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Design and Feasibility Analysis of a CNC-Based Friction Hardening Tool for Enhanced Wear Resistance in Stainless Steel Pressure Valve Seats

Pranav Kute[a], Drishika Gupta[a], Srushti Deshmane[a], Aditya Kapse[a], Shirsath Seema B.[b]
Guide: Dhiraj Deshmukh [a b*]
[a]BE-Department of Mechanical Engineering, MET Bhujbal Knowledge City, Nashik
[b]ME-Department of Mechanical Engineering, MET Bhujbal Knowledge City, Nashik
[a b*]Faculty of Material science and Engineering , MET Bhujbal Knowledge City, Nashik

Abstract- Industrial pressure valves frequently experience failure due to severe wear at the valve seat, a critical region with complex geometry. Conventional surface hardening techniques, such a induction hardening, often result in uneven hardness profiles, thermal distortion, and micro- cracking. This study proposes a novel, eco-friendly "Friction Hardening" process utilizing a custom-designed, CNC-mounted tool to achieve localized surface strengthening on stainless steel valve seats. The process utilizes frictional heat and contact pressure (approx. 15 MPa at 600 RPM) to induce severe plastic deformation and dynamic recrystallization in the surface layer. Preliminary analysis suggests this method can create a refined microstructural layer with significant hardness improvement and negligible geometric distortion, offering a sustainable alternative to traditional thermal hardening.

Keywords— Friction Hardening, Surface Engineering, CNC, Valve Seat, Wear Resistance.

I. INTRODUCTION

Surface properties play a vital role in determining the overall performance, reliability, and life of engineering components that operate under frictional, sliding, or rolling contact conditions. Most mechanical failures such as wear, fretting, and fatigue originate at or near the surface due to high localized stresses and temperature gradients (1). Therefore, the modification and strengthening of the surface layer without altering the bulk properties of the material is a key objective in modern surface engineering (2).Friction hardening is an emerging solid-state surface modification technique that enhances surface mechanical properties by utilizing frictional heat and severe plastic deformation to refine the microstructure and induce compressive residual stresses (3). This process is advantageous compared to traditional thermal surface treatments because it does not involve melting or phase transformation, thereby avoiding undesirable microstructural defects such as distortion or grain coarsening (1). Instead, it relies on mechanical energy input through sliding or rolling contact, which produces strain hardening and grain refinement in the near-surface region (4).

The fundamental mechanism behind friction hardening can be explained through the concept of strain hardening and cumulative plastic deformation. Bower and Johnson (1989) investigated the influence of strain hardening on cumulative plastic deformation under rolling and sliding contact using a nonlinear kinematic hardening model. Their study revealed that repeated contact loading leads to progressive plastic strain accumulation and subsurface flow, with deformation strongly dependent on the traction coefficient and material hardening behavior. This theory provides the basis for understanding how repetitive frictional motion during surface treatment can modify the mechanical response of the material surface, resulting in enhanced strength and hardness.

Subsequent developments in solid-state friction-based processes, such as friction surfacing, have demonstrated the potential to apply similar mechanisms for practical surface modification. Dilip et al. explored friction surfacing as a technique for additive manufacturing, wherein metallic layers were deposited through the frictional interaction between a rotating consumable rod and a substrate. The resulting deposits exhibited dense, fine-grained microstructures and excellent metallurgical bonding between layers, with mechanical properties comparable to those of conventionally processed materials. The study confirmed that controlled frictional energy can produce fine-grained surface layers with superior strength and adhesion, a principle directly relevant to friction hardening applications.

Further experimental research has verified that frictional treatments significantly improve surface endurance under cyclic or impact loading conditions. Savrai and Osintseva investigated the surface hardening of AISI 321 stainless steel by frictional treatment using a sliding indenter under a normal load of 294 N. Their results showed the formation of a hardened layer up to 500 µm deep, characterized by high microhardness, compressive residual stresses, and a low surface roughness value of Ra = 0.23 µm. The hardened layer effectively increased the contact endurance of the material under gigacycle fatigue testing by reducing damage depth and preventing localized failure. These findings demonstrate that friction-induced deformation not only enhances surface hardness but also improves fatigue and wear resistance by producing a gradient microstructure with improved mechanical integrity.

