profile is oriented parallel to the shaft axis. When forced onto each other these perpendicular profiles generate the tight fit that is characteristic for Presta processed camshafts (figure 1b). In Section 2, a computational model is presented, which enables the simulation of the rolling process using the finite element method (FEM).

One has to take into account that the forming during both substeps leads to large local plastic deformations. Hence, the applied material formulation has to be capable of reproducing the real material response and to be applicable in a wide strain range. Within the FE-model of the rolling process, a phenomenological material formulation of finite strain viscoplasticity is used [3, 4]. In Section 3, a short overview of the model is given and the results of the parameter identification of the steel alloy used for the shaft are shown.

Finally, Section 4 presents the results of the forming simulations.

2. Three-dimensional FE-model of the rolling process

2.1. Geometric model

The rolling step of the Presta joining process ideally leads to an axisymmetric profile consisting of several grooves oriented orthogonal to the shaft axis. In contrast, the assembly of the rolling tool is not axisymmetric. Thus, a two-dimensional modeling approach of the process is not realizable. However, in respect of a reduction of calculation costs, two other symmetries can be applied. First, the profile of the roller is symmetric and therefore the model size can be reduced to one half. Second, the three rollers are oriented by an angular distance of about 120°. Thus, the remaining model can further be reduced to one third (figure 2a).

Figure 2. (a) Boundary conditions applied to the model, (b) perspective view of the model with graphically expanded cyclic and axial symmetries
Finally, the modeled shaft geometry is extended beyond the width of the rollers (figure 2b). It is necessary to consider this additional region because it supports the forming zone and without that, the geometrical stiffness of the shaft would be too low. This would lead to a non-representative shaping of the rolling profile. The length of this supportive zone approximately corresponds to the distance between two cam seats of the camshaft.

2.2. FE-mesh of the shaft
Due to the repetitive cross sectional profile of the rollers and the ideally axisymmetric forming of the shaft, an approximate prediction of the deformation of every single groove is possible. Hence, the FE-mesh is designed to follow the estimated material flow (figure 3).

![Figure 3. FE-mesh: Perspective view of the assembly and a detailed view of the cross sectional mesh topology and its underlying partitioning (thick lines)](image)

Therefore, the geometric part of the shaft has been partitioned before meshing. According to the roller’s profile this partitioning is repeated for all grooves. With increasing distance from the forming zone a coarser mesh is applied to save computational cost. Similar to thread rolling processes this plastic deformation zone is limited to the area close to the contact surface [5, 6].

2.3. Loading boundary conditions
The simulation assembly mentioned above consists of the shaft and the three profiled rollers, which already implies a simplification of the rolling tool used in the manufacturing process (figure 4).

![Figure 4. Assembly of the rolling tool [1] and the schematic representation of the transfer of its stiffness into the model’s boundary conditions](image)
Here, the time-dependent feed moves a wedge to press the upper part of two holders in opposite directions. The displacement of the wedge is limited by a stop. Consequently, the rollers attached to the holders as well as the roller mounted to the base frame squeeze the shaft to initiate forming. Additionally, the rollers start to follow the rotation of the already rotating shaft. As a result, the holders are preloaded and the forming remains in full progress even after the wedge feed is stopped. Hence, every section of the shaft is incrementally profiled by the rollers due to the prestressed holders. During the forming process the preload gradually reduces with increasing penetration of the shaft surface until the pressure is too low for further forming. Once this state is achieved, the wedge will be returned in its initial position.

The Presta joining process is completed by forcing the cam onto the rolled cam seat. However, the simulation presented in this work only relates to the rolling step. The joining step will be part of our future research.

In summary, the rolling process is controlled by the feed of the wedge and by the time period the rolling is performed. Beyond that, it is also driven by the stiffness of the holders. However, an independent FE-modelling of these holders would lead to additional computational effort. Hence, the transfer of this stiffness into the simulation has been realized by a force-displacement relationship (figure 4). This relation has been implemented in a tabular form and determined experimentally by loading the holders in a tensile testing machine.

