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Modern Approaches to Extend Tool Life: A Review on Duplex Treatment of AISI H13 Tool Steel

Umesh Subhash Patharkar[1*] and Sunil Apparao Patil[2]

[1]Mechanical Engineering, Government College of Engineering, Aurangabad, Maharashtra, India
[2]Mechanical Engineering, Government College of Engineering, Jalgaon, Maharashtra, India

*Corresponding author: sakpatil67@yahoo.co.in

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ABSTRACT

AISI H13 tool steel serves various high-temperature and high-wear industrial purposes including forging and die casting and extrusion operations. Such operating conditions commonly result in premature wear and thermal stress damage of the material despite its excellent properties. A combination of gas nitriding treatment with following hard coating deposition (including TiC CrN and AlTiN) represents a valuable approach to enhance surface hardness and improve wear resistance and extend tool life duration. The review presents an integrated summary of modern experimental approaches which start with material and sample processing methods before continuing to nitriding parameter plans and coating application techniques and extending through comprehensive surface assessment and mechanical testing stage. The paper explores two statistical optimization approaches called Taguchi analysis together with linear regression modeling for enhancing process optimization. The review investigates how microstructural changes relate to tribo-mechanical performance while proposing new research paths for improving duplex processing methods.

Keywords: AISI H13 tool steel, Duplex surface treatment, Gas nitriding, Coatings, Tribological performance, Wear resistance, Process optimization

The excellent toughness coupled with strength and thermal stability characteristics in tool steel AISI H13 enables its usage in high-temperature industrial applications like forging die

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casting and extrusion. The inherent properties of tool steels make them vulnerable to surface wear caused by abrasive conditions along with exposure to high temperatures and extended cycles of loading. The damage reduces service duration of the component while cutting down its operational performance together with higher maintenance expenses. Advanced surface modification techniques emerged to counteract the challenges that appear in the application. Duplex surface treatment stands out as a highly efficient advanced treatment method. The duplex treatment process consists of two ordered operations where gas nitriding initial treatment introduces nitrogen to steel surfaces to create iron nitrides along with diffusion gradients followed by PVD techniques for applying hard layers from TiC or CrN or AlTiN materials onto the nitrided surface. A nitrided layer behaves as a crucial interlayer that boosts both material surface hardness and binds better to added coatings for generating a functionally graded material platform. The research examines the experimental approach accompanying the tribological and mechanical performance assessments for AISI H13 tool steel after duplex treatment. The document explains the logic of choosing process parameters including nitriding time and temperature alongside the relationship between these variables and steel microstructural development which affects its mechanical and wear behavior. Different hard coatings applied to the nitrided substrate demonstrate their wear reduction and low friction abilities while sustaining high hardness according to this review.

