Experimental and Computational Analysis of Lathe Spline Shaft- A Comprehensive Report

Vikram Singh Purain1 Atul Kumar Soni2
1,2Department of Mechanical Engineering
1,2SSIET Durg, India

Abstract— In conventional machining process using lathe numerous machining process are been performed at wide range of speed and power. To attain this spline shaft plays a major role in transmitting power form one source to another, in order to get desired machined component. For power transmission spline shafts are extensively been used in industrial and automotive sector. With the advancement in science and technology, numerous researchers and design has been delivered by the researcher to prevent catastrophic failure of spline shaft. Moreover, using experimental and computational approach spline shaft design has been improved and implementation of various material such as alloyed and composite material as a spline shaft has been opened. This in this paper a comprehensive report has been presented which reveals the significant contribution of various researchers in improving the technology of Spline shaft.

Keywords: Spline, Experimental, Stress, Failure, Design

I. INTRODUCTION

Spline shafts are widely used to transmit motion or torque between shafts in the mechanical system, and the advantages of spline shaft connection attracted lots of interests attributed to their high connection strength, high reliability, compact structure, and convenient assembly [1]. The various advantages of spline shaft connection bring the extensive application of spline shaft in the industries of aerospace, ship, engineering machinery, and automobile. For instance, a common automobile contains about 30 spline shafts, and their installation positions include half shaft, clutch, differential, transmission, etc. [2]. Furthermore, higher requirement of the performance of spline shaft has been put forward in the modern manufacturing. Thus, it is essential to study the novel manufacture process of spline shaft to obtain higher performance.

II. LITERATURE

Ayma et al. 2017 Internally-spline sleeves have an increased attention since these parts serve as power transmission means in many industrial applications. This research presents using ball spinning process for producing internally-spline sleeves. The process was investigated experimentally and theoretically. The experimentally investigated variables were: the rotational speed of the mandrel 86, 604, 1146 and 1747 rpm; the axial feed, 0.3, 0.6, 0.91 and 1.21 mm/rev; the cross in-feed 1.5, 2, 2.5, 3 and 3.5 mm. An analytical expression was derived to predict the deformation loads. The theoretically investigated variables were: the mentioned axial feed and cross in-feed at 604 mandrel rotational speed; the initial tube thickness of 3.5 to 8 mm with step 0.5 mm; the ball diameters of 16 to 32 mm with step 4 mm; the number of ribs was 4, 5, 6, 8, and 10. The effects of these variables on the forming load and the quality of formed sleeves were investigated. The results showed that, these variables affecting the forming load and product quality. The optimum values of these variables were determined. The theoretical results have been found to be in close agreement with experiment.

Min-Chao et al. 2016 a novel axial-infeed incremental rolling process of spline shaft with 42CrMo steel is proposed to solve the problems of present manufacture process. The principle of the axial-infeed incremental rolling process is introduced firstly, and then the deformation mechanism is analyzed by finite element method (FEM). The numerical results show that the deformation and material flow during the novel process only occurs in the surface layer of the blank, and the metal flow velocity component along the radial direction is significantly higher than that along the axial direction. Next, the experimental research is carried out on axial-infeed incremental rolling equipment, and the microstructure and hardness of the products are evaluated.

Fig. 1: Test rig components of forming process. [3]

Fig. 2: (a) The cross section of internally- spline sleeves at various axial feed and cross in-feed. (b) The internally- spline sleeves at various cross in-feed [3]
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The experimental results show that the microstructure in the surface of tooth profile, and root is fibrous tissue which is continuous, dense, and streamlined, and the hardness of the tooth profile and root area obviously increases.

Fig. 3: Diagram of formation process of the spline shaft by FEM [4]

Fig. 4: The equivalent stress distribution of the spline shaft: a preformation area and b correction formation area [4]

Ning-yu et al. 2018 As an effective method of forming spline shaft, the axial cold forging process is appropriate for long shaft and exhibits high efficiency. The two defects of folds and accumulation were found to result in large forming force and low quality of products in the experiments. To analyse the cause the defects, a finite element model was built with a strain rate-dependent material model, in which the parameters were determined by material test. Metal flow was divided into three different parts, and relevant parameters were proposed to quantify them. An assembling method of three dies and a new die with a variable tooth shape were designed by the fast simulated annealing optimization method using the quantification parameters to improve metal flow and decrease forming force. The differences in metal flow, tooth profile and axial force were compared amongst conventional axial forging, the assembling dies and the new die. The assembling method of three dies decreased the force by 31.2% compared with the conventional axial forging. However, fold defects were significant which might lead to stress concentration. On the basis of the optimisation of the assembling method, the die with a variable tooth shape decreased the load by 55% compared with the conventional axial forging. The shape quality of the product formed by the new die with a variable tooth width was also improved owing to the avoidance of defects.

