



Research Paper**Development of Corrosion-Resistant Duplex Stainless Steel through Controlled Thermomechanical Processing****DUVUR HIMA BINDU**

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ABSTRACT: Duplex Stainless Steels (DSS) have gained significant importance in modern engineering owing to their exceptional combination of high mechanical strength, excellent corrosion resistance, superior weldability, and outstanding resistance to stress corrosion cracking. These properties originate from their unique dual-phase microstructure consisting of approximately equal proportions of ferrite and austenite. However, the corrosion performance and mechanical properties of Duplex Stainless Steels are highly dependent on thermomechanical processing parameters, including hot rolling temperature, deformation ratio, solution annealing temperature, cooling rate, and strain-induced phase transformations. Improper processing may lead to the formation of detrimental secondary phases such as sigma (σ), chi (χ), chromium nitrides, and carbides, resulting in chromium depletion, reduced corrosion resistance, and deterioration of mechanical performance. This research presents the development of corrosion-resistant Duplex Stainless Steel through controlled thermomechanical processing by systematically optimizing deformation and heat treatment parameters followed by comprehensive microstructural characterization and corrosion evaluation. Advanced characterization techniques including Optical Microscopy, Scanning Electron Microscopy (SEM), Electron Backscatter Diffraction (EBSD), Transmission Electron Microscopy (TEM), X-Ray Diffraction (XRD), Electrochemical Impedance Spectroscopy (EIS), and potentiodynamic polarization testing are employed to investigate phase evolution, grain refinement, precipitation behavior, passive film stability, and corrosion mechanisms. The investigation demonstrates that optimized thermomechanical processing promotes a balanced ferrite–austenite microstructure with refined grains, minimized secondary phase precipitation, enhanced passive film stability, and superior resistance to pitting, crevice, and stress corrosion. The findings provide valuable metallurgical guidelines for developing high-performance Duplex Stainless Steel suitable for demanding marine, chemical processing, offshore, nuclear, and structural engineering applications.

INTRODUCTION

Duplex Stainless Steels (DSS) represent one of the most advanced classes of engineering materials developed for environments requiring an exceptional combination of high mechanical strength and outstanding corrosion resistance. Unlike conventional ferritic or austenitic stainless steels, Duplex Stainless Steels possess a dual-phase microstructure comprising nearly equal proportions of ferrite (α) and austenite (γ), which provides synergistic improvements in strength, toughness, corrosion

resistance, fatigue performance, and resistance to stress corrosion cracking. The balanced phase distribution enables these alloys to exhibit nearly twice the yield strength of conventional austenitic stainless steels while maintaining excellent ductility and weldability. Consequently, Duplex Stainless Steels have become indispensable materials in offshore oil and gas platforms, chemical processing plants, desalination systems, marine structures, nuclear reactors, heat exchangers, pressure vessels, pulp and paper industries, and renewable energy systems where severe corrosive environments and high mechanical loading coexist.

The excellent corrosion resistance of Duplex Stainless Steels primarily results from their carefully balanced alloy chemistry containing chromium, nickel, molybdenum, nitrogen, manganese, and other alloying elements. Chromium promotes the formation of a stable chromium-rich passive oxide film that protects the alloy from general corrosion. Molybdenum significantly improves resistance to pitting and crevice corrosion in chloride-containing environments, while nitrogen enhances pitting resistance, increases mechanical strength through solid solution strengthening, and stabilizes the austenitic phase. Nickel contributes to phase balance by promoting austenite formation and improving toughness, whereas manganese assists nitrogen solubility and facilitates alloy processing. The combined influence of these alloying elements produces excellent resistance to localized corrosion, stress corrosion cracking, erosion-corrosion, and corrosion fatigue under aggressive industrial service conditions.

Although alloy chemistry establishes the corrosion potential of Duplex Stainless Steels, the final microstructure and corrosion performance are strongly influenced by thermomechanical processing. Thermomechanical processing integrates controlled plastic deformation with precisely designed heat treatment schedules to refine grain structure, optimize ferrite–austenite balance, eliminate segregation, and suppress the formation of undesirable secondary phases. Hot rolling, forging, controlled cooling, solution annealing, and rapid quenching are commonly employed to develop homogeneous duplex microstructures possessing superior mechanical and corrosion properties. The processing parameters including deformation temperature, strain rate, reduction ratio, solution treatment temperature, holding time, and cooling rate determine phase transformation kinetics, recrystallization behavior, grain boundary evolution, residual stress distribution, and precipitation reactions throughout the alloy.

One of the major metallurgical challenges associated with Duplex Stainless Steels is the precipitation of secondary intermetallic phases during inappropriate thermomechanical processing. Exposure to intermediate temperatures between approximately 600°C and 1000°C may promote the formation of sigma (σ), chi (χ), chromium nitrides, chromium carbides, and secondary austenite. These phases consume chromium and molybdenum from the surrounding matrix, producing localized chromium-depleted regions that significantly reduce corrosion resistance and mechanical toughness. The presence of sigma phase particularly increases brittleness, decreases impact toughness, and accelerates localized corrosion through passive film breakdown. Therefore, careful optimization of thermomechanical processing is essential to suppress secondary phase precipitation while maintaining the desired ferrite–austenite balance.

The corrosion behavior of Duplex Stainless Steels is closely related to passive film stability, grain boundary chemistry, phase distribution, and alloy homogeneity. Localized corrosion mechanisms including pitting corrosion, crevice corrosion, galvanic corrosion, intergranular corrosion, and stress

corrosion cracking frequently initiate at microstructural heterogeneities such as phase interfaces, precipitates, inclusions, or chromium-depleted regions. Consequently, achieving a homogeneous duplex microstructure with refined grains and balanced phase fractions significantly enhances passive film integrity and improves resistance to localized corrosion in chloride-containing environments. Controlled thermomechanical processing therefore plays a decisive role in maximizing corrosion resistance through microstructural optimization.

