1
Introduction

1.1. OVERVIEW

Rapid industrialization and technological development have led to increased consumption of energy throughout the world. The consumption of oil and gas has grown exponentially in the past decade. The share of oil and natural gas towards meeting this increased need is also increasing at a fast rate. Efforts are being made to explore and extract from even the most difficult underwater sites. The offshore oil and gas reservoirs are larger as compared to the onshore reservoirs, and also the production life of the former is higher than the latter. This has caused the drilling companies to shift their focus to offshore sites. This thirst for resources has taken the oil and gas drilling to ultra-deepwater locations. An increase in fuel demand from developing countries has contradicted all forecasts and is driving the oil-gas exploration and production process from the offshore sites. Offshore exploration and production is an extensive capital investment activity. In 2019, the capital expenditure on offshore exploration and production processes had varied broadly across the globe. European investment has increased by $6.7 billion, which is approximately 21%, whereas, for Asia, the figure stands at approximately 11%, which is near about $7.5 billion. Africa and South America have shown an increase of 11% and 6%, respectively. Some parts of the world have also shown a decline in investment, such as 7% in North America and the Middle East. Figure 1.1 below shows the investment in offshore exploration and production activities across the globe for the period 2015-19. For the year 2021, the recovery activity of resources is approximated to stay on track with a projected growth of 8% [Hureau and Serbutoviez, 2020].

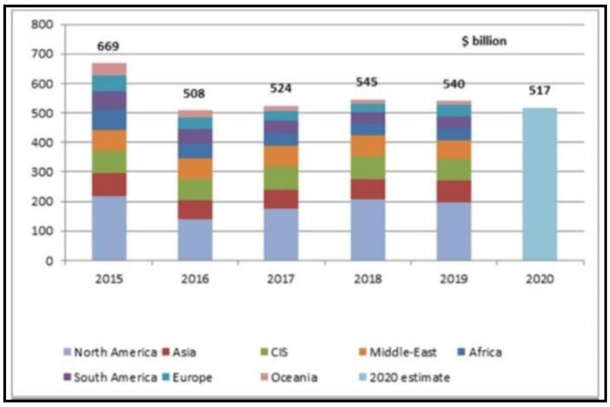

Figure 1.1: Investment in exploration and production activities 2015-19 [Hureau and Serbutoviez, 2020]

A large number of offshore structures are established for successful exploration of products from offshore well and then for transporting them to refineries for converting into a usable form. Offshore installations have definite technical and economic characteristics. History of the offshore structure dates back to Louisiana in 1909-10, where wooden platforms were constructed on the top of timber piles. Later, fixed platforms of steel template and concrete gravity type were developed in the Gulf of Mexico and the North Sea, respectively. In the past decade, the tension leg platform has been designed to explore and drill wells in ultra-deepwater locations (Reedy,2012). The offshore structure majorly constitutes oil-gas transportation pipelines, hydrocarbon drilling risers, platforms, bridges, jack-up rigs, compliant towers, FPSOs, drillships, etc. (Fig 1.2). These structures are expected to perform in severe service conditions such as high temperature-pressure, sub-zero temperature regions, sour fields, highly corrosive environment, to name a few. The material in these structures degrades over a period of time and leads to failure. A failure in such structures causes loss of capital, resources, environment, and human employment at the site. Sometimes the magnitude of losses is considerable and has a long-lasting impact.

Figure 1.2: Examples of offshore structures [Ghosh, 2015]

Material selection for offshore applications is a challenging task. It is preferable to use alloys with high corrosion resistance to ensure smooth and safe operations at offshore sites. High strength low alloy steel is the most preferred material for the transportation of oil and gas. It is economical and offers a good combination of strength, toughness, and modulus of elasticity [Mathias et al., 2013; Hashemi and Mohammadyani, 2012]. These steels are also known as carbon-manganese/low carbon steel because the carbon and manganese content is up to a maximum value of 0.2% and 1.5% by weight, respectively [Morrison, 2000]. Later, different grades were developed as specified by the American Petroleum Industry (API) to meet the service requirement of oil and gas transportation specifically. Hence, they were started to be known as pipeline steel. The earliest generation pipeline steels were X42 developed in 1948, which has now reached to the commercial-grade X120 in recent times [Trench et al., 2001]. The terminology of pipeline steel includes X as a symbolic letter followed by the yield strength of that particular grade in psi. Other corrosion resistant alloys are also increasingly used in different offshore components and structural applications. The demand and selection of corrosion-resistant alloys are driven by the corrosiveness, temperature, and pressure of the service environment. These corrosion resistive alloys also referred to as CRAs, are an alternative to the application of higher thickness low alloy steels. A tradeoff between the cost and required properties is done to decide the most suitable material for a particular location. Figure 1.3 represents the selection criteria and available materials for offshore marine applications. Table 1.1 presents information about some of the recommended corrosion-resistant alloys for offshore applications.