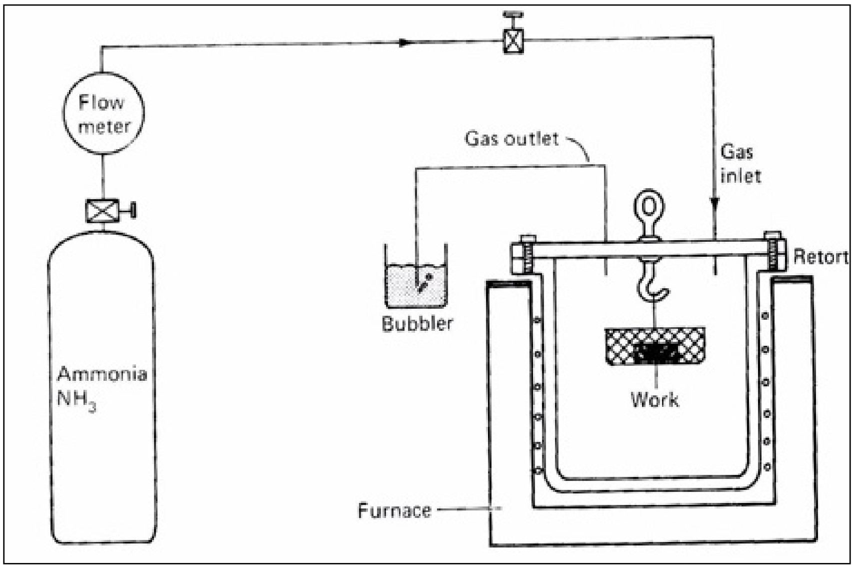

Fig. 1: Gas nitriding

The combination of nitriding treatment and hard coating application reduces surface delamination challenges by smoothing the mechanical property contrast between the softer base material and the harder surface layer. The review adopts an encompassing experimental setup that couples XRD with SEM and EDAX surface characterization and microhardness testing and wear rate evaluations with Taguchi methods and regression analysis for statistical optimization to create an optimized path toward superior tribo-mechanical outcomes of duplex surface treatments. This research aims to guide industry practitioners in creating superior tool steels that withstand extreme operating conditions by combining insights for future advancement.

Gas nitriding employs ammonia (NH3) as its nitrogen-rich donor thus earning it the alternative name of ammonia nitriding. The heated work piece exposure to ammonia leads to ammonia disassociation which produces nitrogen along with hydrogen elemental products. The surface diffusion of nitrogen occurs longitudinally towards the interior section of material. The traditional process first appeared in industrial applications almost a century ago but scientific exploration of its thermodynamic and kinetic aspects began intensively during the last few decades.

HEAT TREATMENT TECHNIQUES AND THEIR EFFECTS

Heat treatment is fundamental to enhancing the performance of tool steels. In AISI H13, conventional heat treatment—comprising austenitizing, quenching, and tempering—creates a martensitic matrix reinforced with finely dispersed carbides. However, residual stresses and retained austenite may adversely affect wear performance.

Conventional Heat Treatments

(a) **Austenitizing:** Heating AISI H13 to around 1000–1050°C transforms the microstructure to austenite, dissolving carbides partially.

(b) **Quenching:** Rapid cooling converts austenite into martensite, resulting in high hardness but also introducing brittleness.

(c) **Tempering:** Subsequent tempering (typically 500–600°C) relieves residual stresses, refines the carbide distribution, and enhances toughness without excessive loss of hardness.

Cryogenic Treatments

Cryogenic treatments supplement conventional heat treatments by cooling the steel to very low temperatures (typically using liquid nitrogen at −196°C). This additional step:

- **Reduces Retained Austenite:** Further converts residual austenite into martensite.
- **Refines Carbide Structure:** Promotes nucleation of ultra-fine carbides, improving wear resistance.

- **Relieves Internal Stresses:** Contributes to improved dimensional stability and reduced risk of brittle failure.

When combined with tempering, cryogenic treatment can significantly enhance the overall tribo-mechanical properties of AISI H13 tool steel.

Effects on Microstructure and Mechanical Properties

- **Increased Hardness:** Martensitic transformation and carbide precipitation yield a surface with high hardness, critical for resisting abrasive wear.
- **Enhanced Wear Resistance:** Fine, uniformly distributed carbides act as barriers to plastic deformation under sliding contact.
- **Optimized Toughness:** Tempering and cryogenic processing achieve a balance between hardness and impact resistance, reducing the risk of brittle fracture.
- **Residual Stress Management:** Controlled treatment processes minimize residual stresses, ensuring better dimensional stability and coating adhesion in subsequent duplex treatments.

DUPLEX SURFACE TREATMENT PROCESS

The duplex surface treatment process is a two-stage procedure designed to significantly improve the tribo-mechanical performance of AISI H13 tool steel. This approach integrates a diffusion-based surface modification method (gas nitriding) with the deposition of hard coatings using physical vapor deposition (PVD) techniques. The overall goal is to create a functionally graded surface where the nitrided layer acts as a robust interlayer to enhance coating adhesion and load-bearing capacity, while the hard coating provides additional wear and friction resistance.