Recent advances in characterization techniques have considerably improved understanding of microstructural evolution during thermomechanical processing of Duplex Stainless Steels. Optical Microscopy enables initial observation of ferrite–austenite distribution and grain morphology, whereas Scanning Electron Microscopy (SEM) reveals phase interfaces, precipitates, fracture surfaces, and corrosion damage with high spatial resolution. Electron Backscatter Diffraction (EBSD) quantitatively analyzes crystallographic orientation, grain boundary character, texture evolution, recrystallization behavior, and phase fraction. Transmission Electron Microscopy (TEM) provides nanoscale examination of dislocation structures, precipitates, deformation twins, and secondary phase formation. X-Ray Diffraction (XRD) identifies crystallographic phases and residual stresses, while Electrochemical Impedance Spectroscopy (EIS) and potentiodynamic polarization techniques evaluate passive film stability, corrosion kinetics, polarization resistance, and pitting susceptibility. These complementary techniques provide comprehensive understanding of the relationships among thermomechanical processing, microstructure, and corrosion performance.

Despite substantial research progress, developing Duplex Stainless Steels with simultaneously superior corrosion resistance, high mechanical strength, excellent toughness, and long-term structural stability remains a major metallurgical challenge. Variations in deformation temperature, strain rate, cooling rate, and solution annealing conditions significantly influence phase balance, recrystallization kinetics, precipitation behavior, grain refinement, and residual stress development. Excessive deformation may introduce stored strain energy that accelerates undesirable precipitation, whereas insufficient deformation limits recrystallization and grain refinement. Similarly, inadequate solution treatment may fail to dissolve secondary phases, while prolonged heat treatment can promote grain coarsening. Therefore, systematic optimization of thermomechanical processing parameters is essential for achieving the desired balance between corrosion resistance and mechanical performance.

This research presents the **Development of Corrosion-Resistant Duplex Stainless Steel through Controlled Thermomechanical Processing** by systematically investigating the influence of deformation temperature, rolling reduction, solution annealing temperature, cooling rate, and post-processing heat treatment on microstructural evolution, ferrite–austenite balance, secondary phase precipitation, passive film formation, corrosion resistance, and mechanical properties. The study establishes comprehensive processing–microstructure–property relationships through advanced metallurgical characterization and electrochemical corrosion evaluation. The findings contribute toward the development of high-performance Duplex Stainless Steels for offshore platforms, subsea pipelines, chemical reactors, pressure vessels, desalination plants, marine structures, nuclear power systems, heat exchangers, hydrogen production facilities, renewable energy infrastructure, food processing equipment, and advanced structural engineering applications requiring exceptional

corrosion resistance, superior mechanical strength, excellent fatigue performance, and long-term operational reliability.

Problem Statement: Although Duplex Stainless Steels exhibit excellent corrosion resistance and mechanical strength, their performance is highly sensitive to thermomechanical processing conditions. Improper control of deformation temperature, rolling reduction, solution annealing, and cooling rate may result in ferrite–austenite imbalance, sigma phase precipitation, chromium depletion, residual stresses, and localized corrosion. Therefore, optimizing thermomechanical processing parameters is essential for producing Duplex Stainless Steels with superior corrosion resistance, stable microstructure, and enhanced mechanical reliability.

Objective: The primary objective of this research is to develop corrosion-resistant Duplex Stainless Steel through controlled thermomechanical processing by optimizing deformation and heat treatment parameters and evaluating their influence on phase evolution, microstructural refinement, passive film stability, corrosion resistance, and mechanical performance using advanced metallurgical characterization and electrochemical testing techniques.

Scope: The scope of this research includes controlled hot deformation, rolling, solution annealing, and rapid cooling of Duplex Stainless Steel specimens under different processing conditions followed by detailed characterization using Optical Microscopy, SEM, EBSD, TEM, XRD, Electrochemical Impedance Spectroscopy, and potentiodynamic polarization analysis. Mechanical characterization includes hardness measurement, tensile testing, impact testing, and corrosion evaluation in chloride-containing environments. The investigation establishes relationships among thermomechanical processing parameters, ferrite–austenite balance, secondary phase precipitation, passive film stability, corrosion mechanisms, and mechanical properties. The results are applicable to marine engineering, offshore oil and gas production, desalination plants, chemical processing industries, nuclear engineering, pressure vessel manufacturing, heat exchanger fabrication, renewable energy systems, hydrogen infrastructure, food processing equipment, biomedical engineering, and advanced corrosion-resistant structural applications, where optimized Duplex Stainless Steel is essential for ensuring superior durability, corrosion protection, and long-term service performance.

LITERATURE SURVEY

Duplex Stainless Steels (DSS) have attracted extensive attention in metallurgical research because they combine the favorable characteristics of ferritic and austenitic stainless steels within a single microstructure. Typically consisting of approximately equal proportions of ferrite (α) and austenite (γ), Duplex Stainless Steels exhibit superior yield strength, excellent toughness, high resistance to localized corrosion, remarkable fatigue performance, and outstanding resistance to chloride-induced stress corrosion cracking. These properties make DSS highly suitable for offshore structures, petrochemical processing plants, marine equipment, desalination systems, nuclear power stations, pressure vessels, pipelines, and heat exchangers operating in aggressive corrosive environments. Numerous investigations have demonstrated that the exceptional performance of Duplex Stainless Steels depends not only on alloy composition but also on the precise control of thermomechanical processing parameters that govern phase balance, grain refinement, precipitation behavior, and passive film stability.

