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Research on Optimal Design of Rotary Forging Shaft Based on Manufacturing Process

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Abstract: This paper studies the design of rotary forging shafts based on the manufacturing process, with a focus on the comparative analysis of the traditional manufacturing process (mandrel-free process) and the improved process (mandrel-included process). By comparing the differences between the traditional and improved products in the manufacturing process, the improvement effects of uniform inner diameter and the mandrel-included process on product performance, manufacturing efficiency and production cost were analyzed. The test results show that the adoption of the mandrel-included process can effectively improve the quality of rotary forging shafts, reduce processing time, expand the range of material selection, and avoid the inner surface defects and low roundness problems that may occur in the traditional mandrel-free process.

Keywords: Rotary Forging Shaft; Manufacturing Process; Mandrel-included; Mandrel-free; Processing Efficiency; Material Selection; Carburizing.

1. Introduction

As a key core component for power transmission and load bearing in the field of modern high-end equipment manufacturing, the performance of rotary forging shafts directly determines the operation accuracy, reliability and service life of the whole machine. They are widely used in key industrial fields such as aerospace, rail transit, precision machinery and new energy equipment. With the development of equipment towards high rotation speed, high load and high integration, the market has put forward more stringent requirements for the dimensional accuracy, surface quality, mechanical properties and cost control of rotary forging shafts [1-2]. The traditional manufacturing process of rotary forging shafts has gradually exposed technical bottlenecks that are difficult to adapt to high-end demands. Process optimization and design improvement have become the core breakthroughs to promote the upgrading of rotary forging shaft products.

Rotary forging technology has become one of the mainstream technologies for the precision manufacturing of shaft parts due to its remarkable advantages in forming accuracy, material utilization rate and mechanical property improvement. However, the traditional mandrel-free rotary forging process widely adopted in the industry is faced with prominent problems of difficult inner surface quality control and low roundness in actual production [3-5]. Due to the lack of support and positioning of the inner diameter by the mandrel, the metal blank is prone to defects such as uneven inner diameter shrinkage, inner surface wrinkles or scratches during the forging process, which not only greatly increases the correction difficulty of subsequent processing, but also may reduce the fatigue life of the product due to internal stress concentration. At the same time, to avoid the risk of defects, the traditional process has extremely high requirements for the material uniformity and plastic index of raw materials, resulting in a limited range of material selection and further increasing the manufacturing cost. In addition, multiple rework and correction also prolong the production cycle and reduce the manufacturing efficiency, which is in sharp contradiction with the development goal of "high efficiency, high quality and low cost" in the current manufacturing industry.

Han Xinghui et al. [6] simulated the radial forging process by using the finite element method of plastic forming and quantitatively analyzed the influence of radial penetration on the quality. Qin Min et al. [7] carried out simulation analysis on the radial rotary forging process of hollow axles and analyzed the deformation mechanism and laws of the radial rotary forging process of hollow axles. This paper innovatively proposes a research on improving the mandrel-free rotary forging to the composite rotary forging of mandrel-free and mandrel-included based on the characteristics of rotary forging process, strength requirements and material mechanical characteristics, which can effectively improve production efficiency, control inner wall quality and thus ensure the product strength requirements.

In view of the technical pain points of the traditional mandrel-free rotary forging process, the industry has gradually explored the introduction of the improved rotary forging process with mandrel, hoping to fundamentally solve the problems of inner surface defects and roundness through the support and positioning of the mandrel on the inner diameter of the rotary forging shaft. However, there is a lack of systematic comparative analysis and experimental verification on the specific improvement mechanisms and quantitative effects of the mandrel-included process on the product performance (such as mechanical strength, dimensional accuracy), manufacturing efficiency (such as processing cycle, process simplification degree) and cost (such as material loss, rework cost) of rotary forging shafts.

Based on this, this paper takes the optimization of the manufacturing process of rotary forging shafts as the core research goal, and carries out a systematic comparative study on the traditional mandrel-free process and the improved mandrel-included process. By analyzing the metal flow law, dimension control mode and defect formation mechanism of the two processes in the rotary forging process, combined with experimental data, the improvement effects of the mandrel-included process on the inner surface quality, roundness and mechanical properties of rotary forging shafts

are quantitatively evaluated, and the differences between the two processes in processing time, material utilization rate and comprehensive cost are compared. The research results of this paper aim to provide theoretical support and experimental reference for the improvement of the manufacturing process of rotary forging shafts, promote the large-scale application of the composite rotary forging process of mandrel-free and mandrel-included in industrial production, and thus enhance the core competitiveness of China's rotary forging shaft products.