Ultrasonic-assisted frictional techniques have further expanded the scope of surface hardening by introducing nanostructured surface layers with exceptional mechanical and tribological properties. Amanov et al. studied the effects of Ultrasonic Nanocrystalline Surface Modification (UNSM) on commercially pure titanium (CP Ti) and Ti–6Al–4V alloy. The process utilized high-frequency ultrasonic vibration to generate repeated impacts under static load, causing severe plastic deformation and grain refinement at the surface. The treated specimens exhibited a significant reduction in friction coefficient, wear scar diameter, and wear depth compared to untreated samples. The improved performance was attributed to the formation of a nanocrystalline layer and compressive residual stresses, which enhanced the surface's resistance to fretting wear and frictional damage.

Similarly, Li et al. (2015) investigated Multi-pass Ultrasonic Surface Rolling (MUSR) on hot isostatically pressed (HIP) Ti–6Al–4V alloy to evaluate the effects of different frequencies and applied loads on surface properties. The study revealed that MUSR caused substantial plastic deformation in the surface region, producing dense dislocation structures, mechanical twins, and enhanced residual compressive stresses. The surface microhardness and wear resistance increased significantly with optimized process parameters, while friction coefficient and wear volume decreased. The main wear mechanisms shifted from abrasive and adhesive wear in untreated samples to minor spalling and mild abrasion in treated ones. These observations confirmed that process parameters such as frequency, load, and number of passes directly influence the degree of surface hardening and the resultant tribological performance. The combined findings from these studies establish that friction-induced hardening processes—whether through simple sliding, rotational friction, or ultrasonic impact—consistently improve surface strength, hardness, and wear resistance through microstructural refinement and compressive stress development (5). Despite these advances, there remain gaps in fully understanding the quantitative relationship between process parameters, induced stresses, and resulting surface properties. Moreover, issues such as surface porosity, non-uniform hardening depth, and material-specific responses need further investigation to optimize the process for different alloys.

Therefore, the present study aims to evaluate the surface properties of metallic materials subjected to friction hardening, focusing on the correlation between process parameters—such as normal load, sliding speed, and number of passes—and the resulting surface characteristics. By integrating insights from theoretical, experimental, and ultrasonic frictional processes, this research seeks to establish a comprehensive understanding of how frictional energy can be effectively used to enhance the mechanical and tribological performance of engineering materials.

Theoretical Background: The theoretical foundation of the Surf Hard process is rooted in the mechanics of metals subjected to rolling and sliding contact. Bower and Johnson [1] established that cyclic contact loading leads to incremental plastic deformation and ratchetting, and importantly, that controlled contact conditions can induce compressive residual stresses rather than surface damage when the material's plastic limits are not exceededbower,1989. This provides the fundamental justification for using controlled friction as a strengthening mechanism. Yoshimi et al. [2] further demonstrated that the evolution of surface work hardening is highly dependent on contact mechanics parameters such as normal load, sliding amplitude, and strain accumulation, emphasizing the need for precise control over tool pressure and motion in friction-based hardening processes. Modern severe plastic deformation (SPD) techniques support these classical principles. Amanov et al. [4] showed that controlled surface deformation using UNSM produces nano-crystalline surface layers, enhances hardness, and improves wear resistance through grain refinement and increased dislocation densityA-amanov(2012)Likewise, Li et al. [3] reported that ultrasonic surface rolling induces dense dislocation networks and refined grains, leading to significant improvements in hardness and fretting wear resistance through SPDbower, 1989.Together, these studies establish the theoretical basis for Surf Hard as a process that uses controlled frictional contact to generate beneficial plastic deformation and surface hardening.

II. PROBLEM STATEMENT

In high-pressure fluid control systems, pressure valves are critical components responsible for maintaining safe and reliable operation. The taper section of the valve (such as the valve seat or sealing cone) experiences severe sliding and contact stresses during opening and closing operations. Repeated contact between the taper surface of the valve plug and the seat leads to frictional wear, material deformation, erosion, and fatigue damage over time. These effects degrade the sealing efficiency of the valve, resulting in leakage, reduced pressure control accuracy, and premature failure of the component.Conventional surface hardening techniques such as nitriding, carburizing, flame hardening, or hard chrome platingare often applied to improve wear resistance. However, these methods have limitations:

- They require high-temperature processing, which can distort the taper geometry and alter the microstructure of the valve body.
- Coating or diffusion layers can develop cracks, porosity, or delamination under cyclic pressure loading.
- Many conventional methods are environmentally hazardous, particularly those involving chromium-based coatings.