Fig. 5: Spline-forming process [5]

Fig. 6: Forging equipment [5]

Fig. 7: Metal flow and distribution of von Mises stress (a) and section at the maximum stress (b) [5]

Altinbalik and Can 2006 investigated load requirement and die filling. A simple empirical relationship between tooth dimensions and barrel profile was provided. However, the metal flow of tooth shape forming such as spline and gear forging is more complicated than that in closed-die forging. Some researchers have optimised the process parameters using FE analysis to eliminate negative effects in tooth forming.
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Li et al. 2013 proposed the principle and deformation characteristic of the traditional open-die extrusion process of spline shaft are analyzed firstly, and then a novel open-die warm extrusion process of spline shaft with 42CrMo steel is proposed to solve the process problems such as high forming loads, poor material plasticity and tooth filled quality. Next, the material characteristic of 42CrMo steel during the warm forming process is investigated through the isothermal compression tests, the microstructure with tempered sorbite and high accuracy constitutive equations of 42CrMo steel are obtained. Besides, the effects of the main process parameters on the forming loads and tooth filled quality during the open-die warm extrusion process are studied, the optimum die angle of entrance section and warm forming temperature are established as 20°C and 650°C, respectively. Finally, the relevant improvement of tooth divided flow method (TDFM) is employed to eliminate the negative effects of the large blank diameter on this novel process.

Fig. 8: (a) Schematic view of lateral extrusion for spline with four teeth and (b) subdivisions of deforming zone [6]

Fig. 9: Distribution of folds at the first step (a), second step (b) and third step (c) in the forming method of assembling dies [7]

Fig. 10: Diagram of the finite element models and practical extrusion die: (a) finite element models and (b) assembled extrusion die of FLESS Company. [7]

Fig. 11: Effective strain of the selected point under different radii. [7]

Zhang et al. 2014 [8] With the advantages of minimized stress concentration and allowing a combination of rotation and axial motion, internal helical splines have been widely used in automotive and aeronautic industries. However, this type of splines can only be manufactured using machining or extrusion method. This paper studied the recess swaging method, a net-shape forming process, for manufacturing the internal helical splines. In order to investigate the deformation tendency of workpiece along the thickness direction, Finite Element (FE) simulations and experiments were firstly performed on the recess swaging of tube without mandrel. Results show that the stress state in the forging zone is triaxial compressive except for the tensile axial stress at the inner surface of the tube. Moreover, during the recess swaging process material mainly flows along the axial and thickness direction, but the axial flow dominates. With increasing the reduction in outer radius and the wall thickness, metal flow along the axial direction increases but along the thickness direction decreases. Furthermore, based on the fundamental research on recess swaging experiments and FE simulations on the recess swaging method for manufacturing the internal helical splines were conducted. After the recess swaging, the hardness at the bottom of the
tooth improved approximately 56.9%, while that at other zones increased 41%. The strength and the wear resistance of tooth were also improved. In summary, the recess swaging process provides an effective method for manufacturing the internal helical splines.

Cui et al. 2017 discussed the principle and deformation characteristic of axial-pushed incremental rolling process of spline shaft, and then, an axial-pushed incremental warm rolling process of spline shaft with 42CrMo steel is introduced and studied to investigate the formation mechanism and analyze the effects of process parameters. In order to improve the accuracy of finite element simulation, the plastic flow behavior and constitutive characteristic of 42CrMo steel during warm forming process are studied through the isothermal warm compression tests, and then, the microstructure of tempered sorbite and high-accuracy constitutive equations of 42CrMo steel are obtained. Next, the effects of die angle and deformation temperature on forming load and toothfilled quality during axial-pushed incremental warm rolling process are analyzed based on finite element analysis (FEA). The optimum die angle of the entrance section and warm forming temperature are determined as 8 and 700 °C, respectively. To verify the results of simulation, the corresponding experiments are carried out on the warm rolling equipment, which is designed by the authors. Finally, the relevant improvement by tooth divided flow method (TDFM) is raised to eliminate the negative effect of blank diameter on this process.

