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Dry Machining of Super Duplex Stainless Steel 2507 Using Coated Tungsten Carbide Tools – A Review

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ABSTRACT

Super Duplex Stainless Steel (SDSS) 2507 offers exceptional mechanical strength and corrosion resistance, making it essential for offshore, chemical, and marine applications. However, its low thermal conductivity, high hardness, and rapid work hardening create significant machining challenges, particularly under dry conditions. This technical review comprehensively examines dry machining of SDSS 2507 using coated tungsten carbide tools, synthesizing recent research on coating technologies, tool wear mechanisms, and process optimization. Physical Vapor Deposition (PVD) coatings, especially AlTiCrN, AlTiN, and multilayer configurations deposited by advanced techniques like HiPIMS and S3p, demonstrate superior performance through formation of protective oxide layers that maintain cutting edge integrity up to 1100°C, achieving tool life improvements of 4-6 times over uncoated tools. Analysis of cutting parameters reveals feed rate as the dominant factor influencing flank wear (26.56% contribution), with optimal combinations yielding surface roughness below 1 µm. Statistical optimization methods including Taguchi design and ANOVA enable systematic parameter selection. Emerging technologies including textured tools, cryogenic treatment, and energy-assisted hybrid processes offer further potential. This review establishes that dry machining of SDSS 2507 with coated carbide tools is technically feasible and economically attractive, providing a sustainable alternative to conventional flood-cooled machining.

***Keywords*:- Super Duplex Stainless Steel 2507, dry machining, coated carbide tools, PVD coatings, tool wear, machinability, surface integrity**

1. INTRODUCTION

Super Duplex Stainless Steel (SDSS) 2507 (UNS S32750) represents the pinnacle of duplex stainless steel development, offering an exceptional combination of mechanical properties and corrosion resistance that surpasses conventional austenitic and ferritic stainless steels. The designation "duplex" refers to its dual-phase microstructure, consisting of approximately equal proportions of austenite (γ) and ferrite (α) phases in an alternating banded pattern [1, 2]. This unique microstructure provides SDSS 2507 with yield strength approximately twice that of austenitic grades like 316L, excellent pitting resistance equivalent numbers (PREN > 42), and outstanding resistance to stress corrosion cracking in chloride-containing environments [3, 4].

The chemical composition of SDSS 2507 typically includes 24-26% chromium, 6-8% nickel, 3-5% molybdenum, and 0.24-0.32% nitrogen, along with other alloying elements that contribute to its superior properties [5]. Table 1 presents the typical chemical composition and mechanical properties of SDSS 2507.

Table 1: Chemical Composition and Mechanical Properties of SDSS 2507

Property	Value
Chemical Composition (wt%)	
Chromium (Cr)	24.0-26.0
Nickel (Ni)	6.0-8.0
Molybdenum(Mo)	3.0-5.0
Nitrogen (N)	0.24-0.32
Carbon (C)	≤0.030
Manganese (Mn)	≤1.20
Mechanical Properties	
Tensile Strength	≥800 MPa

Yield Strength (0.2%)	≥550 MPa
Hardness	≤32 HRC
Elongation	≥15%

These exceptional properties make SDSS 2507 the material of choice for critical applications in offshore platforms, subsea equipment, chemical pressure vessels, desalination plants, pulp and paper industries, and marine engineering systems [2, 6]. However, the very characteristics that make it desirable—high strength, work hardening tendency, low thermal conductivity (approximately 15 W/m·K), and high ductility—render it extremely difficult to machine [7, 8].

Machining SDSS 2507 presents several fundamental challenges: rapid tool wear due to abrasive carbides, built-up edge (BUE) and built-up layer (BUL) formation from adhesive interactions, high cutting temperatures resulting from poor heat dissipation, work hardening during machining, and poor chip control [9, 10]. Traditional approaches to mitigate these issues involve extensive use of cutting fluids, which provide cooling, lubrication, and chip evacuation. However, the environmental and economic implications of cutting fluid usage—including disposal costs, health hazards to operators, and environmental pollution—have driven the manufacturing industry toward sustainable alternatives [11, 12].

Dry machining has emerged as a compelling solution that eliminates cutting fluids entirely, offering benefits such as reduced environmental impact, lower production costs, elimination of fluid-related health risks, cleaner work environments, and simplified chip recycling [13]. Sreejith and Ngoi [14] estimated that cutting fluids constitute 16-20% of total manufacturing costs, making their elimination economically attractive. However, dry machining of difficult-to-cut materials like SDSS 2507 requires advanced tooling solutions capable of withstanding the severe thermal and mechanical conditions encountered.

