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MICROSTRUCTURE AND WELDING BEHAVIOR OF NIOBIUM-STABILIZED DUPLEX STAINLESS STEEL UNDER LASER BEAM WELDING

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ABSTRACT:
This study examines the laser beam welding (LBW) performance and microstructural characteristics of niobium-stabilized duplex stainless steel (DSS). The experiment focuses on the influence of laser power, welding speed, and focal position on weld profile and phase structure. Microstructure testing is also conducted to examine grain morphology, ferrite-austenite balance, and phase transformation. The findings show extensive differences in grain structure and phase composition that influence the weld quality and mechanical integrity of the material. The knowledge of such effects is worthwhile in understanding weldability, microstructural evolution, and performance of niobium-stabilized DSS. Such findings are beneficial to its use in industries demanding high strength, corrosion resistance, and consistent weld performance like marine, chemical, and structural engineering.
Keywords: Hot and Cold rolled Niobium Stabilized duplex stainless steel, Laser Welding, Microstructure testing.

INTRODUCTION :

Duplex stainless steels (DSS) are commonly used in high-strength, corrosion, and endurance-intensive applications. They consist of a combination of ferrite and austenite phase with balanced composition, which has better mechanical properties than conventional austenitic or ferritic stainless steels. The addition of niobium as a stabilizer enhances the material's resistance to sensitization and aids in grain refinement, hence leading to overall performance improvement in high-temperature and corrosive environments. Niobium-stabilized DSS is particularly suited for application in the chemical, marine, and energy markets due to improved weldability and thermal stability.

Laser beam welding (LBW) is a high-precision welding technique with a concentrated laser beam used as the heat source to provide deep penetration and reduced heat-affected zones. The process has a number of advantages, including high speeds of welding, low distortion, and the ability to weld complex geometries. The key parameters that govern LBW are laser power, welding speed, focal position, and shielding gas, all of which have considerable influence on the quality of the weld and microstructure. Each of these parameters must be carefully selected and optimized to produce defect-free welds with acceptable mechanical and metallurgical characteristics.

Microstructure testing becomes absolutely essential in assessing the impact of LBW on phase balance, grain shape, and general material integrity. Post-weld inspection employs etching methods to expose phase distribution and grain structure, enabling detailed evaluation of the welded area. The ferrite-to-austenite ratio, differences in grain size, and possible phase transformations are examined to appreciate the effect of welding on the performance of the material. Such microstructural information is important in assessing the fitness of niobium-stabilized DSS for different engineering applications.

LITERATURE REVIEW :

The pulsed Nd: YAG laser butt welding of 2205 Duplex Stainless Steel. It emphasizes the influence of welding speed on weld quality while maintaining other parameters such as laser power and pulse

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width constant. The results show that weld strength improves with welding speed up to an optimal value, after which it deteriorates. Besides, the study observes that penetration depth and bead width decrease as scanning speed increases. The investigation covers microstructural change and tensile properties, observing that control of welding speed is imperative for the quality and integrity of the weld structure [1]. The optimal focus positioning above the surface enhances weld quality and penetration depth, while excessive cooling rates from laser welding enhance ferrite content, which may reduce corrosion resistance. Regression models used in the study estimate weld geometries, highlighting the need for ferrite and austenite phase balance to ensure weld integrity and resist corrosion [2]. Optimization of laser welding input parameters such as laser power, weld speed, focal position, and shielding gas, etc. It is an illustration of the impact of the same on material responses such as weld width, penetration depth, heat-affected zone details, and tensile strength. Various studies illustrate methodologies such as Design of Experiments, Taguchi methods, and optimization techniques such as genetic algorithms and response surface methodology. The paper invokes the optimization of these parameters in order to realize high-quality welds in various materials, and it introduces new developments in laser welding for higher efficiency, lower costs, and improved mechanical properties [3]. The generation of laser welds free from defects, with martensitic microstructure in heat-affected and fusion zones, high hardness, and mechanical integrity. Tensile and Erichsen cupping tests in experiments illustrate the applicability of welded sheets in industrial processes such as cold stamping. The work is also augmented by finite element simulation to simulate temperature development and mechanical results, which demonstrate very good agreement with experiment [4]. The significance of welding power, speed, and shielding gas on the ferrite/austenite balance of the material and on secondary phase formation like M2N, which are accountable for performance. By thorough analyses, the authors determine the best welding conditions to obtain desired mechanical properties and corrosion resistance with a minimum of undesirable effects such as porosity and grain coarsening [5]. The way welding heat input, under fiber laser control, determines microstructural transformation of these alloys. Duplex stainless steels desire an optimal ferrite-austenite balance, whose management is by composition and cooling rate. Ferritic stainless steels exhibit microstructure transformation to various extents, dominated by martensite formation [6]. The impact of laser welding on the mechanical properties of duplex stainless steel. It emphasizes how tensile strength, hardness, and microstructure are modified as a result of the welding process, considering parameters such as laser parameters and joint quality [7]. Nitrogen shielding gas to be a vital factor in boosting austenite content when welding, and also reheating processes such as post-weld heat treatment to refine phase balance [8]. Dual-beam laser welding technique, the authors analyzed how energy distribution determines the ferrite/austenite ratio, the shape of the fusion zone, and mechanical strength. Results indicate that the dual-beam setup can play a major role in bead shape and phase balance, with the maximum austenite content occurring at a 65:35 beam power ratio [9]. Chemical etching (using a solution of glycerol, HNO3, HCl, and HF) and electrochemical etching (using KOH and NaOH solutions).Results are such that chemical etching and NaOH-based electrochemical etching bring out the ferrite-austenite microstructure, but the latter best unearths secondary intermetallic phases. Heat treatment is attributed to increasing volume fraction of the ferrite and secondary phases and playing a role in the effect on the properties of the material [10]. The metallographic method of selective etching and ASTM E1245 analysis, which provides greater accuracy in measuring phase volumes than conventional methods such as ASTM E562. They illustrate this technique's ability to quantitatively evaluate ferrite, austenite, and σ-phase, on specimens that have been heat-treated in different ways. The research relates results to thermodynamic modelling and XRD data, giving a solid method for the design and evaluation of DSSs [11]. The microstructure presented a balanced composition of austenite and ferrite phases, with varying ferrite content between 35% and 55.8%. This stability is crucial in bestowing DSS's better mechanical properties and resistance to corrosion.Notably, there were no carbides, nitrides, or intermetallic compounds in the grain or within the boundaries, an indicator of stable structure. Absence of such phases assures utmost performance under corrosive environments, further improving the reliability and longevity of the material in applications like oil and gas transportation. Microstructure results emphasize the significance of distribution of phases and absence of unwanted compounds to provide desirable properties for applications in industries [12].

