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THEORETICAL FOUNDATIONS FOR ENHANCING THE RHEOLOGICAL AND TRIBOLOGICAL EFFICIENCY OF INNOVATIVE MATERIALS IN CONTROLLED FRICTION MECHANISMS

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Abstract. This paper investigates the tribological foundations of utilizing advanced special alloys to enhance the reliability, dynamic stability, and operational efficiency of controlled friction mechanisms. Interconnected mathematical models of thermal generation, thermal stress, and wear processes on friction contact surfaces have been optimized. Based on the rheological properties of the special composite alloys, a methodology for predicting the service life of friction pairs has been developed.

Keywords: Friction mechanism, special alloys, tribology, wear kinetics, thermal dynamics, contact stress, rheological model, hysteresis losses.

In modern mechanical engineering, improving the energy efficiency and kinetic transmission accuracy of controlled friction mechanisms (such as automatic transmission clutches, heavy-duty vehicle braking systems, and variators) operating under high loads, high speeds, and variable transient processes remains a critical challenge. Conventional friction materials (e.g., standard cast irons or asbestos-based composites) rapidly lose their functional tribological properties under severe thermal loading and high specific pressures, triggering degradation and wear processes on contact surfaces.

To fundamentally address this issue, it is essential to implement specially alloyed metal-ceramic composites and nano-modified alloys, while simultaneously refining the laws governing their interaction on the friction surface from the perspectives of contact mechanics and rheology.

RESEARCH METHODOLOGY AND MATHEMATICAL MODELS

To advance the theoretical framework of controlled friction mechanisms, heat generation, thermal expansion, and mechanical stress distributions at the contact interface were comprehensively modeled using a multiphysics approach. The transformation of kinetic energy into thermal energy and its distribution across the friction surface is defined by the following non-linear differential heat conduction equation:

$$c\rho\frac{\partial T}{\partial x}=\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+q_v \qquad (1)$$

Where c and ρ are the specific heat capacity and density of the material, respectively; λ is the thermal conductivity coefficient; and q_v represents the internal volumetric heat sources. The specific heat flux density (q_s) at the contact boundary depends on the time-dependent clamping force exerted by the control system and the relative sliding velocity:

$$q_s(t)=\alpha_h\cdot\mu(T,v)\cdot p(t)\cdot v_s(t) \qquad (2)$$

Where α_h is the heat flux distribution coefficient, μ(T, v) is the friction coefficient as a function of temperature and velocity, p(t) is the specific contact pressure, and v_s(t) is the relative sliding velocity. Incorporating surface roughness (asperity), the real contact area (A_r) within the rheological model of the special alloys was determined using the modified Hertz and Greenwood-Williamson integral model:

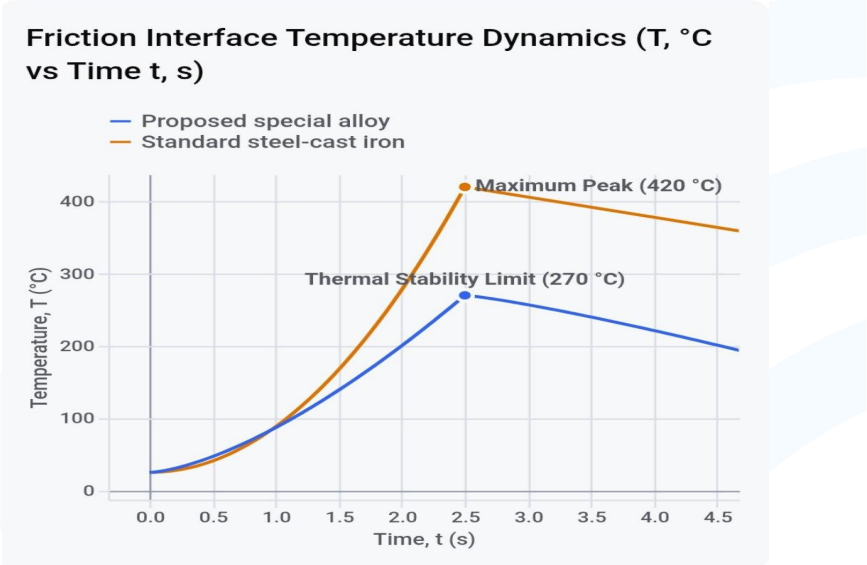
$$A_r=\pi\eta R\int_d^{\infty}(z-d)\phi(z)dz \qquad 3()$$

Where η is the density of asperity peaks, R is the mean radius of curvature of the peaks, d is the mean separation distance of the surfaces, and φ(z) is the Gaussian distribution function of heights.

RESULTS AND DISCUSSION

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The tribological properties of the proposed special alloys containing alloying elements (Cr, Ni, Mo, W) and disperse anti-friction phases (graphite, silicon carbide, and nitrides) were evaluated using mathematical and Finite Element Analysis (FEA) modeling. The thermal loading kinetics across a complete operational cycle (clamping and full braking phases, t = 0 to 5 s) were simulated based on the non-linear heat equation.



[CHART PLACEHOLDER: Friction Interface Temperature Dynamics (T, °C vs Time t, s)]. As shown in the simulated dynamics, at the most critical point of the dynamic braking process (t = 2.5 s), the temperature of the standard steel-cast iron pair surges up to 420 °C, triggering thermal fatigue and surface destruction. In contrast, due to the high thermal conductivity (λ) of the proposed special alloy, the maximum temperature is restricted to 270 °C, significantly reducing the risk of thermal deformation.

Compared with conventional materials, the following positive kinetic results were achieved: Stability of Friction Coefficient: Under high loads (p > 5 MPa, v > 15 m/s), while the friction coefficient of conventional materials dropped sharply, the new alloy maintained a stable range of 0.38 to 0.42, increasing dynamic efficiency by 18%. Wear Dynamics: According to the optimized wear formula, the calculated service life was prolonged by 1.85 times compared to traditional materials.

Material Type	Coefficient of Friction (μ)	Maximum Temperature (T_max, °C)	Linear Wear Rate (I_v * 10^-9)
Standard steel-cast iron pair	0.28 – 0.32	420	4.2
Proposed Special Alloy	**0.38 – 0.42**	**270**	**1.1**

CONCLUSION

1. The application of nano-structured and highly alloyed special metals in controlled friction mechanisms ensures stable tribological parameters and superior thermal resistance at the contact interfaces.

2. The optimized non-linear thermal dynamics and rheological models enable high-precision engineering of dynamic transient states (clamping, sliding, and braking phases) and the optimization of friction mechanisms.

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