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ISTANBUL AYDIN UNIVERSITY

INSTITUTE OF GRADUATE STUDIES

A REVIEW OF THE RESEARCHES ON THE TECHNICAL PROPERTIES OF THE MATERIALS USED IN MACHINERY AND EQUIPMENT IN THE PETROCHEMICAL INDUSTRY

MASTER'S THESIS

Ali Mohtasham TARAR

Department of Engineering

Mechanical Engineering Program

OCTOBER, 2022

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APPROVAL PAGE

DECLARATION

I hereby declare with respect that the study "A Review of The Researches on The Technical Properties of The Materials Used in Machinery and Equipment in The Petrochemical Industry", which I submitted as a Master thesis, is written without any assistance in violation of scientific ethics and traditions in all the processes from the project phase to the conclusion of the thesis and that the works I have benefited are from those shown in the Bibliography. (…/…/2022)

Ali Mohtasham TARAR

FOREWORD

First and foremost, I would like to thank Allah in the most sincere way possible for allowing me to be who I am today and for giving me the perseverance and inner strength to finish this thesis.

I consider myself extremely lucky to have Dr. Öğr. Üyesi Lütfiye DAHL as my supervisor because of the excellent advice, motivation, and conversations he has provided during the entire thesis-writing process. Words alone cannot adequately convey how crucial his support and encouragement were over the entire period. It has been an absolute honor and pleasure for me to work with him.

I want to express my gratitude to Prof. Dr. Oktay Ozcan, the department chair of mechanical engineering, for his unwavering support and patience throughout the research time. Finally, I want to thank Istanbul Aydin University for all that it has done for me, both academically and by introducing me to wonderful individuals who have inspired, challenged, supported, and motivated me.

A special thanks to my family for instilling in me the value of never giving up on your goals. I can't even begin to describe how appreciative I am to have such a supportive family. My devoted parents' labor of love is what has contributed to all of my accomplishments.

October, 2022 Ali Mohtasham TARAR

A REVIEW OF THE RESEARCHES ON THE TECHNICAL PROPERTIES OF THE MATERIALS USED IN MACHINERY AND EQUIPMENT IN THE PETROCHEMICAL INDUSTRY

ABSTRACT

Unconventional reserves must be explored and exploited safely and profitably to meet the world's rising energy demand. Some of these unusual prospects present severe environments that test the limits of conventional engineering alloys as well as our comprehension of the basic degradation processes that could cause a failure. The most significant source of innovation in terms of material technology is found in high-temperature, high-pressure, ultra-deep, Arctic and pre-salt reservoirs, notwithstanding their complexity. With an emphasis on advanced materials, this paper offers a broad review of current development and research trends in materials. For the oil and gas industry, these cutting-edge polymers stand out above their conventional equivalents with improved hardness or strength. Modern metallic materials, unconventional materials (metal or non-metal), or a combination of these are all examples of advanced materials. Numerous stronger, lighter, and multifunctional materials have been created in laboratories over the past few decades. Advanced materials are those with at least one characteristic that is much better than that of standard alloys. The three most promising innovative material types for use in petroleum production are chosen.

Keyword: Petrochemical, Petroleum, Advanced materials, Unconventional materials

PETROKİMYA ENDÜSTRİSİNDE MAKİNE VE EKİPMANDA KULLANILAN MALZEMELERİN TEKNİK ÖZELLİKLERİNE İLİŞKİN ARAŞTIRMALARIN İNCELENMESİ

ÖZET

Dünyanın artan enerji talebini karşılamak için geleneksel olmayan rezervler güvenli ve karlı bir şekilde araştırılmalı ve kullanılmalıdır. Bu olağandışı beklentilerden bazıları, bir arızaya neden olabilecek temel bozunma süreçleri konusundaki anlayışımızın yanı sıra geleneksel mühendislik alaşımlarının sınırlarını test eden zorlu ortamlar sunar. Malzeme teknolojisi açısından en önemli yenilik kaynağı, karmaşıklıklarına rağmen yüksek sıcaklık, yüksek basınç, ultra derin, Arktik ve tuz öncesi rezervuarlarda bulunur. Gelişmiş materyallere vurgu yapan bu makale, materyallerdeki mevcut araştırma ve geliştirme eğilimlerinin geniş bir incelemesini sunmaktadır. Petrol ve gaz endüstrisi için, bu son teknoloji polimerler, geliştirilmiş sertlik veya mukavemet ile geleneksel eşdeğerlerinin üzerinde öne çıkıyor. Modern metalik malzemeler, geleneksel olmayan malzemeler (metal veya metal olmayan) veya bunların bir kombinasyonu, gelişmiş malzeme örnekleridir. Son birkaç on yılda laboratuvarlarda çok sayıda daha güçlü, daha hafif ve çok işlevli malzeme oluşturuldu. Gelişmiş malzemeler, standart alaşımlardan çok daha iyi olan en az bir özelliği olan malzemelerdir. Petrol ve gaz üretiminde kullanım için en umut verici üç yenilikçi malzeme türü seçilmiştir.

Anahtar Kelimeler: Petrokimya, Petrol, gelişmiş malzemeler, alışılmamış malzemeler

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ABBREVIATIONS

ASME : American Society of Mechanical Engineers

AYS : Actual Yield Strength

BMG : Bulk metallic glasses

CCT : Critical Crevice Corrosion Resistance

CP : Cathodic protection

CPT : Critical Pitting Resistance Temperature

CRA : Corrosive Resistive Alloy

CS : Carbon Steel

DBTT : Ductile-to-Brittle Transition Temperature

DLC : Diamond-like carbon

DSS : Duplex Stainless Steel

EAC : Environmentally Assisted Cracking

FRP : Fiber-reinforced polymer

GFA : Glass forming ability

HAZ : Heat Affected Zone

HFO : Heavy fuel oil

HPHT : High Pressure High Temperature

HRSG : Heat Recovery Steam Generator

HSC : High Speed Cutting

HTHA : High Temperature Hydrogen Attack

HVOF : High Velocity Oxy-Fuel

LAS : Low Alloy Steel

MDMT : Minim Design Metal Temperature

MPA : Mega Pascal

PE : Polyethylene

PHNA : PH nickel-based alloys

PREN : Pitting Resistance Equivalent Number

PTFE : Polytetrafluoroethylene

PVC : Polyvinyl Chloride

PWHT : Post Weld Heat Treatment

QT : Quenched and Tempered

RPP : Refined Petroleum Products

SEM : Scanning electron microscope

SiCI : Silicon Cast Iron

SMYS : Specific Minimum Yield Strength

SSC : Sulfide stress cracking

TEM : Transmission electron microscopy

TPF : Thermoplastic forming

YSZ : Yttria-Stabilized Zirconia

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I. INTRODUCTION

As we know that the demand of energy in our daily life is increasing day by day for continuing our daily life's operations. This energy can be in the form of electricity or fuel, mechanical energy or thermal energy especially for transportation and electrical power generation. The main reason for this is the ever-increasing living standards and the increasing population in this world. But the main fact is that we get these energies through fossil fuels and these fossil fuels are oil, natural gas, coal which is basically our petroleum industry. We not only use oil and gas for producing energies but we make different products through oil, gas and petrochemical processes and techniques. Oil and gas production is very important for our world's moving forward, because we mostly rely on the oil and gas for producing or continuing our operations.

This is accomplished by the extraction and transportation of raw materials from subterranean reservoirs, the processing of these materials into fuels, and the delivery of the finished goods to end users worldwide. But this sector covers more than just fuels. Numerous other vital materials are also made from the hydrocarbon molecules which this industry mines from the soil. The majority of synthetic materials, such as plastics, polymers, synthetic rubber, detergents, solvents, and other items, are produced by the petrochemicals sector. Bitumen, lubricants, and waxes are all products of the refining business. Fertilizers, medications, and other vital compounds are made using more specialized petroleum processing (Clews, 2016:1-402). Although a lot of the items from this business are now taken for granted, the ability for the industry to make and transport these products to customers all over the world required significant investment over a long period of time.

According to a dictionary, the word "petroleum" is derived from Latin, meaning "rock oil," and is nearly always used to describe these mineral oils provided from beneath the surface of earth that primarily consist of mixes of hydrogen and carbon molecules which are hydrocarbons (Field & Field, 2009). The phrase has occasionally been expanded to encompass "made" hydrocarbons that are similar to the natural resource, such as liquid oil or natural gas produced from coal or biomass. These so-called “synthetic” goods, nevertheless, haven't yet been mass-produced. As a result of treating the natural resource, refined petroleum goods like motor gasoline and fuel oil are also referred to as “petroleum” (Rosenfeld & Feng, 2011:57-71).

Now I will give overview about the petroleum and petrochemical industry, its processes, terminologies and methods which will help us to understand that how all this industry works. And then we will discuss in detail about the materials that which material mostly use in petroleum industry and which materials used for pipelines, for drilling and other processes and which material further we can use for instead of already used materials which will also cost effective. Also, we will discuss about researches which already have been done on the materials and new technologies and in which area still need to do more research or we have scope for that. Now, I will explain that what is the difference between petroleum and petrochemical industry?

II. PETROLEUM INDUSTRY

The oil and gas industry is divided into six basic segments: reservoir development, production, transmission or transportation, crude oil refining into refined petroleum products, and distribution of these refined goods and of natural gas. The petroleum industry (sometimes known as the "crude petroleum industry") typically refers to exploration, development, and lifting or extractions as "upstream" activities, whereas petroleum refining and marketing are considered "downstream" activities. The connection between the "upstream" and "downstream" parts is provided via transportation. The production of oil will be discussed in the material that follows; unless otherwise stated, same factors apply to the production of natural gas (Gary et al., 2007).

Now, we will talk about upstream activities and then we will explain about downstream activities in petroleum industry and I will explain in definition, what is basically upstream activity is; “activities and operations related to the search for, exploration and development, production, extraction and recovery of crude oil, natural gas, natural gas liquids and sulphur, as well as the production of synthetic oil.”

A. Exploration and Development

Finding the kinds of rock formations that are likely to contain petroleum resources is the first step in exploring for subsurface deposits of natural gas and oil. This often limits the search to areas with thick sedimentary rock overlays (i.e., a sedimentary basin), where it is thought that sufficient source and reservoir rock (geological formations) was deposited over a long period of time. Selecting the areas where effort will be put out is the first step in the exploration process. This depends on a variety of elements, including the likelihood of physically discovering petroleum, accessibility, the local political and economic situation, and closeness to markets. A preliminary geological survey is started after a region is chosen. In order to determine what kind of formations are underlying the location, visible rocks are studied for any hints they may contain. To comparing with data from previously found hydrocarbon sources, rock samples are collected. A thorough geological map is created that details the likelihood of finding gas or oil in the area. Investigating the subterranean rock formations is the next phase (MacFayden and Watkins, 2016:3-18).

Applying physics concepts to the research of subsurface geology is known as geophysical surveying. Geophysical surveys map the morphology of structures inside the sediments and quantify the thickness of the sediments. Seismic geophysical research, in which explosive charges are set off at or close to the ground's surface, is the most popular type. Geophones capture the shock waves that follow when they impact and re-enter beneath rock strata. Geophysicists can find structures that might hold oil or gas using this knowledge. Geophysicists also use magnetic and gravimetric surveys to get information about the subsurface (Rosenfeld & Feng, 2011:57-71). Recent technology advancements have broadened the use of seismic activities and prompted a thorough reevaluation of previously known geological strata, such as 3-D seismic mapping and now 4-D seismic (with duration as the fourth dimension).

B. Exploratory Drilling

Undoubtedly, geophysical and geology surveys increase the likelihood of discovering oil or gas, but they can only, at best, map the fundamental geological features and cannot specifically identify the location of petroleum. Drilling a hole is the only way to confirm the presence of an underground reservoir where significant accumulations of gas and oil occur because many prospective petroleum holding traps are dry. Exploratory or "wildcat" drilling is the next step in the quest for petroleum. This is carried out at a location that the geophysicist or geologist has advised based on earlier survey work. There are times when the first hole drilled in a new area "proves" the presence of natural gas or oil in quantities sufficient for commercial exploitation. However, it is more common to drill a lot of dry holes or holes that indicate only trace amounts of (noncommercial) petroleum (Aguilera et al., 2009:141-174). A final decision regarding whether to continue with more research of the area will be made in light of the new information discovered by these holes. A succession of appraisal (also known as "step out," "extension," or "outpost") wells are often drilled to establish the size of the reservoir after an exploration well is successful. In order to evaluate the porosity, permeability, and oil content of the rock over the oil-bearing portion, cylindrical specimens of the formations drilled (referred to as "cores") are examined. Additionally, samples of the oil are obtained from the well's bottom at full reservoir pressure in order to measure the oil's characteristics as they are in the reservoir, including the unrestricted flow rate (MacFayden and Watkins, 2016:3-18).

C. Development Drilling

As soon as the data from assessment drilling is enough to imply that the oil or gas finding is competitive and that it would be the best strategy to produce and develop the reservoir, development well drilling can start. Since this stage is frequently reached before the field's boundaries have been precisely defined, it is common for additional step out or outlying wells to be drilled concurrently with development wells. The size and nature of the field, in addition to the land tenure structure by which the government sets rules for mineral rights, will influence the number of development wells, their separation, and their depth. Additionally, the space each well can properly drain has an impact on how far apart they are placed. Development wells used to nearly invariably be completely vertical or, in rare cases, tilted at a fixed angle throughout the depth of the well. For instance, if a considerable portion of the reservoir is to be drained from wells that originate from the same site or if the terrain is very vulnerable for environmental reasons right just above part of the reservoir being evacuated, a slant well would be ideal, as a base for offshore production. As a result of recent technological advancements, it is becoming more common to drill so-called "horizontal wells," in which the well bore abruptly deviates from vertical to horizontal as it approaches the producing formation (Rosenfeld & Feng, 2011:57-71). Greater amounts of reservoir rock are in touch with a single horizontal well than a single vertical well. Horizontal wells provide for a quicker recovery of oil in a reservoir with a reasonably high permeability and uniform character. In a reservoir with relatively low permeability and/or that is highly heterogeneous, horizontal wells may extend the "sweep" area and enable a higher overall oil recovery than would be achievable with vertical wells alone (Field & Field, 2009).

D. Production (Lifting or Operation)

Once wells have been drilled, the rate of oil extraction is mostly dependent on the rock's permeability, or how easily oil and gas can move through it. If this is set too low, the output from a single well might not be enough to cover its cost, making it economically impossible to develop the reservoir. Within a given reservoir rock, the porosity and permeability the quantity of gaps and apertures that divide the individual rock grains varies from place to place. These variances can occasionally be so wide-ranging that the production rates of wells in various areas of the reservoir might differ noticeably (Aguilera et al., 2009:141-174). The reservoir crude might be very thick, viscous (thick) oil at very low pressure with little to no dissolved gas, or it can be very light, straw-colored crude at high pressure with a lot of dissolved gas. The amount of gas that the oil holds in solution and its specific gravity both play a significant role in determining the oil's viscosity. Oil will flow more easily through the cracks in the rock to reach the well if it is less viscous and contains more gas. Additionally, water is often present in the pore spaces of an oil or gas reservoir. This "connate" or "interstitial" water is thought to be water that wasn't removed by the petroleum when it gathered and became trapped in the initially water-saturated reservoir. Connate water content plays a significant influence during the reservoir's productive life and can make up 5 to 40% or more of the empty space (Gary et al., 2007).

E. Primary Production Methods

When oil is present in a reservoir, it must be under pressure that is greater than the pressure at the well's bottom in order for the oil to escape via reservoir rock fractures and into the well's bottom. The reservoir's pressure will drop when oil is extracted from the rock, which will also result in a fall in production rate. The overall amount of oil that can be extracted from the reservoir over a certain length of time will be impacted by the amount at which the pressure declines, if only because diminishing output moves the well closer to becoming unprofitable to operate. Connate water present in the storage tank, connected gas, and free gas present in the gas cap are the main sources of energy used to transfer crude oil to the bottom of production wells and then up the pipe tubes to the surface or wellhead. The terms "water drive," "solution gas drive" (also known as "depletion drive"), and "gas cap drive" refer to the manufacturing processes connected to these energy sources, respectively. The three displacement processes—"water drive," "solution gas drive," and "drive"—are typically ranked in order of efficiency. There are frequently multiple mechanisms at play for both the gas cap and the water drive reservoirs (Clews, 2016:11). Thus, the phrases "partial gas cap drive" and "partial water drive" may be used. As reservoir pressure drops, gas from a solution accumulates through gravity segregation to form a gas cap, changing the principal drive mechanism of a reservoir. "Primary recovery" refers to the oil generated as a result of such organic production processes, which are only augmented by pumping and minimal reservoir rock fracture.

F. Recovery Factor

There is no recognized economic method for recovering all of the oil in permeable rocks, as the discussion above shows. The "recovery factor," or the percentage of oil-in-place inside a reservoir that may be brought up to the surface, is determined by a combination of six sets of criteria, which are:

- The characteristics of the reservoir rock, such as its permeability, porosity, structural location, and thickness;
- The parameters of the reservoir fluid, such as pressure, viscosity, and gas saturation;
- Drive mechanism, such as a solution, gravity drainage, or water drive;
- Method of production, such as spacing between wells, rate of extraction, and use of eor;
- Economics, such as the price of oil, gas, and byproducts, as well as the expenses of drilling and completion;
- Rules set forth by the government, such as those governing well-spacing and various "conservation" techniques, royalties, and taxes.

