5 CONCLUSIONS

- A layer of thick copper could be successfully cladded on top of the steel substrate using the existing FSW setup. Thus, establishing an alternative method for thick cladding of materials on the substrate.
- Repetition of pin plunges up to identical heights, offset distance between passes, placement of tool pins to avoid flesh boundaries, and maintaining consistent tool geometry play a crucial role in obtaining defect-free friction stir cladding.
- Critical assessment of tool behaviour reveals that small-grain sized tungsten carbide with low cobalt content is ideally suitable to perform multipass cladding through FSW. A high-cobalt-percent tungsten carbide tool undergoes pin mushrooming, pin periphery wear, and material erosion from the tool pin.
- The process parameters for successful cladding could be established after a series of trial experiments. A tool RPM of 700, a welding speed of 100 mm/min, and a tool tilt of 1.5° were found to work well for the friction stir cladding of copper on steel.
- Tool pin offset variation serves as a key factor for multipass cladding, resulting in higher productivity. An optimal tool pin offset could be established, and a pin offset of 7 mm was found to work well for copper cladding of steel substrate with a tool shoulder of 20 mm diameter and a pin diameter of 6.5 mm. Lower

tool offset results in higher diffusion close to interface boundaries, and vice versa.

- Metallography analysis of the transverse cross section of cladded samples reveals proper bonding between steel and copper with grain refinement in the steel substrate region near the interface, with an average grain size of nearly 5 microns. However, the copper grains were not refined and showed slight grain coarsening.
- Joints free of any oxide contamination with a surface jetting effect were observed near the stir zone interface. The interface showed cross boundary metal movement.
- The mechanical properties of the cladded sample fall between those of base copper and base steel values, and copper-cladded steel displayed yield strength twice that of base copper. The steel-copper bimetal joint has a YS of 261 MPa and a tensile strength of 359 MPa in comparison to base copper, which has a YS of 131 MPa and a UTS of 227 MPa.
- Fractography analysis of fractured tensile test specimens along gauge length revealed stretching marks between copper and steel due to the difference in elongation rates of both materials. However, the cladded materials did not delaminate and fractured as a single material.
- Guided bend tests in all three conditions, i.e., root bend, face bend, and side bend, exhibited no signs of delamination or peeling. Also, no cracks were observed along the convex regions.
- XRD analysis revealed that materials with clad copper top were similar to base copper, confirming no clad material dilution or formation of intermetallic at the top surface of the clad material. However, on performing XRD on the

transverse section, a few intermetallics like $Cu_{0.8}Fe_{0.2}$ and $Cu_{0.3}Fe_{1.7}$ were detected.

- Microhardness carried across the transverse cross section revealed maximum hardness on the steel substrate close to the interface. This increased hardness was because of the finely recrystallized grains, ruling out any possibility of martensite formation.
- The potentiodynamic polarisation test proved conclusively that the corrosion characteristics of cladded samples were quite similar to those of commercially pure copper (base copper). Thus, the cladded samples produced by this novel technique are capable of safeguarding the steel substrate from severe corrosion in service.
- An insignificantly higher corrosion rate of 0.29 mm/yr was observed for the FSWed clad copper top, followed by 0.26 mm/yr for the 1.5 mm removed clad sample, while the least corrosion was observed for base copper at 0.23 mm/yr. No detrimental effect was traced on the corrosion properties of copper due to multipass friction stir cladding.
- SEM images of corroded samples showed oxide layer formation over the clad top, while groove path formation was observed across the 1.5 mm removed sample. XRD analysis post-corrosion revealed the appearance of low-intensity peaks for CuO in the clad top, suggesting the formation of an oxide layer in the sample during the corrosion test.
- AFM results agreed with potentiodynamic test results and show surface morphology containing pits for the corroded clad copper top sample, with an average roughness (Ra) of 0.303 µm and a ten-point mean roughness (Rz) of

0.745 µm, with the highest depth crossing 500 nm in comparison to an average roughness of 14.27 nm and a 20 nm depth for uncorroded copper.