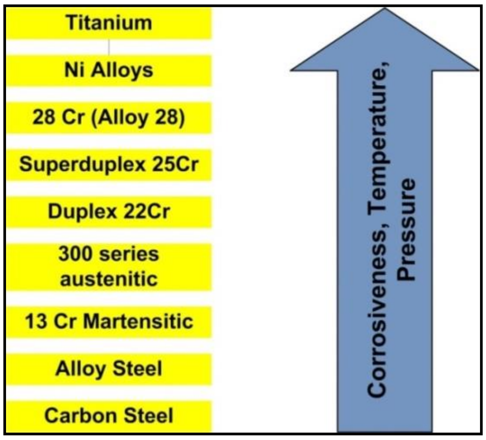

Figure 1.3: Material selection tree [Lipp and Shafer, 2013]

Table 1.1: Corrosion resistant alloys for offshore application [Lipp and Shafer, 2013]

S. No	Material Type	Grade
1	Alloy steel	4145H, 4130, 4140, 4330, 8630, F22
2	Martensitic	13Cr, Super 13Cr, 410, 420, F6NM
3	Austenitic	316, 304, 321, 317L, Nitronic 50/60, 904L, 254SMO
4	Duplex	2205, 2507, LDX2101
5	PH grades	17-4, 15-5, 13-8
6	Ni alloys	825, 625, 718, 925, Alloy 28
7	Non-magnetic	Special chromium manganese austenitic grades

Duplex and super duplex stainless steel is one of the most preferred materials because of their excellent combination of mechanical properties and corrosion resistance owing to balanced austenite ferrite ratio in its microstructure. They offer enhanced corrosion resistance because of the high percentage of chromium in its composition and are also economically viable over Ni-based alloys due to the low presence of nickel. They are an improved version of austenitic stainless steel 304 and 316L used in corrosive applications earlier. Super duplex stainless steel is nowadays increasingly used in various components of chemical refineries, petrochemical industries, offshore drilling risers, structures in the marine splash zone, and are also employed in the branching network and distribution centers of oil and gas pipelines.

Failure due to corrosion and low-temperature impact toughness is one of the major drawbacks with the API grade pipeline steels. They are more prone to failure in the highly corrosive environments of marine splash zone for hydrocarbon drilling riser, branching, and sub branching sections of oil and gas pipeline as there is an increased stress concentration in this region. Mexican petrochemical association suggests employing sleeves and cathodic protection techniques in these regions. The major issue with these methods is the associated regular checking and maintenance. Hence one of the prospective solutions is to weld the pipeline steel with high corrosion resistant and cost-effective super duplex stainless steel in the critical regions.

Super duplex stainless steel has multiple advantages, but one of their major limitations is that they are sensitive to heat treatment. In the case of prolonged thermal exposure, there is a precipitation of intermetallic and secondary phases such as chi, sigma, R, and alpha embrittlement. During the forging and welding process, the steel has to be exposed to high

