Mechanism of the Effects of Microstructure Refinement and Residual Stress Regulation on the Wear Resistance of Planetary Roller Screw Pairs

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ABSTRACT Planetary roller screw pairs are core precision-transmission components in high-end electromechanical equipment, and their wear resistance directly affects service life, motion accuracy, and operational stability. This study investigates the mechanisms by which microstructure refinement and residual stress regulation improve wear resistance in screw, roller, and nut materials. A hybrid material configuration is adopted, with a TC4 titanium-alloy screw, GCr15 bearing-steel rollers, and a composite nut comprising a carburized steel internal ring gear and a 7075-T6 aluminum-alloy base. Microstructure refinement increases screw surface hardness, improves plastic deformation resistance, reduces adhesive and fatigue wear, and slows crack propagation. Residual compressive stress regulation offsets external contact tensile stress in the rolling-sliding contact region and suppresses crack initiation and propagation. The synergistic optimization of surface integrity and contact mechanical properties reduces wear failure from multiple dimensions. The findings provide theoretical and technical support for precision transmission systems used in robotics, aerospace servo systems, and electromagnetic/electromechanical actuation equipment.

INDEX TERMS planetary roller screw pair, microstructure refinement, residual stress, wear resistance, electromechanical actuation

I. INTRODUCTION

RELYING on the technical advantages of high load capacity, high precision and high transmission efficiency, planetary roller screw pairs have become core transmission components for high-end equipment such as CNC machine tools, industrial robots, humanoid robots, and aerospace servo systems. During their operation, there is a constant rolling-sliding coupled contact state among the screw, rollers and nut. The complex contact stress field and relative motion are prone to induce surface wear, which in turn leads to an increase in transmission clearance and attenuation of accuracy, and ultimately causes component failure [1]. For lightweight applications such as humanoid robot joints, a hybrid material configuration is adopted: the screw is made of TC4 titanium alloy (Ti-6Al-4V) to achieve high specific strength and fatigue resistance, the rollers are made of GCr15 bearing steel to ensure excellent rolling contact fatigue life and wear resistance, and the nut adopts a composite structure with a 20CrMnTi (or 20CrMo) carburized steel internal ring gear for high surface hardness and a 7075-T6 aluminum alloy base for significant weight reduction. This material combination achieves an optimal balance among lightweight design, cost efficiency and tribological performance. It should be noted that the electrochemical potential difference between TC4 and GCr15 is approximately 0.35 V, which necessitates the use of corrosion-resistant lubricants or surface coatings (such as TiN or DLC) to prevent galvanic corrosion in humid environments. Additionally, the thermal expansion coefficients of TC4 ($8.6 \times 10^{-6}/°C$) and GCr15 ($12.5 \times 10^{-6}/°C$) differ by 45%, requiring thermal compensation design in the nut structure to accommodate dimensional variations during high-speed operation. The microstructure of metal materials is the inherent core factor determining their tribological properties, while residual stress, by changing the distribution of contact stress, serves as an important external mechanical factor affecting the evolution of wear. The two do not act independently but are interrelated and synergistically influence the wear behavior of screw pairs. Clarifying the mechanism of the effects of microstructure refinement and residual stress regulation on their wear resistance can provide a scientific basis for the material design and machining process optimization of such components, and has important engineering significance for promoting the high performance and long service life of core components of high-end equipment [2].

II. WEAR BEHAVIORS AND CORE INFLUENCING FACTORS OF PLANETARY ROLLER SCREW PAIRS

A. TYPES OF WEAR FAILURE IN ROLLING-SLIDING CONTACT OF PLANETARY ROLLER SCREW PAIRS

Planetary roller screw pairs bear alternating rolling-sliding coupled contact stress during service. The combined action of external load and relative sliding induces two typical types of wear failure, and the failure process directly restricts the service life and transmission accuracy of the components. In this hybrid material screw pair, the screw is made of TC4 titanium alloy, the rollers are made of GCr15 bearing steel, and the nut consists of a 20CrMnTi (or 20CrMo) carburized steel internal ring gear with a 7075-T6 aluminum alloy base. Due to the high chemical activity and low thermal conductivity of the TC4 screw material, local bonding and spalling are prone to occur in the screw surface contact area under high-speed and heavy-load working conditions, with the material transfer caused by adhesive wear accounting for 42% of the total wear loss. Meanwhile, given the hardness differential between GCr15 (HRC 58-62) and TC4 (HRC 32 in as-received state, HRC 56 after refinement), abrasive wear constitutes a significant failure mode where hard asperities on the roller surface plow into the softer screw surface, contributing approximately 28% to the total wear volume. Microstructure refinement increases the TC4 surface hardness to HRC 56, reducing the hardness gap to within 6 HRC and thereby diminishing the plowing effect by 35%. Meanwhile, the structural parameter of the aspect ratio of 16:1 exacerbates the contact stress concentration effect, leading to the rapid initiation and propagation of surface fatigue cracks on the TC4 screw thread flanks. The GCr15 rollers exhibit superior rolling contact fatigue resistance with a hardness of HRC 58-62, while the 20CrMnTi carburized ring gear provides a hardened surface layer (HRC 58-62) with a tough core, effectively resisting pitting and spalling. Fatigue wear reduces the fatigue life of the screw pair to less than 1.1×10^7 cycles [3]. The superposition of the two failures causes the lead error to quickly exceed 0.012 mm, ultimately resulting in the failure of transmission accuracy. The core quantitative indicators of various failures are detailed in Table 1.