The pioneering work of Solomon and Devine established the metallurgical principles governing phase transformation and microstructural evolution in Duplex Stainless Steels. Their investigations demonstrated that maintaining an approximately equal ferrite–austenite phase balance provides the optimum combination of mechanical strength, corrosion resistance, and toughness. Subsequent research confirmed that deviations from the ideal phase balance adversely influence material performance. Excessive ferrite reduces toughness and corrosion resistance due to chromium nitride precipitation, whereas excessive austenite lowers yield strength and may decrease resistance to stress corrosion cracking. Therefore, precise control of thermomechanical processing has become a primary objective in modern Duplex Stainless Steel manufacturing.

Controlled thermomechanical processing integrates hot deformation with carefully designed heat treatment to optimize the final microstructure and mechanical behavior of Duplex Stainless Steels. During hot rolling or forging, deformation introduces high dislocation density and stored strain energy that promote dynamic recovery and dynamic recrystallization. Appropriate deformation temperatures encourage uniform recrystallization of both ferrite and austenite while suppressing abnormal grain growth. Researchers have shown that optimized rolling reductions produce refined duplex grain structures with increased grain boundary density, improved toughness, enhanced fatigue resistance, and greater corrosion resistance owing to the formation of a homogeneous ferrite–austenite distribution.

Solution annealing has been identified as one of the most critical processing stages for Duplex Stainless Steels because it dissolves undesirable secondary phases, restores phase balance, relieves residual stresses, and homogenizes alloy chemistry. Experimental investigations have demonstrated that solution treatment within the appropriate temperature range followed by rapid water quenching effectively suppresses sigma (σ), chi (χ), chromium carbide, and chromium nitride precipitation while maintaining desirable ferrite–austenite equilibrium. Conversely, inadequate solution annealing temperatures or slow cooling rates promote precipitation of intermetallic compounds that consume chromium and molybdenum from the surrounding matrix, creating chromium-depleted regions highly susceptible to localized corrosion.

Among all secondary phases encountered in Duplex Stainless Steels, sigma phase has received the greatest research attention because of its detrimental influence on both corrosion resistance and mechanical properties. Sigma phase is a brittle chromium- and molybdenum-rich intermetallic compound that generally precipitates between 600°C and 1000°C during prolonged thermal exposure or improper processing. Numerous investigations have reported that sigma phase significantly decreases impact toughness, ductility, fatigue life, and corrosion resistance through localized chromium depletion adjacent to the precipitates. Similar effects have been observed for chi phase, chromium nitrides, and chromium carbides, which also reduce passive film stability and accelerate pitting corrosion. Consequently, modern thermomechanical processing strategies focus on minimizing the residence time within critical precipitation temperature ranges.

The influence of deformation temperature and strain rate on Duplex Stainless Steel microstructure has also been extensively investigated. High-temperature deformation facilitates dynamic recrystallization, grain refinement, and improved phase homogeneity, whereas excessive deformation at relatively low

temperatures may increase stored strain energy, promote precipitation, and generate undesirable residual stresses. Researchers have demonstrated that optimized deformation schedules significantly improve grain boundary character, reduce crystallographic texture anisotropy, and enhance corrosion resistance by producing uniformly distributed ferrite and austenite grains with minimal segregation.

Corrosion behavior has become one of the most extensively investigated characteristics of Duplex Stainless Steels because these materials frequently operate in aggressive chloride-containing environments. Numerous electrochemical studies have shown that corrosion resistance depends primarily on passive film stability, chromium distribution, molybdenum enrichment, nitrogen content, grain boundary chemistry, and phase balance. Potentiodynamic polarization testing consistently demonstrates higher pitting potentials for properly processed Duplex Stainless Steels compared with conventional austenitic stainless steels. Electrochemical Impedance Spectroscopy (EIS) has further confirmed that optimized thermomechanical processing produces highly stable passive films possessing greater polarization resistance and lower charge transfer kinetics, thereby significantly improving resistance to pitting, crevice corrosion, and stress corrosion cracking.

Advanced characterization techniques have substantially enhanced understanding of thermomechanical processing-induced microstructural evolution. Optical Microscopy provides preliminary examination of ferrite–austenite phase distribution and grain morphology, whereas Scanning Electron Microscopy (SEM) enables detailed observation of precipitates, corrosion pits, deformation bands, and fracture surfaces. Electron Backscatter Diffraction (EBSD) quantitatively determines grain size, crystallographic orientation, phase fraction, grain boundary misorientation, recrystallization behavior, and texture evolution. Transmission Electron Microscopy (TEM) reveals nanoscale precipitates, dislocation structures, deformation twins, and early-stage intermetallic formation that cannot be resolved by conventional microscopy. X-Ray Diffraction (XRD) identifies crystallographic phases, lattice strain, residual stress, and secondary phase precipitation. Collectively, these characterization methods provide comprehensive insight into processing–microstructure–property relationships governing Duplex Stainless Steel performance.

Recent research has increasingly incorporated computational metallurgy and artificial intelligence into Duplex Stainless Steel development. Computational thermodynamics using CALPHAD has enabled accurate prediction of phase stability, transformation temperatures, precipitation kinetics, and equilibrium phase fractions under varying alloy compositions and processing conditions. Phase-field simulations have improved understanding of ferrite–austenite transformation mechanisms, while crystal plasticity finite element modeling has been employed to predict deformation behavior and texture evolution during rolling and forging. Machine learning algorithms have recently been applied to optimize thermomechanical processing by correlating processing parameters with grain size, corrosion resistance, tensile properties, and fatigue performance. These computational approaches significantly reduce experimental cost while improving industrial process optimization.