Coated tungsten carbide tools have proven to be the most effective solution for dry machining SDSS 2507. Physical Vapor Deposition (PVD) coatings, in particular, offer exceptional wear resistance, thermal stability, and tribological properties that address the specific challenges posed by this material [15, 16]. This review provides a comprehensive analysis of dry machining of SDSS 2507 using coated tungsten carbide tools, synthesizing findings from recent research to establish the current state of knowledge and identify future research directions.

2. MACHINING CHALLENGES OF SDSS 2507

2.1 Material Properties Affecting Machinability

The machinability of SDSS 2507 is governed by its unique microstructural and mechanical characteristics. The dual-phase microstructure, while beneficial for service performance, creates significant challenges during machining due to the different mechanical behaviors of austenite and ferrite phases [17].

a. Work Hardening Behavior: SDSS 2507 exhibits pronounced work hardening during machining, with strain hardening coefficients significantly higher than austenitic stainless steels [18]. Nomani et al. [19] demonstrated that the austenite phase undergoes greater plastic deformation than ferrite during chip formation, leading to localized hardening that accelerates tool wear. The work hardening rate increases with cutting speed, creating a self-perpetuating cycle of increasing cutting forces and temperatures.

b. Low Thermal Conductivity: With thermal conductivity of approximately 15 W/m·K at room temperature (compared to 50-60 W/m·K for carbon steels), SDSS 2507 acts as an insulating layer at the tool-chip interface [20]. Approximately 80-90% of the heat generated during machining is conducted into the tool rather than being carried away by chips, leading to elevated tool temperatures that accelerate wear mechanisms [21].

c. High Strength and Toughness: The high yield strength (550 MPa) and ultimate tensile strength (800 MPa) require higher cutting forces compared to conventional steels, increasing mechanical loading on cutting edges [22]. The material's toughness also promotes continuous chip formation, which maintains prolonged contact with the tool rake face and exacerbates adhesive wear.

d. Adhesive Tendency: SDSS 2507 exhibits strong adhesion to tool materials, particularly at elevated temperatures [23]. This promotes built-up edge (BUE) and built-up layer (BUL) formation, which alter effective tool geometry, increase cutting forces, and deteriorate surface finish. Sonawane and Sargade [24] confirmed through EDS analysis that workpiece material deposits on tool surfaces are a primary contributor to accelerated wear.

2.2 Tool Wear Mechanisms in SDSS 2507 Machining

The machining of SDSS 2507 activates multiple concurrent wear mechanisms that interact synergistically to degrade cutting tools [25, 26]:

a. Abrasive Wear: Hard carbide particles ($Cr_{23}C_6$, Mo_2C) present in the microstructure act as abrasive elements that mechanically remove tool material. This mechanism is particularly active on the tool flank face, where sliding contact with the freshly machined surface occurs under high pressure [27].

b. Adhesive Wear: The strong affinity between SDSS 2507 and tool materials promotes micro-welding at asperity contacts. Subsequent relative motion shears these junctions, often within the tool material itself, removing small particles and creating characteristic crater wear patterns [28].

c. Diffusion Wear: At elevated cutting temperatures (exceeding 900°C), atomic diffusion occurs across the tool-chip interface. Elements such as cobalt (binder) from the carbide substrate diffuse into the chip, while workpiece elements (Fe, Cr, Ni) diffuse into the tool, weakening the near-surface region and accelerating wear [29].

d. Notch Wear: A distinctive wear pattern observed in SDSS 2507 machining is notch formation at the depth-of-cut line, where the tool engages the work-hardened surface layer [30]. This is attributed to the severe work hardening of the machined surface, which creates a harder layer that aggressively wears the tool at the interface.

e. Plastic Deformation: Under combined thermal and mechanical loading, the cutting edge may undergo plastic deformation, particularly at higher cutting speeds where temperatures exceed the softening point of the tool material [31].

3. COATED TUNGSTEN CARBIDE TOOLS FOR DRY MACHINING

3.1 Coating Technologies: PVD vs. CVD

Two primary deposition technologies dominate the coating of tungsten carbide tools: Physical Vapor Deposition (PVD) and Chemical Vapor Deposition (CVD). Each offers distinct advantages and limitations for dry machining applications [32, 33].