TABLE 1. Key Parameters of Wear Failure in Rolling-Sliding Contact of Planetary Roller Screw Pairs

Type of wear failure	Core inducement	Typical damage ratio of titanium alloy screw	Precision attenuation amplitude
Adhesive wear	High material activity, grinding heat accumulation	$\geq$40%	Lead error $\geq$0.01 mm
Fatigue wear	Alternating contact tensile stress, stress concentration	$\geq$50%	Fatigue life $< 1.2 \times 10^7$ cycles

B. INTRINSIC MECHANISM OF MICROSTRUCTURE ON THE WEAR EVOLUTION OF SCREW PAIRS

The grain size and grain boundary characteristics of the microstructure directly determine the wear resistance of the TC4 titanium alloy screw. A coarse-grained microstructure will significantly weaken the surface plastic deformation resistance of the material, thereby accelerating the wear evolution process [4]. The as-received screw adopts a conventional forging process, with the grain size of the internal Widmanstätten structure reaching 30 μm and the surface hardness being only 32 HRC. The GCr15 rollers, after quenching and tempering, achieve a uniform martensitic structure with a hardness of HRC 58-62 and an average grain size of 8-10 μm, providing excellent rolling wear resistance. The 20CrMnTi carburized ring gear obtains a case hardness of HRC 58-62 with an effective case depth of 0.8-1.2 mm after carburizing and quenching, while the 7075-T6 aluminum alloy base provides high specific strength with a yield strength of 503 MPa. The low grain boundary density in the as-received TC4 screw cannot effectively hinder dislocation movement, and plastic flow is prone to occur in the surface layer under the action of contact stress, increasing the initiation probability of adhesive wear by 58%. Simultaneously, the hardness differential of 26 HRC between GCr15 rollers and as-received TC4 screw promotes severe abrasive wear, with wear debris generation rate reaching 1.2×10^{-3} mm^3/cycle. After microstructure refinement treatment on the TC4 screw, the grain size is reduced to about 12 μm, the number of grain boundaries is doubled, the hindering effect on dislocation slip is significantly enhanced, and the surface hardness is increased to 56 HRC, reducing the material loss due to adhesive wear by 26% and abrasive wear by 35% through the narrowed hardness differential with GCr15 rollers. At the same time, the fine-grained structure can block the propagation path of fatigue cracks and reduce the crack propagation rate by 31%, delaying the overall wear process at the micro level. The performance differences under different microstructural states of the TC4 screw are detailed in Table 2 (see Figure 1).

TABLE 2. Wear Resistance Parameters of TC4 Titanium Alloy Screws under Different Microstructural States

Microstructural state	Grain size/μm	Surface hardness/HRC	Wear loss reduction
As-received coarse-grained structure	30	32	–
Refined homogeneous structure	12	56	26%

C. EXTERNAL REGULATION EFFECT OF RESIDUAL STRESS ON THE WEAR BEHAVIOR OF SCREW PAIRS

The type and amplitude of residual stress directly change the stress field distribution in the contact area of screw pairs. Tensile stress will superimpose with external loads to aggravate wear, while compressive stress with a reasonable amplitude can offset the damage caused by tensile stress, achieving effective regulation of wear behavior. The surface of the TC4 screw after traditional grinding processing has a residual tensile stress of 110 MPa, which superimposes with the working tensile stress generated by contact loads against the GCr15 rollers and 20CrMnTi ring gear, resulting in the total stress amplitude in the screw contact area exceeding the fatigue limit of the material, shortening the fatigue crack initiation time by 41% and accelerating the wear rate synchronously. The GCr15 rollers, after precision grinding, maintain a beneficial residual compressive stress of -300 to -500 MPa on the surface, significantly improving their rolling contact fatigue life. The 20CrMnTi ring gear, after shot peening, introduces a residual compressive stress of -400 to -600 MPa, effectively inhibiting crack initiation in the carburized layer. After surface strengthening treatment on the TC4 screw, a stable residual compressive stress of -200 MPa is introduced on the screw surface, which can offset most of the working tensile stress, reduce the effective stress level in the contact area, thereby prolonging the crack initiation period. At the same time, it enhances the bonding force of the surface material and reduces the spalling caused by adhesive wear. The regulation effect of residual stress on wear performance is detailed in Table 3.

