# ABSTRACT

The present thesis deals with the tribology of duplex electroless nickel coatings. To improve the hardness, wear, and corrosion resistance of substrate materials, the duplex electroless nickel coatings are developed on mild steel substrates. Duplex electroless Ni-P/Ni-W-P, Ni-P/Ni-Cu-P and Ni-P/Ni-Mo-P coatings are developed by using dual bath technique. For each set of coatings, two types of coatings are deposited with Ni-P as the inner layer and subsequently with Ni-W-P or Ni-Cu-P or Ni-Mo-P as the outer layer alternately. Also, duplex electrodeposited Ni-P/Ni-W-P coating systems are developed using the electrodeposition technique with Ni-P and Ni-W-P as outer layers alternately. The coatings are subjected to heat treatment at temperatures from 200 to 800 °C and for 1-4 h. The effect of heat treatment on the microstructural characteristics of the coatings was investigated by using scanning electron microscopy, energy-dispersive X-ray analysis, and X-ray diffraction analysis. The influence of heat treatment conditions on microhardness, friction, wear, and corrosion behavior is studied. Heat treatment has a beneficial impact on the coating with the detection of harder crystalline phases. Duplex electroless Ni-P/Ni-W-P and Ni-P/Ni-Cu-P coatings' microhardness and wear resistance increase significantly when heat is treated up to 400℃ temperatures. However, there is a degeneration in the microhardness when the coatings are treated beyond 400℃ and for 4h duration. This is due to coarsening of grains together with the formation of oxides, as indicated by the microstructural studies. At a heat treatment temperature of 800℃ for 4h, the coating exhibits cracks and tends to delaminate. The wear mechanism encountered during the sliding test under dry conditions and at room temperature is predominantly abrasive. The electrochemical-based corrosion studies indicate that corrosion resistance of the present duplex coatings increases after heat treatment which may be due to the coarsening of grains.

In general, the duplex Ni-P/Ni-Mo-P coating with Ni-Mo-P as the outer layer outperforms the coating where Ni-P was the inner layer. For Ni-Mo-P as the external layer coating, the highest microhardness, and the lowest wear rate is obtained when heat treated at 600℃ temperature with 1h duration. This is due to the formation of hard crystalline phases like nickel phosphide phase ($Ni_3P$) and Ni-Mo. However, when heat treated at a higher temperature of 800℃ with 4h, Ni-Mo-P exterior layer exhibits cracks and plastic deformation together with few oxide patches. This deteriorated the wear performance of the coating system. The wear mechanism displayed by both coatings indicates the occurrence of both adhesive and abrasive wear. The corrosion performance of the coatings improved upon heat treatment and enhanced with increasing temperature and time

duration. Ni-Mo-P as outer layer coating, heat treated at 800°C for 4 h, the coating displayed the highest corrosion potential and significantly higher charge transfer resistance than others.

It also compares the tribological behavior of various duplex electroless coatings: Ni-P/Ni-W-P, Ni-P/Ni-Cu-P, and Ni-P/Ni-Mo-P. The tribological behavior of these coatings is influenced by several factors, heat treatment temperature, heat treatment time duration, including the composition of the samples, etc. Above 400°C temperature, all the duplex coatings formed a hard $Ni_3P$, which is good for developing wear resistance. At 400°C temperature for Ni-P/Ni-Cu-P coating, a few copper phosphide phases are obtained with $Ni_3P$ and NiCu phases. For Ni-P/Ni-Mo-P coatings, Ni-Mo phases are also observed at the above conditions. At 400°C temperature for 1h duration, Ni-P/Ni-W-P plating revealed the highest microhardness and lowest wear rate among all duplex coatings. In all three duplex systems, it is obtained that the wear mechanism combines abrasive and adhesive wear.

In as-deposited coatings, Ni-P/Ni-Cu-P duplex coating obtained higher corrosion resistance than other duplex coatings. Mostly, the Ni-P/Ni-Mo- P duplex coating performed better corrosion resistance among the three types of duplex coatings in heat heat-treated state.

Finally, the comparison is made between the performances of the present duplex coatings to the constituent binary coatings. Overall, it is found that upon being subjected to the optimal condition of heat treatment, the duplex coating presents an all-around performance that may be suitable for applications demanding both wear and corrosion resistance.

The duplex electrolyte Ni-P/Ni-W-P coating has been developed to evaluate its microhardness, friction, wear, and corrosion performance. The characterization of duplex electrodeposition Ni-P/Ni-W-P coating has been investigated. Also, duplex electrolytic and electroless Ni-P/Ni-W-P coating are compared both in as-deposited and heat-treated conditions. Mostly, the electroless and electrodeposited Ni-P/Ni-W-P coating have obtained similar trends in microhardness and wear performance. However, electroless Ni-P/Ni-W-P coating performed better than electrolytic coating in all conditions. Both the system obtained optimal microhardness and lower wear rate at 400°C temperature. At a high temperature (800°C) for 4h duration, duplex electrolytic coating observed cracks and more oxide layer that has effects on mechanical, tribological and corrosion properties. At 800°C temperature, the coating exhibits cracks and tends to delaminate both electroless and electrolytic coatings. Both types of duplex coatings indicate the adhesive and abrasive wear in nature. The corrosion performance of duplex electroless Ni-P/Ni-W-P coatings performed better than electrolytic coating.