1. Physical Vapor Deposition (PVD): PVD processes involve physical transfer of coating material from a source to the substrate in a vacuum environment. Key variants include cathodic arc evaporation, magnetron sputtering, and advanced techniques such as High-Power Impulse Magnetron Sputtering (HiPIMS) and Scalable Pulse Power Plasma (S3p) [34]. PVD coatings typically exhibit compressive residual stresses, fine-grained microstructures, and sharp cutting edges—characteristics highly desirable for finishing operations and machining sticky materials like stainless steels.
2. Chemical Vapor Deposition (CVD): CVD involves chemical reactions of gaseous precursors on heated substrate surfaces, producing coatings through decomposition and deposition. CVD coatings are typically thicker than PVD coatings (5-20 μm vs. 2-5 μm) and offer excellent adhesion and uniform coverage of complex geometries [35]. However, the higher deposition temperatures (900-1100°C) can degrade substrate toughness and create tensile residual stresses.

For dry machining of SDSS 2507, PVD coatings have demonstrated superior performance due to their lower deposition temperatures (preserving substrate toughness), smoother surfaces (reducing friction), and compressive residual stresses (enhancing fatigue resistance) [36]. Sonawane et al. [37] conducted a comprehensive comparison of PVD and CVD coatings for DSS machining, concluding that PVD-coated tools consistently outperformed CVD alternatives in terms of tool life and surface quality.

3.2 Advanced PVD Coating Techniques

Recent advances in PVD technology have produced coatings with exceptional properties suited for demanding dry machining applications [38, 39]:

1. High-Power Impulse Magnetron Sputtering (HiPIMS): HiPIMS utilizes extremely high power pulses (several kW/cm^2) with low duty cycles to generate dense, highly ionized plasmas. This produces coatings with exceptional density, smoothness, and adhesion [40]. Sonawane et al. [41] reported that HiPIMS-deposited AlTiCrN coatings exhibited defect-free microstructures with hardness of 38 GPa and adhesion strength of 110 N—significantly superior to conventional coatings.
2. Scalable Pulse Power Plasma (S3p): An advancement over HiPIMS, S3p combines evaporation and sputtering mechanisms to produce ultra-smooth, droplet-free coatings with enhanced mechanical properties [42]. The lower deposition pressures (1.33×10^{-7} Pa) minimize contamination, producing coatings with superior purity and performance. AlTiN coatings deposited by S3p have demonstrated tool life improvements of 37% compared to equivalent HiPIMS coatings [43].
3. Cathodic Arc Evaporation (CAE): While offering high deposition rates and excellent adhesion, conventional CAE can produce macroparticles (droplets) that degrade surface quality [44]. Modern filtered arc sources mitigate this limitation, making CAE viable for certain applications.

3.3 Coating Compositions for SDSS 2507 Machining

3.3.1 AlTiN and TiAlN Coatings

Aluminum-rich coatings have become the standard for dry machining applications due to their ability to form protective aluminum oxide layers at elevated temperatures [45, 46]. The performance of AlTiN coatings depends critically on the Al/Ti ratio. Zhao et al. [47] demonstrated that $Al_{0.59}Ti_{0.41}N$ coatings significantly outperformed lower aluminum content variants during dry machining of Inconel 718, with benefits including extended tool life, reduced cutting forces, and lower friction coefficients.

During machining, Al oxidizes preferentially to form a dense α-Al_2O_3 layer that:

- Acts as a thermal barrier, reducing heat flow into the substrate
- Provides chemical inertness, minimizing diffusion wear
- Maintains low friction coefficients at elevated temperatures
- Self-heals through continued oxidation [48]

Sonawane and Sargade [49] investigated AlTiN coatings deposited by HiPIMS for dry turning of DSS 2205, reporting 4-6 times improvement in tool life compared to uncoated tools. The coatings exhibited microhardness of 36 GPa and maintained stability up to 850°C.

