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Conclusions & Scope for Future Work

The work performed and reported in this study attempts to explore multi-dimensional investigation on dissimilar metal welds for offshore applications. An attempt has been made to design and develop competitive SMAW electrodes for dissimilar pipeline steel API X70 and super duplex stainless steel weld, direct utilization of mining waste in welding consumable development application and investigations on two candidate filler metals for fabricating the above mentioned joint using GTAW process. The obtained results have been discussed in detail previously in chapter 5. Section 6.1 of this chapter presents the conclusions drawn from the investigations performed in this work. Few areas of investigations remained unexplored. These have been summarized in section 6.2 as the scope of future work.

6.1. CONCLUSIONS
6.1.1. DEVELOPMENT OF SMAW ELECTRODES FOR OFFSHORE APPLICATIONS

- The formulated coating compositions have been characterized for physicochemical, thermophysical, structural, and wettability properties. The investigated properties include density, specific heat, thermal conductivity, diffusivity, enthalpy of fusion, structural phases, elemental bonds, and bond length.

- Density of the electrode coating was found to be directly dependent on CaO, SiO_2, and their binary interaction $CaO.SiO_2$. A reaction between calcite and silica leads to the formation of complex silicate ions (SiO_4^{4-}], which makes the diffusion of inclusions difficult and, hence, increases the density.

- Interaction between CaO, TiO_2, and SiO_2 impart thermal stability to the electrode coating mixture. The thermal conductivity was found to be dependent on binary interactions of $CaO.SiO_2$, $TiO_2.SiO_2$, whereas the synergistic factor for specific heat is tertiary interaction $CaO.CaF_2.SiO_2$.

- Available free oxygen plays an important role in contact angle modification. The regression model suggests the binary interaction $CaO.CaF_2$, $CaO.SiO_2$ and $CaF_2.SiO_2$ have a synergistic effect on contact angle property. The individual constituents and the binary interaction of $CaO.CaF_2$ have a synergistic effect on surface tension property.

- CaO and TiO_2 react with sulphur in the weld fusion zone and forms CaS and TiS, thereby releasing oxygen in the process. They thereby help in reducing sulphur content of the weld. When calcium is bonded with F in CaF_2, it behaves differently and contributes to increasing sulphur content of the weld fusion zone. The desulphurization property of CaO also contributes towards enhancing the hardness of weld.

- SiO_2 being an acidic mineral, it individually along with its interactions with other constituent minerals CaO, CaF_2, and TiO_2 are known to contribute synergistically towards hardness.

- Basic fluxes and their interaction tend to increase the carbon concentration. Basicity of the flux has a direct relationship with the amount of oxygen present in the weld. This oxygen is mainly responsible for carrying the carbon from weld to the slag. The transfer of carbon takes place through the chemical reaction: [C] + [O] = CO.

- Basicity is directly proportional to the carbon content in the weld. the binary interaction of CaO and CaF_2 along with tertiary interaction $CaO.CaF_2.TiO_2$ increase the carbon content in weld whereas interactions $CaO.TiO_2$ and $CaF_2.TiO_2$ have an anti-synergistic effect on carbon

- The binary interaction of $CaO.SiO_2$ has an anti-synergism effect on silica content, due to the reduced activity of the SiO_2 by CaO which progresses through the following chemical reaction and forms a complex SiO_4^{4-} : $CaO = Ca^{2+} + O^{2-}$; $SiO_2 + 20_2- = SiO_4^{4-}$.

- The binary mixture of $CaO.CaF_2$, $Cao.TiO_2$ has synergistic effect on chromium content, whereas $CaF_2.SiO_2$ tends to decrease the chromium concentration of the weld deposit.

- Coating composition 16 (E16) and 21(E21) from the design matrix, were found to be most suitable ones after a series of qualitative and quantitative characterizations, which were further used to fabricate dissimilar weld.

6.1.2. FABRICATION & CHARACTERIZATION OF PIPELINE STEEL API X70/SUPER DUPLEX STAINLESS STEEL 2507 WELD USING SMAW PROCESS

- Commercial electrode E309L weld was found to have superior tensile strength than E16 and E21 welds. The tensile specimen from the three welds failed from the X70 side, a little away from the weld fusion line. The fractured surface was found to have a mix of dimples, ductile dimples, cleavage facets, and tear ridges.

- The weakest zone for impact energy was HAZ on the X70 side. Higher silica content in E309L weld influenced its impact energy adversely. E16 made weld had the best impact energy of the weld fusion zone.

- The hardness of the E309L weld fusion zone was found to be superior to the two laboratory-developed electrode-made welds. Due to comparable silica concentrations in E16 and E21 made weld, their hardness remains almost in the same range.

- The welds were found to have P+S (%wt.) concentrations of 0.043, 0.056, and 0.051 respectively for E309L, E16, and E21 made weld, representing good solidification cracking resistance for the three welds.

- Pin on disc sliding wear test results for pins extracted from weld fusion zone reveals E309L weld with its highest hardness has superior wear resistance. The wear resistance of E16 and E21 made welds were marginally inferior to E309L but were satisfactory and in acceptable limits. The material removed from the worn surface of weld pins was found to have happened through the ploughing mechanism. The cracks on the surface running longitudinally along the material plough indicate abrasive wear. Upon maturity of crack, they appear to be leaving the surface as spalling and flacking.