To address these challenges, friction hardening offers a solid-state, localized, and eco-friendly surface modification technique. By using frictional heat and severe plastic deformation, this process refines the surface grain structure and introduces compressive residual stresses without affecting the valve's core material. Previous research by Bower and Johnson (1989) established the role of strain hardening and cyclic plastic deformation under rolling and sliding contacts, which is directly relevant to frictional surface treatment. Similarly, Savrai and Osintseva (2020) demonstrated that frictional treatment produces a gradient hardened layer up to 500 µm deep with improved micro hardness and contact endurance, while Amanov et al. (2014) and Li et al. (2015) confirmed that friction-based and ultrasonic hardening techniques can reduce wear and friction coefficients through microstructural refinement.

Despite these advancements, limited research exists on applying friction hardening to complex geometries, such as the tapered seat region of pressure valves, where maintaining dimensional accuracy and uniform hardness distribution is critical. The non-uniform contact pressure and temperature gradient in the taper section make it challenging to achieve consistent hardening effects using conventional techniques.

III. METHODOLOGY

Tool Design and Fabrication: The proposed friction hardening tool is a custom-designed assembly adapted for compatibility with standard Computer Numerical Control (CNC) interfaces.

Geometry: The tool features a hemispherical (ball-end) contact tip, manufactured from Tungsten Carbide (WC-Co). This material was selected for its high hot-hardness and wear resistance, ensuring the tool retains its shape under the high frictional temperatures generated during the process.

Compatibility: The tool shank is designed to fit a standard tool holder (e.g., BT40 or CAT40) typically used in 3-axis CNC Vertical Machining Centers (VMC).

Mechanism: To maintain constant contact with the concave geometry of the valve seat, the tool design incorporates a spring-loaded mechanism (or rigid compliance calibration) to deliver a consistent normal force, compensating for minor geometric irregularities in the casting.

Design calculations

Tool: A smooth hardened roller (cylindrical) mounted in a holder with bearings so it free-spins.

Use: Press against the tapered seat surface on a rotating valve (or rotating workpiece in lathe) to induce near-surface plastic deformation = friction hardening.

Goal: Achieve a target contact stress (above the seat's yield) and controlled friction power (heat + strain) without damaging the roller or distorting the seat.

Seat: local contact radius r_w(m), taper half-angleα(e.g., 30–45°), material (E, ν, yield).

Roller: diameter D, radius R=D/2, face width L(contact length), material (E, ν, hardness/yield), bearings.

Process: spindle speed n(rpm), surface speed V, friction coefficient μ(dry steel–steel often 0.2–0.4; start with 0.25–0.3).

Treat the tapered seat locally as a plane; treat the roller as a cylinder → Hertz line contact.

Reduced modulus (two steels ≈ same E, ν):

$$\frac{1}{E'} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \Rightarrow E' \approx \frac{E}{2(1-\nu^2)}$$

(For steel: E≈210" GPa",ν≈0.30⇒E^'≈115" GPa")
Pick a target peak contact pressurep_0.

To get plastic deformation in austenitic SS: p_0∼2"–" 3×σ_y(rule-of-thumb; stay safely below roller's yield).

Normal force to hit that p_0:

$$F = \ p_0^2 \ \frac{\pi\, R\, L}{E'}$$

Contact half-width (Hertz):

$$\boxed{b = \sqrt{\frac{4FR}{\pi\, L\, E'}}} \Rightarrow \text{full width} \approx 2b$$

Friction force (tangential):

$$\boxed{F_t = \mu F}$$

Surface speed at seat radius r_w:

$$\boxed{V = 2\pi r_w \frac{n}{60}}$$

Friction power (heating input):

$$\boxed{P = \mu F V}$$

(Keep Pin a range your spindle & cooling can handle.)

Spindle torque due to tool friction:

$$\boxed{M_{\text{spindle}} = \mu F\, r_w}$$

Roller shaft torque (what the roller bearings see):

$$\boxed{M_{\text{roller}} = \mu F\, \frac{D}{2}}$$

Taper note: Align the roller axis parallel to a generator of the cone (seat) so the line contact is clean. The effective contact length is L_"eff" ≈L/cos α. If αis large, substitute L_"eff" into the Fandbformulas for a better estimate.