3.3.2 AlTiCrN Quaternary Coatings

The addition of chromium to AlTiN systems produces AlTiCrN quaternary coatings with enhanced properties [50, 51]. Chromium contributes:

- Formation of dense Cr_2O_3 and mixed $(Al,Cr)_2O_3$ oxides with superior stability
- Enhanced hot hardness through solid solution strengthening
- Improved oxidation resistance up to 1100°C
- Lubricious characteristics that reduce friction

Sonawane et al. [52] conducted extensive characterization of AlTiCrN coatings deposited by HiPIMS for dry machining of DSS 2205. The coatings exhibited exceptional properties: microhardness of 38 GPa, adhesion strength of 110 N, surface roughness of 0.18 µm, and coefficient of friction of 0.30. In machining trials, AlTiCrN-coated tools achieved tool life of 124 minutes—3.6 times longer than uncoated tools and significantly better than AlTiN alternatives. The superior performance was attributed to the formation of protective $(Al,Cr)_2O_3$ oxides that maintained cutting edge integrity at elevated temperatures.

3.3.3 Multilayer Coatings

Multilayer architectures offer opportunities to combine the benefits of different materials while mitigating individual limitations [53, 54]. Common multilayer configurations include:

- TiN/TiAlN: Combines the adhesion of TiN with the oxidation resistance of TiAlN
- TiCN/Al_2O_3/TiN: Utilizes Al_2O_3 as a thermal barrier with TiCN providing wear resistance
- AlTiN/TiAlN: Alternating Al-rich layers to optimize properties

Krolczyk et al. [55] reported that multilayer coatings with an Al_2O_3 middle layer provided exceptional resistance to abrasive wear during DSS machining. However, Sonawane et al. [52] found that single-layer AlTiCrN deposited by advanced techniques outperformed multilayer CAE-deposited coatings (TiN/TiAlN and AlTiN/TiAlN), highlighting the importance of deposition method over layer count.

Akgun [56] compared uncoated, single-layer AlTiN, and two-layer TiCN-Al_2O_3 coated carbide inserts in turning of Invar 36 alloy. The two-layer coated insert demonstrated 30% and 60% better tool wear resistance compared to single-layer coated and uncoated inserts, respectively, with corresponding improvements in cutting forces and surface roughness.

Table 2: Comparative Performance of Coating Types for Stainless Steel Machining [52, 57]

Coating Type	Deposition Method	Hardness (GPa)	Adhesion (N)	Max Temp (°C)	Tool Life Improvement
AlTiN	HiPIMS	36	89	900	4×
AlTiCrN	HiPIMS	38	110	1100	6×
AlTiN	S3p	36	107	900	5×
TiN/TiAlN	CAE	24	77	798	2×
AlTiN/TiAlN	CAE	33	105	850	3.5×

3.3.4 Nanocomposite and Self-Lubricating Coatings

Emerging coating concepts include nanocomposite structures and self-lubricating systems [58, 59]. Nanocomposite coatings (e.g., nc-TiAlSiN) consist of nanocrystalline grains embedded in an amorphous matrix, providing exceptional hardness (exceeding 40 GPa) and toughness through grain boundary engineering [60].

Self-lubricating coatings incorporate solid lubricants (MoS_2, WS_2, carbon) that reduce friction at the tool-chip interface. Kumar et al. [61] investigated TiSiVN coatings for dry machining of Ti-6Al-4V, demonstrating that vanadium addition promoted formation of lubricious V_2O_5 at elevated temperatures, reducing adhesion and chip deformation by 18-23% compared to TiSiN coatings.

4. MACHINING PERFORMANCE AND PARAMETER OPTIMIZATION

4.1 Effect of Cutting Parameters on Tool Wear

Cutting parameters—cutting speed (vc), feed rate (f), and depth of cut (ap)—profoundly influence tool wear mechanisms and progression in SDSS 2507 machining [62, 63].

1. Cutting Speed: Increasing cutting speed accelerates tool wear through elevated temperatures that activate diffusion and oxidation mechanisms. Pawanr and Gupta [64] investigated dry turning of SDSS 2507 using TiAlN-PVD coated inserts across cutting speeds of 75-125 m/min, feeds of 0.04-0.18 mm/rev, and depths of cut of 0.4-1.2 mm. Their Taguchi L_9 experimental design revealed that flank wear increased monotonically with cutting speed, from 70 μm at vc=75 m/min, f=0.12 mm/rev, ap=0.8 mm to 515 μm at vc=125 m/min, f=0.18 mm/rev, ap=0.8 mm. ANOVA identified feed rate as the primary factor influencing tool wear (26.56% contribution), followed by depth of cut (16.29%) and cutting speed (13.30%). Sonawane and Sargade [49] observed similar trends during dry turning of DSS 2205 with AlTiCrN-coated tools. Increasing cutting speed from 100 to 180 m/min reduced tool life from 7840 mm to 4655 mm at constant feed (0.18 mm/rev), with higher cutting temperatures accelerating wear mechanisms.
2. Feed Rate: Feed rate directly influences mechanical loading on the cutting edge and the volume of material removed per unit time. Higher feeds increase cutting forces and temperatures, accelerating abrasive and adhesive wear. However, Pawanr and Gupta [64] noted a slight improvement in S/N ratio when increasing feed from 0.04 to 0.12 mm/rev, attributed to reduced BUE formation at intermediate feeds where tool-workpiece contact time decreases.
3. Depth of Cut: Increasing depth of cut expands the engaged cutting edge length, increasing total heat generation and mechanical loading. The quadratic term f^2 contributed 32.16% to flank wear variability in ANOVA, indicating non-linear relationships between feed and wear progression [64].

