Microstructural and Mechanical Evolution in Stainless Steel Clad Carbon Steels via FSW

Noah Richardson

Department of Metallurgical Engineering, Colorado School of Mines, USA

Abstract: Friction Stir Welding (FSW) has emerged as an effective solid-state joining technique for producing high-quality stainless steel–clad carbon steel structures for advanced structural and corrosion-resistant applications. This study investigates the microstructural transformation and mechanical property evolution occurring during FSW-based cladding of carbon steel with stainless steel. Detailed metallographic and scanning electron microscopy analyses reveal the formation of a refined, dynamically recrystallized stir zone characterized by homogeneous material mixing and the elimination of solidification-related defects typically observed in fusion welding. The interfacial region exhibits continuous metallurgical bonding with limited intermetallic formation, indicating favorable diffusion-controlled interaction between the dissimilar metals. Grain refinement and phase redistribution significantly enhance hardness and tensile strength within the weld nugget, while maintaining acceptable ductility. Mechanical testing demonstrates improved load-bearing capacity and interfacial integrity of the clad system compared to the base materials. The results confirm that FSW enables the production of defect-minimized, mechanically reliable stainless steel–carbon steel composites with superior structural performance and service durability.

Keywords: Friction stir welding, stainless steel cladding, carbon steel, microstructure evolution, mechanical properties

Introduction

The continuous demand for materials that combine high mechanical strength with excellent corrosion resistance has driven extensive interest in bimetallic and clad metal systems. In many engineering sectors, including oil and gas, petrochemical processing, marine infrastructure, and power generation, carbon steels are widely used due to their low cost, good formability, and favorable strength-to-weight ratio. However, their susceptibility to corrosion and oxidation in aggressive service environments significantly limits their durability and lifecycle performance. In contrast, stainless steels exhibit outstanding resistance to corrosion, high-temperature stability, and good mechanical reliability, but their high alloy content results in considerably higher material and fabrication costs. As a consequence, the development of stainless steel–clad carbon steel composites has emerged as a practical and economical solution, enabling the structural efficiency of carbon steel to be combined with the surface protection of stainless steel.

Cladding technologies provide a metallurgically bonded protective layer on a structural substrate, extending service life while minimizing material cost. Conventional cladding and joining methods include fusion welding, roll bonding, explosive welding, laser cladding, and thermal spraying. Although these techniques are industrially established, many of them involve high heat input, leading to solidification defects, porosity, segregation, distortion, and the formation of brittle intermetallic phases at the dissimilar metal interface. In stainless steel–carbon steel systems, excessive thermal cycles often promote carbon diffusion, carbide precipitation, and the development of hard and brittle martensitic structures, which compromise joint integrity and fatigue performance.

Friction Stir Welding (FSW), originally developed for aluminum alloys, has evolved into a versatile solid-state joining and processing technique applicable to a wide range of ferrous and non-ferrous materials. Unlike fusion-based processes, FSW operates below the melting temperature of the base materials, utilizing severe plastic deformation and frictional heating generated by a rotating non-consumable tool to achieve metallurgical bonding. This solid-state nature significantly reduces thermal gradients, eliminates solidification-related defects, and enables superior control over microstructural evolution.

The application of FSW for stainless steel cladding onto carbon steel represents a promising route to produce high-integrity bimetallic structures with refined microstructures and enhanced mechanical performance. During FSW, the combined effects of intense plastic flow, dynamic recrystallization, and diffusion-driven intermixing modify grain morphology, phase distribution, and dislocation density within the stir zone and thermo-mechanically affected regions. These microstructural transformations directly influence hardness distribution, tensile behavior, fatigue resistance, and interfacial bonding strength.

Despite growing research activity, the complex metallurgical interactions occurring in FSW-fabricated stainless steel–carbon steel composites remain only partially understood. The presence of strong chemical and physical gradients, combined with severe thermomechanical conditions, leads to unique microstructural features that differ substantially from those produced by conventional welding. A systematic understanding of these phenomena is essential for optimizing process parameters and ensuring reliable industrial implementation.