These elements work together to calculate the rock's "reserves," or the quantity of natural gas or oil that may be economically retrieved. The estimate of "initial recoverable reserves" that results from applying the oil recovery to the amount of oil in situ is often much lower than the amount of petroleum in place. Although recovery rates differ significantly between reservoirs, on average between 25 and 35 percent of the oil initially present in a conventional oil reservoir and roughly 80 percent of the gas initially present in a non-associated natural gas reservoir may be extracted. Using enhanced recovery procedures throughout the extraction process frequently increases the oil's recovery factor. However, unless the reservoir's behavior has been seen under real-world producing conditions with commercial off take rates, the recovery factor cannot be approximated with sufficient accuracy. The usual practice is to start drilling for development and delineation before putting a field into production. As more productive locations are drilled up, the information on recoverable reserves is thus constantly being updated. In contrast to “new discoveries”, “extensions and revisions” in rocks that had already been identified are typically given more credit for reserve additions (Jahn, Cook, & Graham, 1998). In other words, as development continues, the reserves in a petroleum well often “appreciate”.

Now i will explain about petrochemical section and its processes that how what is petrochemical, and how we differentiate it in petroleum and petrochemical.

III. PETROCHEMICAL INDUSTRY

In last sections, I have concentrated on the usage of petroleum-based fuels, particularly crude oil-based fuels for transportation and natural gas-based fuels for electricity production. However, the use of petroleum for purposes other than fuel has grown in significance, particularly for the petrochemicals sector's manufacturing of synthetic materials. This branch of the oil and gas business focuses on converting hydrocarbon byproducts with poor value into useful materials and aims to outline the major features of the petrochemicals sector (E.F.A., 1937:92-93). Products from the sector are utilized in a wide range of applications, several of which have overtaken petroleum fuel products in importance.

Since the petrochemicals business initially grew in tandem with refining, petrochemicals projects resemble refineries in many ways. Making sure that a refinery's output of finished goods closely meets market demand is one of its key objectives. The three main transportation fuels-gasoline, diesel, and jet fuel-are what refiners are most concerned with supplying to market demand. However, as we've already seen, crude oil is a very intricate concoction of many substances. As a result, it is basically impossible for a refiner to perfectly satisfy market demand, and as a result, refiners sometimes struggle to find profitable markets for all of the streams that fuel refineries create. The market quickly realized that troubled refinery streams may be used as inexpensive feedstock that, with the correct chemical conversion systems, could be transformed into usable and higher-value commodities. In order to discover low-value by-product feedstock from the fuels industry and transform it into higher-value products, petrochemicals producers must have this skill. Although the need for fuels and the processing of crude oil were not aligned at the time the petrochemicals sector was founded, many petrochemical products now have their own markets. The expansion of natural gas processing has made considerable amounts of low-cost feedstock from the gas industry available in extra to distressed refinery streams (Baukal, 2000:1-546). Additionally, the fuels sector of the industry receives a variety of high-value gasoline additives that are produced by the petrochemicals sector. The distinction between fuels and petrochemicals has therefore grown less distinct due to the complex link among refining, natural gas processing, and the petrochemicals industry.

A. Refining

A refinery transforms the crude into a variety of refined petroleum products (RPPs) to provide a range of hydrocarbon products that best satisfy users' needs. Distillation, which is the fundamental refinement procedure, vaporizes various hydrocarbon elements in crude oil at various temperatures, allowing for their separation. The resulting condensed components are then put through a variety of additional chemical industrial operations to produce a wide range of distinct RPPs, ranging in weight from the extremely low (refinery gases) to the very weighty (asphalt) (E.F.A., 1937:92-93). The final RPP mix from any given grade of crude oil is theoretically highly versatile because there are so many additional "cracking," "reforming," and other processing procedures available. It is technically feasible to construct a refinery that could use nearly any specific grade of crude oil to create nearly any combination of final RPPs. However, once a refinery is constructed, it can typically only accept a slightly constrained variety of crude oil grades and create a constrained set of RPPs without any additional capital expenditures... It will be evident that the decision to invest in a refinery is a very complicated one, involving study of the present and future costs and availability of various grades of crude oil as well as the projected current and future demands for a significant number of RPPs. Additionally, it's crucial to remember that refineries are impacted by economies of scale, which means that as refineries grow in size. Due to the limited number of refineries in small regional markets, the refineries may have some market power in their sales of RPPs and purchases of crude oil (International, 2007:1-3).

The potential construction of new, rival refineries and the potential importation of RPPs from other locations serve to constrain the scope of such market power. Although they are easily replaced by natural gas, coal, and even wood in simple combustion processes, heavy RPPs are typically employed due to their high heat content. Because they give refiners a higher yield of more valuable RPPs and/or save money on the expense of additional equipment needed to get a high yield of these RPPs, higher API grades (lighter crudes) are more expensive than heavy oils. Another implication is that if supply and demand conditions for various RPPs, refinery operations, and technological advancements vary over time, so will the relative values of various crude oil grades (also known as crude oil price differentials) (Jahn, Cook, & Graham, 1998). Any RPP's price is determined by the cost of crude oil in the region where it is produced, the cost of refining and transporting that crude, as well as the numerous factors impacting demand for the specific RPP. RPPs all have wildly different prices. For instance, since crude oil can be burned, it makes an ideal replacement for items like heavy fuel oil (HFO). HFO must therefore be sold for less than crude oil in order to be profitable. Note that a refinery is a "joint product process" that inevitably generates more than just HFO if you're wondering how HFO, which has a refining cost, can have a cheaper price than the raw crude oil from which it derives (E.F.A., 1937:92-93).

The economic criteria is not that each RPP must be more expensive than crude oil, but rather that the price of crude oil and refining must be covered by the value of all refined goods combined.

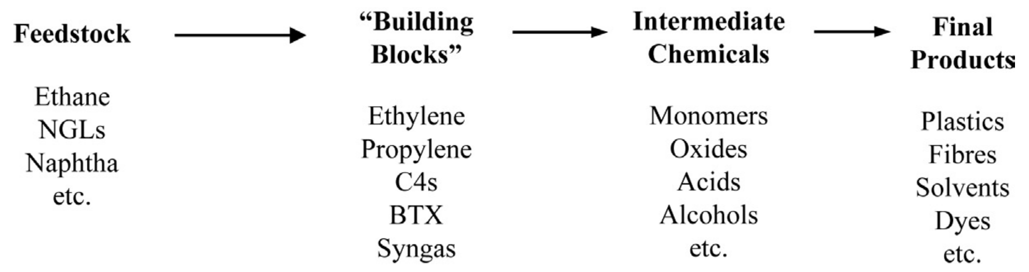

Figure 1 Conversion of Feedstocks into Final Products.

Source: Clews, 2016:11

Petrochemical products have historically found lucrative marketing opportunities due to non-fuel uses, particularly the creation of synthetic materials. These materials perform much better than many naturally occurring materials while costing less to generate. Thus, in many applications, petrochemical chemicals have been able to replace natural materials. Approximately 500 million tons of petrochemical plastics and other materials are produced annually, the most significant items being: Plastics: Plastic bottles, bags, and other packaging materials. For tires and related products, synthetic rubber is used. Synthetic fibers are used in rope, clothing, and other products. For the food sector, fertilizers and agricultural products. Dyes are utilized in a variety of applications. Detergents and surfactants are used in cleaning products. Petrochemical goods often have a life cycle that starts with specialization and ends with maturity and perhaps obsolescence.

Now we will discuss on the researches which already have been done on materials and equipment which used in above discussed procedures. Our main focus will be on drilling and refining, and firstly, we will discuss the equipment and materials of drilling.

B. Equipment Used in Petrochemical Industry

There is a list of main equipment used in petroleum & petrochemical industry.

- Pressure vessels
- Heat Exchangers
- Deaerator
- Steam Reformer and Fired Heaters
- HRSG
- Piping Systems

Now I will explain one by one the working principles of each of equipment with diagrams and its applications.

C. Pressure Vessels

Figure 2 Pressure Vessels

The term pressure vessels refer to the leak-proof containers utilized to store liquids and gases. These vessels come in various shapes and sizes and are produced for a wide range of uses. Their shapes are generally conical, spherical, or cylindrical.

They are an essential part of today's oil & gas, and petrochemical industry. They can conduct both chemical and physical processes while under high pressure and high temperatures. There is a variety of pressure vessels commonly used in the industry. The following explains the various types of pressure vessels that are commonly used for different applications in the oil & gas, and petrochemical industries.

They include:

- *Storage Vessels*– These vessels hold gases and liquids and are used in industrial settings.
- *Boilers*– Boilers are a type of heat transfer equipment powered by electric, fuel, or nuclear energy.
- *Distillation Columns*– Distillation columns are utilized to separate liquid mixtures based on the difference in their volatilities.
- *Process Vessels*– The process vessel category is a broad one. These are containers in which processes occur, such as decantation, distillation, and agitation, among other processes.
- *Decanters*– Decanters are pressure vessels that allow for the separation of liquid-liquid and solid-liquid mixtures.
- *Industrial Mixers*– Industrial mixers are a pressure vessel that includes a blade powered by a motor. This allows them to emulsify and homogenize one or more substances.
- *ASME Pressure Vessels*– ASME pressure vessels are sometimes referred to as ASME boilers. They are any pressure vessel that carries with it the ASME accreditation. This certification designates that the pressure vessel has been subjected to a detailed inspection and meets the strictest code standards.

D. Heat Exchangers

There are many types' heat exchangers but which is mostly used in oil and gas industry that is Shell and tube heat exchanger.

A form of exchanger used to transmit heat energy between two or more fluids is the shell and tube heat exchanger. The two fluids are not indirect contact; one pass in the tubes and the other in the shell. Shell and Tube Heat exchangers are one of the most common equipment found in all oil and gas plants, petrochemical and power plants.

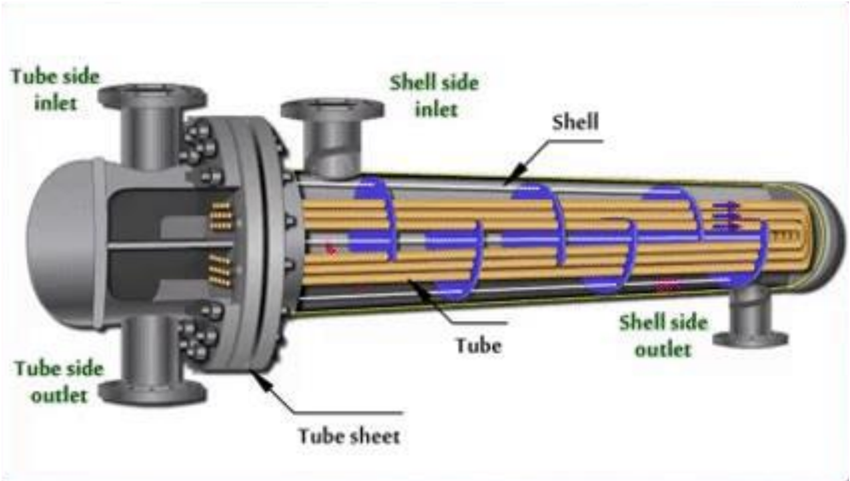

Figure 3 Construction and Main Parts of Shell and Tube Heat Exchanger

Source: Elsheikh, 2020

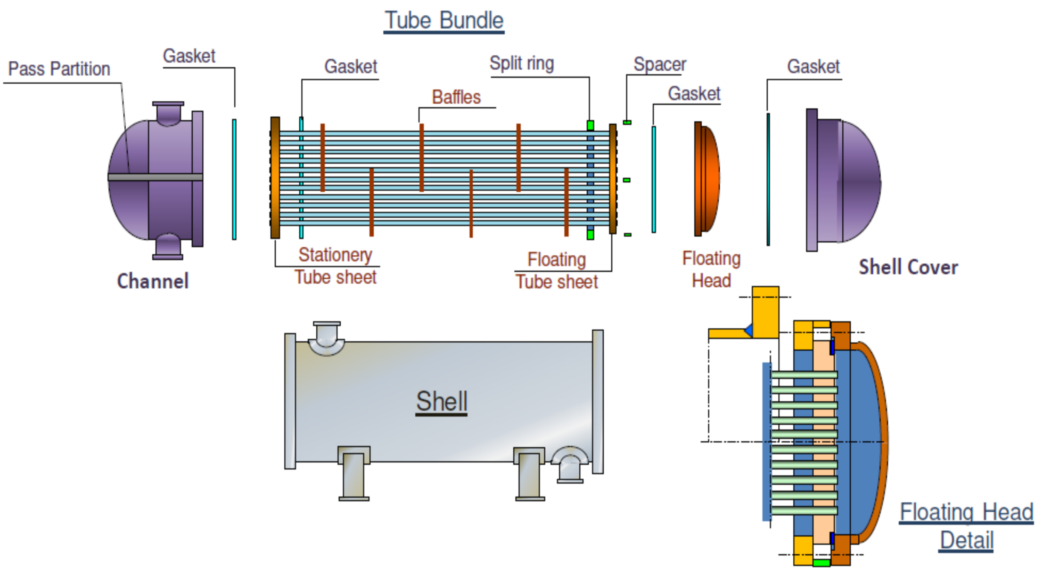

Figure 4 Function and Classification

Source: Elsheikh, 2020

Heat exchanger: Single phase, process stream on both sides

Heater: One heating source and one stream of process fluid (steam)

Cooler: A two-stream process fluid cooler with water or air as the secondary cooling medium.

Condenser: Vapor is condensed in one stream while cooling medium (air/water) is used in the other.

Re-boiler: One bottom stream from the distillation column and one hot utility stream from the process.

Figure 5 Application in Process Plants

E. Deaerators

Oil and gas and other liquid products can be separated and have entrained gas and air removed using deaerators, particularly in metering applications. Any metering system that has the potential for air to be added or entrained must include a deaerator since doing so ensures that gas and air are eliminated, which is crucial for accurate measurement. When a hydrocarbon liquid is moving under pressure through pipelines, deaerators are employed to remove any free air or gas. At which liquid flow is being metered, it is particularly applicable (gas deaerators EN FAB Inc., 2022).

Figure 6 Deaerators

1. Fundamental Operating Principles

Depending upon the type of applications and available space, the Gas Deaerator may be a vertical or horizontal vessel. The vessel is sized to allow the gas/air bubbles to rise to the top of the vessel with enough retention time. The interior of the deaerator will feature a number of sloped steel scrubber plates to collect and sort these bubbles in order to aid in this gas/air removal. The bubbles then combine and ascend to the vessel's top.

2. Particle Separation by Differential Gravity: General Theory

Gravity clarification enables the separation of particles from their liquid medium that has different densities. By stopping or significantly slowing down the flow stream, separation can be achieved. This enables the separation of the particles. The particles (bubbles) that rise to the liquid's surface have negative velocities and a "rise rate." The predicted terminal velocities of the expanding bubbles are established by Stokes Law. The effectiveness of separation increases with the length of the single particle (Eriksen, 2017).

Vp = [G(dp - dc) D]/ 18n

where Vp = rising velocity of discrete particle

G = gravity constant

n = absolute viscosity of carrier fluid

dp = density of discrete particle

D = diameter pf discrete particle

dc = density of carrier fluid

A horizontally unit performs better than a vertical one for deaerators with the same dimensions. This is made possible by the bubble's reduced vertical ascent and larger horizontal ascent distances. By generating laminar flow, parallel plates further improve this performance. The bubbles can also escape through slots in the scrubber plates. In a vertical unit, bubbles rise upward in a counter-flow direction to the liquid carrier, where they are ejected by an air eliminator valve, which is a pneumatic float-actuated control valve. The Deaerators ought to be set up as near to the meter as is practical on a level foundation. The eliminator valve's discharged vapor needs to be piped to a comfortable and safe location (gas deaerators EN FAB Inc., 2022). The vapor eliminator discharge piping needs an appropriate flame arrestor attached at the end.

F. Steam Reformer and Fired Heaters

Overall endothermic processes occur during steam reforming. As a result, the required heat of reaction is produced using a furnace. Infrared radiation is the main type of heat transfer. The furnace is a fired heater with radiating tubes loaded with a catalyst for reforming fuel made of nickel (s). As a result, the steam reformer is more than just a simple catalyst reactor; it also functions as a heat exchanger.

There are two primary sections to the steam reformer:

- Furnace (radiant section); and
- Convection section.

Elements of the furnace include:

- Steel casing;
- Heat resistant insulation;
- Combustion air system;
- Burners;
- Flue gas collection system; and
- Reformer tubes.

By burning a fuel and air mixture, the furnace creates heat for the steam reforming reaction. It uses radiant heat transfer to function at a small negative pressure at temperatures above 1832 °F (1000 °C). An even stream of hot gas through into the furnace is made possible by the steam reformer's design, which distributes heat as evenly as possible throughout the device and gathers the combusted gas (AIGA, 2012).

There are three categories in which steam reformers might be placed:

- Top-fired
- Side-fired; or
- Bottom-fired.

1. Top-Fired Steam Reformers

The below figure illustration depicts a typical top-fired steam reformer, with process gas flowing downhill through several tubes arranged in one or more rows, all of which are housed inside a single furnace box. The flue gas is removed from the furnace at the bottom, and the burners are situated on the furnace roof. To guarantee a uniform flow of flue gas through the furnace, flue gas collection tunnels with apertures, also known as coffin tunnels, are widely utilized. The primary characteristics of a top-fired furnace are:

- Co-current circulation of process gas and flue gas;
- A small amount of large burners on the top of the furnace (compared to a side-fired reformer); and - One level of operation for burner access.