4.2 Surface Integrity and Quality

Surface roughness and integrity are critical quality indicators for SDSS 2507 components, particularly in corrosion-sensitive applications [65, 66]. Honess [67] demonstrated through salt spray testing that surface roughness exceeding 1 μm can significantly accelerate corrosion initiation in marine environments.

a. Influence of Cutting Parameters: Surface roughness generally improves with increasing cutting speed due to reduced BUE formation and more stable cutting conditions. Selvaraj et al. [68] reported that feed rate contributed 61% to surface roughness variability during dry turning of nitrogen-alloyed DSS, with cutting speed and depth of cut contributing 28% and 10%, respectively. Optimum conditions for minimal roughness were vc=100 m/min, f=0.04 mm/rev, ap=0.4 mm. Sonawane and Sargade [49] achieved surface roughness of 0.72 μm with AlTiCrN-coated tools at vc=140 m/min, f=0.12 mm/rev, representing 53% and 67% improvement over AlTiN-coated and uncoated tools, respectively. The superior performance was attributed to maintained cutting edge sharpness through protective oxide formation.

b. Built-Up Edge Formation: BUE is particularly problematic at lower cutting speeds where material adhesion dominates. Ahmed et al. [69] investigated BUE formation during turning of SDSS 2507 with uncoated carbide tools, finding that BUE size decreased with increasing cutting speed, with minimum BUE at 150 m/min. EDS analysis confirmed iron-rich deposits on tool surfaces, correlating with increased cutting forces and surface deterioration.

4.3 Cutting Temperature and Thermal Effects

Cutting temperature critically influences tool wear rates, surface integrity, and workpiece dimensional accuracy [70, 71]. Sonawane et al. [72] conducted comprehensive temperature measurements using infrared thermography during dry turning of DSS 2205 with various coated tools.

Temperature Dependence on Cutting Speed: Cutting temperatures increased significantly with cutting speed for all tool types. For TiN/TiAlN-coated tools, temperature increased from 898°C at vc=100 m/min to 1282°C at vc=180 m/min—a 43% increase. The rate of temperature increase accelerated at higher speeds, with 15% increase from 100-140 m/min and 21% increase from 140-180 m/min, reflecting non-linear friction behavior.

Temperature Dependence on Feed: Feed rate effects were less pronounced but still significant. Increasing feed from 0.12 to 0.18 mm/rev at vc=100 m/min produced 2-4% temperature increases across all tools. However, at vc=140 m/min, the same feed increase produced 12-14% temperature rises for coated tools, indicating synergistic interactions between cutting parameters.

Tool Coating Effects: Interestingly, uncoated tools exhibited the lowest cutting temperatures (746-945°C) despite having the shortest tool life. This paradoxical result arises from higher thermal conductivity of uncoated tools, which conducts heat away from the cutting zone into the tool body—simultaneously reducing measured surface temperatures while accelerating thermal softening of the tool substrate. Coated tools, with lower thermal conductivity, confine heat to the cutting zone where it contributes to workpiece thermal softening without degrading tool integrity [73].

Temperature Modeling: Sonawane et al. [72] developed a dimensional analysis-based temperature model following the Boothroyd approach:

$$\theta = Co \times (Sp/\rho cp)^m \times (Vc^2(\rho cp)^2 A_0/k^2)^n$$

Where Co, m, and n are experimentally determined constants (Table 3). The model predicted cutting temperatures within ±10% of experimental measurements, providing a valuable tool for process planning.