MATERIALS AND METHODS :

Materials :

Niobium-stabilized duplex stainless steel (DSS) is a high-performance variant of DSS with high strength, corrosion resistance, and thermal stability. It is a combination of balanced austenite and ferrite phases, which exhibits better mechanical properties than regular stainless steels. The alloy consists mostly of iron (Fe) with major elements like chromium (Cr), nickel (Ni), molybdenum (Mo), and nitrogen (N). Chromium and molybdenum improve corrosion resistance, nickel contributes to austenite formation, and nitrogen enhances strength and phase stability. Niobium (Nb) addition is effective in grain refinement, carbide precipitation prevention, and high-temperature performance improvement. Niobium precipitates like niobium carbide (NbC) and niobium nitride (NbN) suppress grain coarsening and increase mechanical properties. This alloy is extensively utilized in offshore oil and gas, power generation, chemical processing, and marine structures because of its superior SCC resistance, high tensile strength and excellent toughness.

Hot-rolled and cold-rolled conditions of niobium-stabilized DSS are examined with a view to determining the effect of prior material processing on weldability and microstructure. Hot-rolled DSS, rolled at high temperatures, has a coarse grain size with residual stresses being relieved through rolling, being highly tough but having reduced hardness. Cold-rolled DSS, which is deformed at lower temperatures, acquires a finer grain size, greater hardness, and better strength owing to strain hardening but accompanied by residual stresses that can impact weldability. The addition of niobium improves thermal stability during welding and minimizes the likelihood of sensitization and intergranular corrosion. It also minimizes the quantity of adverse phase formation such as sigma (σ) and chi (χ) phases that degrade mechanical properties and corrosion resistance. In maintaining the duplex phase balance even when subjected to high temperature under laser beam welding, niobium-stabilized DSS proves to be an extremely reliable material for demanding engineering purposes.

LASER BEAM WELDING :

Laser Beam Welding (LBW) is an accurate welding process that uses a concentrated laser beam as the source of heat to join materials with very small heat-affected zones and penetration depth. The process works by subjecting the workpiece to a concentrated laser beam, where high intensity energy will melt the material, creating a fusion weld upon solidification. LBW is especially useful for welding niobium-stabilized duplex stainless steel (DSS) because it can deliver deep penetration with minimal distortion, preserving the duplex phase balance of the material. Welding begins with appropriate material preparation, including cleaning of the surface to remove contaminants. The laser beam is then concentrated on the joint, and welding parameters are fixed in terms of material thickness and final weld properties. During the welding operation, a protective gas, such as argon or nitrogen, is used to avoid oxidation and contamination of the molten pool. Post-weld cooling and inspection follow to check for weld integrity and microstructural stability. The efficiency of LBW in this project comes from its ability to make high-quality welds with controlled heat input, limiting the phase imbalance and microstructural degradation in niobium-stabilized DSS. By optimizing some important LBW parameters, welds with no defects and improved mechanical properties and resistance to corrosion are possible. Laser Beam Welding Parameters are

• Laser Power: Governs energy input and impacts penetration depth along with weld quality.