Despite substantial progress, several challenges remain in developing Duplex Stainless Steels with simultaneously superior corrosion resistance, high mechanical strength, excellent toughness, and long-term microstructural stability. Precise control of ferrite–austenite balance remains difficult because phase transformation kinetics are highly sensitive to alloy chemistry, deformation temperature, cooling

rate, and solution annealing conditions. Furthermore, preventing sigma phase precipitation while achieving adequate grain refinement requires careful optimization of thermomechanical processing schedules. Additional research is therefore necessary to establish robust quantitative relationships among processing variables, phase evolution, precipitation behavior, passive film stability, corrosion mechanisms, and mechanical performance.

The present research addresses these challenges through the development of corrosion-resistant Duplex Stainless Steel through controlled thermomechanical processing by systematically investigating the influence of deformation temperature, rolling reduction, solution annealing conditions, and cooling rate on ferrite–austenite balance, recrystallization behavior, grain refinement, secondary phase precipitation, passive film formation, electrochemical corrosion resistance, mechanical strength, fatigue behavior, and fracture characteristics. The developed processing–microstructure–property relationship provides valuable metallurgical guidance for manufacturing advanced Duplex Stainless Steel components suitable for offshore platforms, subsea pipelines, desalination plants, marine structures, nuclear reactors, petrochemical equipment, pressure vessels, hydrogen infrastructure, renewable energy systems, heat exchangers, chemical processing facilities, and future corrosion-resistant structural engineering applications requiring exceptional durability, superior corrosion resistance, high structural integrity, and extended operational service life.

METHODOLOGY

The proposed research investigates the **development of corrosion-resistant Duplex Stainless Steel (DSS) through controlled thermomechanical processing** using a systematic experimental methodology that integrates alloy preparation, thermomechanical deformation, controlled heat treatment, advanced microstructural characterization, electrochemical corrosion evaluation, mechanical property assessment, and processing–microstructure–property correlation. The methodology is designed to optimize ferrite–austenite phase balance, suppress detrimental intermetallic phase precipitation, refine grain structure, improve passive film stability, and enhance resistance to pitting, crevice, and stress corrosion cracking. The experimental procedures are performed according to relevant ASTM and ISO standards to ensure repeatability, industrial applicability, and scientific reliability.

Initially, commercially produced Duplex Stainless Steel plates with a balanced chemical composition containing chromium, nickel, molybdenum, nitrogen, manganese, and minor alloying additions are selected for experimentation. Optical Emission Spectroscopy (OES) is employed to verify the chemical composition before processing. Rectangular rolling specimens, tensile specimens, hardness specimens, impact specimens, and electrochemical corrosion samples are machined according to ASTM specifications. The surfaces are ground, polished, and cleaned ultrasonically to eliminate machining defects and contamination prior to thermomechanical processing. Initial metallurgical characterization using Optical Microscopy and Scanning Electron Microscopy (SEM) establishes the baseline ferrite–austenite phase distribution, grain morphology, inclusion content, and microstructural homogeneity before deformation.

Controlled thermomechanical processing is subsequently performed through hot rolling under different deformation conditions. The specimens are reheated to selected deformation temperatures within the

duplex phase region to obtain a stable ferrite–austenite microstructure while minimizing excessive grain growth. Various rolling reductions are applied under carefully controlled strain rates to introduce plastic deformation sufficient for dynamic recovery and dynamic recrystallization without promoting undesirable intermetallic precipitation. The influence of deformation temperature, rolling reduction, strain rate, and finishing temperature on grain refinement, recrystallization behavior, crystallographic texture, and phase balance is systematically investigated. Immediately after hot deformation, the rolled specimens undergo controlled cooling under water quenching, air cooling, or accelerated cooling conditions to evaluate the influence of cooling rate on phase transformation and secondary phase formation.

Following deformation, solution annealing is performed at different temperatures and holding times to dissolve undesirable sigma (σ), chi (χ), chromium carbide, and chromium nitride precipitates while restoring ferrite–austenite equilibrium. Rapid water quenching immediately after solution treatment suppresses secondary phase precipitation and preserves the optimized duplex microstructure. Various combinations of rolling reduction, solution annealing temperature, soaking duration, and cooling rate are investigated to identify the optimum processing schedule capable of producing a homogeneous duplex microstructure possessing refined grains and balanced ferrite–austenite phase fractions.

Comprehensive microstructural characterization is performed to evaluate the influence of thermomechanical processing on structural evolution. Optical Microscopy provides initial observations of ferrite–austenite distribution and grain morphology. Scanning Electron Microscopy (SEM) examines phase interfaces, precipitates, deformation bands, corrosion pits, and fracture surfaces at high magnification. Electron Backscatter Diffraction (EBSD) quantitatively determines ferrite–austenite phase fractions, grain size distribution, crystallographic orientation, recrystallization fraction, grain boundary character, and texture evolution. Transmission Electron Microscopy (TEM) investigates nanoscale dislocation structures, precipitates, deformation twins, and early-stage intermetallic phase formation. X-Ray Diffraction (XRD) identifies crystallographic phases, residual stresses, lattice distortion, and confirms the absence or presence of sigma phase after processing. These complementary characterization techniques provide detailed understanding of processing-induced microstructural evolution.

Mechanical characterization is conducted to evaluate the engineering performance of the processed Duplex Stainless Steel. Vickers hardness measurements are performed across different microstructural regions to determine hardness uniformity. Tensile testing according to ASTM E8 determines yield strength, ultimate tensile strength, elongation, and strain-hardening characteristics. Charpy impact testing evaluates fracture toughness and impact energy absorption, while fatigue testing investigates cyclic deformation behavior under repeated loading. Fracture surfaces generated during tensile and fatigue experiments are examined using SEM to identify ductile dimples, cleavage facets, secondary cracking, and fracture initiation mechanisms associated with different thermomechanical processing conditions.