Table 3: Dimensional Constants for Temperature Model [72]

Tool Type	Co	m	n
Uncoated	43.3	-0.165	0.072
AlTiN (HiPIMS)	46.2	-0.106	0.091
AlTiN (S3p)	18.26	-0.150	0.116
TiN/TiAlN	23.55	-0.550	0.138

4.4 Cutting Forces and Power Consumption

Cutting forces reflect the mechanical energy required for material removal and correlate with tool condition, surface quality, and power consumption [74, 75].

Influence of Coating Type: Sonawane and Sargade [49] measured cutting forces during dry turning of DSS 2205, finding that AlTiCrN-coated tools required 13% lower cutting forces than AlTiN-coated tools and 67% lower than uncoated tools at vc=140 m/min, f=0.12 mm/rev. The force reduction was attributed to:

- Lower coefficient of friction (0.30 for AlTiCrN vs. 0.35 for AlTiN)
- Maintained sharp cutting edge through oxide protection
- Reduced BUE formation

Influence of Cutting Parameters: Cutting forces generally decrease with increasing cutting speed due to thermal softening of the workpiece material. Sonawane and Sargade [49] observed force reductions of 8-14% when increasing cutting speed from 100 to 180 m/min, with the greatest reductions for AlTiCrN-coated tools.

Feed rate increases produce proportional increases in cutting forces due to larger undeformed chip cross-sections. At constant speed (140 m/min), increasing feed from 0.12 to 0.18 mm/rev increased forces by 20-30% across all tool types.

Power Consumption: Akgun [56] investigated power consumption during turning of Invar 36 alloy, finding that two-layer TiCN-Al_2O_3 coated inserts reduced power consumption by 10.22% compared to uncoated inserts, with AlTiN-coated inserts providing 3.77% reduction. Power consumption increased by 40-50% with increasing cutting speed and 30-40% with increasing feed, emphasizing the importance of parameter optimization for energy-efficient machining.

5. OPTIMIZATION METHODS FOR SDSS 2507 MACHINING

5.1 Taguchi Methodology

The Taguchi method has been widely employed to optimize machining parameters for SDSS 2507, offering efficient experimental design through orthogonal arrays and robust analysis through signal-to-noise (S/N) ratios [76, 77].

Pawanr and Gupta [64] applied Taguchi L_9 orthogonal array to investigate dry turning of SDSS 2507 with three factors at three levels. The "smaller-the-better" characteristic was employed for flank wear:

$$S/N = -10 \log(1/n \Sigma y_i^2)$$

Main effects analysis revealed optimal parameter levels for minimizing flank wear: vc=75 m/min (Level 1), f=0.12 mm/rev (Level 2), ap=0.4 mm (Level 1). The S/N response table identified feed rate as the most influential parameter (delta = 11.52), followed by depth of cut (delta = 6.83) and cutting speed (delta = 5.94).

Selvaraj et al. [68] successfully applied Taguchi optimization to dry turning of nitrogen-alloyed DSS, identifying optimal parameters for surface roughness, cutting force, and tool wear simultaneously.

5.2 Analysis of Variance (ANOVA)

ANOVA quantifies the statistical significance of individual factors and their interactions, providing insights into the underlying mechanisms controlling machining responses [78, 79].

Pawanr and Gupta [64] performed ANOVA on flank wear data from SDSS 2507 turning, including both linear and quadratic terms. The model explained 96.51% of variability (R^2=96.51%, adjusted R^2=86.03%), with linear terms contributing 56.14% and quadratic terms 40.37%. Feed rate dominated linear effects (26.56% contribution, F=15.21), while the quadratic feed term (f^2) contributed 32.16% (F=18.41), indicating significant non-linearity in feed-wear relationships.

Sonawane and Sargade [49] used ANOVA to establish regression models for surface roughness prediction during DSS 2205 turning, achieving 95% confidence levels and enabling accurate pre-machining process planning.

5.3 Multi-Objective Optimization

Real-world machining requires simultaneous optimization of multiple, often conflicting, responses [80, 81]. Several approaches have been applied to SDSS machining:

1. Grey Relational Analysis (GRA): GRA converts multiple responses into a single Grey Relational Grade for simultaneous optimization. Dinde and Dhende [82] applied Taguchi-GRA to wet turning of SDSS UNS S32760, simultaneously optimizing cutting force, surface roughness, and material removal rate. Optimal parameters (vc=120 m/min, f=0.20 mm/rev, ap=2.0 mm) achieved minimum surface roughness while maintaining MRR of 48 cm^3/min.
2. Desirability Function Approach: Kumar and Misra [83] employed desirability functions for multi-response optimization of DSS 2205 dry turning, achieving balanced improvements in surface roughness and MRR.
3. TOPSIS and MADM Methods: Koyee et al. [84] applied AHP-TOPSIS (Analytic Hierarchy Process-Technique for Order Preference by Similarity to Ideal Solution) for comprehensive optimization of turning DSS 2205 and 2507, considering productivity, quality, and sustainability metrics simultaneously.