Nitriding Treatment

In the first stage of the duplex process, the tool steel samples are subjected to a gas nitriding treatment. This process involves diffusing nitrogen into the surface at elevated temperatures, forming a hardened diffusion zone enriched with iron nitrides. Key steps include:

- **Parameter Variation:** Nitriding is performed at different temperatures (200°C, 300°C, and 400°C) and durations (12, 24, and 36 hours) to determine the optimum conditions for maximizing microhardness. The nitriding process results in a graded diffusion layer where the surface exhibits a significant increase in hardness compared to the core.
- **Optimization:** Through systematic testing, the optimal temperature–time combination is identified, ensuring a uniformly hardened layer without the excessive formation of brittle compound layers (often referred to as white layers). Once optimal parameters

Table 1: Comparison of Heat Treatment Techniques for AISI H13 Tool Steel: Process, Microstructure, and Mechanical Effects

Technique	Process Description	Microstructural Changes	Mechanical Effects	Advantages / Disadvantages
Conventional Heat Treatment	Austenitize (1000–1050°C) → Quench (oil/air) → Temper (500–600°C)	Austenitizing dissolves carbides and forms a uniform austenitic phase Quenching transforms austenite to martensite, creating a supersaturated, highly strained structure. Tempering precipitates fine carbides and reduces residual stresses; some retained austenite may remain if not optimized.	High hardness and strength; balanced toughness after proper tempering	Predictable, well-established process with controllable parameters. Risk of retained austenite or over-tempering leading to carbide coarsening if parameters are not carefully controlled.
Cryogenic Treatment	Deep cryogenic processing is applied after conventional quenching (typically at –196°C using liquid nitrogen) before or after tempering	Additional transformation of retained austenite to martensite. Promotion of ultra-fine carbide nucleation and refinement, leading to a more homogeneous microstructure.	Increases hardness and wear resistance; further reduces residual stresses and can improve fatigue performance	Enhances hardness and wear resistance beyond conventional treatments. Requires precise control to avoid embrittlement; additional processing cost and complexity.
Cryogenic Treatment	Deep cryogenic processing is applied after conventional quenching (typically at 196°C using liquid nitrogen) before or after tempering	Additional transformation of retained austenite to martensite. Promotion of ultra-fine carbide nucleation and refinement, leading to a more homogeneous microstructure.	Increases hardness and wear resistance; further reduces residual stresses and can improve fatigue performance	Enhances hardness and wear resistance beyond conventional treatments Requires precise control to avoid embrittlement; additional processing cost and complexity.
Plasma Nitriding	Surface treatment performed at 500–600°C in a controlled nitrogen-rich atmosphere (often using a mixture of N_2 and H_2) to diffuse nitrogen into the surface	Formation of a hardened diffusion layer enriched in iron nitrides (e.g., γ' and ε phases Development of a graded structure with fine nitrides and an increased concentration of nitrogen near the surface.	Increases surface hardness and wear resistance; improves load-bearing capacity and enhances subsequent coating adhesion	Produces a functionally graded surface that minimizes the mechanical mismatch between the substrate and later-applied coatings Requires precise process control to prevent formation of brittle compound (white) layers.

are determined, additional samples are processed using these conditions to provide a consistent substrate for the subsequent coating step.

Coating Deposition

Following nitriding, the next stage involves depositing hard coatings on the pre-treated surface. Three distinct coating TiC, CrN, and AlTiN are applied using a PVD process. Key aspects of this stage include:

- **Uniform Pre-treatment:** All samples used for coating are nitrided under the same optimized conditions to isolate the effect of each coating on performance. This uniformity is critical for direct comparisons between coatings.
- **Coating Application:** The PVD process is employed to deposit thin, dense films of TiC, CrN, or AlTiN onto the nitrided substrate. Each coating is expected to impart different benefits:
- **TiC:** Known for its excellent hardness and wear resistance.
- **CrN:** Offers a balanced combination of high hardness, low friction& superior corrosion resistance.
- **AlTiN:** Provides high oxidation resistance and outstanding thermal stability, making it particularly effective under elevated temperatures.
- **Process Consistency:** Parameters such as chamber temperature, bias voltage, and deposition time are maintained constant across all samples. This consistency ensures that differences in performance can be directly attributed to the inherent properties of the coatings rather than variations in the deposition process.

Integration and Functional Grading

The duplex treatment approach leverages the effects of nitriding and hard coating deposition:

- **Interlayer Functionality:** The nitrided layer not only enhances the surface hardness but also serves as a diffusion barrier that improves the adhesion of the subsequently deposited coating. This graded transition minimizes the mismatch in mechanical properties between the soft substrate and the hard coating, thereby reducing the risk of coating delamination during service
- **Enhanced Tribo-Mechanical Performance:** The final duplex-treated surface exhibits significantly improved resistance to abrasive wear and reduced friction coefficients under high-temperature conditions. The optimized nitriding followed by the appropriate coating selection results in a surface that can endure severe operating conditions, leading to extended tool life.