2. Theoretical Basis

(1) Basic Principle of Rotary Forging Processing

Rotary forging processing is a precision forming technology based on metal plastic deformation. Its core principle is that multiple groups of symmetrically distributed hammers (usually 2-6) make high-speed rotational movement around the blank axis, and at the same time apply periodic forging force to the blank in the radial direction, so that the metal blank undergoes plastic deformation in both axial and radial directions, and finally obtains shaft parts that meet the requirements of dimensional accuracy and shape. In the rotary forging process, the deformation behavior of metal follows the law of constant volume and the law of minimum resistance: the volume of the blank remains constant before and after deformation, and metal particles will flow preferentially in the direction with the least resistance. The movement track of the hammer, the magnitude and frequency of the forging force, the feeding speed of the blank and other parameters directly determine the direction and rate of metal flow, and thus affect the forming quality of parts [8-9].

From a mechanical point of view, the blank bears complex three-dimensional stress during the rotary forging process: radial compressive stress from the hammer, axial tensile stress due to blank feeding, and circumferential stress due to the rotational constraint of the hammer. Plastic deformation occurs when the stress on the blank exceeds the yield limit of the metal material; and by reasonably controlling the process parameters (such as forging temperature, deformation amount, hammer fillet radius), the dislocation density inside the metal can be increased to realize work hardening, thereby improving the mechanical properties (such as tensile strength, hardness) of the rotary forging shaft.

(2) Introduction to Mandrel-included and Mandrel-free Rotary Forging

The mandrel-free rotary forging process is the traditional basic process for manufacturing rotary forging shafts, which refers to a process method in which no mandrel is used to support the inner diameter of the blank during the rotary forging process, and the metal blank is only subjected to radial forging force by multiple groups of symmetric hammers rotating at high speed around the blank axis, so that the metal blank realizes axial extension and radial contraction relying on its own plastic deformation, and finally forms a solid shaft or hollow shaft. The core feature of this process is that no additional design and installation of mandrel is required, and the process is relatively simple. The forming process is mainly adjusted by controlling hammer parameters (frequency, forging force), blank temperature and feeding speed, which is suitable for scenarios with low requirements for inner diameter accuracy.

The mandrel-included rotary forging process is an improved process for the quality optimization of hollow rotary forging shafts, which refers to a process method in which a mandrel adapted to the inner diameter of the blank is pre-installed inside the blank before rotary forging, the mandrel and the blank rotate synchronously during the rotary forging process, and the metal is uniformly deformed with the radial support and size limitation of the mandrel on the inner diameter of the blank combined with the forging force of the hammer, finally forming a high-precision hollow shaft. The core of this process is to use the mandrel to solve the quality problems caused by the lack of support for the inner diameter. The mandrel needs to be designed with adapted material and size according to the blank material and forging temperature, which is the key to realize the high-precision manufacturing of hollow shafts.

3. Design and Manufacturing Process of Rotary Forging Shaft

(1) Process Analysis of Existing Products

This paper takes the intermediate rotary forging shaft of constant velocity universal joint transmission of a car as the research object. The transmission shaft is made of 25CrMo4 material, which needs to bear complex working loads of large torque and large rotation angle during vehicle operation. Therefore, dual performance requirements are put forward for the rotary forging shaft: it needs to have high static strength to resist impact and static load effects, and have excellent fatigue strength and fatigue life to avoid fatigue failure during service.

The structural dimensions of the intermediate rotary forging shaft of the constant velocity universal joint transmission are shown in Figure 1. According to the structural dimensions, the shaft can be divided into shaft section I, shaft section II and shaft section III, among which shaft section I is a fixed section and shaft section III is a sliding section, which are matched with the fixed universal joint and the sliding universal joint respectively; shaft section I and shaft section III are hollow shaft sections with variable wall thickness and variable cross-section, formed by multi-pass mandrel-free rotary forging, and then processed by involute spline cold extrusion; shaft section II is a hollow shaft section with equal wall thickness, formed by single-pass mandrel-included rotary forging. The initial dimensions of the blank of the rotary forging shaft are an outer diameter of 37mm and an inner diameter of 27mm.