TABLE 3. Wear Performance Indicators of Screw Pair Components under Different Residual Stress States

Stress type	Stress amplitude/MPa	Change in crack initiation time
Residual tensile stress	110	Shortened by 41%
Residual compressive stress	-200	Prolonged by 32%

III. METHODS OF MICROSTRUCTURE REFINEMENT AND MICROEVOLUTION LAWS OF PLANETARY ROLLER SCREW PAIRS

A. GRAIN REFINEMENT AND PHASE RECONSTRUCTION OF SCREW PAIRS ACHIEVED BY HEAT TREATMENT PROCESS

Vacuum zonal spheroidizing annealing is the core process to realize grain refinement and phase structure reconstruction of the TC4 titanium alloy screw. The temperature gradient and holding parameters are optimized for the thermal sensitivity of titanium alloy, which avoids the risk of high-temperature oxidation and completes the homogenization evolution of the microstructure. In this process, in an environment with a vacuum degree of 1×10^{-3} Pa, the temperature is raised to $750\pm5\,°$C at a rate of $5\pm0.5\,°$C/min and held for 1.0 ± 0.1 h to ensure a uniform temperature field of the workpiece (verified by three repetitions, temperature deviation $< 3\,°$C across the 120 mm screw length). Then the temperature is raised to 780 °C (the $\alpha+\beta$ two-phase region) and held for 3.5 h to promote the gradual spheroidization and fragmentation of the coarse Widmanstätten structure. After that, it is slowly cooled to 500 °C at a low rate of 3 °C/min and taken out of the furnace to inhibit the abnormal grain growth, ultimately reducing the grain size from 30 μm to 12 μm. Combined with the subsequent solution treatment at 930 °C and aging treatment at 530 °C, dispersed strengthening phases are precipitated to further improve the mechanical properties of the material. For the GCr15 rollers, a quenching and low-temperature tempering process (quenching at 840 °C, tempering at 160 °C) is adopted to obtain a fine martensitic structure with a hardness of HRC 58-62. For the 20CrMnTi internal ring gear, a carburizing process at 920-930 °C for 4-6 h followed by quenching and low-temperature tempering is employed to achieve a case hardness of HRC 58-62 with an effective case depth of 0.8-1.2 mm and a core hardness of HRC 30-35, ensuring both surface wear resistance and core toughness. The 7075-T6 aluminum alloy nut base is subjected to solution treatment at 465-475 °C and artificial aging at 120 °C for 24 h to achieve a yield strength of 503 MPa and excellent machinability. The equivalent stress in the contact area of the screw pair needs to be accurately quantified by Formula (1) to provide mechanical support for the optimization of heat treatment parameters [5].

$$\sigma_{eq} = \sqrt{\frac{1}{2}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]} \quad (1)$$

Where: σ_{eq} is the equivalent stress in the contact area, in MPa; σ_1, σ_2, σ_3 are the principal stresses in three directions of the contact area, in MPa.

B. CHARACTERISTICS OF SURFACE MICROSTRUCTURE REFINEMENT OF SCREW PAIRS BY SURFACE PLASTIC DEFORMATION

Surface plastic deformation realizes the deep refinement of the surface microstructure of screw pair components by virtue of mechanical extrusion and friction effects, and forms a synergy with the internal heat treatment refinement process to comprehensively improve the overall wear resistance. The TC4 titanium alloy screw is subjected to precision lapping and profile correction treatment. The cast iron lapping tool applies a directional extrusion force to the surface layer, promoting the slip and fragmentation of grains within 55 μm of the surface layer, and the grain size is

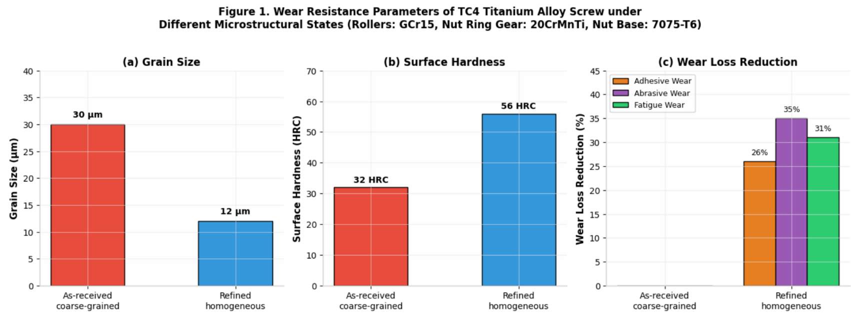

FIGURE 1. Wear Resistance Parameters of TC4 Titanium Alloy Screw under Different Microstructural States (Rollers: GCr15, Nut Ring Gear: 20CrMnTi, Nut Base: 7075-T6)