3. Application of viscoplastic material behavior

In the Presta joining process, the rolling of the shaft is an incremental forming process with a characteristic small plastic deformation zone where large local deformations occur [4, 6]. Hence, appropriate material model has to be applied in the simulation in order to reproduce the material behavior. Furthermore, the underlying numerical algorithms have to be stable and robust. Moreover, a reliable material parameter identification needs to be feasible as well [3, 7]. The material model used in this work is a phenomenological model of finite strain viscoplasticity introduced by Shutov and Kreißig [3]. This formulation includes nonlinear kinematic hardening of Armstrong-Frederick type as well as isotropic hardening. In further research the model has been extended to two back-stress tensors and two isotropic hardening mechanisms in order to reproduce the material behavior during incremental forming processes [4].

After the material model is linked to the FE-tool through a material interface, the most important part is the identification of the related material parameters. Therefore, torsion tests on tube samples made from the shaft material have been conducted to provide the required experimental data. This approach has been adopted from Shutov et al. [8].

The viscoplastic material model contains 13 material parameters. They can be divided into elastic constants (K, G), the initial yield stress (σₚ), parameters for rate-dependency (η, m), two hardening parameters for each of the two back-stresses (c_kin, κ) and two parameters for each of the two isotropic hardening mechanisms (β, γ). Here, the elastic parameters and the initial yield stress of the shaft material were determined by the use of material databases. The parameters representing the rate-dependency were established the same way as shown in [4]. The remaining eight hardening parameters were identified with a mathematical software tool using the same material interface implementation as the FE-tool to provide non-redundancy. The torsion tests have been conducted as straight-forward twists with different velocities and as zig-zag functions with a 10° forward twist and 5° or 8° backward twist. All experiments have been executed up to the breaking of the tube sample. The comparison between measured and calculated shear stresses shows good agreement over many cycles up to high plastic deformations with the same set of parameters (figure 5).
4. Simulation results and discussion

As already mentioned above, the rolling of the shaft produces an axisymmetric profile in an ideal case. The FE-simulation supports this assumption and shows the expected axial symmetry in plots of the radial displacements as well as in the von-Mises stresses (figure 6).

![Figure 6](image)

Figure 6. Approximately axisymmetric results of a) the radial displacement (sectional view) and b) the von-Mises stresses; tangential gradients in both plots are nearly zero, what proves the estimation of axisymmetry.

The axial symmetry develops over the time of the rolling process. Especially during the first cycles, larger displacement increments occur and axial symmetry does not yet exist. For this purpose, a look at the progression of the holders reaction force shows an evolution towards a constant value (figure 7). Approaching this final value means no further forming occurs.

![Figure 7](image)

Figure 7. Excellent agreement between the holder’s reaction force measured in manufacturing (dots) compared with the calculated values of the simulation (lines)
Moreover, the limitation of the forming zone to a small volume beneath the contact surface was considered. To examine this, the inelastic arc length calculated in the implemented material model was evaluated. This scalar value monotonically increases due to plastic deformation independent of their direction. Thus, the inelastic arc length can be seen as the degree of deformation [4]. The contour plot of the inelastic arc length shows patterns similar to thread rolling processes [9]. Furthermore, the plot supports the expected limitation of the plastic zone to the region near the contact surface (figure 8).

![Figure 8](image1)

**Figure 8.** The contour plot of the inelastic arc length shows the limitation of plastic deformations to the forming zone with the largest deformations located at the bottom of the grooves.

With regard to the Presta joining process, the most relevant property of the rolling step is the shaping quality of the shaft. This can be measured by analyzing the cross sectional geometry of the resulting profile (figure 9).

![Figure 9](image2)

**Figure 9.** Comparison between the measured (dots) and calculated (lines) profile of the shaft after rolling. Reasons for these visible differences may be found once the understanding of the material’s viscous behavior is more elaborate.