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- Welding Speed: Controls laser-material interaction time and therefore bead shape in a weld.
- Focal Position: Affects energy concentration in the weld zone, optimizing fusion and penetration.
- Shielding Gas Type and Flow Rate: Protects weld pool from oxidation and stabilizes the welding operation.
- Beam Mode (Continuous or Pulsed): Influences the heat distribution and response of the material.
- Spot Size/Diameter: Influences energy density and weld shape.

Table1: Laser beam parameters

Laser power	Voltage	Frequency	Wavelength
2400V	240V	50Hz	1070Hz

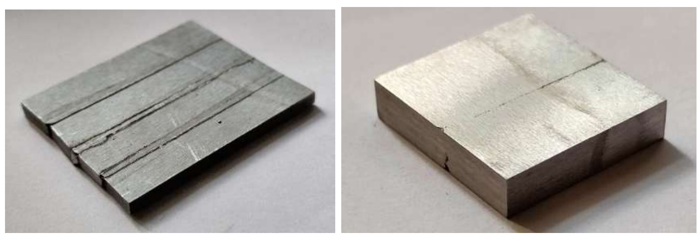

Figure 1: Laser welded part of (a) Cold rolled (b) Hot rolled

MICROSTRUCTURE TESTING :

Microstructure testing is a crucial analysis technique that determines the internal material structure and is useful for verifying phase distribution, grain morphology, and any inner flaws which play a role in determining mechanical properties as well as corrosion resistance. Microstructure testing in this research work is conducted to study how laser beam welding (LBW) impacts the niobium-stabilized duplex stainless steel (DSS). The process involves three main steps: surface preparation, etching, and microscopic examination, which all have crucial roles to play in establishing the microstructural characteristics of the weld region with maximum precision. It begins with the surface preparation process, where the specimen to be welded is cross-sectioned for improved observation of the weld zone. A series of grinding and polishing processes are applied to the surface to give it a polished and reflective look. It is ground using progressively finer abrasive papers, starting with coarse to fine, followed by polishing using diamond or alumina suspensions. It is a critical step because an improperly prepared surface with scratches or imperfections will interfere with microstructural observation. Chemical etching is subsequent to surface preparation with oxalic acid being the etchant. Oxalic acid is specifically well-adapted for duplex stainless steel because it selectively marks the austenite and ferrite phases without undue attack on the material. Among the several advantages of employing oxalic acid in this research is that it is used to produce a very good phase contrast, hence making it possible to easily study the equilibrium of the phases and possible phase transformations with laser welding. In addition, oxalic acid etching allows the effects of sensitization and grain boundary structure to be easily and quickly identified, which are crucial in examining the corrosion resistance of the material after welding. Etching is also strictly controlled not to over-etch, altering the microstructural characteristics.

The specimen is then examined under a microscope, e.g., an optical or a metallurgical microscope, to observe the microstructural features of the weld zone. When placed under magnification, it is possible to detect the austenite and ferrite phases and make a determination of grain morphology, phase distribution, and any microstructural changes produced by LBW. The examination will then determine whether the welding process maintains the desired duplex phase balance and structural

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integrity so that niobium-stabilized DSS continues to possess its high mechanical properties and corrosion resistance.

RESULT AND DISCUSSION :

Microstructural analysis of laser beam welds in niobium-stabilized duplex stainless steel (DSS) under hot-rolled and cold-rolled conditions demonstrates extensive differences between the base metal (BM), heat-affected zone (HAZ), and weld metal (WM). Such differences have direct effects on weldability, mechanical properties, and corrosion resistance.

Microstructural Observations

In the hot-rolled DSS, the base metal has a balanced ferrite-austenite microstructure with elongated grains based on hot rolling. The austenite phase is present as dark areas, and the ferrite phase as light ones. The heat-affected zone (HAZ) indicates moderate grain growth resulting from the heat of welding with some potential carbide/nitride precipitation at grain boundaries.

Figure 2: Hot rolled microstructure

The weld metal (WM) shows a finer, equiaxed grain structure, and large ferrite pools with surrounding austenite, implying ferritic-austenitic solidification. The overall structure indicates excellent thermal stability and low residual stress, which is a good material for welding purposes.