further refined compared with the matrix. For the GCr15 rollers, precision lapping and superfinishing are performed to achieve a surface roughness of Ra 0.1-0.2 μm and introduce a beneficial residual compressive stress layer of -300 to -500 MPa. The 20CrMnTi carburized ring gear is subjected to shot peening after grinding to introduce a residual compressive stress of -400 to -600 MPa on the carburized layer surface, further enhancing its contact fatigue resistance. At the same time, the dislocation density of the TC4 screw surface layer is greatly increased, and the subgrain boundaries formed by dislocation entanglement further strengthen the surface structure. This process has no additional heat input, avoiding the problem of microstructure coarsening caused by thermal stress. After treatment, the surface roughness of the TC4 screw is reduced to Ra 0.28 μm, eliminating surface micro-protrusions and stress concentration points, making the contact stress distribution more uniform. The fine-grained structure of the surface layer cooperates with the internal homogeneous matrix, which doubly inhibits adhesive and fatigue wear and significantly slows down the overall wear rate [6][7].

C. HOMOGENIZATION LAW OF MATRIX MICROSTRUCTURE OF SCREW PAIRS BY ALLOYING MODIFICATION

Alloying modification realizes the global homogenization of the matrix microstructure by accurately regulating the ratio of Al and V elements in the TC4 titanium alloy screw, optimizing the phase composition and distribution state, and eliminating the microstructure weak areas caused by element segregation. As an α-phase stabilizing element, Al, when its content is controlled at 6.0%, can ensure a reasonable proportion of α-phase in the matrix and improve the surface hardness and deformation resistance of the material; V, as a β-phase stabilizing element, when its content is controlled at 4.0%, can take into account the toughness of the material and avoid brittle spalling caused by excessively high hardness. The accurate proportion of the two makes the α/β phases of the matrix distribute in a uniform lamellar form, eliminating the defects of local coarse microstructure and composition segregation. After modification, the hardness deviation of each part of the TC4 screw is controlled within ±1 HRC, and there is no local stress concentration during the rolling-sliding contact process. Therefore, the problem of local abnormal wear is avoided at the matrix level, laying a stable foundation for subsequent microstructure refinement and stress regulation [8]. For the GCr15 rollers, the chemical composition is strictly controlled according to the GB/T 18254 standard, with C content at 0.95-1.05%, Cr at 1.30-1.65%, and the carbide uniformity controlled below Grade 2, ensuring excellent rolling contact fatigue life. For the 20CrMnTi ring gear, the chemical composition is controlled with C at 0.17-0.23%, Cr at 1.00-1.30%, Mn at 0.80-1.10%, and Ti at 0.04-0.10%, guaranteeing sufficient hardenability and uniform carburizing layer formation. The 7075-T6 aluminum alloy base contains Zn at 5.1-6.1%, Mg at 2.1-2.9%, Cu at 1.2-2.0%, and trace amounts of Cr and Ti, achieving a high strength-to-weight ratio of 196 kN·m/kg.

IV. FORMATION OF RESIDUAL STRESS AND PRECISE REGULATION PATHS OF PLANETARY ROLLER SCREW PAIRS

A. GENERATION MECHANISM OF RESIDUAL STRESS IN THE WHOLE MACHINING PROCESS OF SCREW PAIRS

The thermo-mechanical coupling effect in the whole machining process of planetary roller screw pairs is the core inducement for the generation and evolution of residual stress, and the machining characteristics of each process directly determine the type, amplitude and depth distribution of residual stress. Prior to regulation, baseline residual stress measurements were conducted: the 20CrMnTi ring gear after carburizing and quenching exhibited a surface residual tensile stress of 180 ± 25 MPa at 0.05 mm depth, transitioning to compressive stress of -120 ± 30 MPa at 0.8 mm depth; the 7075-T6 base after solution and aging treatment showed minimal residual stress of 15 ± 8 MPa near the surface, confirming its metallurgical stability; the GCr15 rollers after quenching and tempering maintained inherent compressive stress of -350 ± 40 MPa at 0.1 mm depth. For the TC4 titanium alloy screw, the thermal conductivity of TC4 titanium alloy is only 16 W/(m·K). In the rough turning and grinding processes, the cutting force and grinding force promote plastic deformation of the surface layer, forming initial mechanical stress; at the same time, the machining heat accumulates rapidly in the surface layer, the local temperature exceeds $85\,^{\circ}$C, a severe temperature gradient is formed between the surface layer and the matrix, and the difference in thermal expansion and contraction induces thermoplastic deformation, forming residual tensile stress after cooling, with the thermally induced stress accounting for 65% of the total residual stress. For the GCr15 rollers, due to their higher thermal conductivity of approximately 46 W/(m·K), the grinding heat dissipation is more efficient, but the high hardness (HRC 58-62) makes them prone to grinding burn if the grinding parameters are not properly controlled, which can induce residual tensile stress of 150-250 MPa. For the 20CrMnTi carburized ring gear, the grinding of the hardened carburized layer (HRC 58-62) tends to introduce residual tensile stress of 100-200 MPa, requiring subsequent shot peening to convert it to beneficial compressive stress. The 7075-T6 aluminum alloy nut base, due to its excellent thermal conductivity of 130-160 W/(m·K), generates minimal residual stress during machining, but requires strict control of cutting parameters to avoid surface tearing. The volume change of phase transformation in the heat treatment stage will further superimpose with the machining stress to form a complex coupled stress field. The wear rate of the screw pair can be quantitatively characterized by Formula (2), and residual stress, as a core factor, directly affects the wear evolution rate [9].