Literature Review

Conventional Cladding and Joining of Dissimilar Steels

Traditional approaches for cladding stainless steel onto carbon steel primarily rely on fusion-based or high-energy bonding techniques. Roll bonding has been widely used to produce large-area clad plates; however, it requires high rolling forces and elevated temperatures, which may induce residual stresses and interfacial defects. Explosive welding produces strong metallurgical bonds through high-velocity impact, but its applicability is limited by safety concerns, geometric restrictions, and the formation of wavy, highly strained interfaces.

Fusion welding and laser cladding are commonly employed for localized cladding and repair. Nevertheless, the high heat input associated with these methods often results in coarse-grained heat-affected zones, dilution of alloying elements, and the formation of brittle phases such as martensite and chromium carbides. These microstructural issues are frequently accompanied by reduced toughness, increased hardness gradients, and susceptibility to hydrogen-induced cracking and corrosion attack.

The limitations of fusion-based cladding have motivated the exploration of solid-state techniques, among which FSW has gained particular attention.

Fundamentals of Friction Stir Welding in Ferrous Alloys

FSW involves the insertion of a rotating tool with a shoulder and pin into the joint interface, generating frictional heat and severe plastic deformation. The material is softened and mechanically mixed without reaching the melting point, resulting in a consolidated joint upon cooling. In ferrous alloys, higher tool strength and optimized thermal management are required due to elevated flow stress and melting temperatures.

Several studies have shown that FSW of steels promotes extensive dynamic recrystallization, producing ultrafine equiaxed grains within the stir zone. The combination of high strain rate and moderate temperature activates continuous and discontinuous recrystallization mechanisms, leading to grain refinement and homogenization. These microstructural features are directly responsible for enhanced strength and hardness via the Hall–Petch effect.

Methodology

The experimental program was designed to investigate the microstructural evolution and mechanical performance of stainless steel–clad carbon steel produced using the friction stir welding process. Commercially available low-carbon structural steel plates and austenitic stainless steel plates of identical dimensions were selected as the substrate and cladding materials, respectively. Prior to welding, the faying surfaces were mechanically ground and degreased to remove oxides, contaminants, and surface irregularities, ensuring intimate contact and consistent material flow during processing.

The cladding operation was carried out on a rigid FSW machine using a non-consumable tool manufactured from a wear-resistant, high-temperature tool steel alloy. The tool consisted of a concave shoulder and a cylindrical pin designed to promote effective plasticization and mixing of both materials. A series of trials were conducted by varying the rotational speed, traverse speed, and axial force to establish a stable processing window that ensured defect-free bonding. The tool was positioned with a slight offset toward the stainless steel side to facilitate material transport into the carbon steel substrate and to enhance interfacial mixing.

After welding, transverse cross-sections of the clad joints were prepared using standard metallographic techniques, including mounting, grinding, polishing, and etching with appropriate reagents for both ferrous alloys. Optical microscopy and scanning electron microscopy were employed to characterize grain morphology, phase distribution, and interfacial features within the stir zone, thermo-mechanically affected zone, and heat-affected zone. Microhardness measurements were performed along the cross-section using a Vickers indenter under a constant load and dwell time to evaluate hardness gradients. Tensile specimens were extracted perpendicular to the welding direction and tested at room temperature following relevant ASTM standards to assess joint strength and ductility.

Results

The friction stir cladding process produced continuous, defect-free stainless steel layers metallurgically bonded to the carbon steel substrate. Macrostructural examination revealed a well-defined stir zone with smooth surface finish and no evidence of voids, tunnel defects, or interfacial separation. The stainless steel was effectively plasticized and transported into the carbon steel side, forming a mechanically interlocked and diffusion-assisted bonded region.

Microstructural analysis demonstrated pronounced grain refinement within the stir zone for both materials. The original coarse grains of the stainless steel and carbon steel were transformed into fine, equiaxed recrystallized structures, indicative of dynamic recrystallization under severe plastic deformation. The interface exhibited gradual compositional and structural transition, with limited formation of brittle intermetallic compounds. In the carbon steel region adjacent to the stir zone, partial phase transformation was observed, including localized martensitic structures resulting from rapid cooling, which contributed to increased hardness.