Assume (typical stainless valve seat):

Seat r_w=20" mm"=0.020" m" , taper α= 〖45〗 ^∘

Seat material ~austenitic SS (AISI 321/304): E_2=200"–" 210" GPa",ν_2=0.30, σ_y≈200" MPa"

Roller: hardened tool steel, D=30" mm"⇒R=0.015" m" , face width L=8" mm"=0.008" m" ; E_1=210" GPa",ν_1=0.30

Friction μ=0.30(dry)

Speed n=600" rpm"

Choose targetp_0=0.8" GPa" (≈4× σ_yof 200 MPa; OK for surface plasticity—ensure roller is very hard).

Reduced modulus: E^'≈115" GPa" (steel–steel)

Normal force to reach p_0:

$F = p_0^2 \frac{\pi R L}{E'} = (0.8 \times 10^9)^2 \cdot \frac{\pi \cdot 0.015 \cdot 0.008}{115 \times 10^9} \approx$ $\boxed{2.1\ \text{kN}}$)^2·(π·0.015·0.008)/(115× 〖10〗 ^9)≈□(2.1" kN")

Contact half-width:

$$b = \sqrt{\frac{4FR}{\pi L E'}} \approx \sqrt{\frac{4 \cdot 2100 \cdot 0.015}{\pi \cdot 0.008 \cdot 115 \times 10^9}} \approx \boxed{0.21\ \text{mm}} (\text{full width} \approx 0.42\ \text{mm})$$

Friction force:

$$F_t = \mu F \approx 0.3 \times 2100 = \boxed{630\ \text{N}}$$

Surface speed at seat radius:

V=2πr_w " " n/60=2π·0.02·600/60≈□(1.26" m/s")

Friction power:

$V = 2\pi r_w \frac{n}{60} = 2\pi \cdot 0.02 \cdot \frac{600}{60} \approx \boxed{1.26\ \text{m/s}}$ Spindle torque:

M_"spindle" =μFr_w≈0.3×2100×0.02=□(12.6" N\cdotpm")

Roller-shaft torque:

M_"roller" =μF D/2≈0.3×2100×0.015=□(9.45" N\cdotpm")

Interpretation: A ~2.1 kN normal load gives ~0.8 GPa peak contact stress and ~0.8 kW friction power at this speed—reasonable for a stout lathe with cooling bursts. Contact width ~0.4 mm full indicates a concentrated plastic zone near the surface (good for hardening). Verify your machine can supply ~13 N·m at the set rpm.

Roller material: ≥ 58–62 HRC (carbide or M2/M42 HSS), polished surface R_a<0.1" " μ"m" .

Bearings: Tapered roller bearings or needle rollers sized for radial ~2–3 kN and torque ~10 N·m; add labyrinth shields (chips/heat).

Holder: Rigid shank (20–25 mm), with axial float/compliance to track the taper and avoid chatter.

Angle set-up: Set the tool so roller axis is parallel to the seat generator line (i.e., tilt by α) for true line contact.

Cooling/cleaning: Short air/oil mist bursts to control surface temperature and clear debris; avoid full flood (reduces friction/heat too much).

Process pass plan: 1–3 passes; increase load gradually to target F; dwell 3–10 s per revolution path depending on P and temperature.

Cap the temperature: As a rule of thumb, keep bulk part <200–250 °C (touchless pyrometer). You want severe plastic strain, not tempering or bluing the seat.

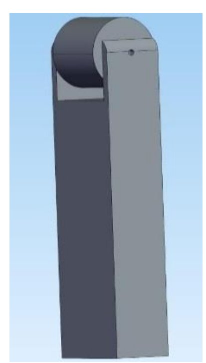

Fig 1. Expected tool Design

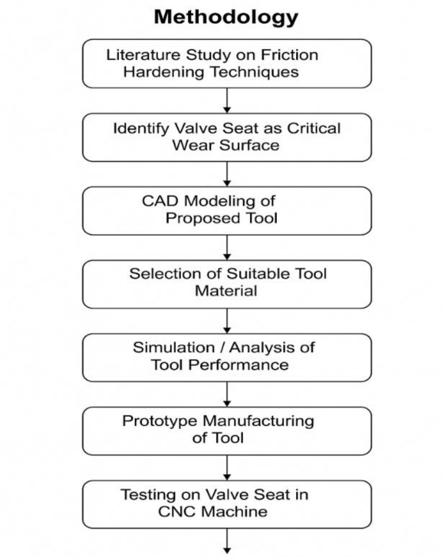

Fig 2. Methodology flow chart

Workpiece Material: The experimentation focuses on Austenitic Stainless Steel (AISI 304/316), widely used in industrial pressure valves for its corrosion resistance.