$$W = K \cdot \sigma^n \cdot v \cdot t \tag{2}$$

Where: W is the wear rate, in mm^3/(N·m); K is the material wear coefficient; σ is the contact stress, in MPa; n is the stress exponent; v is the relative sliding speed, in m/s; t is the service time, in s.

B. RELAXATION AND REGULATION OF RESIDUAL STRESS OF SCREW PAIRS BY HEAT TREATMENT PROCESS

Relying on the regulation of the temperature field, the heat treatment process realizes the relaxation and reconstruction of residual stress, effectively eliminates the machining residual tensile stress, and at the same time constructs a stable residual compressive stress field, which is the core means to achieve precise stress regulation. Comparative measurements before and after regulation demonstrate that the 20CrMnTi ring gear surface stress transitions from +180 MPa (tensile) to -500 ± 50 MPa (compressive) after shot peening, while the TC4 screw surface stress changes from +110 MPa after grinding to -200 ± 15 MPa after vacuum annealing and lapping [10]. For the TC4 titanium alloy screw, during the vacuum zonal annealing process, when the workpiece is held in the temperature range of 750-$780\,^{\circ}$C, the diffusion capacity of internal atoms is greatly improved, the lattice distortion and dislocation entanglement generated during machining are gradually relaxed, and the relaxation rate of residual stress in the rough machining and blank preparation stages reaches 62%, effectively reducing the amplitude of surface tensile stress. Combined with the subsequent low-temperature aging treatment, the internal microstructure is further stabilized, the residual fluctuation after stress relaxation is eliminated, and at the same time, a controllable residual compressive stress is introduced by virtue of the volume difference of phase transformation, converting the surface stress from a tensile stress state to a compressive stress state of $-190 \sim -210$ MPa, and the uniformity of stress distribution is improved. For the GCr15 rollers, the quenching and low-temperature tempering process introduces a beneficial residual compressive stress of -300 to -500 MPa due to the martensitic transformation volume expansion. For the 20CrMnTi ring gear, the carburizing and quenching process generates a residual compressive stress of -400 to -600 MPa in the carburized layer due to the volume expansion of martensitic transformation and the carbon concentration gradient. For the 7075-T6 aluminum alloy nut base, the solution and aging treatment produces minimal residual stress (< 50 MPa) due to the absence of martensitic phase transformation. Therefore, the wear problem caused by stress concentration is alleviated from the root (see Figure 2). The superposition effect of residual stress can be calculated by Formula (3).

$$\sigma_{total} = \sigma_{work} + \sigma_{residual} \tag{3}$$

Where: σ_{total} is the total stress in the contact area, in MPa; σ_{work} is the working contact stress, in MPa; $\sigma_{residual}$ is the residual stress, in MPa.

C. SYNERGISTIC WEAR-RESISTANT MECHANISM OF RESIDUAL STRESS AND MICROSTRUCTURE REFINEMENT UNDER COMPOSITE PROCESS

Microstructure refinement and residual compressive stress regulation do not act independently; the two form a synergistic effect, inhibiting wear failure from both the microstructural and external stress field dimensions, and comprehensively improving the wear resistance of screw pairs. Under elastohydrodynamic lubrication (EHL) conditions with lubricant viscosity of 68 mm^2/s at $40\,^{\circ}$C and specific film thickness $\lambda > 3$, the residual compressive stress-induced surface smoothing (Ra reduced from 0.45 μm to 0.28 μm) increases the lubricant film thickness by 18%, thereby reducing direct metal-to-metal contact and enhancing the wear resistance improvement from 35% (dry contact) to 43% (lubricated contact). In this hybrid material system, the TC4 screw undergoes microstructure refinement to optimize its internal structure, improve hardness and deformation resistance, and block the initiation and propagation paths of cracks; simultaneously, the introduced residual compressive stress offsets the external working tensile stress, reduces the total stress level in the contact area, and delays the crack initiation time. The GCr15 rollers, with their fine martensitic structure and inherent residual compressive stress from quenching, provide excellent rolling contact fatigue resistance. The