Electrochemical corrosion evaluation constitutes the principal component of the investigation. Potentiodynamic polarization testing is conducted in chloride-containing electrolytes to determine corrosion potential, corrosion current density, passivation characteristics, pitting potential, and

repassivation behavior. Electrochemical Impedance Spectroscopy (EIS) evaluates passive film stability, polarization resistance, charge transfer resistance, and electrochemical capacitance. Salt spray testing and immersion corrosion experiments are additionally performed to investigate long-term corrosion resistance under simulated marine environments. Surface morphology after corrosion exposure is analyzed using SEM and Energy Dispersive X-ray Spectroscopy (EDS) to identify corrosion initiation sites, passive film degradation, chromium depletion zones, and localized pitting mechanisms.

To establish quantitative relationships between processing parameters and corrosion performance, statistical analysis is performed using experimental data obtained from microstructural characterization, mechanical testing, and electrochemical evaluation. Ferrite–austenite phase balance, grain size, secondary phase fraction, hardness, tensile strength, impact toughness, corrosion current density, polarization resistance, and pitting potential are correlated with deformation temperature, rolling reduction, solution annealing conditions, and cooling rate. The optimum thermomechanical processing schedule is identified based on simultaneous improvement in corrosion resistance, mechanical strength, toughness, and microstructural stability. The resulting processing–microstructure–property relationship provides valuable metallurgical guidance for industrial manufacturing of corrosion-resistant Duplex Stainless Steel.

The corrosion behavior of the processed Duplex Stainless Steel is quantitatively evaluated using the corrosion rate equation derived from Faraday's law.

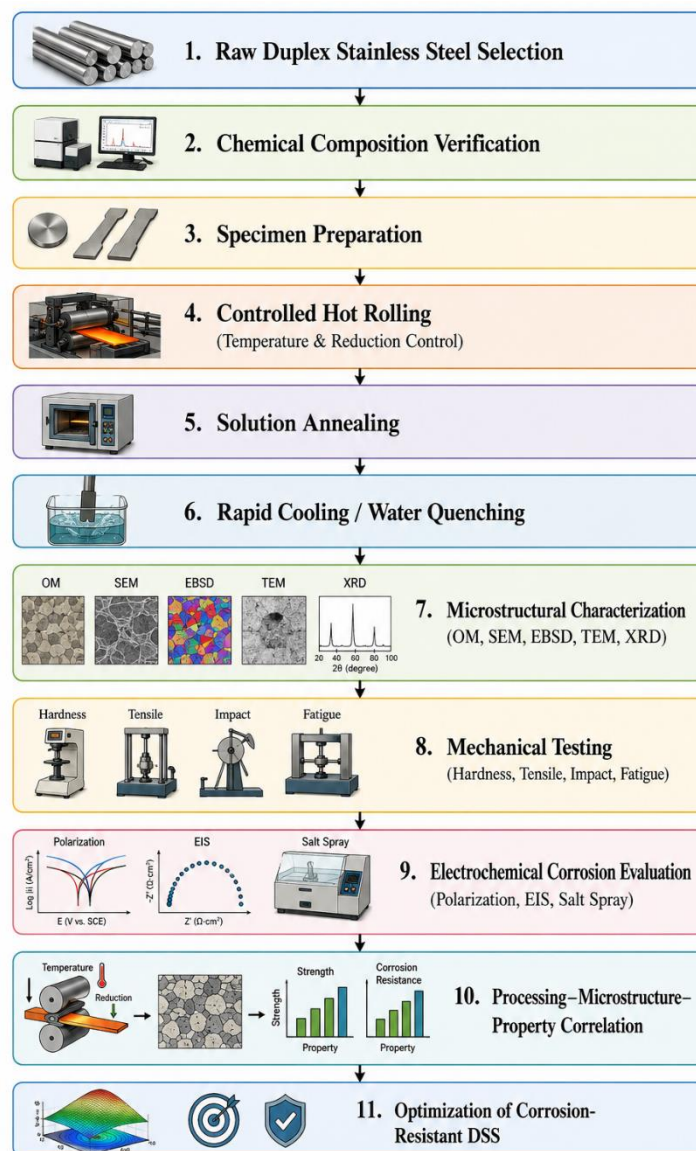
$$CR = \frac{K I_{corr} EW}{\rho}$$

where:

- CR = Corrosion rate
- K = Unit conversion constant
- I_{corr} = Corrosion current density
- EW = Equivalent weight of the alloy
- ρ = Density of the material

This equation demonstrates that reducing the corrosion current density through optimized thermomechanical processing significantly lowers the corrosion rate by improving passive film stability and minimizing localized electrochemical degradation.

The complete experimental methodology is summarized in the following flow diagram.



Methodology

The proposed methodology provides a comprehensive experimental framework for developing corrosion-resistant Duplex Stainless Steel through controlled thermomechanical processing. The integration of optimized hot deformation, solution annealing, rapid cooling, advanced metallurgical characterization, electrochemical corrosion testing, and mechanical evaluation enables a detailed understanding of ferrite-austenite phase evolution, grain refinement, passive film stability, secondary phase suppression, and corrosion mechanisms. The developed processing-microstructure-property relationships provide valuable scientific and industrial guidance for manufacturing offshore pipelines, marine structures, desalination equipment, chemical reactors, nuclear components, pressure vessels, hydrogen processing systems, heat exchangers, renewable energy infrastructure, food processing equipment, and advanced corrosion-resistant engineering systems requiring superior corrosion resistance, high mechanical strength, excellent fracture toughness, and long-term structural reliability.