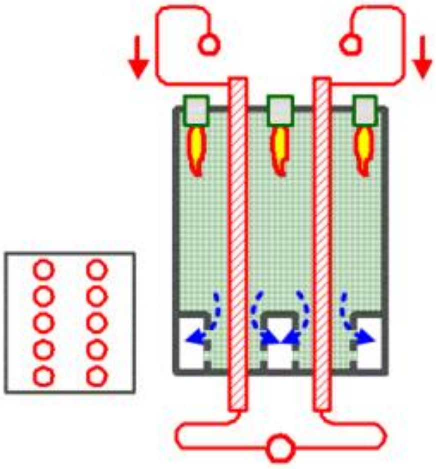

Figure 7 Top-Fired Steam Reformers

Source: AIGA, 2012

2. Side-Fired Steam Reformers

The image below depicts a typical side-fired steam reformer with process gas flowing downward through several tubes arranged in a single row, all of which are housed inside one or more sections known as furnace cells. By placing the catalyst tubing in the middle of the furnace cell and using burners all the way along the sidewall of the furnace as heat input, uniform heat flux is produced. The convection portion is directly connected to the flue gas exhaust, which is located at the top of the furnace. Two furnace cells frequently run parallel to one another and share a convection section. Among a side-fired furnace's primary characteristics are:

- Process gas and flue gas flow cross-currently;

- There are a lot of small burners (in comparison to a top-fired reformer) positioned on the both edges of the furnace;
- There are several operational levels for burner access.

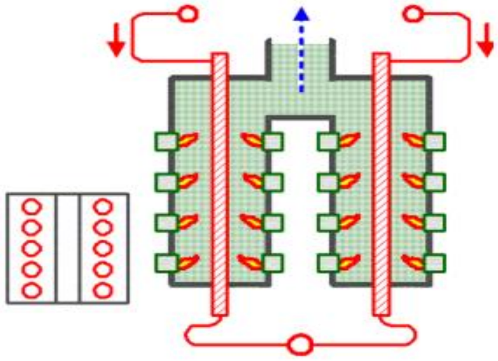

Figure 8 Side-Fired Steam Reformers

Source: AIGA, 2012

3. Bottom-Fired Steam Reformers

In the figure below, a basic bottom-fired reformer is seen. Since the burners are at floor level, the firing configuration is basically the opposite of a top-fired machine. The top is where the flue gas is removed. The following are the main characteristics of a bottom-fired furnace:

- Co-current or counter-current flow of the process gas and flue gas;
- A small number of huge burners on the bottom of the furnace (compared to a side-fired reformer); and
- Burners on a single working level those are reachable from grade.

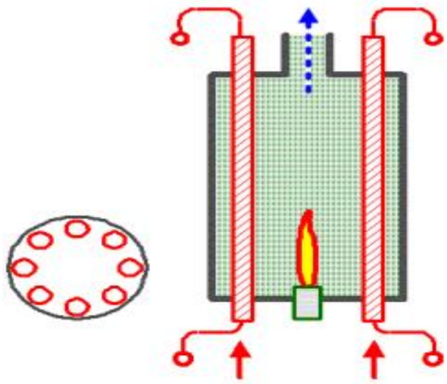

Figure 9 Bottom-Fired Steam Reformers

Source: AIGA, 2012

G. Fired Heaters

In order to achieve a physical or chemical transformation, heat is released and transmitted either directly or indirectly to a solid or fluid mass in a furnace, which belongs to a diverse family of equipment. These furnaces can be categorized according to their function, like roasting or smelting, or according to their overall shape, such as shafts, hearths and crucibles. They can also be categorized according to their mode of firing, such as solar, nuclear, electrical and combustion blast furnace. There are two main categories of combustion furnaces: converters and fired heaters. In a converter, the impurities or other components of the substance to be heated are oxidized to produce heat. On the contrary hand, fired heaters are furnaces that generate heat by the burning of fuel. In internally heated furnaces, the heat released is either directly or indirectly delivered to the substance to be heated. Blast furnaces and submerged heaters both use hot gas explosions to quickly warm solid objects, are two examples of internally-heated furnaces. Ovens, fire-tube boilers, and tube heaters are examples of externally heated furnaces (Ibrahim, 2010:327-364). Process fluids running through tubes positioned within the furnace are overheated by gases generated during the combustion of a liquid or gaseous fuel in tubular or pipe-still heaters. In petrochemical factories, oil refineries, and other businesses that involve chemical processes, these heaters are frequently used for heating purposes. One of the most significant uses of heat transfer, in particular, is the modeling and construction of fired heaters in petroleum refineries. The construction of tubular fired heaters typically includes two distinct heating sections: a radiant section, often known as a combustor or firebox, and a convection section followed by the stack (E.F.A., 1937:92-93). Hot flue gases proceed from the radiation stage to the convection portion after which they swiftly flow through a tube bundle before venting the furnace through the stack. The two main heating parts are separated by a third section, also referred to as a shield or shock section. It contains the tubes that screen the remaining tubes in the convection section from radiation coming directly from the radiation section. Fired heaters are used in chemical plants for a variety of purposes, from basic heating to delivering sensible heat and raising the charge's temperature to heating and partial evaporation, where equilibrium is achieved between the vaporized liquid and the vapor (Baukal, 2000:1-546). The charge exits the furnace as an equilibrium liquid that has partially evaporated. It is also possible to employ fired heaters to supply the heat needed for cracking or reforming reactions. In this instance, the furnace would be split into two sections: a heater where the charge's temperature is raised and a soaker where heat is delivered to keep the charge at a set temperature. Either the radiation or convection portions may contain the soaker. The radiant section's tubes can be arranged either horizontally or vertically along the heater walls, including the hip, and the burners are located on the floor or the bottom half of the longest side wall in which there are no tubes (Ibrahim, 2010:327-364).

H. HRSG (Heat Recovery Steam Generator)

Within the more general category of heat recovery boilers, the HRSG is a unique type of boiler. The term "heat recovery boiler" refers to a broad class of boilers and boiler systems that extract energy from a variety of various heat sources. A heat recovery boiler allows for the possibility of either an inside or outside gas flow. When the gas flow is within the tubes, the boiler is known as a fire tube heat recovery boiler. Water-tube heat recovery boilers, also known as HRSGs, are the largest category of heat recovery boilers in terms of both the quantity and size of the units produced (Eriksen, 2017). Evaporators, economizers, and super-heaters are only a few of the components HRSGs share in common with traditional boilers. They also differ greatly from conventional boilers in that they seldom have a water-cooled combustion chamber, frequently use tubes of a smaller diameter, and frequently employ finned tubing. In air-cooled heat exchangers, many of the features that set HRSGs apart from conventional boilers are also present. Consequently, the HRSG combines an air-cooled heat exchanger and a standard boiler (Boyce, 2010).

The component that begins at the gas turbine exhaust and ends at the stack outlet where exhaust gas is released into the atmosphere is typically thought of as the basic HRSG. In its simplest form, the HRSG consists of ductwork and a casing, economizers that heat water to almost saturation, evaporators and steam drums that separate steam from water after it has been heated by the economizers, super heaters and re-heaters that heat the steam above saturation, and a stack that consumes to the atmosphere. The HRSG requires a significant quantity of plumbing, valves, controllers, platforms, and stairways.

Figure 10 Typical Large HRSG

Source: Eriksen, 2017

1. Types of HRSGs

To serve the various needs of various applications and the various client preferences, there are numerous various varieties of HRSGs. The HRSG technology has developed through time, and new ideas have been put forth. The following list includes the most prevalent types of HRSG, and more information will follow.

2. Horizontal Gas Flow, Vertical Tube, Natural Circulation Design

Natural circulation, vertical tube, and horizontal gas flow By far, the most popular design used on the market today is the HRSG, as indicated in the picture below. On the left side of the HRSG, gas enters and travels up the stack before crossing the vertical tubes whereby steam is produced. Almost any application up to 3000 psi steam pressure can be satisfied by this design, which circulates the combination using the natural buoyant forces of the steam/water mixture in the vertical evaporator tubes. It is simple to use, adaptable, responsive, and reliable, and it only needs a small amount of control.

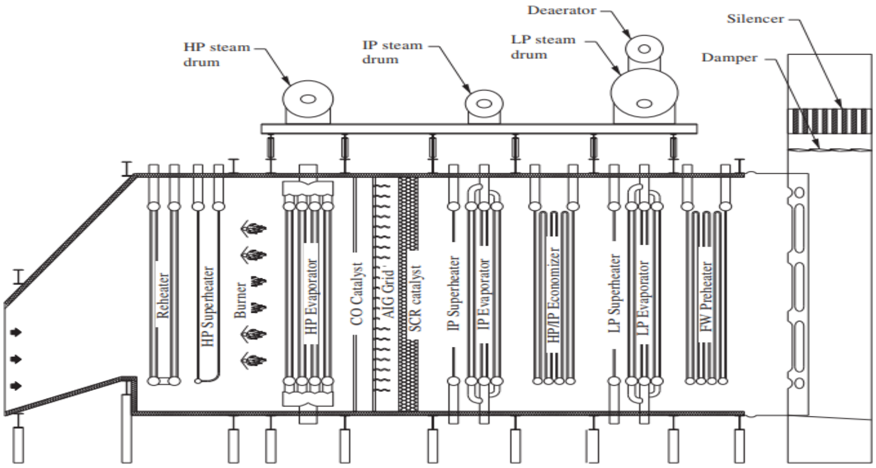

Figure 11 Schematic Representation Showing A Vertical Tube, Horizontal Gas Flow, Natural Circulation HRSG

Source: Eriksen, 2017

3. Vertical Gas Flow, Horizontal Tube, Forced Circulation Design

The horizontal tube, forced circulation, depicted in the picture below. Steam is produced as gas runs over the horizontal tubes and turns upward as it enters from the left. Pumps are needed in this arrangement to move the steam drum is filled with water after being forced through tubes.

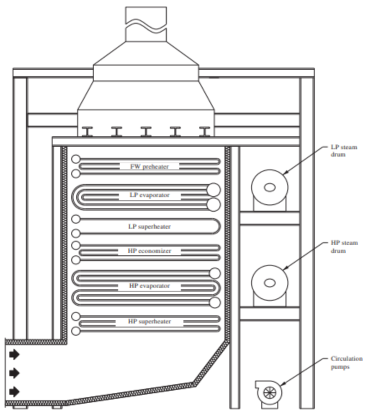

Figure 12 Schematic Drawing of a Vertical Gas Flow, Horizontal Tube, Forced Circulation HRSG

Source: Eriksen, 2017

4. Vertical Gas Flow, Horizontal Tube, Natural Circulation Design

Natural circulation, horizontal tube, and vertical gas flow the vertical gas flow, horizontal tube, forced circulation unit previously described evolved into the HRSG depicted in the image below. The fundamental motivation behind this design's creation was the need to do away with circulating pumps and the accompanying power usage and maintenance (Boyce, 2010). The two styles resemble one another. The position of the steam drums is the primary distinction.

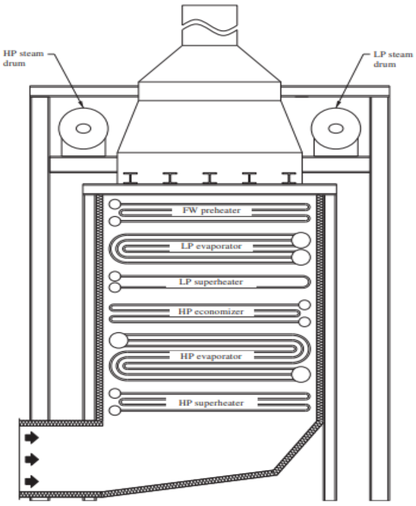

Figure 13 Schematic Drawing of a Vertical Gas Flow, Horizontal Tube, Natural (Or Assisted) Circulation HRSG.

Source: Eriksen, 2017

5. Very High Fired Design

Burners are added to the HRSG to improve its output when more steam is needed than the gas turbine's exhaust gas can provide. In order to prevent harm to the HRSG's inside walls, the temperature that can leave the burner is often restricted to no more than 1600F. A water-cooled wall is created all around combustion chamber and the first few rows of tubes when much higher output is necessary. Given that the combustion air is already heated, combustion in traditional HRSGs with a burner is extremely efficient (McCoy Power Reports, 2015).

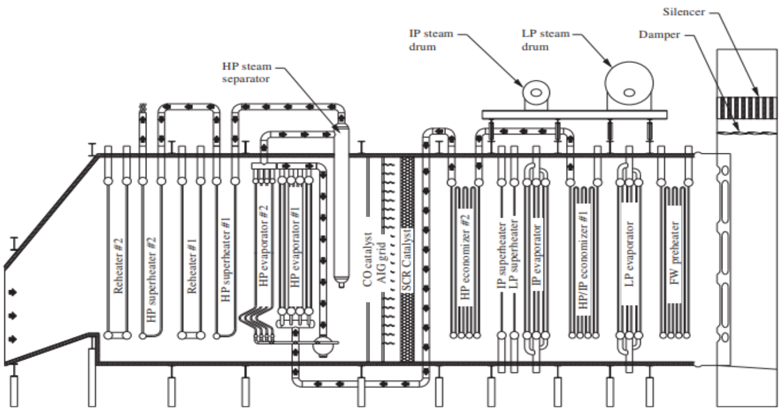

Figure 14 Schematic Drawing of a Horizontal Gas Flow, Vertical Tube, Benson HRSG.

Source: Eriksen, 2017

I. Piping System

Pipeline and piping system is very important in petroleum and petrochemical industry. Piping within the oil and gas industry is a system of pipes used to transport liquids and gases from one location to another. An Industrial Piping System includes all the materials and instruments for the construction of a complete piping system. In this research work, we are looking closely at the Industrial Piping System. How good your piping system is, is directly impacted by the materials used for building the piping system (Centaur, 2022). It's critical to weigh all options and account for the factors that will affect the piping material selection process. Here are a few factors to take into consideration: The Type, The Temperature, The Pressure

Figure 15 Piping System

1. Exposure to External Elements

It is inevitable that piping systems will be exposed to the elements. Both within and outside, external factors are present. Mold, humid environments, and corrosive gases in the air can cause exterior corrosion indoors as well as other problems. Seawater salt, weather, plant overgrowth, and other factors all provide risks for exterior corrosion and damage to piping systems when they are outdoors. We require piping material that can survive environmental conditions if even a small portion of our piping system is exposed to elements.

There are different types of piping in oil and gas industry but we categorize them on the basis of codes and standards, and according codes, we have given them names for our usage. I've given list below of piping system with codes in petrochemical industry on which engineers mostly spend their time, which I will discuss in detail in my research work

ASME B31.1 Power Piping

ASME B31.3 Process Piping

B31.4 Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids

B31.8 Gas Transportation and Distribution Piping

2. ASME B31.1 Power Piping

In this section, "power piping" refers to the piping used around boilers. Because a boiler is frequently used to produce steam for power production, it is known as power pipework. This is accomplished by transforming the kinetic energy from pressure and temperature into electrical energy in a turbine. The technical discipline concerned with turning energy into work is known as mechanical engineering. A prime example of such is a steam generator. The pipe found in commercial and institutional buildings, oil and gas facilities, geothermal facilities, and facilities for central heating and cooling is specifically covered by this code (Megahed, 2015). The effects of the pressure and temperature on the piping components are the main topics of this code.

The area covered by B31.1 around a boiler starts either: where the boiler proper finishes.

- The initial joint of a circumferential weld
- The first flange's face
- The initial threaded connection

Since it is not regarded as a component of the boiler, this piping is collectively referred to as "boiler exterior piping." Steam, water, oil, gas, and air services are all possible in power piping.

3. ASME B31.3 Process Piping

Any piping that does not come under one of the other B31 classifications might be thought of as "process piping." It is typically thought of as the pipe that may be found in chemical plants, refineries, paper mills, and other production facilities (Silowash, 2010). The ASME B31.3 Code is primarily applicable to the design and construction of pressure pipes found in petroleum refineries, chemical plants, pharmaceutical, food, textile, paper, paint, cryogenic, and any other process plants and terminals.

4. B31.4 Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids

The pipelines that move liquids between factories, terminals, and pumping control stations must adhere to the ASME B31.4 Code. These liquids include crude oil, condensate, natural gas, liquefied petroleum gas, carbon dioxide, liquid alcohol, and liquid petroleum products. One example of a pipeline carrying these liquids is one that runs from upstream to midstream or downstream (Edwards, 2004:735-736).

5. B31.8 Gas Transportation and Distribution Piping

For gas transportation pipelines between sources and terminals, ASME B31.8 Code is applicable. Additionally, it applies to gas compressor stations, metering and regulation stations, and pipelines (Megahed, 2015).

IV. USED MATERIALS AND THEIR TECHNICAL PROPERTIES IN PETROCHEMICAL INDUSTRY

For the materials, which we used in petrochemical industry, they are selected first based on the application types and it varies application to application and equipment to equipment. Which materials we want to use, they are examined before according to our application that for which purpose and where we want to use them, then we see the mechanical and physical properties of materials.

There's a criteria for the selection of materials, basically these are the factors on the basis we use materials for our application

- Mechanical and physical properties
- Corrosion resistance
- Fabricability
- Cost and availability

Now I will explain each of these criteria in details that which are the factors we observe in these four sections.