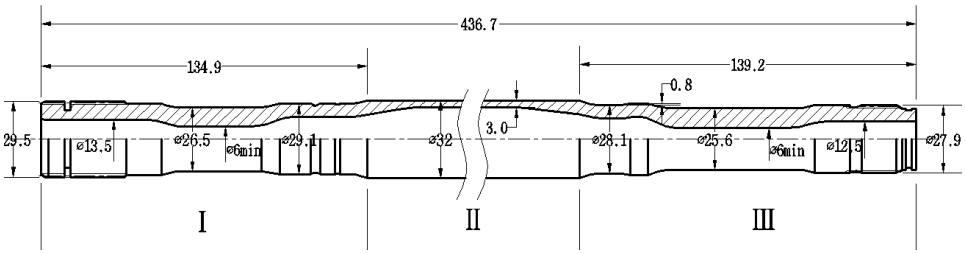


Figure 1. Schematic diagram of product dimensions

The process route of the existing product is: mandrel-free rotary forging → mandrel-included rotary forging → mandrel-free rotary forging → spline pushing → carburizing heat treatment. For the mandrel-free rotary forging link, the radial feeding amount and feeding passes under rough forging, medium forging and finish forging processes are determined respectively based on the two dimensions of stress constraint and geometric constraint. The specific design ideas and parameters are as follows:

Radial feeding for rough forging: Based on the mechanical properties of the blank, to avoid damage to the rotary forging shaft caused by excessive radial feeding amount, the stress constraint limits the radial feeding amount to no more than 1.0mm when the initial outer diameter is 37mm; from the perspective of geometric constraint, different radial feeding amounts will make the inner circle present a morphological change of convex - critical - concave. To avoid geometric defects, the rounded value of 0.5mm is selected as the radial feeding amount. Multiple passes of radial feeding are adopted to avoid inner circle depression, and it is determined that in the process of reducing the outer diameter of the blank from 37mm to 34mm, a radial feeding amount of 0.5mm is adopted with a total of 3 passes.

Radial feeding for medium forging: To meet the requirements of the subsequent involute spline cold extrusion forming process, the maximum radial feeding amount is determined to be 0.6mm by stress constraint when the outer diameter of the blank is 34mm; combined with the requirements of geometric constraint on internal quality, the rounded value of 0.3mm is selected as the radial feeding amount. In the stage of reducing the outer diameter from 34mm to 29.2mm, a radial feeding amount of 0.3mm is adopted with 8 passes required; in the stage of reducing the outer diameter from 29.2mm to 26mm, the radial feeding amount is adjusted to 0.2mm, also with 8 passes required.

Radial feeding for finish forging: A small radial feeding amount of 0.1mm is adopted to complete the final rounding and finishing of mandrel-free rotary forging, ensuring the roundness quality of the inner and outer circles of the rotary forging shaft. This parameter is applied in the process of reducing the outer diameter of the blank from 26mm to 25.6mm.

Combined with the requirements of improving the roundness of the inner and outer circles after rotary forging, the forging coverage requirements of the unforged area and the forging efficiency, on the basis of the radial feeding parameters, the circumferential feeding parameters for rough forging, medium forging and finish forging are further formulated, with a unified circumferential feeding amount of 25°. The specific pass design is as follows:

Circumferential feeding for rough forging: Due to the adoption of a large radial feeding amount of 0.5mm, the roundness quality of the inner and outer circles after rotary forging is poor, requiring multiple circumferential feeding for rounding; combined with the distribution of the maximum/minimum deformation positions after rotary forging and the requirements of process unification, 7 times of circumferential feeding are required in the stage of outer diameter from 37mm to 34mm.

Circumferential feeding for medium forging: With the reduction of the blank size, its mechanical properties change, and the radial feeding amount is adjusted to 0.3mm and 0.2mm; 6 times of circumferential feeding are required in the stage of outer diameter from 34mm to 29.2mm, and 5 times of circumferential feeding are required in the stage of outer diameter from 29.2mm to 26mm to realize effective roundness correction.

Circumferential feeding for finish forging: Finishing processing is completed with a radial feeding amount of 0.1mm, and the final roundness quality control is completed through 3 times of circumferential feeding in the stage of outer diameter from 26mm to 25.6mm.

Based on the above radial and circumferential feeding parameters, the complete process parameters of mandrel-free rotary forging for the sliding section (shaft section III) are obtained, as shown in Table 1.