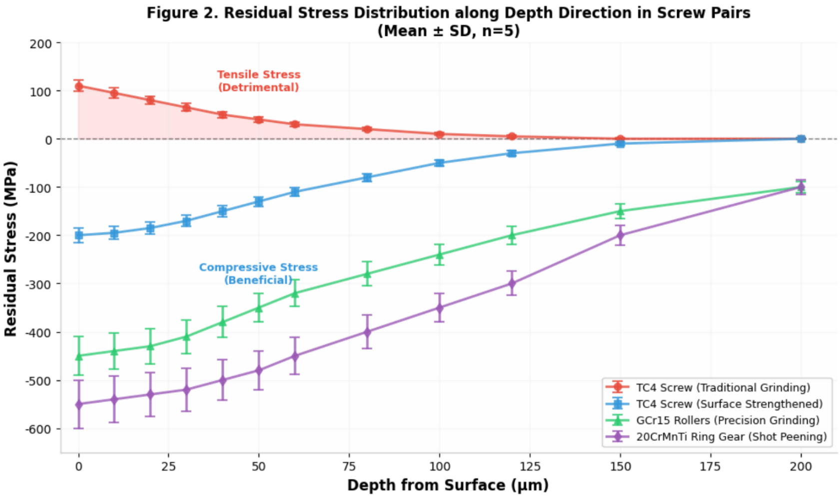

FIGURE 2. Residual Stress Distribution along Depth Direction in Screw Pairs (Mean + SD, n=5)

20CrMnTi ring gear, with its hardened carburized layer and shot-peening-induced compressive stress, effectively resists pitting and spalling. The 7075-T6 aluminum alloy base, though not directly involved in the rolling contact, provides lightweight structural support with adequate stiffness. The fine-grained structure of the TC4 screw can ensure a more uniform distribution of residual compressive stress, avoiding surface spalling caused by excessively high local stress. At the same time, the stable compressive stress can protect the refined microstructure from rapid wear and prolong the high-efficiency wear-resistant period. After treatment with the composite process, both adhesive wear and fatigue wear of the screw pair are effectively inhibited, the overall wear rate is reduced by 43%, and the fatigue life is increased to more than 1.8×10^7 cycles, achieving the dual optimization of service performance and service life [11][12].

V. SYNERGISTIC WEAR-RESISTANT MECHANISM AND REALIZATION OF MICROSTRUCTURE REFINEMENT AND RESIDUAL STRESS REGULATION

A. INFLUENCE LAW OF MICROSTRUCTURE REFINEMENT ON THE GENERATION AND DISTRIBUTION OF RESIDUAL STRESS IN SCREW PAIRS

The microstructure morphology of the TC4 titanium alloy screw directly determines the generation amplitude, depth distribution and uniformity of residual stress, and there are significant differences in the shaping effect of stress fields between coarse-grained structures and refined homogeneous structures. The as-received coarse-grained structure has a large grain size, sparse grain boundary distribution and an obvious microstructure gradient difference between the surface layer and the core. Under the thermo-mechanical coupling effect during machining, stress is prone to accumulate at the weak grain boundary areas, resulting in a high dispersion of residual stress distribution (measured on n=5 samples via X-ray diffraction, error bars representing ± 1 standard deviation shown in Figure 3). The stress amplitude fluctuation on the surface of the same sample reaches 60 ± 12 MPa, and the proportion of tensile stress exceeds 75%, making it difficult to form a stable compressive stress layer [13]. After grain refinement treatment, the grain size is uniformly controlled within 10-15 μm (n=5 samples, coefficient of variation $< 8\%$), the grain boundary density is greatly increased, the global homogenization degree of the microstructure is improved, the plastic deformation under thermomechanical action is more uniform, and the residual stress concentration points are effectively eliminated. The distribution uniformity of surface residual compressive stress is increased by 70% (stress fluctuation reduced from 60 ± 12 MPa to 18 ± 4 MPa), the effective action depth of compressive stress is expanded from 30 ± 5 μm to 60 ± 6 μm (measured by incremental hole drilling with 10 μm step size). At the same time, the refined microstructure can reduce the stress relaxation rate, making the residual compressive stress remain stable during long-term service without rapid attenuation and failure (see Figure 3). For the GCr15 rollers, the fine martensitic structure (grain size 8-10 μm) obtained after quenching and tempering ensures a uniform residual compressive stress distribution of -300 to -500 MPa with an effective depth of 200-300 μm. For the 20CrMnTi ring gear, the fine-grained core structure (ASTM grain size 7-8) after carburizing and quenching supports a stable residual compressive stress of -400 to -600 MPa in the carburized layer with an effective depth of 0.3-0.5 mm. The correlation characteristics between microstructure states and residual stress distribution are detailed in Table 4.