A. Mechanical and physical properties

- Strength
- Toughness
- Ductility
- Hardness
- Creep resistance
- Fatigue resistance
- Thermal Conductivity
- Thermal expansion
- Compliance with applicable design code

B. Corrosion Resistance

- Corrosion (Internal/External), erosion
- All operating conditions to be considered
- Availability of corrosion control techniques
- Experience in similar application or design
- Lining and protecting Layers
- Applicability of CA consideration

C. Fabricability

- Weldability
- Formability
- Machinability

D. Cost & Availability

- Lifecycle Cost Consideration
- Availability in desired form
- Listed in design code
- Future inspection and maintenance requirements

Now there are some Factors which affect the mechanical properties of our materials during the operations in petrochemical industry.

- Forming (Hot/Cold)
- Composition & Alloying Elements
- Welding
- Matrix structure & Grain Size
- Heat treatment

There are many properties of materials in our industries but here in oil, gas and petrochemical industries, engineers or our materials mostly interact with three properties of materials, so we will explain only these three here in below given list.

- Ductility
- Toughness

- Hardness

Now we will explain in detail about these mechanical properties with graphs and diagrams for better understanding.

1. Ductility

A material's ductility is a measurement of how much it will deform before breaking. When taking into account shaping operations like rolling and extrusion, the degree of ductility is a crucial consideration (Elsheikh, 2021).

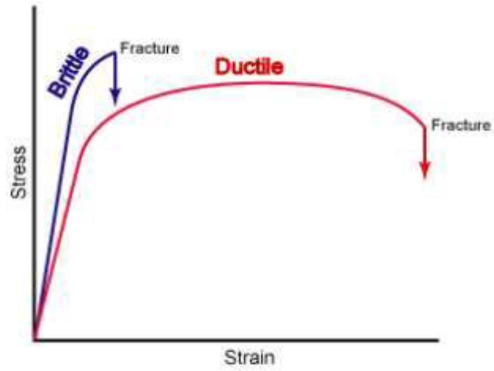

Figure 16 Stress Strain Curve

Figure 17 Brittle vs Ductile

2. Hardness

A material's resistance to localized deformation is referred to as hardness and is typically assessed through indentation. The phrase can refer to bending, cutting, scraping, or indentation-related deformation. Carbon and low alloy steels' SSC resistance is significantly influenced by the hardness of the source materials, the welds, and the HAZ. Hardness management may be a suitable strategy for achieving SSC resistance. High Hardness is desirable in applications require abrasion resistance. Hardness testing used to indicate change in material strength without destructive mechanical testing. In situ Hardness testing is widely used to indicate embrittlement damage mechanisms.

There are 3 tests which are used for checking the hardness of materials.

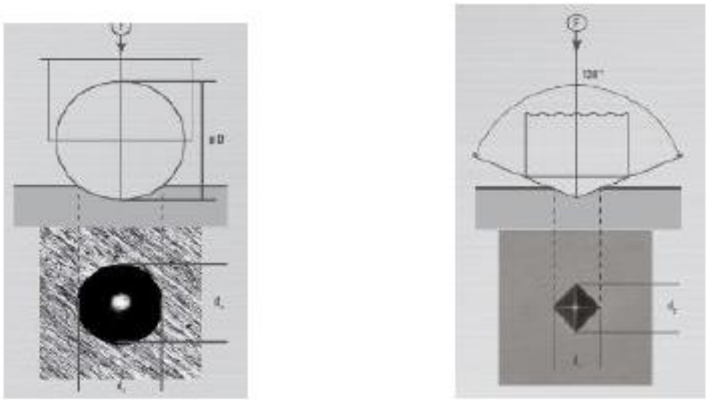

Figure 18 Brinnel Hardness Test & Vickers Hardness Test

Source: International, 2007:1-3

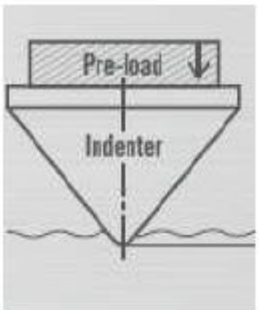

Figure 19 Rckwell Test

Source: International, 2007:1-3

3. Toughness

A material's capacity to withstand failure caused by the start of crack extension leading to fracture is measured by its fracture toughness. Toughness is an important factor. When the material will be subjected to low temperature service

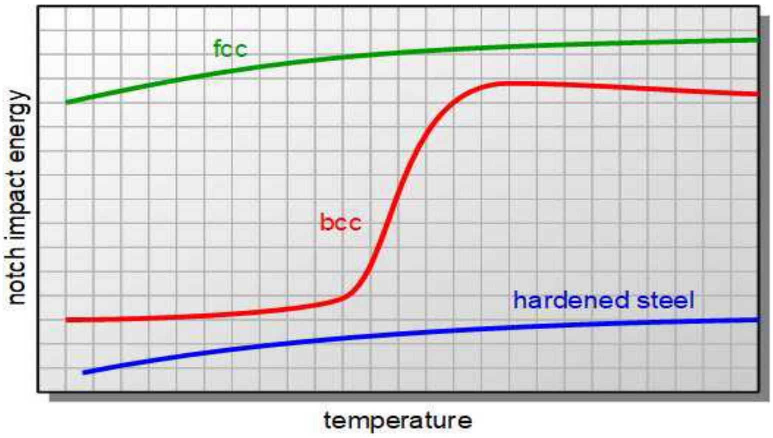

Figure 20 Temperature vs Impact Energy

Source: Megahed, 2015

4. Effect of Material Compositions and Microstructure

- The temperature little affects the toughness of materials with FCC lattice structures compared to materials with BCC lattice structures.
- Some materials, like aluminum, exhibit relatively tough behavior across the entire temperature range, while others, like hardened steels, exhibit relatively brittle behavior (not tempered).

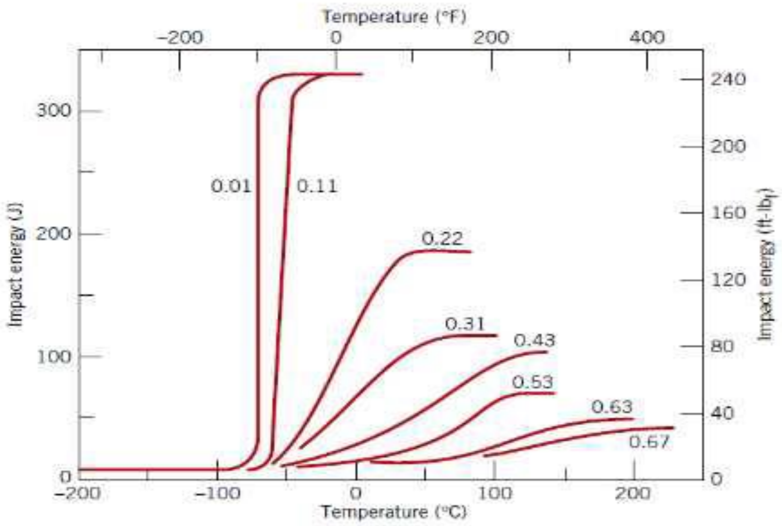

Figure 21 Influence of Carbon Content on V-Notch Energy vs Temperature Behavior of Steel

a. Effect of Thickness

Impact test exemption figure also indicates that by increasing the thickness, the exemption temperature increases as well. Which points out reduction in toughness (increase in DBTT).

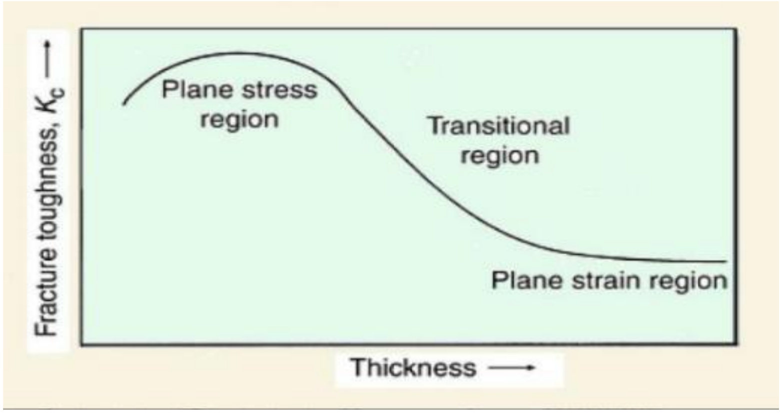

Figure 22 Impact Test Exemption

Source: Materials Testing, Non-destructive Testing, Calibration Services, 2022

The stress condition in the plate, which is controlled by plate thickness, is shown in Figure as having an impact. The predominant stress state for thin plates is plane stress, and Kc is a measure of fracture toughness.

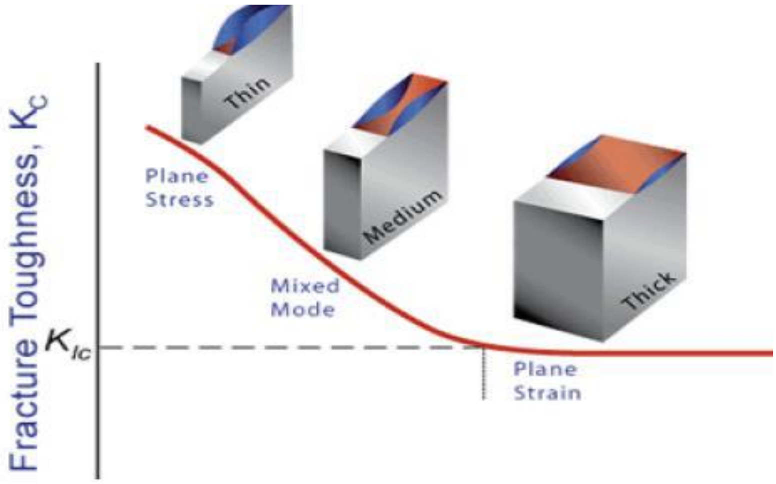

Figure 23 The Effect of Plate Thickness

Source: Elsheikh, 2021

As the plate thickness increases, stress state transitions to plane strain conditions, where fracture toughness is represented by KIc which is lower than Kc. KIc can be used to obtain fracture toughness of brittle materials or thick sections.

DBTT and toughness is traditionally measured by impact test as per the below figure;

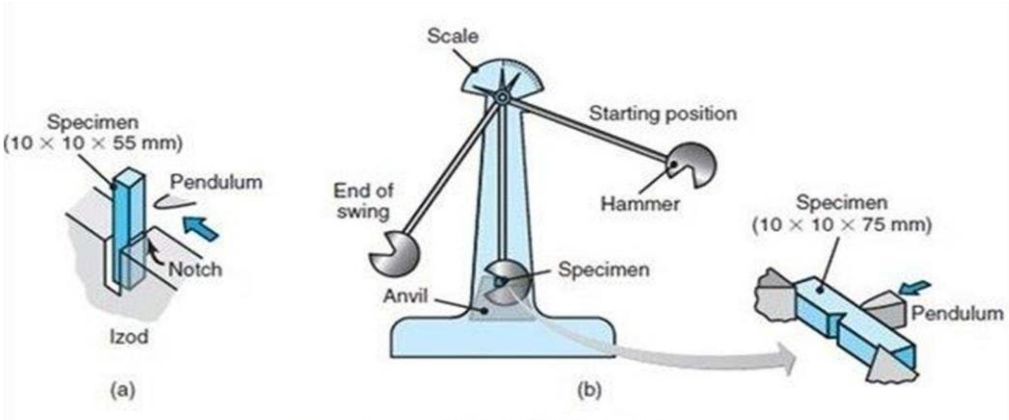

Figure 24 Impact Test Specimens (a) Charpy; (b) Izod

Source: Materials Testing, Non-destructive Testing, Calibration Services, 2022

b. Effect of Temperature

Effect of temperature on toughness is very important factor and it shows that toughness fracture increased with the temperature increase. The below figure is the impact test exemption curve from ASME BPVC Sec. VIII Div.1 which used for the determination of the Minim Design Metal Temperature (MDMT) (Serda, 2013:343-354). The figure indicates how the toughness fracture reduced with temperature decrease. The figure is colored so that for group D, green portion indicates impact test is required and in red part exempted.

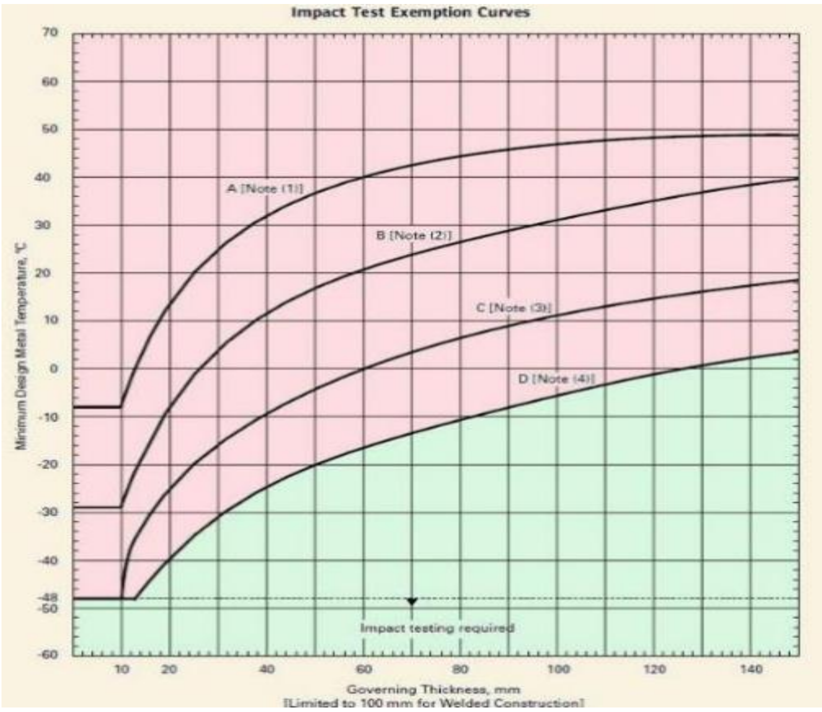

Figure 25 Impact Test Exemption Curves

Source: Engineering Solutions Pune

V. MAJOR MATERIALS USED IN PETROCHEMICAL INDUSTRY

Now I will provide the list of materials which majorly used in petrochemical industry and will explain about these materials in details and will highlight the roles of these materials.

1) Ferrous Alloys
    a) Steel (C<2%)
        i) Plain carbon steel
        ii) Low Alloy Steel
        iii) High Alloy Steel
    b) Cast Iron [High Carbon Iron Alloy (C >2%)]
        i) Gray CI
        ii) White CI
        iii) Malleable CI
        iv) High Si CI
2) Nickel Based Alloys
3) Refractory Lined
4) Nonmetallic piping and vessels

Now I will briefly explain these materials one by one and their pros and cons and their usage and properties and applications of these materials.

First, I will explain about ferrous alloys and its branches and factors, on which we have categorized them.

A. Ferrous Alloys

Ferrous alloys are categorized in two forms. One of them is steel in which carbon quantity is less than 2% and second is cast iron which also named high carbon alloy in which carbon quantity is more than 2%. Further steel is categorized in more three forms named as plain carbon steel, low alloy steel and high Alloy steel (Elsheikh, 2021). First I will give overview about Steel and its types.

1. Plain Carbon Steel

Plain carbon steel is further divided in three different types on the basis of carbon quantity, which is listed below.

- Low CS

- Medium CS
- High CS

In low carbon steel, carbon quantity is less than 0.2% which is in mathematically as C < 0.2%

In Medium carbon steel, carbon quantity is between 0.2% to 0.5% which is in mathematically as C 0.2% - 0.5%.

In High Carbon steel, carbon quantity is more than 0.5% which is in mathematically as C > 0.5%

2. Low Alloy Steel

Low Alloy steel is the type of steel in which steel is formed with other alloying elements for making steel useable according to our different applications.

In low alloy steel, alloying element is lower than 8%. And its good example is Cr-Mo steel. Cr is for chromium and Mo is for Molybdenum

Examples: Cr-Mo Steels

3. High Alloy Steel

In High alloy steel, alloying element is greater than 9%. And its good example is stainless steel, in which cr quantity is more than 9%. Cr is for chromium.

Examples: Stainless steel

You can also view in below graph and figure about the plain carbon steel family and its property related to temperature and its strength.

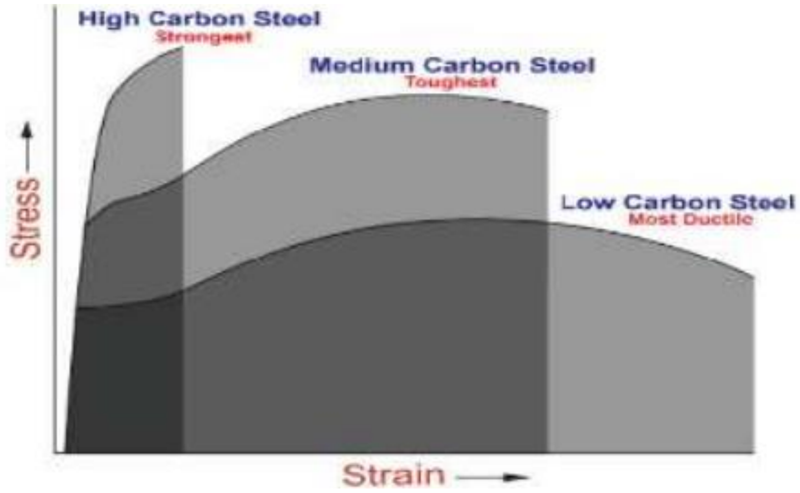

Figure 26 Plain Carbon Steel Properties Graph Between Temperature vs Strength

Source: Materials, 2001:3470

In this picture you can clearly view about High carbon steel, medium carbon steel and low carbon steel, about their toughness their strength.