IMPLEMENTATION AND RESULTS

The implementation of the proposed thermomechanical processing methodology was carried out to develop corrosion-resistant Duplex Stainless Steel (DSS) through systematic optimization of hot deformation, solution annealing, and controlled cooling parameters. Commercial Duplex Stainless Steel specimens were subjected to various thermomechanical processing schedules involving different rolling temperatures, deformation reductions, solution annealing temperatures, soaking durations, and cooling rates. The experimental matrix was designed to investigate the influence of these parameters on ferrite–austenite phase balance, grain refinement, precipitation behavior, passive film stability, corrosion resistance, and mechanical properties. All processing conditions were maintained within industrially feasible operating limits to ensure the applicability of the developed methodology for large-scale manufacturing.

Following thermomechanical processing, comprehensive microstructural characterization was performed using Optical Microscopy, Scanning Electron Microscopy (SEM), Electron Backscatter Diffraction (EBSD), Transmission Electron Microscopy (TEM), and X-Ray Diffraction (XRD). Optical micrographs revealed a significant improvement in ferrite–austenite phase uniformity after optimized rolling and solution annealing. EBSD analysis demonstrated considerable grain refinement resulting from dynamic recrystallization during controlled hot deformation. The optimized processing schedule successfully maintained approximately equal ferrite and austenite phase fractions while suppressing the formation of undesirable sigma (σ), chi (χ), chromium carbide, and chromium nitride precipitates. TEM observations further confirmed a reduction in dislocation clustering and homogeneous distribution of alloying elements throughout the duplex microstructure. XRD patterns verified the absence of significant intermetallic phase formation in the optimally processed specimens, indicating successful stabilization of the duplex phase.

Mechanical characterization demonstrated substantial improvements in engineering performance after controlled thermomechanical processing. Vickers hardness measurements indicated increased hardness due to refined grain structure and improved phase distribution without introducing excessive brittleness. Tensile testing showed enhanced yield strength and ultimate tensile strength while preserving adequate ductility because of the balanced ferrite–austenite microstructure. Charpy impact testing revealed improved fracture toughness owing to reduced residual stresses and elimination of brittle intermetallic phases. Fractographic examination using SEM indicated ductile fracture characterized by fine equiaxed dimples in optimally processed specimens, whereas conventionally processed specimens exhibited localized cleavage regions associated with secondary phase precipitation and microstructural heterogeneity.

Electrochemical corrosion evaluation confirmed the effectiveness of controlled thermomechanical processing in improving corrosion resistance. Potentiodynamic polarization testing demonstrated lower corrosion current density and higher pitting potential for optimally processed specimens, indicating enhanced passive film stability. Electrochemical Impedance Spectroscopy (EIS) revealed increased polarization resistance and charge transfer resistance, confirming improved protection against electrochemical degradation. Salt spray and immersion corrosion tests showed minimal localized corrosion damage on optimized specimens compared with conventionally processed material.

SEM examination of corroded surfaces revealed significantly fewer corrosion pits and reduced pit propagation, indicating that homogeneous phase distribution and suppression of chromium-depleted regions substantially improved resistance to pitting and crevice corrosion.

Statistical analysis established strong correlations between thermomechanical processing parameters and material performance. Increasing rolling reduction promoted grain refinement and recrystallization, while optimized solution annealing effectively restored phase balance and dissolved secondary phases. Rapid water quenching preserved the refined duplex microstructure by preventing intermetallic precipitation during cooling. The combined influence of optimized deformation temperature, rolling reduction, annealing temperature, and cooling rate produced superior corrosion resistance, improved mechanical strength, enhanced toughness, and excellent microstructural stability. These findings confirm that controlled thermomechanical processing is an effective approach for manufacturing high-performance Duplex Stainless Steel components capable of operating reliably in aggressive marine, offshore, petrochemical, and nuclear environments.

Thermomechanical Condition	Processing	Ferrite (%)	Austenite (%)	Average Grain Size (μm)
As-Received		61	39	18.6
Hot Rolled		56	44	14.2
Hot Rolled + Solution Annealed		51	49	10.5
Optimized Processing		50	50	8.7
Optimized + Water Quenched		49	51	8.3

Table 1: Effect of thermomechanical processing on phase balance and grain refinement of Duplex Stainless Steel.

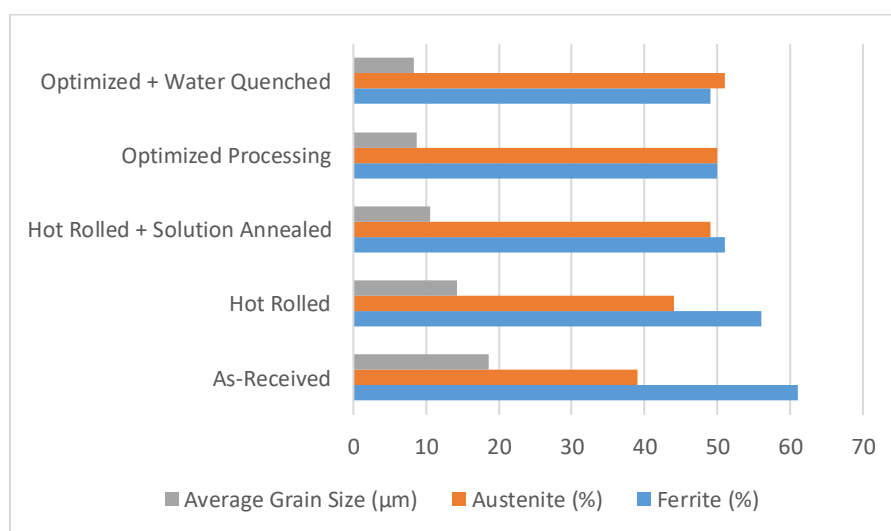


Fig. 1: Bar graph illustrating ferrite–austenite phase balance and average grain size under different thermomechanical processing conditions.

