Performance Improvement and Parameter Influence of Thread Shaft by Axial Self-infeed Rolling Process

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Abstract. The rolling process is an important processing technology for improving the performances of thread shaft. In this paper, the axial self-infeed rolling process is investigated. The principle of the axial self-infeed rolling process is introduced and the performances of the formed thread shaft with copper T2 are evaluated. In addition, the major diameter of the formed thread shaft and the rolling torque during the axial self-infeed rolling process are studied. The hardness of the formed thread shaft with copper T2 is improved 74.2% and the microstructure is fibrous tissue in the bottom of the tooth groove. The size of the blank has greater impact on the major diameter and the forming torque than the rotating speed of the blank.

1. Introduction
The thread shaft is widely used in the industry which has important effects on the reliability and security of machine. The rolling process for thread shaft manufacturing is an advanced manufacturing technology which has the advantages: high fatigue strength and high reliability [1-3]. The rolling process of thread shaft is similar to forming the spline [4-6] and the gear [7,8].

Domblesky et al. modeled two-dimensional and three-dimensional rolling process with the help of finite element analysis to study the effect of material and technological parameters on the rolling process [9,10]. Peter et al. proposed a new method for the thread shaft manufacturing with special flat dies and conducted the finite element analysis and the laboratory research [11]. Lee et al. studied the forming process using a rigid-plastic finite element method and analyzed the thread rolling of fasteners and the results of the finite element analysis were compared with the experiments [12]. Qi et al. studied the forming hollow threads through three dies cold rolling and the stress state of the hollow blank was also analyzed. The minimum thickness equations were derived [13]. Peter Groche et al. analyzed the rolling process with flat dies and the influence of friction was investigated by three-dimensional simulation [14]. Philipp Kramer et al. studied the defect detection in thread rolling processes with flat die. The effects of process parameters on the quality of formed threads were systematically studied [15]. The radial feed rolling process has some disadvantages: huge forming force and torque, harsh demands for the forming equipment and the length of the formed thread shaft limits by the rolling dies. In order to solve the existing problems of the radial feed rolling process, the axial self-infeed rolling process of thread shaft is applied to form the long screw [16]. But the axial
rolling process was rarely studied. In this paper, the principle of the axial self-infeed rolling process is described. The axial self-infeed rolling process experiments are carried out on a self-developed equipment and the performances of the formed thread shaft with copper T2 are studied. In addition, the major diameter and the forming torque with various materials and different parameters are analyzed in detail.

2. The Principle of The Axial Self-infeed Rolling Process

The rolling die system mainly consists by three rolling dies (rolling die-A, rolling die-B and rolling die-C) which is shown in Figure 1(a). The structures of rolling die are shown in Figure 1(b), which includes three parts: the exit part, the correction part and the pre-rolling part. The pre-rolling part has the angle $\alpha_p$ which is convenient for entrancing and pre-rolling the blank. The correction part calibrates the pre-forming tooth and ensures that the formed tooth profile is standard. The exit part has the angle $\alpha_e$ which benefits the formed thread shaft to return smoothly.

![Figure 1. The schematic diagrams of rolling die: (a) the rolling die system (b) the structure of rolling die.](image)

Figure 2 shows the procedures of the axial self-infeed rolling process of thread shaft which include before rolling, during rolling and after rolling. The working procedures are listed as follows: (1) Before the rolling process, the blank rotates with the speed $n_b$ and the rolling dies remain stationary. (2) During the rolling process, the rolling dies are pushed to contact with the rotating blank. Due to the role of the meshing, with the rotation of the blank the rolling die also begins to rotate and the rotating speed is $n_d$. Meanwhile, the rolling dies feed along axial direction with the speed $v$. The metal deformation occurs on the blank under the action of the pre-rolling part and the correction part. (3) After the rolling process, the blank reversal rotating and the rolling dies return to their initial position, the rolling process end.

![Figure 2. The working process of the axial self-infeed process: (a) before rolling (b) during rolling (c) after rolling](image)

Figure 3(a) shows the local structure of rolling die system and Figure 3(b) shows the structure of the self-developed experimental equipment. The experimental equipment mainly includes four parts: the driving part, the deceleration part, the clamping part and the rolling die system. The driving part is composed of a servo motor which is used to rotate the blank. The deceleration part mainly includes the planetary reducer which is used to improve the torque and ensure the blank rotation with desired speed. The clamping part is a three-jaw chuck which is used to fix the blank. The rolling die system consists
of three rolling dies and various accessories which is the vital component for the forming equipment. The rolling die system is the forming part for the thread shaft.

In these experiments, the blank materials are AISI 1045, AISI 1035 and copper T2. The major diameter and pitch of the formed thread shaft respectively are 24mm and 3mm. The rotating speed of the blank is from 10r/min to 60r/min. And without lubricant was applied in the rolling process.