Now I will provide a graph which will show the effect of temperature on plain carbon steel.

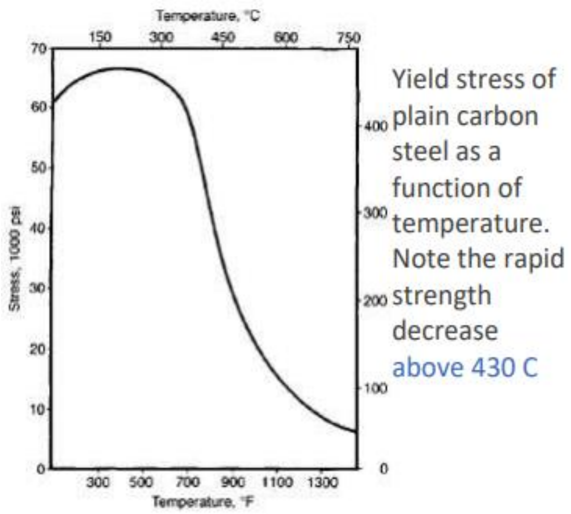

Figure 27 Yield Stress of Carbon vs Temperature

Source: Elsheikh, 2021

B. Cast Iron [High Carbon Iron Alloy

And, so on cast iron high carbon alloy is categorized in four forms named as Gray CI, White CI, and malleable CI and high Si CI. Now I will explain the High carbon iron alloy in which quantity of carbon is more than 2%. This is all about Cast iron and here is listed its all types.

- Gary CI
- White CI
- Malleable CI
- High Si CI

Now I will explain in detail about these one by one.

1. Gray CI

Gray cast iron is the iron in which carbon quantity is between 2 to 4% carbon and silicon quantity is between 1 to 3%

Its example is graphite flake which is very useful for corrosion as compared to steel.

2. White CI

White cast iron is the iron in which less quantity of silicon. And it is called iron carbide. And it's hard and brittle.

3. Malleable CI

Malleable cast iron is produced by heat treatment of white irons. And it has good workability.

4. High Si CI

High silicon cast iron is the alloy in which Gray cast iron is mixed with silicon and silicon quantity in this is greater than 14%. If we mixed 0.95% carbon with 14.5% silicon then it will be good corrosion resistance and inherent hardness.

VI. CLASSIFICATION OF STEEL

In oil and gas industry we make classification of steel according to our need and our strength.

And on the basis of their composition we categorized on above three forms. High strength steel is carbon steel in which carbon quantity is higher to all of these three.

Intermediate strength steel is the steel which is mixture of chromium and molybdenum, in this alloying elements quantity is greater than 8%. And mostly it is used for creep resistance. And in coming detail I will also share the diagram of low alloy steel and we create thickness from different grades according to our need.

In low strength steel, alloying elements quantity is greater than 9% and its best example is stainless steel and it is widely used in oil and gas industry for different applications, it is used for high temperature applications, for corrosion resistance etc.

Now I will explain about high strength materials which are widely used in oil and gas industry

A. High Strength Materials

In order to meet the designing requirements forced by the high pressures of HPHT wells and the arctic areas' subfreezing temperatures, Materials with increased fatigue life and high strength are preferred, if not necessary. Unfortunately, as strength increases, so does EAC resistance and, more specifically, the performance of hydrogen assisted cracking (Milne, Ritchie, & Karihaloo, 2003:5232). Thus, there is a maximum level for the secure usage of engineering metals in oil and gas environment of production, which is perhaps more cautious than in other sectors (Rhodes, Skogsberg, & Tuttle, 2007:63-100). The definition of a high strength material varies depending on a number of variables, such is the application, the family of alloys, and the component's size or weight. High strength in this section is defined as materials with Specific Minimum Yield Strength (SMYS) values greater than the average maximum generally advised for LAS and forged carbon subjected to manufacturing fluids, i.e., 550-586 MPa (80–85 ksi) (Iannuzzi, Barnoush, & Johnsen, 2017).

B. Low Alloy Steels

Contrary to popular belief, LAS are some of the most cutting-edge technical materials. By volume, LAS is used in more important O&G applications than any other alloy family. Therefore, improvements in LAS performance and characteristics may have a significant effect. Despite their benefits, LAS have nevertheless seen catastrophic environmental assisted failures, such as those caused by hydrogen produced by CP systems and settings containing H2S (Craig, 2015:66-71). It is crucial to comprehend the underlying processes that result in appropriate EAC resistance, particularly when H2S is present. If qualified, low alloy steel and carbon steel that don't fulfill the necessary standards can still be utilized for durability, toughness, and chemical composition. However, hardness is a poor predictor of SSC resistance. The sensitivity to EAC varied greatly across different microstructures even at the same levels of hardness and strength. Despite these drawbacks, limiting the base metal and weld hardness significantly decreased the frequency of the early SSC failures (Iannuzzi, Barnoush, & Johnsen, 2017).

C. Moving Beyond Current Limitations

Within the parameters of ISO 15156, SMYS values for Cr-Mo steels up to 760 MPa (110 ksi) are commonly acceptable. However, in fact, LAS with SMYS of 550–586 MPa or higher (80-85 ksi) are rarely used for large forgings since restricting the strength reduces the possibility of reaching 250HV in weldments. Similarly, commercial LAS with an extraordinary mix of qualities, including strength, toughness, weldability, fatigue life, and hardenability, are not covered by ISO 15156's restriction on the permitted nickel concentration (Kappes, et al., 2014:101-128). Similar to ASTM A707, ISO 15156 forbids the copper-bearing, low-carbon, precipitation hardenable LASs35, which combines high strength, weldability and toughness as stated in the table below. (Table 1). These kinds of LAS could be altered for use in sour service applications, for instance by reducing their amount of carbon, adjusting their carbon equal amount, and trying to impose strict control of the factors that cause temper embrittlement. This could lead to significant weight savings, improved through-thickness properties, and extended fatigue life (ASTM International, 2019). The impact of the intricate LAS microstructures on SSC and HSC performance is still a hot topic of discussion in this area. According to their threshold stress (th) in H2S-saturated electrolytes, tempered martensite and lower bainite are the microstructures that are most resistant to SSC. Hydrogen has a negative impact on new martensite steels and normalized and tempered LAS. Snape has shown that small levels of untempered martensite have significant influence on SSC performance, even on steels that met the macroscopic hardness limit required by ISO 15156. Furthermore, Fig. 28 shows that the QT and bainitic steels' threshold stress was greater than the permissible stress in Pressure Vessel Design Code and Division 2 of the ASME Boiler, equivalent to an AYS of around 700 to 750 MPa. Above 750 MPa, the threshold stress significantly dropped.

Table 1 Nominal Composition of Typical Low Alloy and Carbon Steels for Use in Oilfield Applications

Alloy Designation	Standard Nominal Composition (wt%)												SMYS
	Cr	Mo	Ni	W	N	Fe	Nb or (Nb+Ta)	Ti (Al)	Cu	C	Si	Mn	MPa (ksi)
Carbon and Low Alloy Steels													
API 5L-X65Q (PSL 2)	-	-	-	-	-	bal.	§	§	-	0.18 (max.)	0.45 (max.)	1.70 (max.)	450 (65)
ASTM A694 F65	1.50 to 2.0	0.40 to 0.6	2.80-3.90	-	-	bal.	-	-	-	0.30 (max.)	0.15-0.30	1.60 (max.)	450 (65)
ASTM A508 Gr. 4	1.50 to 2.0	0.40 to 0.6	2.80-3.90	-	-	bal.	-	-	-	0.23 (max.)	0.40 (max.)	0.20 to 0.40	690 (100)
UNS K32047	1.50 to 1.90	0.50 to 0.65	3.00-3.50	-	-	bal.	-	-	-	0.14 to 0.20	0.15-.038	0.10 to 0.14	690 (100)
10GN2MFA	0.30 (max.)	0.40 to 0.70	1.80-2.30	-	-	bal.	-	-	-	0.08 to 0.12	0.17-0.37	0.80 to 1.10	414 (60)
UNS K21590	2.00 to 2.50	0.90 to 1.10	0.25 (max.)	-	-	bal.	-	-	-	0.11 to 0.15	0.10 (max.)	0.30 to 0.60	517-586 (75-85)
UNS G43200	0.40 to 0.60	0.20 to 0.30	1.65-2.00	-	-	bal.	-	-	-	0.17 to 0.22	0.15 to 0.35	0.45 to 0.65	414 (60)
Precipitation-Hardened Low Alloy Steels													
ASTM A707-L5	0.60 to 0.90	0.15 to 0.25	0.70 to 1.00	-	-	bal.	-	-	1.00 to 1.30	0.07 (max.)	0.35 (max.)	0.09 (max.)	517 (75)
Solution Annealed Nickel-Based Alloys													
UNS N06625	20.00 to 23.00	8.0 to 10.0	58.0 (min.)	-	-	5.0 (max.)	(3.15 to 4.15)	-	-	0.10 (max.)	0.50 (max.)	0.50 (max.)	290-414 (42-60)[a]
Precipitation-Hardened Nickel-Based Alloys													
UNS N07718	17.0 to 21.0	2.80 to 3.30	50.0 to 55.00	-	-	bal.	(4.87 to 5.20)	0.80 to 1.15	0.23 (max.)	0.045 (max.)	0.010 (max.)	0.35 (max.)	827-965 (120-140)
UNS N07725	19.0 to 22.5	7.00 to 9.50	55.00 to 59.0	-	-	bal.	2.75 to 4.00	1.00 to 1.70	-	0.030 (max.)	0.020 (max.)	0.35 (max.)	827 (120)
UNS N07716	19.0 to 22.0	7.00 to 9.50	59.00 to 63.0	-	-	bal.	2.75 to 4.00	1.00 to 1.60	0.23 (max.)	0.030 (max.)	0.020 (max.)	0.20 (max.)	827-965 (120-140)
UNS N06059	22.0 to 24.0	15.0 to 16.5	bal.	-	-	1.50 (max.)	-	(0.1 to 0.40)	-	-	0.10 (max.)	0.50 (max.)	450 (65ksi)[b]
UNS N06680	20.5	6.5	bal.	6.5	-	0.1 (max.)	3.5	1.5	-	0.010 (max.)	-	-	550-665 (80-95)
UNS N06686	19.0 to 23.0	15.0 to 17.0	bal.	3.0 to 4.0	-	5.0 (max.)	-	-	-	0.010 (max.)	0.08 (max.)	0.75 (max.)	760 (110)[d]
Duplex and Super Duplex Stainless Steels													
UNS S32205	21.0 to 23.0	2.50 to 3.50	4.50 to 6.50	-	0.08 to 0.20	bal.	-	-	-	0.03 (max.)	0.2 to 0.70	2.0 (max.)	450 (65)
UNS S32750	24.0 to 26.0	3.0 to 5.0	6.0 to 8.0	-	0.24 to 0.32	bal.	-	-	-	0.03 (max.)	0.8 (max.)	1.2 (max.)	550 (80)
UNS S32760	24.0 to 26.0	3.0 to 4.0	6.0 to 8.0	0.50 to 1.0	0.20 to 0.30	bal.	-	-	0.5 to 1.0	0.03 (max.)	1.0 (max.)	1.0 (max.)	550 (80)
UNS S39274	24.0 to 26.0	2.50 to 3.50	6.0 to 8.0	1.5 to 2.5	0.24 to 0.32	bal.	-	-	0.20 to 0.80	0.03 (max.)	0.8 (max.)	1.0 (max.)	550 (80)
Austenitic and Highly Alloyed Austenitic Stainless Steels													
UNS S31603	16.0 to 18.0	2.0 to 3.0	10.0 to 14.0	-	-	bal.	-	-	-	0.03 (max.)	1.0 (max.)	2.0 (max.)	182 (27)[a]
UNS S31254	19.5 to 20.5	6.0 to 6.5	17.5 to 18.5	-	0.18 to 0.22	bal.	-	-	0.50 to 1.0	0.020 (max.)	0.80 (max.)	1.0 (max.)	310 (45)
Martensitic and Precipitation Hardened-Martensitic Stainless Steels													
UNS S41000	11.5 to 13.5	-	-	-	-	bal.	-	-	-	0.15 (max.)	1.0 (max.)	1.0 (max.)	550 (80)[e]
UNS S17400	15.0 to 17.5	-	3.0 to 5.0	-	-	bal.	0.15 to 0.45	-	3.0 to 5.0	0.07 (max.)	1.0 (max.)	1.0 (max.)	724 (105)[f]

Source: Iannuzzi, Barnoush, & Johnsen, 2017

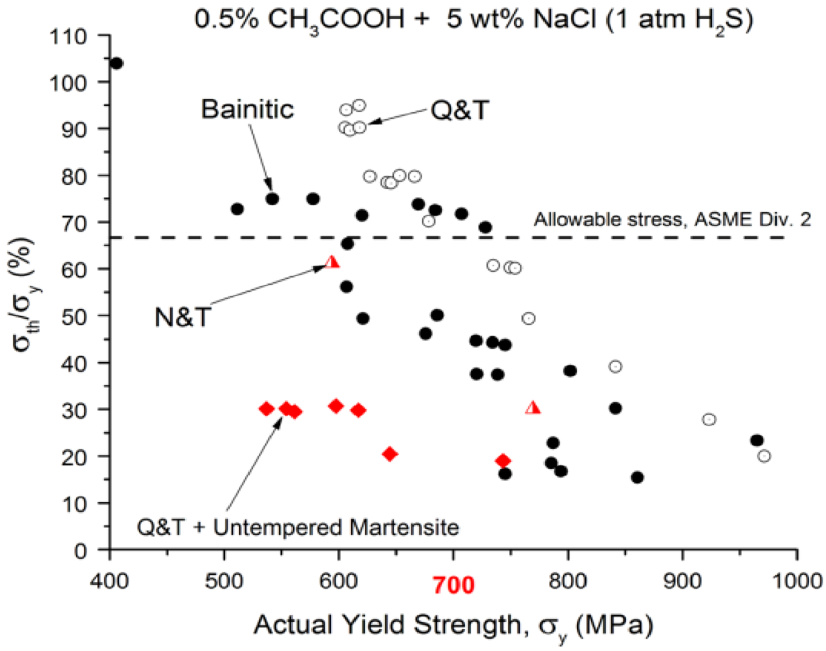

Figure 28 Threshold stress (σth) of low alloy steels with different microstructures exposed to 0.5 wt% CH3COOH + 5 wt% NaCl in 1 atm H2S at 24 °C, normalized to the actual yield strength (σy) versus σy

Source: Iannuzzi, Barnoush, & Johnsen, 2017

It's interesting to note that the dispersion in Fig. 28, especially for bainitic steels, is linked to an incorrect microstructure characterization. Since most authors did not indicate the kind of martensite, such as plate, lath, or a mixture of both, or the type of bainite, such as upper or lower, it was necessary to make assumptions based on the published heat treatment techniques and alloy compositions to create Fig. 28. Even today, there are important parts of the bainitic and martensitic phase transitions in steels that are still unclear and may hinder technical advancement, such as the mechanisms for carbide precipitation. According to phenomenological observations, hydrogen dislocation interactions may be facilitated by untempered martensite's high residual strain, the ferrite-carbide interface present in ferritic-pearlitic alloys, as well as the carbides present at the GB in upper bainite needles.

D. Precipitation Hardened (PH) Corrosion Resistant Alloys (CRA)

Generally speaking, huge bore (i.e., having an internal diameter more than 50 cm) components used in subsea production, including valves, connections, and pipelines, are frequently constructed from LAS covered or clad with a CRA. The strength and affordability of the LAS core are benefited by fully or partially clad designs, while the CRA inlay reduces the corrosion risks brought on by LAS exposure to aqueous electrolytes including CO2 and H2S (ISO_21457, 2010). Although other stainless steels and nickel alloys may be utilized, in subsea oil and gas production, LAS are commonly welded topped with UNS N06625 (NA625), a nickel-based seawater resistant CRA. Despite the fact that the surface in contact with production fluid is formed of a CRA, the base LAS must nevertheless meet ISO 15156's standards for strength, hardness, and alloy chemistry. When an application calls for strength values greater than those permitted by ISO 15156 for LAS, i.e., SMYS above 690-760 MPa, PH CRA are employed (100–110 ksi). Numerous uses for stainless steel and PH nickel-based alloys (PHNA) can be found in the production of oil and gas. Due to its strength and EAC resistance, PHNA in particular are often employed in wellbore components (Bhavsar, Collins, & Silverman, 2001:47-55). Although not all PHNA families can survive seawater, all PHNA are capable of withstanding the hardest industrial environments. Uns N07718 (NA718), a super nickel alloy with a composition of 50–55 percent Ni, Nb, Ta, and Ti, is the most popular PHNA. It contains 17–21% wt% Cr and 2.8–3.3 wt% Mo. (Table 1). The NA718's intermediate Cr and Mo content causes pitting and crevice corrosion in situations with oxidizing halides, despite the material's excellent performance in sour manufacturing environments. According to ISO 21457, NA725 and NA716 are classified as seawater resistant due to their ability to withstand the harshest sour situations. There is currently no standard that specifies the highest temperature at which NA725 and NA716 can be used in seawater, although NA625 is limited by ISO 21457 to 30 °C because of concerns about crevice corrosion in chlorinated systems. Although it is generally known that NA718's HSC and SSC resistance is substantially compromised by the presence of -phase56, PHNA has traditionally been thought to be resistant to hydrogen embrittlement under the age-hardened conditions found in O&G applications (Iannuzzi, Barnoush, & Johnsen, 2017). However, throughout installation and operation, reports of rapid cleavage failures of the subsea components NA71857, NA71658, and NA72559, all linked to HE, have been made in comparatively benign conditions. Although the source of the hydrogen in these failures has not always been clearly identified, it is thought that either CP, electroplating, galvanic coupling to carbon steel, or fluid deterioration from non-production fluids may have contributed to the H. More concerning, the majority of materials and production techniques complied with international standards, indicating that current best practices may not account for all the factors that influence an ideal microstructure. After appropriate sample preparation procedures, GB ornamentation was evident in the scanning electron microscope (SEM) and could only be identified by transmission electron microscopy (TEM) (Milne, Ritchie, & Karihaloo, 2003:5232).