temperatures; hence these phases play a fair share of role in influencing the performance. These secondary phases have a negative impact on many of its properties.
Another issue with super duplex steel is the solidification cracking of its welds. Hence, filler and parameters should be chosen accordingly to avoid the same. Dissimilar welding of two metals will ensure that the material with high corrosion resistance and better mechanical properties is exposed to a more severe environment. Marine splash zone experiences cyclic high-low tide, which is accompanied by the deposition of salt, gradually corroding the metal in contact. Drilling riser is important offshore equipment which is responsible for drilling the hydrocarbon from underground resource well to the surface facility for being transported further to the refineries. Hence, the protection of corrosion in such components is very important. Dissimilar welding has its own challenges in terms of mechanical property mismatch, microstructural instability, the difference in thermal expansion coefficient, residual stress, and different responses to the thermal treatment [Chhibber et al., 2006]. In the present era of rapid industrialization, requirement of components and structures with enhanced structural integrity is a focus of all sectors. The dissimilar weld between ferritic and austenitic stainless steel is increasingly employed in high temperature fossil and nuclear fuel based power generation plants with specific application in boiler and tubing assemblies [Thakare et al., 2019]. Similarly application of dissimilar welding is also being witnessed in mining and mineral processing operations where medium carbon steel (EN8) is joined with stainless steel (SS304) [Singh et al., 2019]. It is essential to choose the process, parameters, and welding consumables wisely to achieve desirable joint properties from a dissimilar weld. Shielded metal arc welding (SMAW) and gas tungsten arc welding (GTAW) is the most preferred conventional arc welding processes used for joining dissimilar metal at offshore sites. Coated electrodes used in the SMAW process not only protect the molten weld pool from ambient impurities but also adds alloying elements in the weld zone. Common electrode coating constituents' calcite, fluorspar, rutile, silica, bauxite, etc. are known to influence the weld profile and its properties. They are added in different compositions to obtain different performance behaviors. Similarly, the solidification of filler wire in the weld fusion zone has an influential role in lowering down the cracking susceptibility of joint and also imparts strength and properties as required for the application [Rathod et al., 2020]. Heat input in the GTA welding process is very important as the heating, and cooling cycle leads to precipitation of austenite and their reformation in the weld fusion zone. Moreover, these thermal cycles in multi-pass welding also influence the heat-affected zone (HAZ) microstructure, which is often regarded as the weakest zone in the weldments. Heat input also causes precipitation of intermetallic/secondary phases in the super duplex steel, which is deleterious in nature and influence properties. Elemental diffusion occurring due to the gradient in alloying element compositions leads to significant carbon activity. Carbon migration further leads to the formation of carbon depleted and carbon-rich zones. The formation of carbides again has a detrimental effect on the weld performance and influences the structural integrity as a whole. Precipitation of carbide occurs at the grain boundary. The chromium rich carbides, reduces the Cr concentration in the grains adjacent to the grain boundaries, thus creating a favorable condition for the intergranular corrosion. Dissimilar welds in the offshore application need a comprehensive evolution in terms of mechanical properties, microstructural stability, and performance characteristics. These are needed to ensure the sound performance and fulfillment of the objective with which the joint was fabricated. Recent researches have also shown the use of non-conventional welding processes to join the offshore materials, but due to their lacking flexibility for onsite application, they are still not much in practice as compared to the conventional arc welding processes. Characterization of joining metals and their welds will help to suggest changes required in process parameters and consumables to achieve joints with enhanced structural integrity. Design and development of welding consumable will increase the options of available welding consumables.

1.2. ORGANISATION OF THE THESIS

This thesis is divided into six chapters. The brief introduction about the content of each of these chapters is given below:

Chapter 1: Introduction to the offshore oil and gas drilling activities, major offshore structures and components, and materials used in these applications. A brief idea about the need of dissimilar joint in offshore structures and methods for their fabrication along with a discussion of issues in the dissimilar weld.

Chapter 2: This chapter presents a review of available literature about the offshore structures, specifically the drilling riser and oil-gas transportation pipeline. The materials of interest i.e. HSLA API X70 steel and super duplex stainless steel has been discussed in detail along with their failure issues at the site of application. Dissimilar joining of pipeline steel to corrosion-resistant alloys has been discussed along with SMAW and GTAW as the prospective joining processes. The chapter also presents information about the design and development of SMAW electrode coatings. Discussion about the experimental investigation of the dissimilar weld as conducted by different researchers along with their conclusive study has been presented systematically in this chapter.

Chapter 3: Problem identification from the gap in literature and work plan.

Chapter 4: This chapter carries the experimentation details of the thesis. Different materials used in this work, along with welding procedure and characterization techniques, have been discussed here. Along with experimental methods, the chapter also gives an insight into the statistical method of regression analysis used in this study.

Chapter 5: Results obtained from experimentations conducted in this work along with discussions and inferences drawn from the same has been presented.

Chapter 6: This chapter mentions the major conclusions drawn from work carried out in this work along with providing a future scope for work that can be carried out in this particular research area.

<u>Summary of Chapter 1:</u>

This chapter introduced the readers to the offshore oil-gas exploration and production activities. Different offshore structures have been discussed along with mentioning various materials used for their fabrication. API grade pipeline steel is the most preferred material for drilling riser and pipeline application, but they suffer from severe damage due to corrosion. Hence corrosion resistant alloys such as super duplex steel are preferred for dissimilar joining with them in critical locations. This joint is usually fabricated with SMAW and GTAW process. SMAW electrode coating has an influential role on weld properties; same thing goes for filler metal in GTAW process. The dissimilar weld calls for extensive mechanical and microstructural investigations to ascertain their suitability and successful applicability at the desired offshore locations.