![Figure 3](image)

**Figure 3.** The experimental equipment of the axial self-infeed rolling process: (a) the local structure of rolling die system (b) the whole experimental equipment

3. **The Experimental Results**

The formed thread shaft with copper T2 was cut the cross-section for the microhardness tests and metallographic analysis. The hardness values of formed thread shaft were measured through a micro-sclerometer (Type: HVT-100A). Figure 4 shows the measuring device and points. In order to ensure the accuracy, three teeth (tooth I, tooth II and tooth III) were measured and each tooth includes seven points.

![Figure 4](image)

**Figure 4.** The hardness measuring device and points

![Figure 5](image)

**Figure 5.** The measuring hardness values of the formed thread shaft with copper T2

Figure 5 shows the hardness values of formed thread shaft with copper T2 in different teeth and positions. The hardness values gradually increase from HV 103.5 to HV 182.1 corresponding to the points from P1 to P7. P1 represents the hardness value of the core of the formed thread shaft and P7 represents the hardness value of the bottom of tooth space of the formed thread shaft. The differential value of the hardness values between the P1 and P7 is 76.8 (ΔHV=76.8). In the core region of the
formed thread shaft, the hardness value is equal to that of the blank. The maximum hardness value of the formed thread shaft is improved 74.2% than that of the core of the formed thread shaft.

The microstructures of the formed thread shaft with copper T2 show in Figure 6. The microstructure in the bottom of tooth groove region is obviously fibrous tissue and the grain elongated (Figure 6(a)). The streamlines are also obvious which are extended from the bottom of tooth groove to the two flanks of tooth profile, the microstructure in the flank of tooth profile is also dense and streamlined, but the degree of fibrosis is less than that in the bottom of tooth groove (Figure 6(b)). In the top of tooth profile, the grain is slightly refined and the grain size slightly decreases (Figure 6(c)). With the increase of depth inward from the tooth surface to the center of the formed thread shaft, the fibrous tissue gradually disappears and the grain size increases. The influent degree in different region through axial self-infeed rolling process for the formed thread shaft in descending order is the bottom of tooth groove, the flank of tooth profile and the top of tooth profile. The characteristics of the microstructure are corresponding to the hardness distribution of the formed thread shaft.

**Figure 6.** The microstructure of the formed thread shaft with copper T2: (a) the bottom (b) the flank (c) the top

3.1. The Major Diameter Analysis

The major diameter of thread shaft is an important indicator for forming precision. In this section, the major diameter is selected as representation to evaluate the influences of the various materials, the blank diameter and the rotating speeds. In these experiments, the blank diameter increase from 22.2mm to 22.8mm and the length is 200mm.

**Figure 7.** The major diameter of the formed thread shaft with various materials under different blank diameters

**Figure 8.** The major diameter of the formed thread shaft under different rotating speeds

Figure 7 shows the major diameter of the formed thread shaft with various materials under the different sizes of the blank when the rotating speed of the blank is 10r/min. When the blank diameter is less than 22.75mm, the blank with copper T2 forms the thread shaft with the largest major diameter and the blank with AISI 1045 forms the thread shaft with the smallest major diameter. With the size of the blank is gradually increasing, when the blank diameter is larger than 22.75mm the major diameters of the thread shafts with different materials are almost equal.
Figure 8 shows the major diameter of the formed thread shaft under various rotating speeds when the blank diameter is 22.75mm and the material of the blank is copper T2. When the rotating speed of the blank increases from 10r/min to 60r/min, the major diameter of thread shaft increases from 24.21mm to 24.45mm.

When the blank diameters are less than 22.75mm, the addendum of the formed thread shaft is no constraint by the dedendum of the roller which is shown in Figure 9(a). The height of tooth is determined by the material hardness and the material flow velocity. Under the same blank diameter, the blank with AISI 1045 steel has higher hardness therefore the material flow is difficult which leads to the size of the formed thread shaft is less. And the rotating speed of the blank determines the deformation velocity on the surface of the blank. With the increasing rotating speed of the blank, the material flow velocity is large. The size of the formed thread shaft increases slightly as well.

As shown in Figure 9(b), when the blank diameters are larger than 22.75mm, the dedendum of the roller contacts with the addendum of the formed thread shaft and the tooth profile of the roller is filled to the full. Therefore, the major diameters with different materials are almost the same.

3.2. The Rolling Torque Analysis

The rolling torque is an important parameter for the forming equipment which limits the development of forming process. The rolling torque under different sizes and rotating speeds of the blank with various materials are studied. The torque value was calculated by the output current of the servo motor and the maximum rolling torque values are selected to analyze in this section.