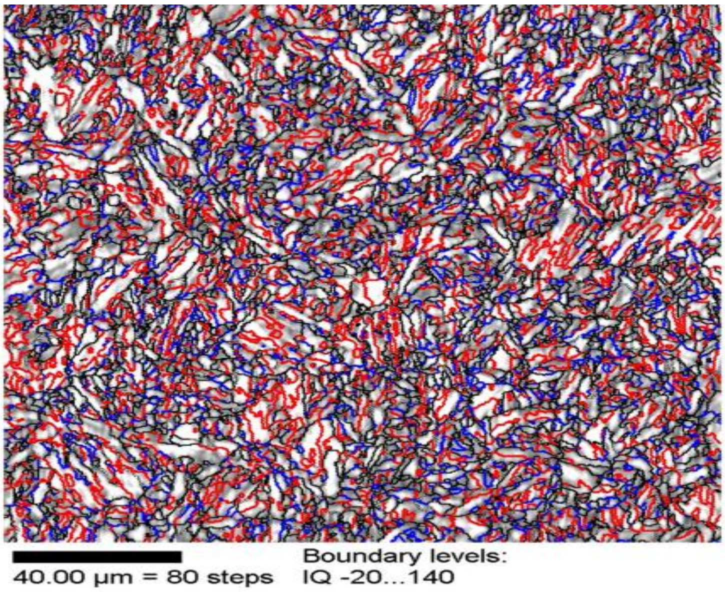

Figure 29 An electron backscatter diffraction analysis of a QT pipeline steel revealed the qualitative distribution of specific grain boundaries (: 3 in red: 11, 25b, 33c, and 41c in blue).

Source: Iannuzzi, Barnoush, & Johnsen, 2017

VII. STAINLESS STEEL FAMILIES

Now I will explain stainless steel types which I will name as stainless-steel families. I will list below the families of stainless steel and also, I will show the chart of these families with their usage and applications that where we can use them according our needs and what their properties.

- Austenitic Stainless Steels
- Ferritic Stainless Steels
- Duplex Stainless Steels
- Martensitic Stainless Steels
- PH Stainless Steels

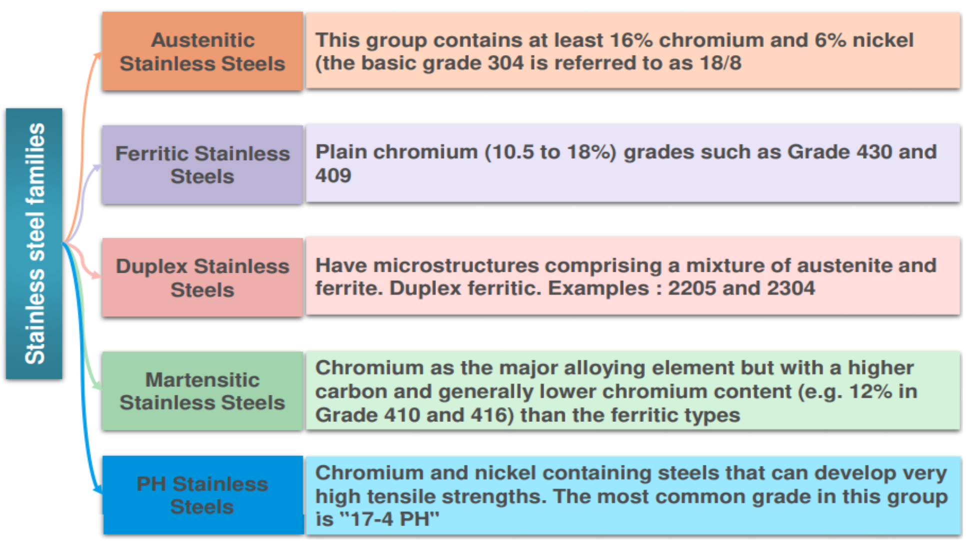

Figure 30 Stainless Steel Family Chart

Source: Elsheikh, 2021

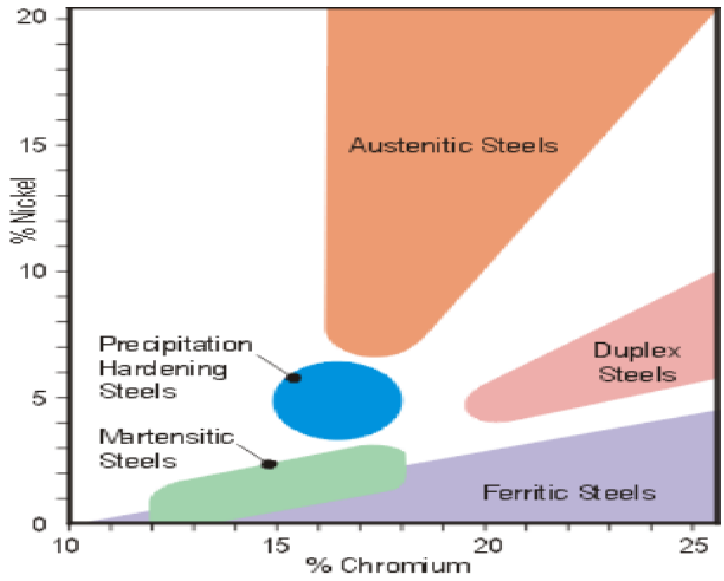

Figure 31 Chromium vs Nickel

Source: Elsheikh, 2021

A. Relative Mechanical and Physical Properties of Stainless-Steel Families

Through graphs I will show the mechanical and physical properties of stainless-steel families for better understanding.

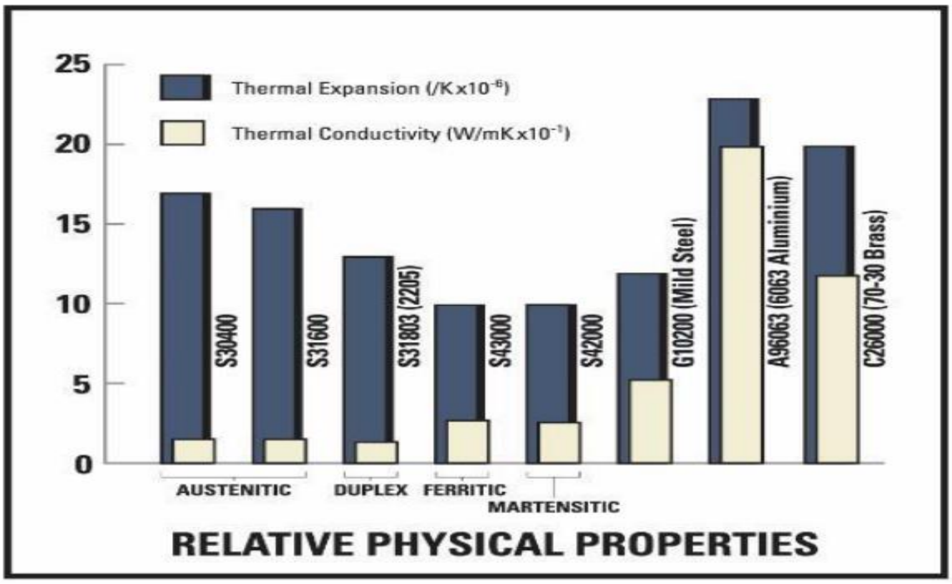

Figure 32 Thermal Expansion and Thermal Conductivity

Source: McGuire, 2008:69-90

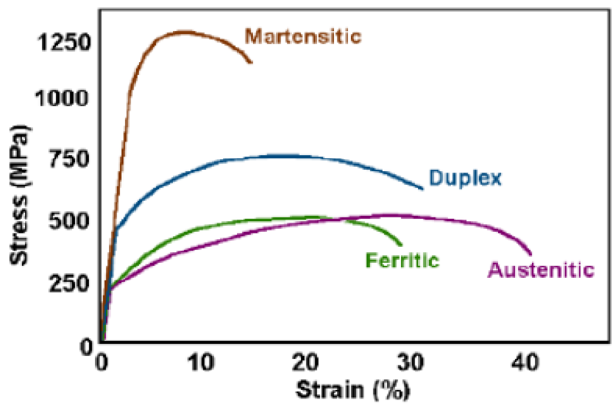

Figure 33 Typical Tensile Properties

Source: Elsheikh, 2021

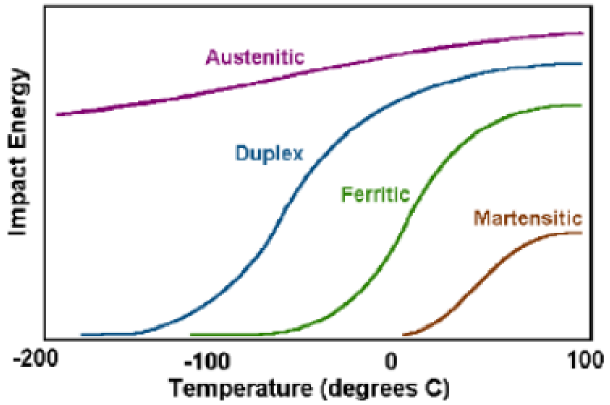

Figure 34 Typical Impact Properties

Source: Elsheikh, 2021

1. Austenitic Stainless-Steel Families

At least 6% nickel and 16% chromium are included in this group (the basic grade 304 is known as 18/8).

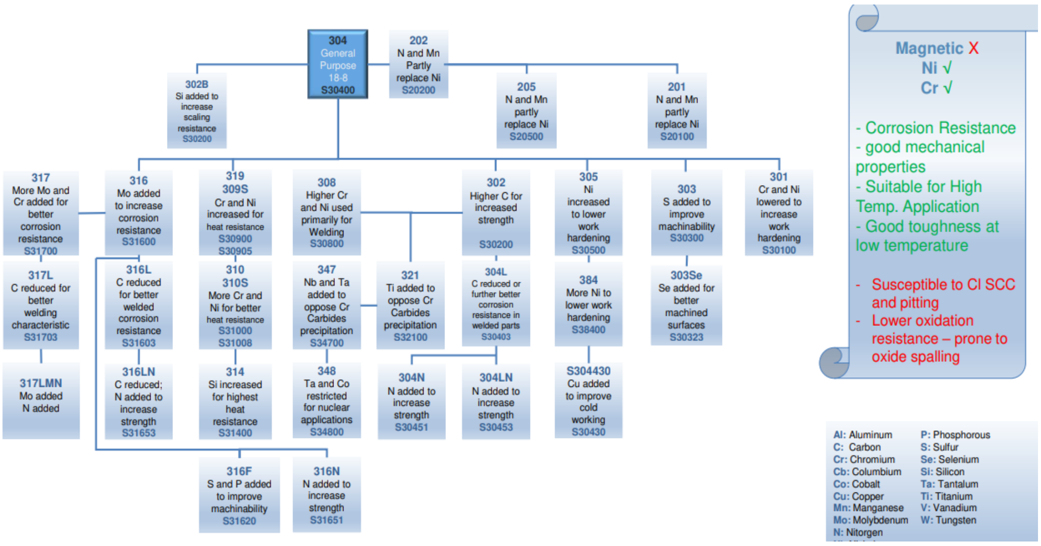

Figure 35 Family Tree and Properties of Austenitic Stainless-Steel Families

Source: McGuire, 2008:69-90

2. Ferritic Stainless-Steel Families

Grades of pure chromium (10.5 to 18%) like Grade 430 and 409

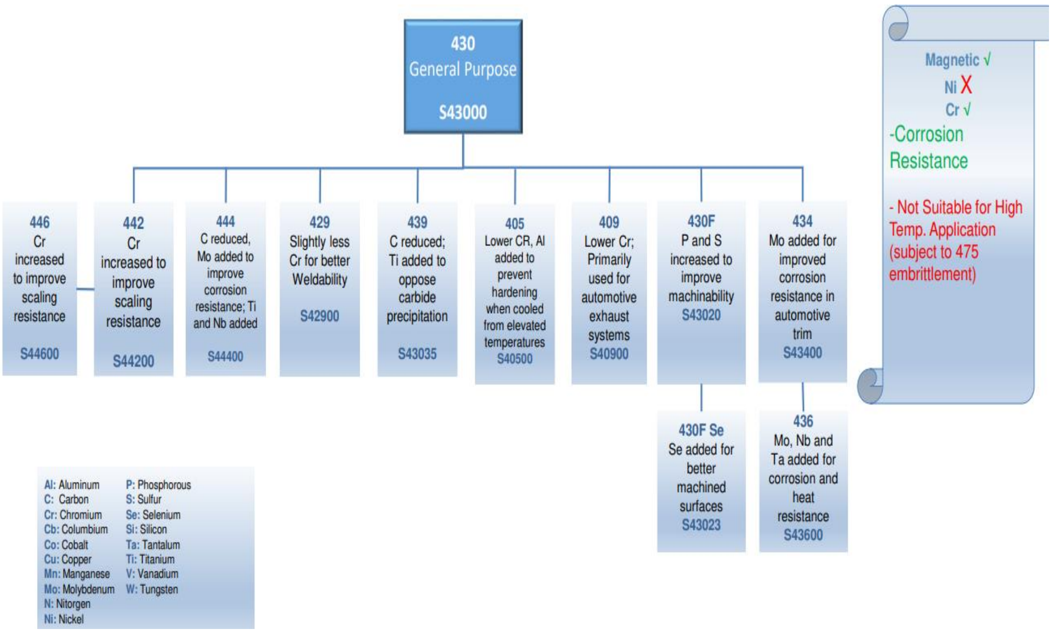

Figure 36 Family Tree of Ferritic Stainless-Steel Family

Source: Davis, 2001:192-203

3. Martensitic Stainless-Steel Families

Chromium is the main alloying element, but there is more carbon and typically less chromium (12% in Grades 410 and 416) than there is in ferritic kinds.

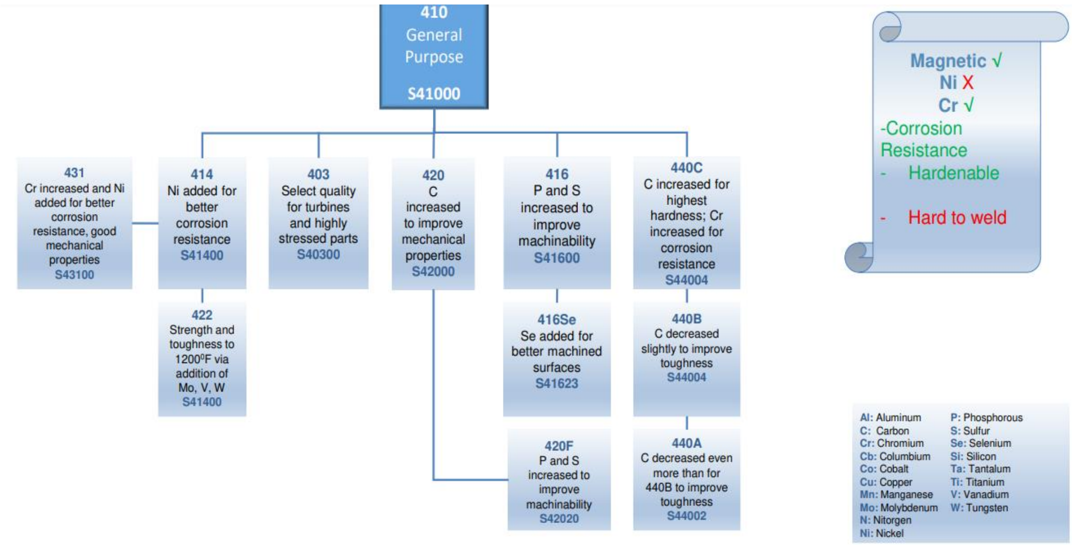

Figure 37 Family Tree of Martensitic Stainless Steel Family

Source: Davis, 2001:192-203

4. Duplex Stainless-Steel Families

Possess microstructures that are a combination of ferrite and austenite. Duplex ferritic. Examples are 2205 and 2304.