6. COMPARATIVE ANALYSIS: SDSS 2507 VS. OTHER STAINLESS STEELS

Understanding the relative machinability of SDSS 2507 compared to other stainless steel grades provides context for process development and tool selection [85, 86].

Table 4: Comparative Machinability of Stainless Steel Grades

Property	Austenitic 316L	DSS 2205	SDSS 2507
Hardness (HRC)	15-20	28-32	30-35
Yield Strength (MPa)	290	450	550
Thermal Conductivity (W/m·K)	16	19	15
Work Hardening Rate	Moderate	High	Very High
Tool Life (relative)	100	65	45
Cutting Force (relative)	100	125	150

Koyee et al. [87] conducted systematic comparison of austenitic EN 1.4404, standard DSS EN 1.4462, and super DSS EN 1.4410 under identical cutting conditions. Results confirmed that machinability decreases with increasing alloy content, with SDSS 2507 requiring 20-30% higher cutting forces and exhibiting 40-50% shorter tool life compared to austenitic grades. The radial cutting force increase was significantly higher for SDSS 2507 than DSS 2205, reflecting its greater work hardening tendency.

Nomani et al. [88] compared drilling performance of SAF 2205, SAF 2507, and austenitic 316L, finding that both duplex grades exhibited poorer machinability with higher BUE tendency, cutting forces, and surface roughness. Abrasion and adhesion were identified as dominant wear mechanisms for all grades, but their severity increased with alloy content.

7. EMERGING TECHNOLOGIES AND FUTURE DIRECTIONS

7.1 Textured Cutting Tools

Surface texturing of cutting tools has emerged as a promising approach to enhance dry machining performance by modifying tribological conditions at the tool-chip interface [89, 90]. Micro- and nano-scale textures (grooves, dimples, channels) fabricated by laser ablation, EDM, or focused ion beam machining can:

- Reduce contact area, lowering friction coefficients
- Entrap wear debris, minimizing three-body abrasion
- Act as reservoirs for solid lubricants
- Alter chip flow dynamics

Kawasegi et al. [91] pioneered textured tool development, demonstrating 10-20% reductions in cutting forces with microscale textures on cemented carbide tools. Siju et al. [92] investigated dual-textured (grooves and dimples) carbide tools for dry machining of Ti-6Al-4V, reporting 16.2% reduction in cutting force, 31.2% reduction in thrust force, and 17.8% reduction in friction coefficient.

For SDSS applications, texturing offers potential to mitigate adhesion and BUE formation, though limited research exists specifically for this material. Future work should explore texture geometry optimization, hybrid textured-coated tools, and performance validation across cutting conditions.

7.2 Cryogenic Treatment of Tools

Cryogenic treatment—controlled cooling to liquid nitrogen temperatures (-196°C) followed by tempering—has demonstrated significant improvements in tool performance through microstructural refinement and enhanced carbide precipitation [93, 94].

Dhananchezian [95] investigated cryogenically treated PVD-TiN/TiCN/TiN coated cermet inserts for dry turning of AISI 4340 steel. Treated inserts exhibited 0.7% increase in microhardness, 5-29% reduction in surface roughness, and reduced tool wear compared to untreated inserts. XRD analysis revealed new and sharper carbide peaks in treated tools, confirming microstructural enhancement.

Akincioglu et al. [96] reported similar benefits for cryogenically treated carbide tools in turning of Hastelloy C22, with treated tools demonstrating improved wear resistance and surface finish. For SDSS 2507 applications, cryogenic treatment could potentially enhance coating adhesion, substrate hardness, and thermal stability—areas warranting systematic investigation.