Table 1. Process parameters of mandrel-free rotary forging for shaft section III

Process parameters of shaft section III	Outer diameter (mm)	Radial feeding (mm)	Radial feeding passes	Circumferential feeding	Circumferential feeding passes
Rough forging	37-34	0.5	3	25°	7
Medium forging	34-29.2	0.3	8	25°	6
	29.2-26	0.2	8	25°	5
Finish forging	26-25.6	0.1	2	25°	3

The existing process has obvious technical shortcomings: the matching technical difficulty of the pass and feeding process parameters of mandrel-free rotary forging is high, and the multi-pass processing method leads to a cumbersome production process and a significant reduction in production efficiency, which is difficult to adapt to the industrial production requirements of large-scale and high efficiency.

(2) Process Improvement of Existing Products

Improvement Principles:

To realize the optimization and upgrading of the manufacturing process of rotary forging shafts, combined with the product structural characteristics and the technical characteristics of rotary forging processing, three core improvement principles are formulated to ensure the scientificity and practicability of process improvement:

Match structural characteristics with rotary forging process, make the product structure adapt to the metal plastic deformation law of rotary forging processing, and reduce forming difficulty;

Match technical difficulty with rotary forging process, simplify the design and control difficulty of process parameters, and improve the on-site operability of the process;

Match production efficiency with process route, streamline processing passes, shorten production cycle, and realize the high-efficiency manufacturing of rotary forging shafts.

Improvement Scheme:

This process improvement adopts a collaborative optimization scheme of structural modification + process modification, the core of which is to upgrade the traditional single mandrel-free rotary forging process to a composite rotary forging process combining mandrel-free and mandrel-included.

To adapt to the inner diameter support and positioning requirements of the mandrel, it is necessary to optimize the

structure of the inner diameter of the original mandrel-free rotary forging section and modify it to a unified diameter, providing a structural basis for the installation, use and synchronous rotation of the mandrel. An example of the partial sectional view of the target structure is shown in Figure 2.

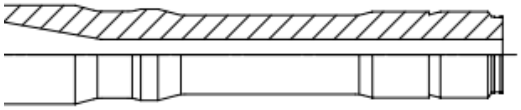


Figure 2. Example of partial sectional view of the target structure

(3) Dimensional Design of Rotary Forging Shaft

The core of the dimensional design of the rotary forging shaft in this paper is the accurate determination of the inner diameter size. Based on the maximum torque transmitted by the transmission shaft assembly as the core load basis, combined with the static strength requirements, the mechanical properties of 25CrMo4 material and the hardness distribution characteristics after carburizing and quenching, the theoretical calculation and optimal design of the inner diameter size are carried out.

It is known that the maximum torque transmitted by the transmission shaft assembly is 4000 Nm. For a variable cross-section transmission shaft, according to the principle of static equilibrium, if the shaft is a statically determinate structure (only subjected to couple forces at both ends and no other constraints), according to the section method, the torque of any cross section in the shaft must be balanced with the external couple moment, so the torque of each cross section is equal in magnitude and opposite in direction. The change of cross-sectional size only affects the stress distribution and torsional deformation, but does not change the magnitude of the torque.

The shear stress formula on the cross section of the hollow shaft is:

$$\tau=T\rho/Ip$$

Where ρ is the distance from the axis,
and the polar moment of inertia

$$Ip=\pi(D4-d4)/32$$

Where D is the outer diameter and d is the inner diameter. The change of cross-sectional size will change Ip, thus affecting the maximum shear stress.

It can be seen from the formula that when the inner diameter is the same, the smaller the outer diameter, the smaller the polar moment of inertia and the greater the shear stress. Therefore, the point with the maximum stress is on the outer surface with an outer diameter of 25.6mm. According to the shear stress formula, we can get:

$$\tau_{max}=4000*0.128/[\pi\ (0.2564-d4\ )/32]$$

The inner diameter size of the dangerous section meets the static strength requirements as follows:

$$d=\sqrt[4]{D^4-\frac{16TD}{\tau_{max}\cdot\pi}}$$

In the formula, d is the inner diameter size (mm); D is the outer diameter size (mm); T is the maximum torque of 4000 (Nm); τmax is the maximum torsional stress (MPa).

Since the inner diameter is the same, only the cross section with the smallest outer diameter needs to be considered when determining the inner diameter size, which is the dangerous section, and the maximum stress point is on the surface, i.e., the depth is 0. It can be seen from the figure that the strength at this point is about 625×4.27=2668.75 MPa, so the maximum torsional stress cannot exceed 2668.75 MPa.