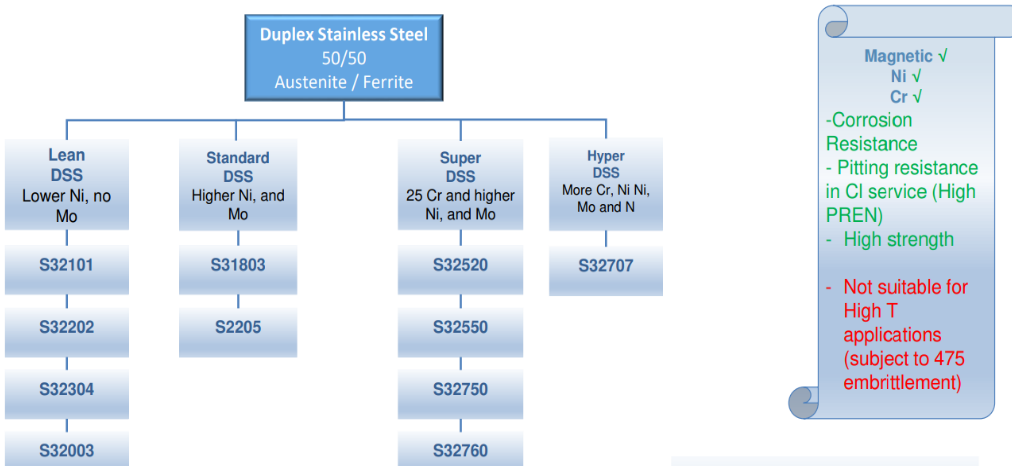

Figure 38 Family Tree of Duplex Stainless-Steel Families

Source: API 938C, 2011

Here are some formulas for checking critical resistance temperature and critical resistance corrosion in duplex stainless-steel families.

$$PREN = \%Cr + 3.3Mo + 16N$$

$$PREN: \%\,Cr + 3.3 \times (\%\,Mo + 0.5 \times \%\,W) + 16\,\%\,N$$

PREN: Pitting Resistance Equivalent Number

CPT: Critical Pitting Resistance Temperature

CCT: Critical Crevice Corrosion Resistance

With the help of this formula there is a chart between grading and their calculated numbering for understanding of materials code in duplex stainless-steel family (Elsheikh, 2021).

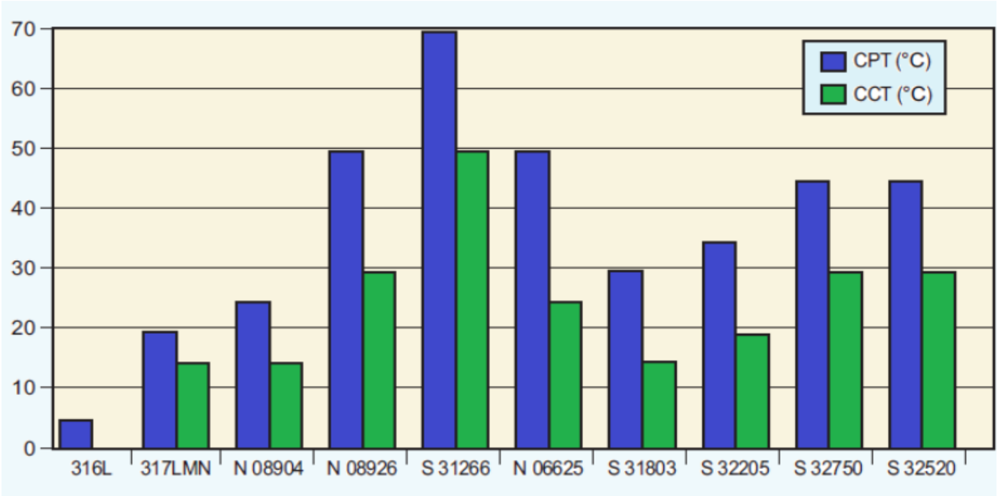

Figure 39 Chart Between Grading and Their Calculated Numbering

Table 2 Grading and Their Calculated Numbering

Grade	Pren
304L	19
316L	24
2205 S3205	35
2507 S32750	43

5. Precipitation Hardening Stainless Steel (PHSS) Family

Steel made of chromium and nickel has the ability to reach extremely high tensile strengths. This group's most prevalent grade is "17-4 PH."

With one or more of the following elements: copper, aluminum, titanium, niobium, and molybdenum, PHSS are commonly based on iron, chromium, and nickel. After that, a last tempering procedure strengthens the precipitation.

Alloy	UNS No.	Composition, %								
		C	Mn	Si	Cr	Ni	Mo	Cu	Ti	Other
Martensitic										
PH 13-8 Mo	S13800	0.05	0.10	0.10	12.8	8.0	2.3			Al=1.1
15-5PH	S15500	0.07	1.0	1.0	14.8	4.5	-	3.5		Nb=0.3
17-4PH	S17400	0.09	1.0	1.0	16.3	4.0	-	4.0		Nb=0.3
Semi-austenitic										
PH15-7Mo	S15700	0.09	1.0	1.0	15.0	7.1	2.5	-	-	Al=1.1
17-7PH	S17700	0.08	0.9	0.5	16.5	7.5	-			Al=1.0
Austenitic										
A-286	S66286	0.08	2.0	1.0	15.0	25.5	1.25	-	-	Ti: 2.1 Al: ≤0.35 V: 0.3

Figure 40 Precipitation Hardening of Stainless Steel (PHSS) Family

Source: Precipitation hardened stainless steels - Sandvik Materials Technology, 2018

VIII. APPLICATIONS OF MATERIALS IN PETROCHEMICAL INDUSTRY

Now I will explain common applications of these materials in petrochemical industry. Carbon steel application, Low Alloy Cr-Mo Steel, Stainless Steel, Nickel Based Alloys, Refractory Lined, Non-Metallic Piping and Vessels,

A. Application of Carbon Steel

Figure 41 Carbon Steel

Carbon Steel is widely used in oil and gas industry mainly due to its cost, availability and easy fabrication and welding.

Low corrosion resistance in many applications. Limitations in low temperature < -29 C. Carbon Steel loose toughness. High Temperature: > 425 C. CS low creep strength, high oxidation rate, and susceptibility to carburization

B. Application of Low Alloy Cr-Mo Steel

Low alloy Chromium Molybdenum (Cr-Mo) Steels are replacing the Carbon steels as a candidate material where: - Temperature is higher than the maximum limits of carbon steels - In application where Hydrogen is present at relative high temperature and partial pressure to resist High Temperature Hydrogen Attack (HTHA).

Common Grades:

- P11 (1.25 Cr- 0.5 Mo)

- P22 (2.5 Cr – 0.5 Mo)
- P5 (5 Cr- 0.5 Mo)
- P91 (9 Cr- 1 Mo)

Cr-Mo steel is usually requiring application of Post Weld Heat Treatment (PWHT) during fabrication or repair, which sometimes are difficult to apply at site.

C. Application of Stainless Steel

Stainless steels is a material of Cr > 11 % where Cr formed the distinguishing surface oxide layer of the stainless steels.

Figure 42 Stainless Steel

Austenitic stainless steels is applied widely where; Higher Corrosion resistance is required, Temperature is higher than the maximum limits of Cr-Mo Steels, Temperature is lower than the lower limit of CS to avoid brittle fracture and toughness loss (Elsheikh, 2021).

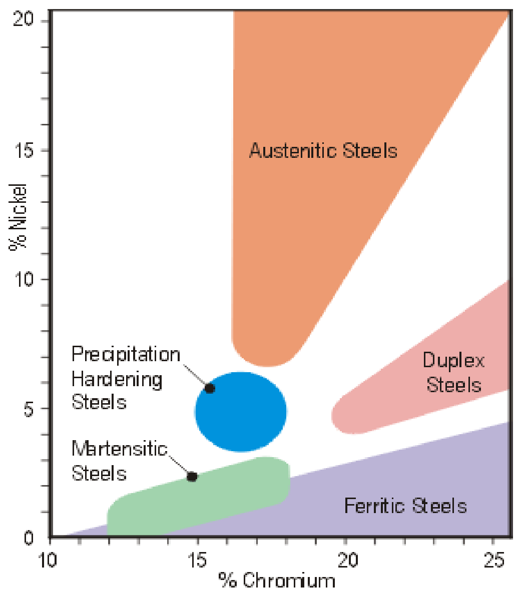

Figure 43 Chromium vs Nickel

A main concern of austenitic SS is the susceptibility to pitting and cracking in Cl services, Where DSS is preferred for this aspect. Duplex and ferretic stainless steels limited for Temp. <=316 C to avoid 475 C (885 F) embrittlement (Elsheikh, 2021).

D. Application of Nickel Based Alloys

Ni Based alloys (Incoloy, Inconel, Monel…) are replacing Stainless steels when:

- Higher Corrosion resistance is required
- Temperature is higher than the maximum limits of stainless Steels (oxidation, metal dusting, Nitriding, carburization...)

Figure 44 Nickel Based Alloys

Ni Alloys are of much higher cost compared to stainless steels which limits its application.

Alloys with Ni >42% is almost immune for chloride SCC. Alloy 825 (42% Ni) is often specified for applications requiring resistance to chloride SCC (Elsheikh, 2021).

E. Application of Refractory Lined

Refractory lining is applied where the metals cannot withstand the operating temperature and / or to reduce the cost of the equipment by using lower design temperature and hence lower material grade.

Figure 45 Hot Spots Due to Degradation of Refractory

Hot Spots due to degradation of refractory or quality issues once occurred; damage of the metallic enclosure can be very fast with potential catastrophe failure.

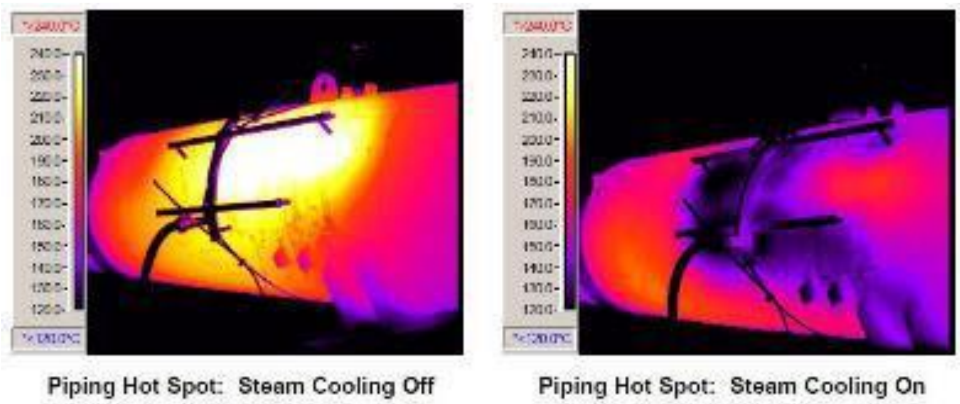

Figure 46 Steam Cooling Off vs On

1. Application of Non-Metallic Piping and Vessels

Nonmetallic materials include wide range of different materials like: FRP, PVC, PE, Cement, lined equipment.

Usually applied where corrosion resistance is required.

Limited in temperature application. Special precautions (Protection from UV, vent holes for PTFE lined, ……..)

Preferred application for underground piping to have good corrosion resistance without need of Cathodic Protection.

Figure 47 Non-Metallic Piping and Vessels

IX. LITERATURE REVIEW

This review article seeks to give readers a general understanding of the high-performance polymers frequently used in the oil and gas sector, including their characteristics, uses, and resistance to reactivity and degradation. One of the key considerations in the design of equipment for chemical processes has been the proper material selection. Most structural parts, coatings, equipment parts, and the like now mostly use non-metals instead of metals, especially in the oil and gas industry (e.g. sophisticated and high-performance polymeric materials). Understanding the advantages and disadvantages of various polymer materials is therefore crucial before they can be effectively used for a given application. These comprise fluoropolymers, polysulfone, polyetheretherketone, polyphenylene sulfide, polyetherimide, elastomers, polymer nanocomposites, and other highly efficient thermosets. The current research initiatives to enhance the qualities of high efficiency polymers and broaden their uses (including additive manufacturing or 3D printing) in the industry of oil and gas are also covered in this article (de Leon, et al., 2021).

The use of microwave radiation for drilling alloys and non-metals is briefly described in this review article along with a number of other criteria, such as immersion depth, concentrator material, kind of insulating material, subsector powder, and specimen. Microwaves are electromagnetic radiation with frequency between 300 MHz and 300 GHz and wavelengths ranging from around 1 m to 1 mm. Electromagnetic radiation at a frequency of 2.45 GHz is focused into a small area during the machining process known as microwave drilling. The following methods are used to characterize drilling: scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS), micro tensile test, impact test, 3-point bending test, fractography, and porosity (Katti, et al., 2021).

This essay focuses on the effects of corrosion on alloy steel-made conveyance media, such as pipes and tanks. The 3 samples of crude oil from northern Iraq used in this study are based on the regions of Kirkuk, Makhmour, and Qayara. In the oil industry, crude oil is moved from the location of extraction to the refinery, where it's preserved in tanks before being piped to the refining towers to begin the separation process. The corrosion impact on alloy steel material sample experiment is carried out by submerging the metal specimens in crude oil at a temperature of 25 [o C]. By weighing the alloy steel specimens both before and after submerging them in crude oil over time, the loss weight method is used to determine the corrosion effect. A mechanical tensile test was performed on the samples both before and after to determine the corrosion effect (Kanam, Ahmed, & Mahmood, 2021).

The corrosion problems at the various refinery units are discussed in this review article. One of the biggest problems facing oil refineries is corrosion. Due to the continuous reliance of the global economy on sectors dependent on the production of petroleum, in recent decades, it has drawn a lot of interest. Effective corrosion mitigation techniques are required to avoid property failure brought on by the danger of corrosion, as the yearly cost of corrosion is projected to be in the billions of dollars. However, it is widely dispersed in a number of scientific journals, and obtaining such data is essential to creating a body of knowledge on the corrosion problems brought on by refinery operations. Additionally, the causes of the corrosion issue and contemporary solutions, such as cathodic protection and engineering design, Metal coating and the application of corrosion inhibitors were addressed. The development of novel smart nanomaterial coatings, accurate real-time prediction models, adequate data collection on ammonium bisulfide (NH4HS) corrosion in the refinery plant, and environmentally friendly high temperature substances are required for efficient refinery corrosion mitigation (Perepezko, 2009).

This article briefly reviews the origin and background of the petrochemical industry, as well as the type of plant that is utilized and its layout. It also describes certain pieces of equipment and their typical modes of breakdown in service. Consideration is given to the utilization of many material categories, including carbon steel, medium- and high-tensile steel, corrosion- and heat-resistant steel, low-temperature materials, and nonferrous metals. The difficulties that arise in the manufacturing and use of these materials, in particular those issues that could lead to dangerous circumstances, are highlighted (Lancaster, 1978).

X. MATERIALS ADVANCEMENT IN PETROCHEMICAL INDUSTRY

In the last a couple of decades, there have been a number of stronger, lighter and multifunctional materials developed in the laboratory. Advanced materials are those with at least one characteristic that is much better than that of standard alloys. Without exception, their distinctive features result from either the non-equilibrium microstructure or the novel chemical composition. Three types of advanced materials are picked as the most promising for applications in oil and gas production.

A. Nanocrystalline Materials

Enhancement of both strength and toughness can be achieved simultaneously by reducing the grain size, schematically shown in below Figure 48. In contrast to conventional metallic alloys with typical grain sizes in the range of 10 to 100 μm or even higher for some cast materials, Nano crystalline (NC) materials are characterized by grain size of typically 10-100 nm. However, a softening effect by grain boundary sliding begins to take a dominant role when grain size is further reduced under 10 nm (Safer, Smarter, & Greener, 2014). In principle, processing of bulk Nano crystalline alloys can be accomplished by either the ‘‘two step bottom up’’ methods which assemble Nano scale clusters and subsequently consolidate into bulk material, or the ‘‘one step top-down’’ methods which break down the bulk microstructure into the Nano scale, as illustrated in Figure 49. The consolidation step involved with high pressure and heat should be carefully done without significant coarsening of the grain size and introduction of artifacts. In contrast, “one-step” processes such as electrode position and mechanical attrition, are beneficial for the dense and artifact-free NC materials (Koch, 2007).

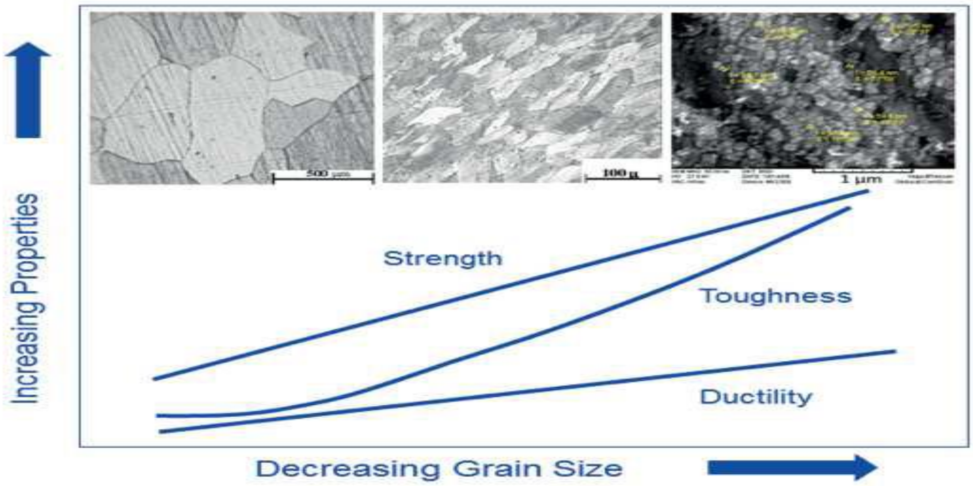

Figure 48 shows schematic representation of how various material properties are affected by smaller grains; Optical image of coarse-grained iron specimen: (left) annealed, (middle) as cast, and (right) SEM image of Nano crystalline iron deposit

Source: Ma, 2003; Afshari, & Dehghanian, 2009.