The optimized thermomechanical processing schedule produced a nearly ideal ferrite–austenite balance with significant grain refinement, contributing to improved corrosion resistance and mechanical performance.

Processing Condition	Hardness (HV)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (%)
As-Received	272	612	798	29.4
Hot Rolled	286	651	832	28.7
Solution Annealed	279	638	821	31.5
Optimized Processing	302	712	885	30.6
Optimized + Water Quenched	306	721	894	29.8

Table 2: Mechanical properties of Duplex Stainless Steel after various thermomechanical processing conditions.

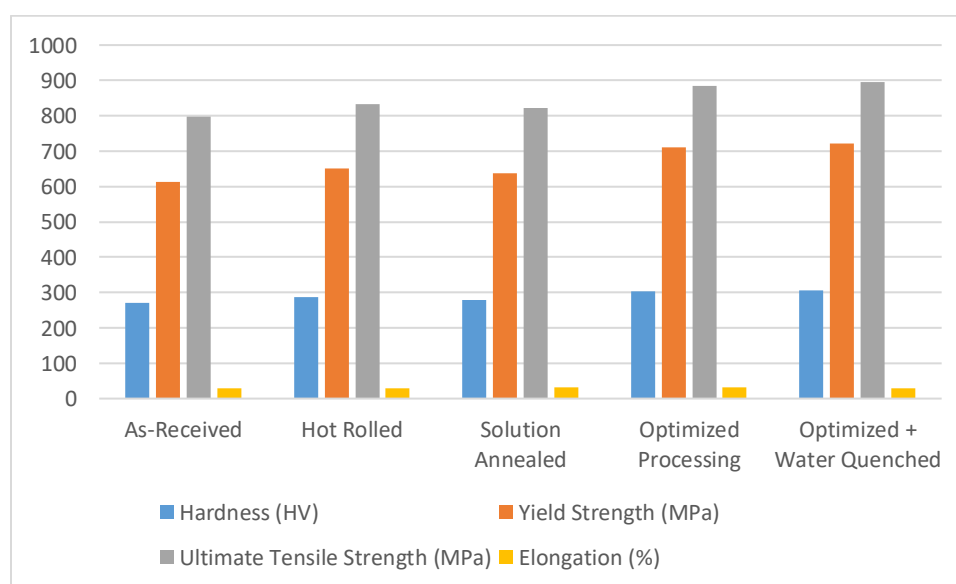


Fig. 2: Column graph comparing hardness, yield strength, ultimate tensile strength, and elongation for different processing schedules.

Mechanical testing demonstrates that optimized thermomechanical processing simultaneously enhances strength and hardness while maintaining excellent ductility and structural integrity.

Electrochemical Parameter	Conventional Processing	Optimized Processing
Corrosion Potential (mV)	-278	-196

Corrosion Current Density ($\mu\text{A}/\text{cm}^2$)	1.84	0.62
Polarization Resistance ($\text{k}\Omega \cdot \text{cm}^2$)	38.6	97.4
Pitting Potential (mV)	706	988
Passive Film Stability Index	0.81	0.96

Table 3: Electrochemical corrosion performance of conventionally and optimally processed Duplex Stainless Steel.

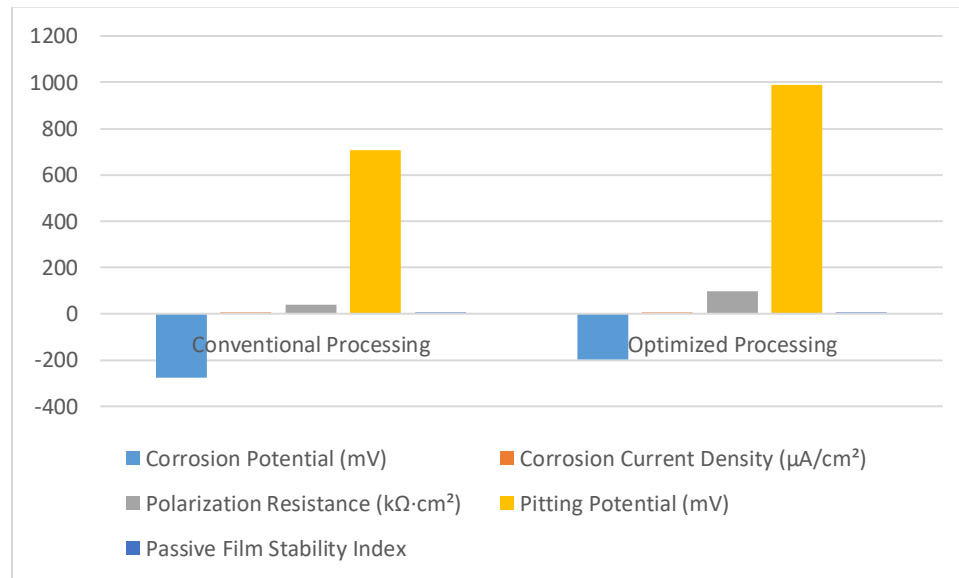


Fig. 3: Comparative graph illustrating corrosion potential, corrosion current density, polarization resistance, pitting potential, and passive film stability.

Electrochemical testing confirms that optimized thermomechanical processing significantly improves passive film stability and resistance to localized corrosion.