7.3 Hybrid and Assisted Machining

Energy-assisted machining processes combine conventional material removal with external energy inputs to modify workpiece material properties and enhance machinability [97, 98]:

Laser-Assisted Machining (LAM): Localized preheating by laser beam softens the workpiece material ahead of the cutting tool, reducing cutting forces and tool wear. Attia et al. [99] demonstrated 800% improvement in material removal rate for Inconel 718 under LAM, with 25% better surface finish and compressive residual stresses. For SDSS 2507, LAM could mitigate work hardening effects by maintaining workpiece temperatures above the hardening range.

Ultrasonic Vibration-Assisted Machining (UVAM): High-frequency vibration of tool or workpiece creates intermittent cutting conditions, reducing average cutting forces and improving chip control. Hu et al. [100] achieved surface roughness of 100 nm in dry UVAM of TC4 titanium alloy, with significant force reductions. The intermittent contact also improves coolant access and chip evacuation—benefits directly transferable to SDSS machining.

Hybrid Laser-Ultrasonic Assistance: Combining thermal softening (laser) with force reduction (ultrasonic) offers synergistic benefits. Deswal and Kant [101] demonstrated that ultrasonic vibration-laser-assisted turning (UVLAT) outperformed conventional, laser-assisted, and ultrasonic-assisted turning in cutting forces and surface quality, producing crack-free chip edges through combined thermal and mechanical effects.

7.4 Sustainable Manufacturing Integration

1. Future development of dry machining technologies for SDSS 2507 must align with broader sustainability objectives [102, 103]:
2. Life Cycle Assessment (LCA): Comprehensive evaluation of environmental impacts across the entire machining system—tool production, machining process, waste management, and component service life—will guide technology selection and optimization [104].
3. Industry 4.0 Integration: Smart machining systems incorporating real-time monitoring, adaptive control, and predictive maintenance can maximize the benefits of dry machining while minimizing risks of tool failure and quality deterioration [105].
4. Circular Economy Principles: Tool recycling, coating recovery, and closed-loop material flows will become increasingly important as sustainability regulations tighten [106].

8. CONCLUSIONS

This technical review has comprehensively examined the dry machining of Super Duplex Stainless Steel 2507 using coated tungsten carbide tools, synthesizing findings from recent research to establish the current state of knowledge:

1. Material Challenges: SDSS 2507 presents exceptional machinability challenges due to its high strength, low thermal conductivity, rapid work hardening, and strong adhesive tendency. These characteristics activate multiple concurrent wear mechanisms—abrasion, adhesion, diffusion, and notch wear—that rapidly degrade uncoated tools.
2. Coating Solutions: PVD-coated tungsten carbide tools, particularly those deposited by advanced techniques (HiPIMS, S3p), provide effective solutions for dry machining. AlTiCrN quaternary coatings demonstrate superior performance through formation of protective $(Al,Cr)_2O_3$ oxides that maintain cutting edge integrity up to 1100°C. Tool life improvements of 4-6× compared to uncoated tools are achievable with optimized coatings.
3. Parameter Optimization: Cutting parameters critically influence machining responses. Feed rate dominates tool wear (26.56% contribution), followed by depth of cut (16.29%) and cutting speed (13.30%). Optimal parameter combinations for minimal wear (vc=75 m/min, f=0.12 mm/rev, ap=0.4 mm) and optimal surface quality have been identified through Taguchi methodology.
4. Surface Integrity: Surface roughness values below 1 μm—critical for corrosion resistance in marine applications—are achievable with coated tools (0.72 μm demonstrated). Higher cutting speeds reduce BUE formation and improve finish, though at the expense of accelerated tool wear.
5. Thermal Management: Coated tools exhibit higher cutting zone temperatures (900-1280°C) than uncoated tools (750-950°C) due to lower thermal conductivity, but maintain structural integrity through protective oxide formation. The Boothroyd model predicts cutting temperatures within ±10% accuracy.
6. Optimization Methods: Statistical techniques (Taguchi, ANOVA, GRA, TOPSIS) enable systematic optimization of multi-response machining problems, identifying parameter combinations that balance productivity, quality, and sustainability.

7. Future Directions: Emerging technologies including textured tools, cryogenic treatment, and energy-assisted machining offer potential for further enhancement. Integration with Industry 4.0 and life cycle assessment frameworks will ensure alignment with sustainability objectives.

   The body of research confirms that dry machining of SDSS 2507 with coated tungsten carbide tools is technically feasible and economically attractive, offering a sustainable alternative to conventional flood-cooled machining. Continued development of advanced coatings, optimization methodologies, and hybrid processes will further expand the capabilities and applications of this technology.

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