Figure 10 is the rolling torque under different sizes of the blank and the rotating speed of the blank is 10r/min. For the same blank diameter, the rolling torque with kinds of materials is different. The rolling torque of forming copper T2 blank is smallest, but which of forming AISI 1045 steel blank is largest. And when the size of the blank is less than 22.75mm, the rolling torque increases slowly. The diameter of the blank increases from 22.75mm to 22.85mm the rolling torque rises sharply.

Figure 11 shows the effect of the rotating speed of the blank on the rolling torque when the blank diameter is 22.75mm. With the increasing of rotating speed of the blank, the rolling torque increases but the amplitude of increasing is small.
Under the same rotating speed of the blank, the rolling torque of the blank with copper T2 is smallest and which of the blank with AISI 1045 steel is largest.

The material with high hardness is difficult to deform, therefore the blank with AISI 1045 steel needs largest torque to be formed. When the blank diameter is larger than 22.75mm, the radial force between the blank and the dies increases dramatically and the addendum of the formed thread contacts with the dedendum of the rolling die, as shown in figure 9. The frictional force between the blank and the rolling die causes a significantly increase of the torque during the forming process. With the increasing of the rotating speed of the blank, the material strain rate increases and which causes an increase of the rolling torque.

4. Conclusion
From the above, the experiments of the thread shaft were carried out. Following is the results:

(1) The maximum hardness value of the formed thread shaft with copper T2 distributes in the bottom of the tooth groove and which is improved 74.2%. Through axial self-infeed rolling process, the microstructure in the bottom of tooth groove and the flank of tooth profile is dense and streamlined.

(2) When the blank diameter is larger than 22.75mm, the major diameter of the formed thread shaft remains consistent but the rolling torque increases sharply. With the rotational speed of the blank increase the major diameter and the torque are slightly increased.

(3) The size of the blank has greater impact on the major diameter of the formed thread shaft and the rolling torque than the rotating speed of the blank.

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References
[1] Lange K 1985 Handbook of Metal Forming (New York:McGraw-Hill)
[2] Tschätsch H 2006 Metal Forming Practice: Processes -Machines-Tools (Berlin: Springer)
[3] Song J L, Liu Z Q and Li Y T 2017 Cold Rolling Precision Forming of Shaft Parts (Beijing: Springer)
[4] Cui M Cao, Zhao S D, Chen C, Zhang D W and Li Y Y 2017 Process parameter determination of the axle-pushed incremental rolling process of spline shaft. Int J Adv Manuf Technol 90 1-11.
[5] Cui M C, Zhao S D, Zhang, D W, Chen C, Fan S Q and Li Y Y. Deformation mechanism and performance improvement of spline shaft with 42CrMo steel by axial-infeed incremental rolling process. Int J Adv Manuf Technol 88 1-10.
[6] Zhang D W, Li Y Y, Fu J H and Zheng Q G 2007 Mechanics analysis on precise forming process of external spline cold rolling. Chin Journal Mech Eng 20 54–58.
[7] Amir A K, Jun N, David S and Richard V 2007 Investigation of work hardening of flat-rolled helical-involute gears through grain flow analysis, FE-modeling, and strain signature. Int J Mach Tool Manu 47 1285–1291.
[8] Amir A K, Jun N, David S, Richard V and Garrold D 2007 Diagnosis of involutometric issues in flat rolling of external helical gears through the use of finite-element models. Int J Mach Tool Manu 47 1257-1262.
[9] Domblesky J P, and Feng F 2002 A parametric study of process parameters in external thread rolling. J Mater Process Technol 121 341–349.
[10] Domblesky J P and Feng F 2002 Two-dimensional and three-dimensional finite element models of external thread rolling. Proc Instrn Mech Engrs Part B, Journal of Engineering Manufacture 216 507–517.
[11] Pater Z, Gontarz A, and Weroński W 2004 New method of thread rolling. J Mater Process Technol 153–154 722–728.
[12] Lee M C, Jang S J, Han S S, Yoon D K and Joun M S. New finite-element model of thread rolling. Steel Res. Int. 81 214–217.
[13] Qi H P, Li Y T, Fu J H and Liu Z Q 2008 Minimum wall thickness of hollow threaded parts in three-die cold thread rolling. Int J Mod Phys B, 22 6112–6117.
[14] Peter G and Philipp K 2018 Numerical investigation of the influence of frictional conditions in thread rolling operations with flat dies. Int J Mater Form, 11 687-703.
[15] Philipp K and Peter G 2018 Defect detection in thread rolling processes-experimental study and numerical investigation of driving parameters Int J Mach Tool Manu, 129 27-36.
[16] Ivanov, V 1998 Rolling of long screws. J Mater Process Technol, 82 1-12.