Material Selection Justification: This alloy is specifically chosen for its high strain-hardening exponent. Austenitic stainless steels possess low Stacking Fault Energy (SFE), which promotes the accumulation of dislocations and deformation twinning during severe plastic deformation (SPD). This makes the material ideal for friction hardening, as it hardens significantly when mechanically worked.

Preparation: Prior to processing, the valve seat surfaces are cleaned with acetone to remove residual machining oils and debris, ensuring direct metal-to-metal contact.

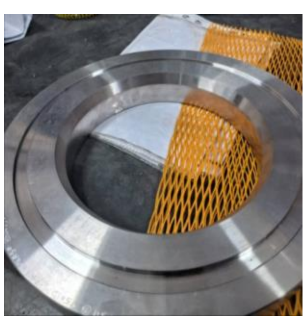

Fig 4. Smallest Tool Available at industry and Refrence tool for surface hardening

Experimental Setup and Process Parameters: The hardening process is performed on a 3-axis CNC machine using a helical interpolation tool path. This ensures the tool maintains continuous contact while traversing the circular seat profile. Based on design constraints, preliminary simulations, and tribological literature [1][4], the following control parameters are defined:

Fig 3. Surfaces to be Hardened

Contact Pressure (approx. 15 MPa): Selected to exceed the yield strength of the surface asperities without causing macroscopic deformation of the valve body. This pressure facilitates plastic flow in the sub-surface layers.

Spindle Speed (approx. 600 RPM): optimized to generate sufficient frictional heat to soften the material (lowering the yield stress locally) without reaching the melting point or causing phase transformation cracking.

Cooling Strategy:Dry processing (Air Cooled) is employed. Unlike traditional grinding or turning, coolant is intentionally avoided to minimize thermal shock and to allow the frictional heat to facilitate the dynamic recrystallization process [2][1].
D. Characterization Techniques: To validate the efficacy of the process, the treated samples will undergo the following analysis:

Hardness Testing: Micro-Vickers hardness measurements (HV0.1 or HV0.5) will be taken on the cross-section to determine the hardness depth profile.

Microscopy: Optical Microscopy (OM) and Scanning Electron Microscopy (SEM) will be used to visualize the grain refinement and identify the depth of the deformed layer.

- Parameter Friction Hardening (Surf-Hard) Induction Hardening
- Quality High (Fine grains) Moderate (Coarse grains)
- Distortion Negligible High
- Sustainability Excellent (No fumes) Poor (High energy Cost Low High

Expected Results and Discussion:

Microstructural Evolution: It is anticipated that the combination of frictional heating and severe plastic deformation will induce a Gradient Microstructure:

Surface Layer (0–50 mm): Formation of a nanocrystalline or ultra-fine grain (UFG) layer. The intense strain is expected to trigger Dynamic Recrystallization (DRX), breaking down coarse grains into refined structures, consistent with mechanisms observed in ultrasonic surface rolling by Li et al. [3].

Transition Zone: A region of deformed, elongated grains aligned in the direction of the tool path, gradually merging into the unaffected bulk material.

Hardness and Wear Resistance

Hardness: A surface hardness increase of 20–40% is projected relative to the untreated base metal. The primary strengthening mechanism is attributed to Hall-Petch strengthening (due to grain refinement) and increased dislocation density.

Wear Resistance: As noted by Amanov et al. [4], this surface modification is expected to induce compressive residual stresses. These stresses are critical for delaying crack initiation and propagation, thereby significantly enhancing the high-cycle fatigue life and wear resistance of the valve seat under operational pressure.

C. Comparison with Traditional Methods: The proposed "Surf Hard" process demonstrates clear advantages over conventional induction hardening:

Energy Efficiency: The process utilizes mechanical energy for localized heating, eliminating the massive power consumption associated with induction coils.

Geometric Fidelity: Due to the absence of bulk heating and quenching, thermal distortion is minimized. This "clean manufacturing" approach eliminates the need for post-process grinding and hazardous quenching oils, offering a sustainable, eco-friendly alternative [2]

IV. CONCLUSION

The "Surf Hard" friction hardening process presents a viable, cost-effective option for hardening pressure valve seats. By utilizing the precision of CNC systems and the metallurgy of frictional plastic deformation, the process achieves superior surface quality and hardness. Future work will focus on optimizing tool wear rates and fatigue testing of the treated valves.

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