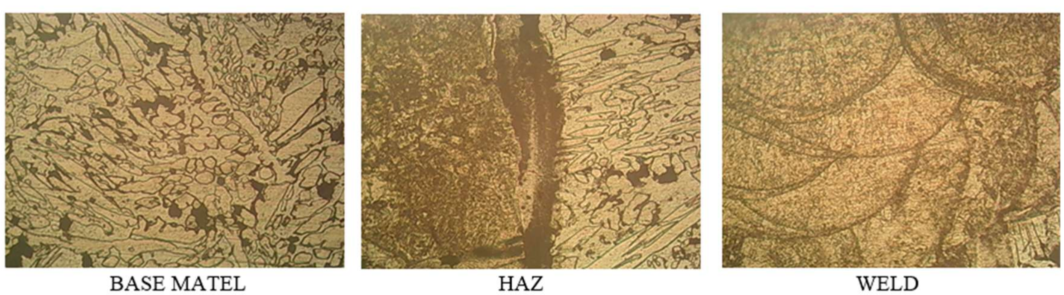

Figure 3: Cold rolled microstructure

Cold-rolled DSS, on the other hand, has a finer and deformed grain structure in the base metal resulting from strain hardening by rolling. Austenite and ferrite phases are more evenly distributed, lending to greater strength and less ductility. The HAZ of cold-rolled DSS experiences greater grain coarsening as a result of high-temperature exposure, with more carbide and nitride precipitation along grain boundaries. This precipitation can cause sensitization, which will increase the tendency of the material to intergranular corrosion. The weld metal exhibits a higher degree of ferrite pools and solidification bands, indicating that the previous work hardening affected the solidification behavior. Higher residual stresses in cold-rolled DSS increase its tendency towards distortion and cracking upon welding.

The microstructural contrast between cold-rolled and hot-rolled DSS largely determines their adaptability to different applications. In weldability, hot-rolled DSS is more desirable because of its

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reduced residual stresses, which minimize the potential for cracking and distortion upon welding. Cold-rolled DSS has higher residual stresses transferred from the rolling operation, which enhance the likelihood for warping, cracking, and stress concentration in the weld joint. At a mechanical properties level, cold-rolled DSS possesses higher strength and hardness due to strain hardening but lower ductility and increased susceptibility to brittle failure at the expense thereof. Hot-rolled DSS maintains an optimum balance between ductility and strength, which is of more usefulness in structural applications. Resistance to corrosion is also a significant parameter, and cold-rolled DSS tends to have greater susceptibility to carbide and nitride precipitation in the heat-affected zone (HAZ) resulting in sensitization and possible intergranular corrosion.

Table 2: Comparison of Hot-Rolled and Cold-Rolled DSS Properties

Feature	Hot rolled DSS	Cold rolled DSS
Microstructure	Coarse, elongated grains, stable phase balance.	Refined, elongated grains, altered phase balance due to work hardening.
Hardness & Strength	Moderate hardness due to annealing.	Higher hardness due to strain hardening.
Ductility	Higher, improved grain recovery.	Lower, increased brittleness.
Residual Stress	Low, stress relieved during rolling.	High, retained strain from cold rolling.
Grain Growth in HAZ	Moderate, some carbide/nitride precipitation.	Pronounced grain coarsening.
Cracking Risk	Lower due to stable phase balance.	Higher due to stored stress.
Corrosion Resistance	Better, minimal carbide precipitation.	Reduced, risk of sensitization.
Solidification Mode in Weld Metal	Ferritic-Austenitic, balanced phase.	More ferrite pools, increased brittleness.

However, hot-rolled DSS is more resistant to corrosion in weld conditions owing to its more stable microstructure and reduced phase transformation susceptibility. Lastly, stability at thermal conditions is important, as cold-rolled DSS, with increased residual stresses, is more susceptible to microstructural instability at higher temperatures, which tends to increase the possibilities of grain coarsening and undesirable phase transformations. Hot-rolled DSS, having a recrystallized grain structure, is more thermally stable compared to cold-rolled DSS and is more appropriate for use in applications where high-temperature exposure exists.

CONCLUSION :

The present work puts forward a comparative investigation of the laser beam welding (LBW) characteristics of hot-rolled and cold-rolled niobium-stabilized duplex stainless steel (DSS) based on microstructural contrasts and their significance in welding purposes. Hot-rolled DSS exhibited improved weldability, thermal stability, and corrosion resistance owing to its balanced ferrite-austenite microstructure and lower residual stresses, suitable for welded structures in marine, offshore, and chemical applications. Cold-rolled DSS exhibits enhanced strength and hardness as a consequence of strain hardening but faces welding complexities including greater residual stress, ductility loss, and carbide formation in the HAZ. Post-weld heat treatment (PWHT) becomes necessary due to these properties for enhancing the weld quality as well as resistance against corrosion.

In general, hot-rolled DSS is ideal for applications requiring mechanical reliability and corrosion resistance in welded parts, and cold-rolled DSS is appropriate for non-welded precision parts with higher strength requirements. This research improves the knowledge of the effects of material preprocessing on LBW microstructure, which will help in optimal material selection for different engineering applications.

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