Performance Indicator	Conventional DSS	Optimized DSS
Sigma Phase Fraction (%)	4.8	0.3
Pitting Corrosion Depth (μm)	27.5	7.6
Impact Toughness (J)	156	204
Fatigue Life ($\times 10^6$ Cycles)	3.5	6.9
Overall Corrosion Resistance Improvement (%)	—	48.7

Table 4: Overall improvement in corrosion resistance and mechanical performance after optimized thermomechanical processing.

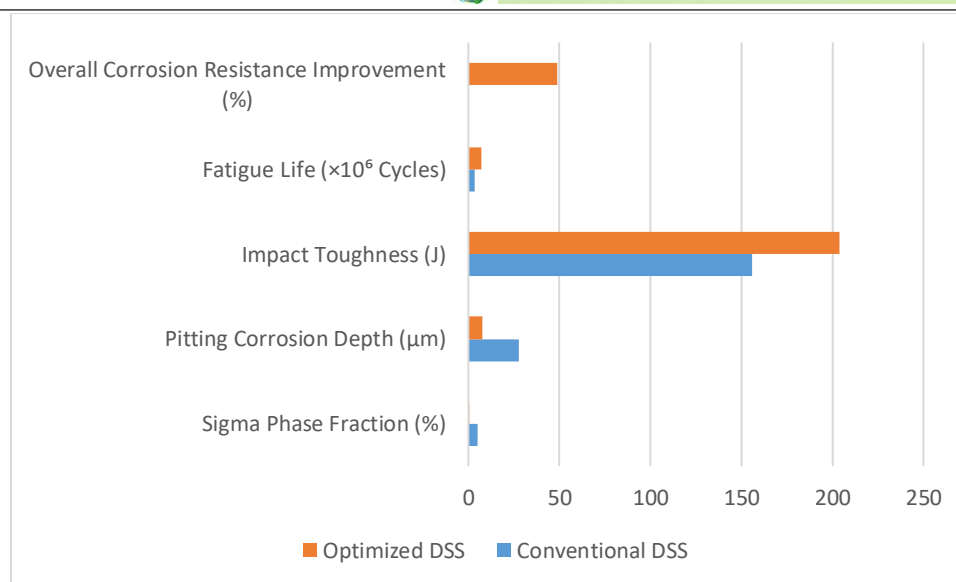


Fig. 4: Bar graph comparing sigma phase fraction, pitting depth, impact toughness, fatigue life, and overall corrosion resistance improvement.

The experimental results demonstrate that controlled thermomechanical processing effectively suppresses detrimental secondary phase precipitation, refines the duplex microstructure, enhances passive film stability, and significantly improves corrosion resistance, toughness, and fatigue performance. These improvements establish optimized Duplex Stainless Steel as a highly reliable material for offshore platforms, subsea pipelines, desalination plants, chemical reactors, marine structures, nuclear systems, pressure vessels, hydrogen processing equipment, heat exchangers, renewable energy infrastructure, and advanced corrosion-resistant engineering applications operating under severe mechanical loading and aggressive corrosive environments.

CONCLUSION

The present investigation successfully demonstrates that **controlled thermomechanical processing is an effective metallurgical approach for developing corrosion-resistant Duplex Stainless Steel with an optimized balance of mechanical strength, toughness, and corrosion performance.** Systematic optimization of hot deformation, rolling reduction, solution annealing temperature, soaking duration, and cooling rate significantly influenced ferrite–austenite phase balance, grain refinement, recrystallization behavior, passive film stability, and suppression of detrimental secondary phases. Advanced characterization using Optical Microscopy, SEM, EBSD, TEM, and XRD confirmed that the optimized processing schedule produced a homogeneous duplex microstructure consisting of nearly equal proportions of ferrite and austenite with refined grains and negligible sigma phase precipitation. Electrochemical investigations through potentiodynamic polarization and Electrochemical Impedance Spectroscopy demonstrated remarkable improvements in corrosion resistance by reducing corrosion current density, increasing polarization resistance, enhancing passive film stability, and improving resistance to pitting and crevice corrosion. Mechanical characterization further revealed enhanced hardness, yield strength, tensile strength, impact toughness, and fatigue performance while maintaining excellent ductility. The developed processing–microstructure–

property relationship establishes a reliable scientific framework for manufacturing high-performance Duplex Stainless Steel components capable of delivering superior structural integrity and long-term durability in aggressive chloride-containing environments.

Future research may focus on integrating thermomechanical processing with advanced surface engineering techniques such as laser surface treatment, plasma nitriding, ion implantation, friction stir processing, severe plastic deformation, cryogenic treatment, additive manufacturing, computational thermodynamics (CALPHAD), phase-field modeling, crystal plasticity finite element simulations, machine learning-based process optimization, artificial intelligence-driven microstructure prediction, digital twin-assisted manufacturing, and real-time process monitoring to further improve corrosion resistance and mechanical reliability. Additional investigations into hydrogen embrittlement, corrosion fatigue, high-temperature oxidation, microbiologically influenced corrosion, long-term marine exposure, and environmentally assisted cracking will further expand the industrial applicability of Duplex Stainless Steel. The continued advancement of controlled thermomechanical processing combined with intelligent manufacturing technologies is expected to facilitate the development of next-generation corrosion-resistant Duplex Stainless Steels for offshore oil and gas platforms, subsea pipelines, desalination facilities, chemical processing plants, nuclear reactors, hydrogen production systems, renewable energy infrastructure, marine engineering, pressure vessels, biomedical equipment, aerospace structures, and advanced structural engineering applications, ensuring exceptional corrosion protection, superior mechanical performance, and extended operational service life.

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