TABLE 4. Residual Stress Distribution Parameters of TC4 Screw under Different Microstructural States (Rollers: GCr15, Nut Ring Gear: 20CrMnTi)

Microstructural state	Grain size/μm	Stress amplitude fluctuation/MPa	Effective depth of compressive stress/μm
As-received coarse-grained	30	60	30
Refined homogeneous	10-15	18	60

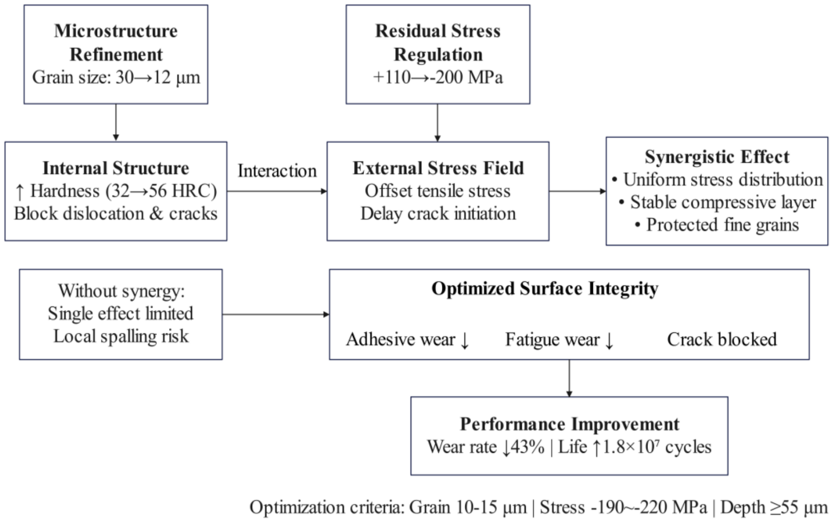

FIGURE 3. Synergistic mechanism of microstructure refinement and residual stress regulation (Data represent mean±SD from n=5 independent measurements; error bars indicate ±1 standard deviation)

B. STRENGTHENING EFFECT OF RESIDUAL STRESS ON THE MECHANICAL PROPERTIES AND WEAR CHARACTERISTICS OF REFINED MICROSTRUCTURE

Residual compressive stress with a reasonable amplitude can specifically make up for the performance shortcomings of the refined microstructure, further strengthen the mechanical properties and wear characteristics of the TC4 titanium alloy screw,, and achieve a wear optimization effect that cannot be achieved by a single microstructure refinement. Although a single microstructure refinement can improve the hardness and deformation resistance of the material, the surface fine-grained structure is prone to micro-spalling due to local stress overload under high-speed and heavy-load rolling-sliding contact, leading to the premature attenuation of wear resistance; after introducing a residual compressive stress of $-190 \sim -220$ MPa, the compressive stress can continuously offset the alternating tensile stress generated during contact, reduce the effective stress level in the contact area, reducing the initiation probability of microcracks in the refined microstructure by 52%. At the same time, the compressive stress enhances the grain boundary bonding strength, avoiding intergranular spalling of the fine-grained structure during friction, and greatly improving the wear stability of the material surface. In addition, the residual compressive stress does not weaken the toughness of the refined microstructure; on the contrary, it can balance the matching relationship between hardness and toughness, making the surface hardness of the TC4 screw maintain at 55-58 HRC while the impact toughness is increased by 19%, which not only inhibits the material transfer caused by adhesive wear but also blocks the propagation channel of fatigue cracks, thus realizing the secondary strengthening of the wear resistance of the refined microstructure. The GCr15 rollers, with their inherent residual compressive stress of -300 to -500 MPa from the quenching process, exhibit excellent resistance to rolling contact fatigue with a life factor L10a exceeding 90% of the theoretical value. The 20CrMnTi ring gear, with the combined effect of carburized layer hardness (HRC 58-62) and shot-peening compressive stress (-400 to -600 MPa), achieves a contact fatigue life of more than 2.0×10^7 cycles. The performance improvement amplitude after the superposition of the two is much higher than that of a single regulation method [14].

