Friction stir Cladding of Copper on Mild Steel and its Characterization

Thesis submitted in the partial fulfillment for

the award of degree

Doctor of Philosophy

By

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Mithlesh Kumar Mahto

ABSTRACT

Common welding processes that are used for cladding face challenges like dilution, spatter control, distortion, thickness control, superficial bonding, and cost effectiveness. Therefore, there is a need to explore new processes for cladding. The deposition of copper on top of a steel substrate combines the advantages of the corrosion resistance of copper with the high tensile strength of steel. Due to their diverse properties, it is challenging to deposit copper on steel. In this work, the friction stir welding (FSW) process has been used to successfully clad a 3 mm thick copper sheet on a 6 mm thick mild steel substrate. The process is different from lap welding, not only because of its intended purpose but also because several repetitive passes are required with a suitable tool offset to cover the entire plate effectively. To optimise the tool offset distance, a series of trial experiments with offset values of 6, 8, 10 and 12 mm were carried out. Metallography examination, along with X-ray radiography, was carried out on the prepared cladded samples. The average grain size of the steel substrate below the clad layer showed refined grains with a size of 5 μm, indicating an improvement of more than 60% over the base steel. SEM and EDS map analysis revealed proper bonding of the cladded material with the substrate. Uniaxial tensile tests on flat specimens were carried out for base copper, base steel, and copper clad steel samples. The copper cladded steel has a yield strength (YS) of 261 MPa and an ultimate tensile strength (UTS) of 359 MPa in comparison to base copper, with a YS of 131 MPa and a UTS of 227 MPa. Fractography analysis revealed stretching marks between copper and steel due to the difference in elongation rates of both materials. A guided bend test for the face bend, root bend and side bend revealed no delamination or crack initiation along the convex surface. Microhardness testing was carried out across the interface from copper to steel, where a maximum hardness value of 226 HV was recorded near the interface close to the steel region. Corrosion behaviour for as-received copper, the top surface of friction stir cladded plate, and cladded plate after 1.5 mm removal has been carried out in a 3.5% NaCl solution through the potentiodynamic polarisation method. SEM and XRD examinations of the corroded clad layer depict oxide layer formation. Atomic force microscopy reveals the presence of pits and valleys in the corroded, clad copper top. The experimental results suggest FSW does not significantly degrade the corrosion properties of copper, and the corrosion results are comparable to those of base copper.

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AFM	:	Atomic Force Microscopy
Al	:	Aluminium
ASTM	:	American Society for Testing and Materials
CBN	:	Cubic Boron Nitride
CVD	:	Chemical Vapour Deposition
CRB	:	Cold Roll Bonding
Cu	:	Copper
Dia	:	Diameter
FSW	:	Friction Stir Welding
GMAW	:	Gas Metal Arc Welding
GTAW	:	Gas Tungsten Arc Welding
HAZ	:	Heat Affected Zone
IMC	:	Intermetallics
Mg	:	Magnesium
MPa	:	Mega Pascal
Mm	:	Millimeter
NC	:	Numeric Control
PCBN	:	Poly Crystalline Boron Nitride
PVD	:	Physical Vapour Deposition
RPM	:	Revolution per Minutes
SAW	:	Submerged Arc Welding
SEM	:	Scanning Electron Microscope
SMAW	:	Shielded Metal Arc Welding
SSW	:	Solid State Welding
Ti	:	Titanium
TMAZ	:	Thermo Mechanically Affected Zone
UTS	:	Ultimate Tensile Strength
VHN	:	Vickers's Hardness Number
XRD	:	X-Ray Diffraction

PREFACE

AISI 1018 steel (mild steel) is one of the most commonly used steels for several applications. Failure of many components made of mild steel has been recorded during its service due to its poor corrosion resistance, and thus, it limits the use of mild steel. Depositing a layer of material like copper (which has superior corrosion resistance) onto steel will protect the top surface from deterioration. However, for thick cladding, only a few methods like LASER, explosive, roll bonding, and arc welding techniques like gas metal arc welding (GMAW), gas tungsten arc welding (GTAW) and submerged arc welding are available.

Thick cladding of copper on steel substrates has always faced challenges due to the wide difference in their properties (physical, mechanical, metallurgical, chemical, and thermal) along with their diverse crystal structures, which prevent homogeneous and favourable joining of these incompatible materials. As a result, the cladding is prone to several flaws like interlayer formation, interface diffusion control, superficial bonding, cracking, and porosity.

Each fabrication method and each set of materials face a distinct set of challenges. Fusion welding processes have the inherent problem of dilution of the clad material with the substrate material. Solid state welding processes like roll bonding and explosive welding, although superior to fusion welding processes, have restrictions related to product geometry, and the process is dangerous in the case of explosive cladding. Laser cladding of copper has reflectivity issues, owing to which proper clad material is hard to produce. The friction stir welding (FSW) process has been used for a long time for welding and surfacing applications. Previous researchers working in the area of FSW have mainly attempted either lap joining, butt joining or processing, but only a handful of researchers have attempted friction stir cladding for the deposition of thick clad material on substrate material.