Shen and Lohrengel 2013 The dynamically loaded spline shaft-hub connection that without macro relative movement between shaft and hub are exposed to the danger of fretting fatigue in the contact zone of teeth flank and plain fatigue at teeth fillet at the same time. The competition of fretting fatigue and plain fatigue determines that which one dominates the failure of it and therefore the fatigue performance of it. In order to deal with this plain-fretting fatigue coexisted situation, a plain-fretting fatigue unified prediction model is introduced in this paper and implemented in the representative spline teeth pair. Predicted by this model, the failure of involute spline shaft-hub connection teeth DIN 5480 45 × 2 × 21 is plain fatigue at teeth fillet dominated. Corresponding to the theoretical modeling efforts, a representative teeth pair fatigue test apparatus was developed. With this test apparatus, the initiation and propagation of fatigue cracks can be detected on line by monitoring the change of resonant frequency. The test results also showed that the crack occurs at teeth fillet at first.
Zhang et al. 2017 investigate the differences between the OCF and CCF, forming experiment, hardness test and micro observation were performed. In consideration of the different friction condition and variational velocity, a friction modal considering sliding and velocity was used in simulation. The force-stroke curve got from the horizontal oscillating extrusion machine shows that OCF can reduce the load about 25% than CCF and that oscillating frequency affects the friction as well as the forming force. Moreover, the results of experiment and simulation indicate the surface quality of OCF is better than CCF because lower friction leads to less metal pileup.

Barsoum et al. 2014 presents a finite element modeling framework to determine the torsion strength of hardened splined shafts by taking into account the detailed geometry of the involute spline and the material gradation due to the hardness profile. The aim is to select a spline geometry and hardness depth that optimizes the static torsion strength. Six different spline geometries and seven different hardness profiles including non-hardened and through-hardened shafts have been considered. The results reveal that the torque causing yielding of induction hardened splined shafts is strongly dependent on the hardness depth and the geometry of the spline teeth. The results from the model agree well with experimental results found in the literature and reveal that an optimum hardness depth maximizing the torsional strength can be achieved if shafts are hardened to half their radius.

Barrot et al. 2009 presents an analytical study of axial torque transfer in a spline coupling. The model developed by Tatur has been extended in order to consider different loading cases and geometries. A demonstration of the extended model in a design process is described. A spline coupling is first calculated in accordance with standards. Then the extended model is used to optimize two design options: the best positions for a flange on the sleeve and for a step in the external diameter of the sleeve are determined. A finite element study has also been performed and shows that the extended model can be used to obtain excellent designs. It is also shown that the axial torque distribution mainly influences the damage related to fretting, without changing the maximum stress coefficient factor at the root of the shaft.
### III. Conclusion

- The number of inner ribs significantly affect the consuming loads in the deformation process when using mandrel with four ribs; the spline configuration forces are large, while when using mandrel with ribs greater than ten the forming load is less.
- The plastic deformation mainly occurs on the surface layer of the spline shaft, and the deformation degree decreases along the inward radial direction. The deformation degree in the tooth root area is larger than that in the tooth profile area and it (both tooth root area and tooth profile area) decreases as the axial distance of section increases.
- The material flow mainly occurs in the surface layer of the spline shaft and almost no material flow in the center of spline shaft. In the tooth profile area, the flow of material along the radial outward direction is more obvious. But in the tooth root area, the flow of material along the radial inward direction and two side direction is more remarkable.
- The metal flow in spline shaft forming could be divided into three parts, namely, axial direction, radial direction and accumulation. The relevant parameters were proposed to quantify them. The two defects of folds and accumulation resulted in large forming force and low quality of products.
- The forming load decreases with a decreasing billet diameter for a given number of teeth. On the other hand, the die filling is not affected by the billet diameter. The forming load increases with an increasing number of teeth for a given billet diameter.
- The deformation during the open-die extrusion process of spline shaft only occurs in the surface layer of the blank.

### References


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**Fig. 21: Schematic figure of the spline coupling. [13]**

**Fig. 22: FE-predicted product of local slip and local contact pressure along the axial position of the spline at the pitch radius [13]**