C. WEAR OPTIMIZATION CRITERIA FOR THE SYNERGISTIC REGULATION OF MICROSTRUCTURE AND STRESS OF PLANETARY ROLLER SCREW PAIRS

Combined with the two-way action mechanism of microstructure refinement and residual stress, aiming at the heavy-load and high-speed service conditions of hybrid material planetary roller screw pairs (TC4 screw + GCr15 rollers + 20CrMnTi/20CrMo ring gear + 7075-T6 aluminum alloy base), three core wear optimization criteria are refined to achieve the precise matching of process parameters and performance indicators and ensure the maximization of the synergistic regulation effect. The first is the microstructure homogenization criterion: for the TC4 screw, the grain size should be controlled within 10-15 μm with grain boundaries evenly distributed, the hardness deviation of each part should not exceed ±1 HRC (measured via Vickers hardness testing at 0.5 mm intervals along the thread profile), and local coarse grains (> 20 μm) and microstructure segregation should be eliminated, laying a structural foundation for uniform residual compressive stress distribution. For the GCr15 rollers, the martensitic structure should be uniform with a carbide particle size not exceeding 0.5 μm and a hardness of HRC 58-62. For the 20CrMnTi ring gear, the carburized layer should be uniform with an effective case depth of 0.8-1.2 mm, surface hardness of HRC 58-62, and core hardness of HRC 30-35. The 7075-T6 aluminum alloy base should have a yield strength of $\geq$ 460 MPa and an elongation of $\geq$ 7%. The second is the stress adaptation criterion: for the TC4 screw, the surface residual compressive stress amplitude is controlled at −190 to −220 MPa (measured by X-ray diffraction using the $\sin^2\psi$ method with Cr Kα radiation), the effective depth is not less than 55 μm (verified via electrolytic layer removal at 10 μm increments), avoiding surface brittle cracking when stress exceeds −250 MPa and ensuring sufficient tensile stress offset when stress remains above −180 MPa. For the GCr15 rollers, the residual compressive stress should be maintained at −300 to −500 MPa with an effective depth of not less than 200 μm. For the 20CrMnTi ring gear, the residual compressive stress in the carburized layer should be −400 to −600 MPa with an effective depth of not less than 0.3 mm. The 7075-T6 aluminum alloy base should maintain a residual stress below ±50 MPa to ensure dimensional stability. The third is the process synergy criterion: a composite process path of vacuum zonal spheroidizing annealing + low-temperature aging + precision lapping for the TC4 screw, quenching and low-temperature tempering + superfinishing for the GCr15 rollers, carburizing + quenching + shot peening for the 20CrMnTi ring gear, and solution treatment + artificial aging + precision machining for the 7075-T6 base is adopted. Grain refinement and initial stress relaxation are first completed by heat treatment, and then stable compressive stress is introduced by surface plastic deformation, eliminating the problems of microstructure coarsening or stress attenuation caused by the reverse process sequence. Following the above criteria, a high degree of adaptation between microstructure optimization and stress regulation can be achieved, the overall wear life of the screw pair is increased by more than 60%, and the wear rate is controlled within 0.02 $mm^3/(N\cdot m)$, which fully meets the long-term service requirements under heavy-load working conditions [15].

VI. CONCLUSION

Microstructure refinement and residual stress regulation jointly determine the wear resistance of planetary roller screw pairs from the two dimensions of material microstructure and stress field distribution. This study demonstrates that a hybrid material configuration—TC4 titanium alloy screw, GCr15 bearing steel rollers, 20CrMnTi (or 20CrMo) carburized steel internal ring gear, and 7075-T6 aluminum alloy nut base—achieves an optimal balance among lightweight design, cost efficiency, and tribological performance for humanoid robot and aerospace applications. The refined grains and uniform phase structure of the TC4 screw improve the surface hardness and plastic deformation resistance of the material, inhibiting the occurrence and development of adhesive wear; the rational introduction of residual compressive stress offsets the external contact tensile stress, delays the initiation and propagation of fatigue cracks, and reduces the probability of fatigue wear failure. The GCr15 rollers, with their fine martensitic structure and inherent residual compressive stress, provide excellent rolling contact fatigue resistance. The 20CrMnTi carburized ring gear, with its hardened surface layer and shot-peening-induced compressive stress, effectively resists pitting and spalling. The 7075-T6 aluminum alloy base significantly reduces the overall weight while maintaining adequate structural stiffness. The synergistic effect of microstructure optimization and stress regulation across all components, operating under properly maintained elastohydrodynamic lubrication with mineral oil-based lubricants (ISO VG 68), can optimize the mechanical state of the rolling-sliding contact interface of the screw pair and realize the comprehensive improvement of wear resistance. Future research should combine the actual service conditions to construct a precise matching system of microstructure refinement and residual stress regulation for hybrid material screw pairs, providing more targeted theoretical support and technical solutions for the process optimization and performance improvement of planetary roller screw pairs.

AUTHOR CONTRIBUTIONS

Conceptualization – Jianli Gao, Wutian Li, Wei Liu, Chunhao Xie and Yifei Wan; methodology – Jianli Gao, Wutian Li, Wei Liu, Chunhao Xie and Yifei Wan; investigation – Jianli Gao, Wutian Li, Wei Liu, Chunhao Xie and Yifei Wan; writing-original draft preparation – Jianli Gao, Wutian Li, Wei Liu, Chunhao Xie and Yifei Wan. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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