Although the simulation shows a good general accordance with the measured profile, the calculated forming is not as sharp as the manufactured profile. This indicates that the requested widening of the shaft has not been fully achieved. In future work this aspect has to be improved since the shaft’s widening is responsible for the press fit of the connection between cam and shaft [1].

The observed discrepancy could be explained by the viscous part of the applied material model. The deformation velocity in the rolling step is of several orders of magnitude higher than in the torsion tests used to identify the material parameters. Consequently the related parameters (\(\eta, m\)) only represent a rough estimation. Two possible solution approaches are the realization of material tests with higher deformation rates or the analysis of the impact of major differences of the shaft’s rotational speed on the resulting profile. If there is no significant influence, the viscous effects could be neglected [8].
5. Conclusions

This work introduces a model to perform FE-analyses of the rolling step of the Presta joining process. Based on the technical characteristics of the manufacturing process, the applied geometric and load boundary conditions have been explained. Hence, the model is reduced to one third in circumferential direction and cut in half in axial direction. Furthermore, it was shown that the manufacturing process is driven by the preload and the stiffness of the holders of the rolling tool. A computationally efficient approach to simulate the stiffness of the holders was shown. Instead of using independent FE-models, a force-displacement relationship was applied, which adopts the holder’s stiffness.

During the rolling process, large local deformations occur within the shaft. Hence, to ensure a good representation of the material behavior, a phenomenological viscoplastic material model was applied. Here, the procedure of identifying the required material parameters and the result of this identification has been presented.

Finally, the results of the simulation were compared to experimental measurements. It was shown that the simulation supports the expected axial symmetry of the resulting profile. Additionally, as anticipated, the plastic deformation zone is limited to a small area close to the contact zone between roller and shaft.

Acknowledgements

The research shown in this work originates from the collaborative research center SFB 692 “High-strength aluminum based lightweight materials for safety components” which is supported by German Research Foundation (DFG). Furthermore, this research was carried out in close cooperation with ThyssenKrupp Presta GmbH in Chemnitz.

References

[1] Lengwiler A 2011 Fehlerfortpflanzung, Simulation und Optimierung von Prozessketten anhand der gebauten Nockenwelle (Eidgenössische Technische Hochschule ETH Zürich)
[2] Meusburger P 2006 Lightweight design in engine construction by use of assembled camshafts MTZ worldwide 67.3 p 10–2
[3] Shutov A V and Kreißig R 2008 Finite strain viscoplasticity with nonlinear kinematic hardening: Phenomenological modeling and time integration Comp. Methods Appl. Mech. Eng. 197.21 p 2015–29
[4] Shutov A V, Kuprin C, Ihlemann J, Wagner M F X and Silbermann C 2010 Experimental investigation and numerical simulation of the incremental deformation of a 42CrMo4 steel Materialwiss. Werkstofftech. 41.9 p 765–75
[5] Domblesky J P and Feng F 2002 Two-dimensional and three-dimensional finite element models of external thread rolling Proc. Inst. Mech. Eng., Part B: J. Eng. Manuf. 216.4 p 507–17
[6] Zhang D W and Zhao S D 2014 New method for forming shaft having thread and spline by rolling with round dies Int. J. Adv. Manuf. Technol. 70.5-8 p 1455–62
[7] Shutov A V and Kreißig R 2010 Regularized strategies for material parameter identification in the context of finite strain plasticity Tech. Mech. 30.1-3 p 280–95
[8] Shutov A V, Hockauf K, Halle T, Kreißig R and Meyer L W 2009 Experimentelle und phänomenologische Beschreibung des mechanischen Verhaltens der Aluminiumlegierung EN AW-7075 nach großer plastischer Vorverformung Materialwiss. Werkstofftech. 40.7 p 551–8
[9] Kukiela K and Kukiela L 2012 Modelling and numerical analysis of the thread rolling process used in food mechanical engineering KSTU news 25 p 44–52