It can be determined from the product drawing that the outer diameter of the dangerous section is 25.6mm, i.e., D=25.6mm.

$$\tau_{max}=25.6*10^{-}9*16*4000/[\pi*(25.6*10^{-}3)^4-\pi*(d*10^{-}3)^4]$$

It is calculated that when d=21.9mm, τ_{max} is about 2668.75 MPa. At this time, the relationship between the torsional stress τ at any point of the cross section and its depth x is:

$$\tau=x*10^{-}9*16*4000/[\pi*(25.6*10^{-}3)^4-\pi*(21.9*10^{-}3)^4]$$

After converting τ according to the strength-hardness relationship, the depth-hardness relationship of the dangerous section needs to be compared and analyzed with that of the structure after carburizing and quenching.

The material of the rotary forging shaft is 25CrMo4, and the hardenability of 25CrMo4 material is shown in Table 2 and Figure 3. The hardness of the rotary forging shaft blank and during the rotary forging process is very low. For the convenience of unified consideration of the hardness of the rotary forging shaft blank, during the rotary forging process and after heat treatment, the HV hardness is used as the scale to study the hardness distribution of the rotary forging shaft after heat treatment strengthening. The conversion relationship between microhardness and strength is taken as 1 HV≈4 MPa.

Table 2. Hardenability of 25CrMo4 material

Depth from surface (mm)	Minimum hardness (HV)	Maximum hardness (HV)
1.50	513	471
3.00	499	465
5.00	499	458
7.00	492	417
9.00	485	380
11.00	478	343
13.00	458	314
15.00	440	295
25.00	390	268

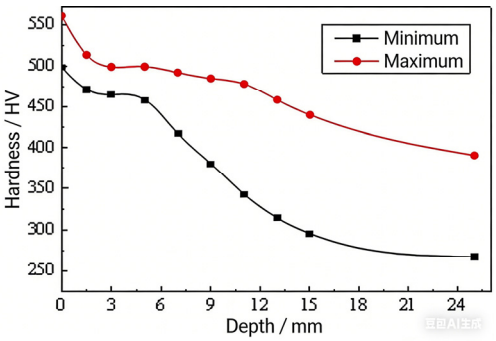


Figure 3. Hardenability curve of 25CrMo4

The depth-hardness relationship of 25CrMo4 after carburizing and quenching is shown in Figure 4:

The depth-stress relationship of the dangerous section with an inner diameter of 11mm is compared and analyzed with the depth-hardness of the structure after carburizing and quenching, and its function image is shown in Figure 5:

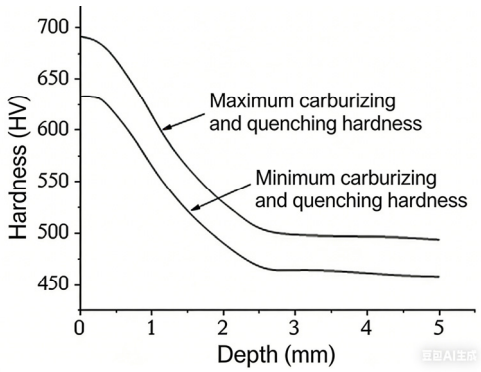


Figure 4. Depth-hardness of the constrained section of the transmission shaft

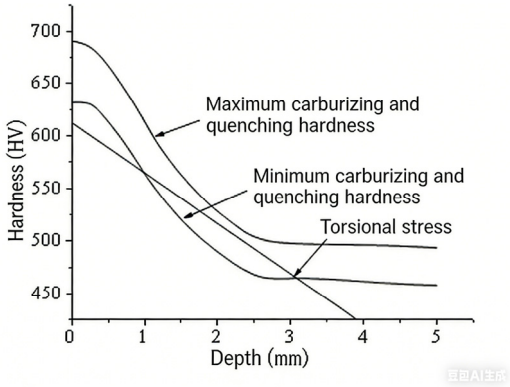


Figure 5. Depth-hardness comparison of 11mm inner diameter

It can be seen from the figure that when d=21.9mm, the internal hardness of the dangerous section is less than the torsional stress, which does not meet the design requirements, so the inner diameter of the product should be reduced.