Table 2: Comparative Analysis of Coating Types for Duplex Surface Treatment of AISI H13 Tool Steel

Coating Type	Hardness	Friction Coefficient	Wear Resistance	Oxidation Resistance	Comments
TiC	Very High	Moderate–Low	Excellent	Moderate	Offers exceptional hardness and abrasive wear resistance; ideal in severe wear conditions but moderate oxidation stability.
CrN	High	Low	Good	Good	Provides balanced performance with low friction and good corrosion resistance; widely used for its overall robust performance.
AlTiN	Very High	Very Low	Excellent	Excellent	Exhibits outstanding thermal stability and oxidation resistance; particularly effective for high-temperature applications.
TiN	High	Low	Good	Moderate	Well-established for its low friction and decent hardness, though its oxidation resistance is lower than that of AlTiN.
TiCN	High to Very High	Low	Excellent	Moderate to Good	Combines the properties of TiC and TiN; improved hardness and wear resistance compared to TiN alone, with intermediate oxidation performance.
CrAlN	High	Low	Very Good	Good to Excellent	Incorporation of aluminum improves oxidation resistance and hardness over pure CrN, making it suitable for demanding service conditions.

CONCLUSIONS AND FUTURE DIRECTIONS

Conclusion

The combination of gas nitriding with hard PVD coating deposition through duplex surface treatment has shown itself as a reliable method for improving both tribo-mechanical properties of AISI H13 tool steel. Using gas nitriding for the generation of a diffusion layer with graded hardness results in improved surface properties of tool steel after high-performance coating deposition including TiC CrN AlTiN TiN TiCN and CrAlN layers. Key findings include:

1. The combined methodology produces stronger material because it forms iron nitrides in the diffusion layer which are strengthened by added surface coatings. Better microstructure development results in stronger abrasive wear performance according to the lower wear rates measured in optimized samples.

2. The nitridged interlayer creates an excellent bonding area which minimizes the mechanical conflicts between the base material and applied hard coating. Better adhesive properties along with minimized chance of delamination and improved load resistance capabilities become achievable through these service conditions.
3. AlTiN coatings display remarkably stable thermal behavior together with excellent resistance to oxidation which enables their application in high-temperature tool steel components because of their exposure to thermal cycling.
4. A combination of Taguchi design and linear regression modeling through statistical methods proves successful for discovering ideal nitriding and coating process parameters. The combination of statistical methods guarantees experimental results can be both duplicated and forecast with low variations between experimental and theoretical values.

Future Directions

Future studies need to determine how processing temperature along with nitriding time and N2:H2 ratios modify both the diffusion layer size and its microhardness. The use of in-situ diagnostics and advanced kinetic models helps explain the mechanisms of nitride formation and white layer development while making possible precise process control. The research will investigate modern multilayer and nanolayer coatings including TiC and CrN and AlTiN and TiCN and CrAlN to merge properties of hardness and wear resistance and improved thermal characteristics. The optimization of PVD deposition techniques alongside research about coating-substrate interfacial bonding will lower the chance of delamination failures. The research proposes to use Taguchi methods and response surface methodology for statistical and computational analysis of multi-variable processing conditions. Finite element modeling used with machine learning simulations enables the prediction of temperature gradients and residual stresses and microstructural evolution for data-driven duplex treatment optimizations. Repeated durability tests on duplex-treated surfaces should run under industrial conditions for an extended period to determine their service lifetime. Tests under different conditions involving instantaneous and long-term exposure to wet and corrosive substances combined with performance testing will enable predictions about sustained surface behavior. An investigation of the effects on residual stress levels microstructure and hardness of the treated surface during post-cladding machining which includes grinding and polishing operations. The research needs to protect all beneficial duplex treatment characteristics while upholding all application standards for the final surface. A program of industrial testing should be implemented through partnerships with industries to evaluate duplex-treated dies and molds under actual service conditions. An in-depth economic study between duplex treatment methods and conventional manufacturing processes needs to happen for determining practicality regarding costs and large-scale deployment options.

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