- The corrosion resistance of E16 and E21 weld was comparable and marginally higher than E309L weld in the aqueous environment of 3.5% NaCl solution. Corrosion potential has been used as a sensitive indicator of corrosion performance.
- The laboratory-developed electrodes represented good mechanical and microstructural properties for the fabricated dissimilar weld.

6.1.3. FABRICATION & CHARACTERIZATION OF PIPELINE STEEL API X70/SUPER DUPLEX STAINLESS STEEL 2507 USING GTAW PROCESS

- The dissimilar weld between pipeline steel API X70 and super duplex stainless steel SDSS2507 was also fabricated using the GTAW process employing two candidate fillers: (i) austenitic stainless steel (ASS) 309L and (ii) super duplex stainless steel (SDSS) 2594.
- The solidified microstructure of super duplex filler made weld consists of grain boundary austenite (GBA), widmanstatten austenite (WA), intergranular austenite (IGA), and partially transformed austenite (PTA) in the ferrite matrix. The δ/γ ratio was found to be 38/62. The microstructure of austenitic stainless steel filler metal weld is composed of δ-ferrite in skeletal morphology. The δ/γ ratio was found to be 11/89.
- The welds made with super duplex 2594 filler and austenitic 309L filler were found to have approximately 38.32% and 37.37% dilutions, respectively.
- Non-homogeneity between filler metals and API X70 steel leads to the formation of a partially mixed zone on the X70/weld interface. EPMA results indicate a significant gradient of Cr, Ni, Si, and other alloying elements. This gradient in elemental composition can lead to significant carbon activity and precipitation of carbides; make it more susceptible to failure.
- HAZ on the super duplex side due to cyclic heating and cooling in multi-pass welding undergoes a process of γ-δ transformation, grain growth and coarsening during the heating cycle and δ-γ transformation during the cooling phase.
- The tensile strength of both the welds was superior to API X70 steel, and SDSS2594 filler weld was found to have higher tensile strength and elongation as compared to 309L filler weld. The weakest region in terms of the impact energy was the HAZ on the API X70 side.
- The microhardness profile for both the weld was almost similar, with a sharp increase in the X70/weld interface. The austenitic stainless steel filler weld has lower hardness in fusion zone as compared to super duplex filler weld.
- Ranking the corrosion resistance (CR) of different zones of dissimilar weld: $CR_{HAZ/SDSS} > CR_{Weld} > CR_{HAZ/X70}$. A lower proportion of high angle grain boundaries (HAGBs), the lesser spread of Kernel average misorientation (KAM), and lesser variation in grain size of austenitic stainless steel 309L filler weld fusion zone makes its corrosion resistance higher than super duplex filler wire. Maximum pitting was observed in the HAZ region of X70 steel.

6.1.4. EFFECT OF HEAT TREATMENT ON WEAR & CORROSION BEHAVIOUR OF SUPER DUPLEX STAINLESS STEEL 2507

- The super duplex stainless steel 2507 was subjected to three heat treatments for intermetallic and secondary phases precipitation based on the TTT diagram of duplex stainless steel. Steel is expected to precipitation of these deleterious phases when exposed to high temperature working conditions such as heat exchangers and petrochemical refinery components and manufacturing processes.

- The wear resistance of the heat-treated specimen was found to be better than the SDSS 2507 steel in an as-received state, with the 875-180 (σ precipitated) specimen having the best performance.

- The wet sliding wear test results in 3.5% NaCl solution and 1M HCl reveals that hydrogen in acidic medium accelerates the reaction kinetic and induces greater material loss due to wear. The overall wear in the wet medium was more severe than in a dry environment.

- Wear mechanism investigation indicates material removal through ploughing mechanism, presence of abrasive cuts on surface, and material coming out of the surface as flacking and spalling.

- The cyclic dry-wet corrosion study of API X70, SDSS 2507 in as received and 875-180 heat treated condition was performed for 44 days in 3.5% NaCl solution and artificial ocean water. The super duplex stainless steel had better corrosion resistance than API X70 steel, but the heat treatment and possible precipitation of σ phase lowers its corrosion resistance.

6.2. FUTURE SCOPE OF WORK

- To explore more filler metals from austenitic stainless steel and duplex stainless steel families for developing competitive coated SMAW electrodes.
- Utilization of mining waste as a complete replacement of mineral constituents in electrode coating composition.
- Fabrication of graded dissimilar API X70/SDSS2507 weld with Ni interlayer from GTAW process with filler metals same as that used in this study. This would be done to lower the gradient at X70/weld interface and evaluate its effect on properties.
- Application of GMAW process for fabrication of API X70/SDSS2507 weld.
- Bio-corrosion investigations of the welds fabricated in this study in the atmosphere of sulphate reducing bacteria (SRBs) matching the actual service condition.
- A tribo-corrosion study of base metals and welds to estimate the role of wear and corrosion acting on the steel surface and welds in synergy.
- Calculation of flux coating properties using rule of mixture and comparison of values with experimental results.
- Experimental estimation of weld's ferrite number and microstructure correlation.