By continuously changing the inner diameter parameter in the formula in Origin software and observing the change of the torsional stress curve, it is found that when d=21.6mm, the design requirements are just met. At this time, the stress curve and the mandrel-free hardness curve are shown in Figure 6:

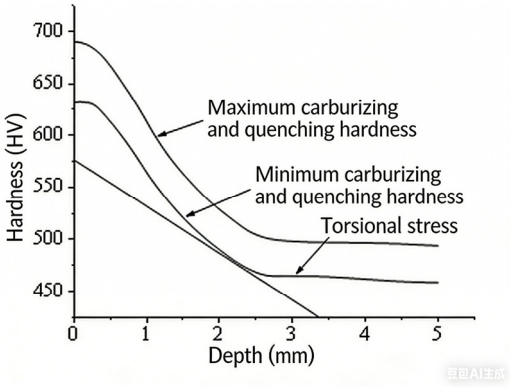


Figure 6. Depth-hardness comparison of 21.6mm inner diameter

To ensure the safety of the transmission shaft, referring to the inner diameter of the traditional product of the research group's research project, the inner diameter of the constrained section is initially taken as d=10mm.

4. Experimental Verification

Combined with the previous research results of the research group, it is determined that the single-pass radial feeding amount of 25CrMo4 material in rotary forging processing is 0.6mm, and for every 4.8mm of total radial feeding amount completed (i.e., 8 processing passes), the mandrel needs to be used for one support and rounding treatment to effectively ensure the forming quality of the inner surface.

In this study, the outer diameter of the rotary forging shaft blank is reduced from 37mm to 25.6mm, and the total unilateral radial feeding amount is 5.7mm. Combined with the above process requirements, the mandrel needs to be used for two times of support and rounding. To keep the roundness deviation of the inner surface uniform before the two mandrel supports, the node design of mandrel support is optimized as follows:

The first mandrel support and rounding are carried out when the radial feeding amount reaches 3mm (i.e., 5 processing passes);

The second mandrel support and rounding are carried out when the radial feeding amount reaches 5.7mm (i.e., 10 processing passes).

Process tests are carried out based on the above optimized parameters. The test results show that after adopting the composite rotary forging process of mandrel-free and mandrel-included, the total number of radial feeding passes of rotary forging is only 10, which is reduced by about 50% compared with 21 passes of the traditional mandrel-free rotary forging; the rotary forging processing time is shortened by about 50% synchronously, and the production efficiency is improved substantially; at the same time, the support and positioning function of the mandrel effectively avoids the problem of uneven inner diameter shrinkage, the roundness accuracy of the product inner diameter is significantly improved, there are no wrinkles, scratches and other defects on the inner surface, and the surface forming quality is fundamentally improved. The physical object of the product after test processing is shown in Figure 7.



Figure 7. Test photos

5. Conclusion

Taking the intermediate rotary forging shaft of constant velocity universal joint transmission of a car as the research object, aiming at the technical shortcomings of the traditional mandrel-free rotary forging process such as poor inner surface quality, low roundness and low production efficiency, this paper adopts the design idea of collaborative optimization of structure and process, improves the single mandrel-free rotary forging process to the composite rotary forging process combining mandrel-free and mandrel-included, and carries out systematic theoretical analysis and process tests through structural reconstruction, inner diameter size optimization and precise design of process parameters. The following core conclusions are finally obtained:

The improved composite rotary forging process has greatly streamlined the processing passes. The total number of radial

feeding passes of rotary forging is reduced from 21 to 10, a reduction of about 50%, and the rotary forging processing time is shortened by 50% synchronously, realizing a substantial improvement in production efficiency and adapting to the development goal of "high efficiency and high quality" in the manufacturing industry;

The inner diameter support and positioning function of the mandrel has fundamentally solved the problem of uneven inner diameter shrinkage in the traditional mandrel-free rotary forging, the roundness accuracy of the product inner diameter is significantly improved, the defects such as wrinkles and scratches on the inner surface are completely avoided, and the surface forming quality is greatly improved;

The optimal design of the inner diameter of the rotary forging shaft comprehensively considers the static strength requirements of the material and the hardenability characteristics after carburizing and quenching, and at the same time refers to the design parameters of mature products, which not only meets the mechanical property requirements, but also ensures the structural safety and reliability of the product during service.

The composite rotary forging process of mandrel-free and mandrel-included proposed in this paper provides a feasible technical scheme for the high-efficiency and high-precision manufacturing of rotary forging shafts. Its research results can provide theoretical support and experimental reference for the process optimization and design improvement of similar rotary forging shaft products in the fields of aerospace, rail transit, precision machinery and new energy equipment, and have important engineering application value for enhancing the core competitiveness of China's rotary forging shaft products.

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