The hardness profiles showed a clear maximum within the stir zone, exceeding that of both base materials. This enhancement is attributed to grain refinement, increased dislocation density, and transformation-induced strengthening. Tensile testing indicated that the clad joints possessed strength comparable to or higher than the carbon steel substrate, with failure predominantly occurring away from the interface. The joints maintained acceptable elongation, confirming that the solid-state nature of FSW preserved ductility while enhancing load-bearing capacity.

Overall, the results confirm that friction stir welding is an effective technique for producing stainless steel–clad carbon steel with superior interfacial integrity, refined microstructure, and enhanced mechanical performance suitable for demanding structural and corrosive service environments.

Discussion

The experimental observations clearly demonstrate that friction stir welding (FSW) provides a unique thermomechanical environment that facilitates the production of high-integrity stainless steel–clad carbon steel composites. Unlike conventional fusion welding, FSW operates below the melting points of both constituent materials, which suppresses solidification defects, reduces residual stresses, and prevents excessive intermetallic formation. The refined, equiaxed grain structures observed in the stir zone for both the stainless steel and carbon steel layers indicate that dynamic recrystallization is the dominant microstructural evolution mechanism. Severe plastic deformation, coupled with frictional heating, promotes the breakup of coarse grains and enhances the homogeneity of material flow. This refinement not only increases hardness within the stir zone but also contributes to improved load transfer across the interface, which is consistent with the enhanced tensile strength measured in the experiments.

The interfacial region between the stainless steel cladding and the carbon steel substrate plays a critical role in determining the overall mechanical performance of the joint. Microstructural analysis revealed a continuous, metallurgically bonded interface, characterized by a gradual transition in composition and grain morphology. Limited diffusion of chromium, nickel, and carbon atoms was observed, but without the formation of thick, brittle intermetallic layers, which are commonly reported in fusion-welded dissimilar steels. This indicates that the solid-state nature of FSW minimizes undesirable chemical reactions and allows the formation of a strong, ductile interface capable of sustaining high loads. The slight presence of martensitic structures in the carbon steel near the interface contributed to localized hardness enhancement, but did not compromise ductility due to the fine distribution and small volume fraction of transformed regions.

The observed hardness distribution across the welded joint further underscores the influence of FSW-induced microstructural transformations. Peak hardness values were recorded within the stir zone, reflecting the combined effects of grain refinement, work hardening, and transformation-induced strengthening. The thermo-mechanically affected zone exhibited moderate hardness, while the heat-affected zone of carbon steel experienced limited softening due to partial stress relief and tempering effects. These gradients are indicative of the delicate balance between thermal input and mechanical deformation in FSW and highlight the importance of process parameter optimization. Rotational speed, traverse speed, tool offset, and axial force collectively control the heat generation, plastic flow, and interfacial mixing, all of which directly affect the microstructural uniformity and mechanical integrity of the clad joint.

From a mechanical perspective, tensile testing revealed that the failure of the joint predominantly occurred away from the interface, demonstrating that the interfacial strength exceeded the intrinsic strength of the carbon steel substrate. This finding confirms that FSW can produce stainless steel–clad carbon steel with load-bearing capacity superior to the base substrate, while maintaining ductility and toughness. The enhanced performance is attributable to the combination of refined microstructure, uniform interfacial bonding, and the absence of fusion-related defects. Furthermore, the absence of pores, voids, and solidification cracks enhances fatigue and wear resistance, which is critical for structural applications exposed to cyclic loading and harsh environmental conditions.

Conclusion:

This study demonstrates that friction stir welding (FSW) is a highly effective technique for producing stainless steel–clad carbon steel composites with superior microstructural integrity and mechanical performance. The process enables solid-state bonding, which eliminates common fusion-related defects such as porosity, cracks, and brittle intermetallic formation. Microstructural analyses revealed that the stir zone undergoes extensive dynamic recrystallization, producing fine equiaxed grains in both the stainless steel cladding and the carbon steel substrate. The interface exhibited continuous metallurgical bonding with limited diffusion-induced transformations, ensuring excellent interfacial strength and mechanical continuity.

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