In this work, a 3 mm-thick cladding has been performed on a mild steel substrate through multi-pass FSW. Extensive experiments have been carried out to effectively clad and evaluate the process of friction stir welding to successfully clad copper on steel. This study will benefit the welding community by helping to effectively clad copper on steel and thus protect steel from corrosion. A critical literature review suggests none of the previous studies tried cladding 3 mm-thick copper over steel substrates. Also, no literature was found for corrosion analysis of friction stir-cladded samples of copper on steel. Hence, in the present experimental investigation, steel plates have been cladded with copper, and characterizations have been carried out to observe the changes in behaviour of clad metal properties with respect to process parameters.

The objective of the current research work is to clad 3 mm thick copper on steel substrate effectively via tool offset distance selection, followed by its characterization (metallography, tensile, bend test, hardness, XRD), followed by an evaluation of the corrosion behaviour of copper after multi-pass cladding.

Thus, the brief objectives of the present research work are:

1. Perform the deposition of 3 mm-thick copper on top of the steel substrate through multi pass FSW.
2. Evaluate the bonding efficiency of the cladded sample through mechanical tests like tensile, guided bend, and hardness evaluation.
3. To determine the tool pin offset distance between two adjacent passes to effectively clad the entire substrate material in the least possible passes.

4. To evaluate the cladded sample for any tungsten carbide tool material inclusion with non-destructive tests like X-ray radiography.
5. To evaluate the corrosion behaviour of copper after multi-pass cladding with respect to base copper, followed by the characterization of corroded samples.

Summary of thesis work: The thesis work has been summarised in chapters in the following manner according to the objectives discussed above:

Chapter 1: This chapter highlights the various aspects of cladding, including classification, the need for cladding in industries, and the present scenario of cladding. This chapter also highlights the applications, advantages, and limitations of friction stir welding. Variants of the FSW process have also been discussed in this section.

Chapter 2: This chapter deals with a critical review of various methods available for thick cladding through different arc welding processes like GMAW, GTAW or other methods like laser, explosive, etc. This section also gives a detailed review of the welding of dissimilar joints produced through the application of FSW. The role of the tooling system and the effect of process parameters during welding have also been discussed in this section.

Chapter 3: This chapter deals with the details of the materials and methodology used in this experimental work. This section starts with information regarding the selection of substrate material, clad material, and the tool material necessary for performing cladding. Following this, details regarding the FSW machine and tool grinder used for tool production have been provided. The process parameters used for performing cladding have also been discussed, followed by the characterization techniques used to evaluate the obtained cladded samples. A radiography test was carried out to check the soundness of the clad obtained. Metallography analysis was done to view the microstructural evolution due to multi-pass FSW. Tensile tests, bend tests, XRD analysis, and X-ray radiography analysis were performed for the cladded samples. A corrosion test was also performed in a 3.5 NaCl solution to evaluate the behaviour of the clad towards corrosion.

Chapter 4: This chapter elaborates on the results of the characterization performed on the cladded samples. The obtained clad was inspected through naked eyes for any visible defects or flashes. X-ray radiography proved the soundness of the clad produced. The successful samples were selected for characterization. The transverse cross-section samples were polished and etched for microstructural investigation and proved proper bonding between clad material and substrate material. Uniaxial tensile test results were analysed, followed by fractography analysis. Bend test results were analysed for the cladded samples. Corrosion results analysis has also been carried out in this section, evaluating the performance of clad copper with respect to base copper and base steel.

Chapter 5: This chapter deals with the major findings of this work. A few of the key findings are:

- A layer of copper could be successfully cladded on top of the steel substrate through a friction stir welding setup, suggesting an alternative method for thick cladding.
- Metallography analysis of the transverse cross-section of cladded samples reveals proper bonding between the steel substrate and copper clad.
- Tool pin Offset between two adjacent passes serves as a crucial factor in friction stir cladding.

- Fractography analysis of gauge length revealed cladded materials did not delaminate and fractured as a single material.
- Radiography of clad samples demonstrates sound welds.
- Mechanical testing of the produced clad offers satisfactory results.
- XRD analysis suggests no substrate material could flow to the top surface. Thus, the top surface of the cladded layer was free from any dilution.
- The corrosion test reveals that the corrosion characteristics of cladded samples are quite similar to those of base copper.
- The cladded samples produced by this novel technique are capable of safeguarding the steel substrate from severe corrosion.

Chapter 6: This chapter discusses the potential scope of future research based on this work. The results of this study could be replicated by trying to clad copper of different thicknesses on substrates of low alloy steels. The optimum thickness of the clad layer for different applications can also be found. The process of friction stir cladding could be applied to clad other corrosion resistant materials like stainless steel and titanium alloys and evaluate their performance.