Compared to their microcrystalline counterparts, NC metals in general exhibit high yield strength and hardness, excellent wear resistance, and enhanced super plasticity. However, the expected ductility increase is typically limited by processing artifacts. Fracture and fatigue resistance are found to be superior as well. Due to the high portion of grain boundaries, high temperature creep rate of NC materials may be increased by the enhanced diffusivity. NC materials are therefore not heat treatable. The increased diffusivity of NC materials, on the other hand, contributes to faster protective passive film formation and thus increases corrosion resistance. NC materials are mainly limited to coatings and thin films due to the difficulty of retaining the ultra-small grain sizes in thick cross-sections. NC coatings are used to improve hardness and toughness coupled with better corrosion and wear resistance for structural applications, i.e. Fe/Ni-W, WC-Co- Cr, TiN/TiCN, yttria-stabilized zirconia (YSZ) and other metallic or cermet nanostructured coatings. It is likely that NC materials would see service in specialty applications such as valve seats and stems, components of compressor or pump, and surfaces such as the riser tensioning system where wear and corrosion resistance are required. Nowadays, more than a dozen of companies in U.S. are involved in the manufacture of nanostructured materials on an industrial scale and probably more than 1600 organizations world-wide are involved in the development, production, and services related to such materials (Lancaster, 1978).

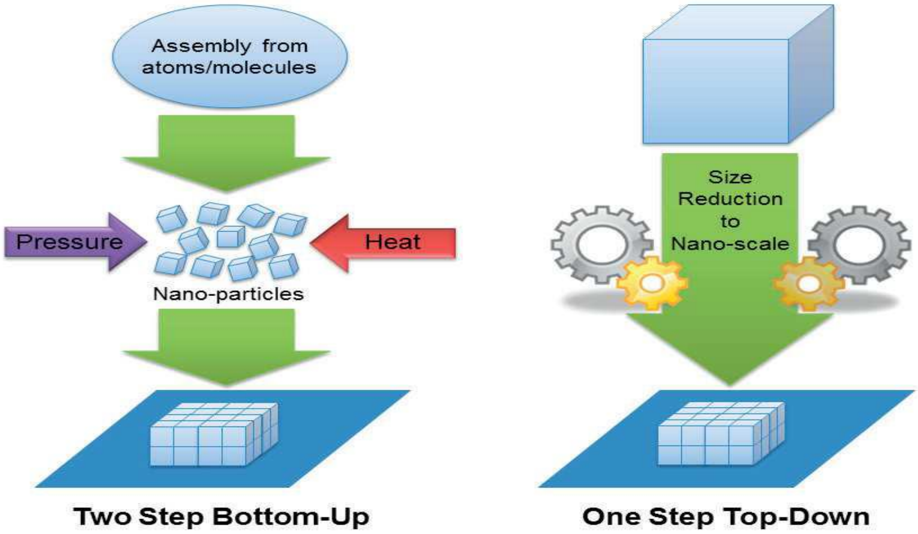

Figure 49 Schematic Drawing to Illustrate “Bottom-Up” and “Top-Down” Fabrication Methods of Nanocrystalline Materials

Source: Safer, Smarter, and Greener, 2014

B. Bulk Metallic Glass

Bulk metallic glasses (BMG) have appealing features that come from their amorphous condition when combined with some desired qualities of metals and the process ability of glasses. Theoretically, every metallic alloy can achieve a glassy state through incredibly quick solidification. However, such extreme cooling rates yield thin materials in small quantities. BMG strictly refers to those multicomponent alloys system developed since 1980’s with high glass forming ability (GFA). GFA refers for the capability of creating materials with a glassy state thickness more than 1 mm at a reasonably slow cooling rate. (< 100 K/s) (Kumar, Desai, & Schroers, 2011).

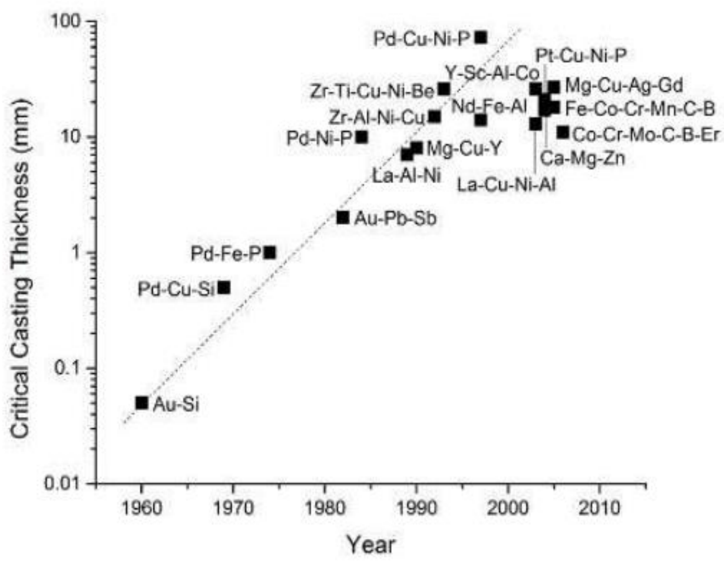

Figure 50 Typical various alloy systems of BMG's were reported with critical casting thickness for glass formation and the calendar year when the first synthesis was discovered

Source: Greer, & Ma, 2007.

Fabrication methods of BMG's all result from different non-equilibrium processing techniques to avoid crystallization. Solidification processes via direct casting and thermoplastic forming (TPF) are the most widely used. Direct casting requires relatively rapid cooling from melting temperature to glass transition temperature by bypassing crystallization. Thermoplastically formed BMGs with high GFA can be produced in the TPF while still being super cooled liquids above their glass transition temperature (Schroers, 2010). Because of the absence of grain microstructure, well-defined crystal defects, and chemical in-homogeneities, BMG's possess outstanding mechanical properties compared to their crystalline counterparts, such as much higher tensile strengths and hardness, near theoretical high yield strength with more than 2% elastic deformation, lower Young's modulus, low internal friction and wear coefficients, high fracture strength, and superior fatigue resistance. Some BMG alloy systems, e.g. Zr-, Pd–Cu-, Fe-, and Mg based systems, also possess excellent corrosion resistance and repassivation ability under extremely corrosive environment (Yavari, Lewandowski, & Eckert, 2007). However, due to the highly constrained plastic low and the lack of microstructural features. BMG's usually are ''brittle'' and lack plasticity under tension, which results in low fracture toughness and impact resistance. It is suggested that applications with small dimension would benefit the most from BMG's with enhanced plasticity and the low material cost. In oil and gas production, BMG can be used on valves and springs, strengthened edges of tools, wear resistant surface of drill head, high corrosion resistant coating, pipes for mass low meter, precise miniature parts of pressure sensors, etc. Due to their high cost and low impact toughness, the principal applications for BMG will be constrained to small, crucial components with high performance requirements. A recently developed Fe-based BMG (Fe–Ni–Cr–C–B) with an exciting combination of moderate cost and properties may have a greater resistance to localized corrosion than a conventional Ni-22%Cr-9%Mo-3%W alloy. Thermal spray-coated layer of high-performance Fe-based BMG's (SAM2X5, SAM1651) were developed to protect substrate under fairly aggressive conditions, in Figure 50. It has been suggested that 316L stainless steel plates coated with these Fe-based amorphous metals layer outperform conventional Ni-Cr-Mo alloys, but at a third of the cost (George, Letfullin, & Zhang, 2011).

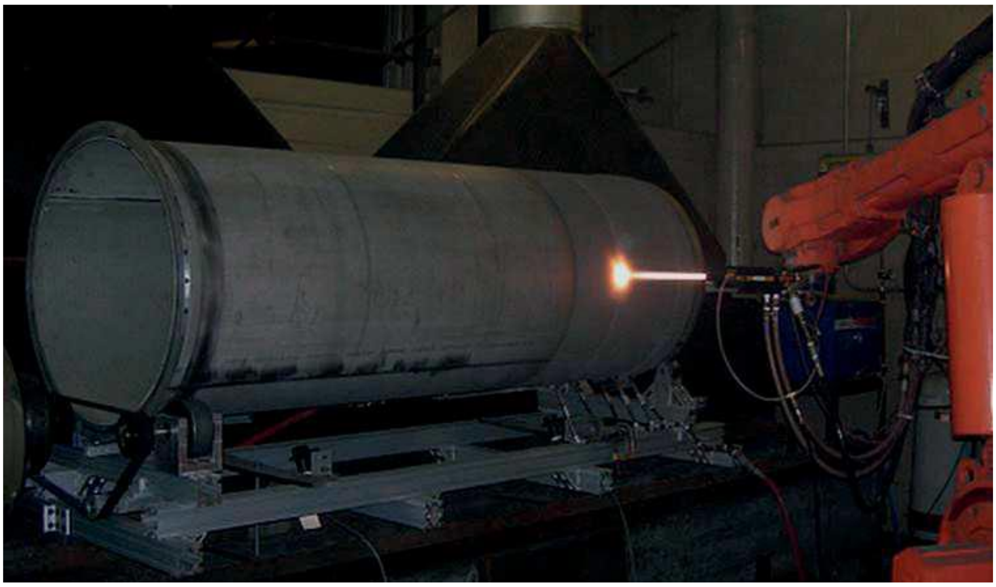

Figure 51 High Velocity Oxy-Fuel (HVOF) process is used to coat a container with SAM1651 amorphous metal with quality assurance monitoring the thickness and roughness of BMG coating

Source: Farmer, et al., 2009.

C. Diamond-Like Carbon

A range of amorphous carbon compounds that have a large portion of carbon-carbon bonds with the sp3 electron configuration make up diamond-like carbon (DLC), lending these materials similar mechanical performance of diamond. The properties of DLC films are determined by the ratio of sp3 and sp2 electron configuration of bonding and hydrogen content, as shown in Figure 52. DLC films often exhibit better mechanical properties when their sp3/sp2 ratios are high, whereas their optical and electrical properties are better when their sp3/sp2 ratios are low (Dwivedi, et al., 2011).

The excellent chemical inertness of DLC films makes them a promising coating material in corrosive environments as a physical barrier. The most attractive features of DLC films are: i) their wide range of properties that can be tailored by deposition methods with doping, ii) low cost to coat, and iii) low deposition temperature, i.e. almost any materials can be DLC coated at room temperature. Depending on the carbon source and deposition process, there are two main types of DLC films in Table 3: i) hydrogenated amorphous carbon (a-C:H) and ii) hydrogen-free tetrahedral amorphous carbon (ta-C). The a-C:H was earlier developed from hydrocarbon plasma. The hydrogen is required to tie-up the dangling bonds and to keep the carbon in sp3 bonding configuration for obtaining "diamond like" properties. The a-C:H films are relatively soft

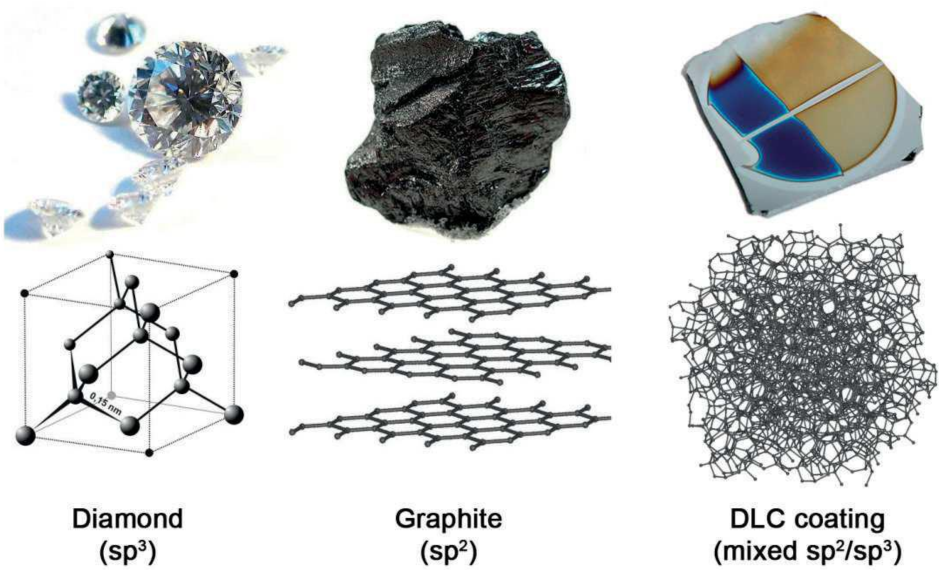

Figure 52 Structure and carbon-carbon bonding of diamond (sp3), graphite (sp2), and DLC coating (mixed sp2/sp3) are compared

Source: Safer, Smarter, and Greener, 2014

Compared to diamond, and exhibit some of the lowest friction coefficients (0.001-0.1) and wear coefficients in the dry and lubricant-free conditions (but increase considerably with humidity). Recently improved by a filtering technique, ta-C films were able to be deposited from pure carbon source with good quality at comparable growth rates of a-C:H film. Due to a predominant fraction of sp3 carbon, ta-C film exhibits high hardness and wear resistance close to those of diamond. As complement to a-C:H, ta-C shows lower friction coefficients for most surfaces (0.1–0.15) especially in a humid environment, and much higher thermal stability. The only drawback of ta-C films is their high intrinsic compressive internal stress arising from the ion bombardment for the formation of metastable sp3 bonding, which often limits the maximum thickness of an adhesive ta-C film to less than 1 μm (Robertson, 2008).

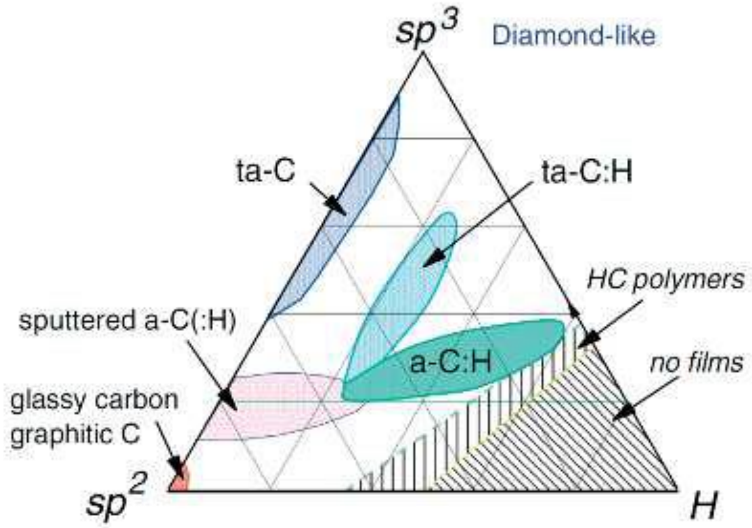

Figure 53 a-C:H, ta-C, and other types of DLC film are shown in the ternary phase diagram of the C, H system

Source: Erdemir & Donnet, 2006

In addition to carbon and hydrogen, DLC films can be doped with nitrogen (N-DLC or CNx films), silicon (Si-DLC), fluorine (F-DLC), and metal atoms (Me - DLC). Most modifications have been made to DLC are to reduce its high internal compressive stresses, to increase the adhesion between film and substrate, to decrease its surface energy for further lowered friction coefficients, or to modify its electrical properties.

Table 3 Comparison of Structure and Properties of A-C:H and Ta-C DLC ILMS with Those of Diamond and Graphite

	Sp^3 content, %	H content, %	Density, g cm^3	Hardness, GPa	Young's modulus, GPa	Fracture toughness, MPa $m^{1/2}$	Residual stress, GPa	Thermal stability, ºC
Graphite	0	0	2.267	0.2	9-15	-	-	-
a-C:H	20-60	20-50	1.2-2.2	<20	50-200	1.2-3.3	<3	<250[1], <350[2]
ta-C	70-90	<5	1.9-3.1	40-90	300-900	-	<12	<500[1], <1100[2]
Diamond	100	0	3.515	100	1144	3.4	-	<700[1], <1700[2]

* 1 oxidization temperature in air, 2 oxidization temperature in vacuum or inert gas.
Source: Robertson, 2002; Lifshitz, 1999.

Figure 54 a) Selection of automotive engine components that have been coated successfully with DLC. b) DLC (WC/C multilayer) c11oated spur gear. c) Hydrogen-free DLC coating for tools

Source: Hainsworth & Uhure, 2007

The major application for DLC is as a tough, low-friction, durable, wear- and corrosion-resistant coating material. Commercial providers provide DLC coatings with various compositions that are applied using various techniques. The automotive sector has made extensive use of DLC film as a trustworthy tri-biological coating. The uses of DLC films in the oil and gas industry can be broadened to include drilling instruments, chemical pumps or multiphase pumps, valves, thread connections, elastomer seals, and other components.

XI. SUMMARY AND OTHER POSSIBILITIES

Certain mechanical properties of these three types of advanced materials are illustrated in diagram, Figure 55, in comparison with conventional metals and ceramics. These advanced materials stand out above those conventional counterparts with enhanced hardness or strength, which is desirable for oil and gas industry. In addition, there are a few novel materials drawing attentions for their promising applications in the oil and gas production.

1. High catalytically active nanoparticles can be used as high-performance inhibitor in upstream and catalyst for chemical processes in downstream.
2. Self-assembled monolayers (SAMs) are organic molecules that have strong chemisorption to metal surface and spontaneously aligned to form a monolayer, which makes SAMs an inexpensive and versatile surface coating.
3. Concept of smart coating is similar to chromate conversion coating, which is developed with ability to “smartly” heal or release corrosion inhibitor from coating damage.
4. Shape memory alloy (SMA) could be used as critical component of safety valves or other applications trigged by temperature variation.
5. Precipitation harden able CRA provide unique combinations of strength via heat treatment and corrosion resistance. This enables them to be used for components requiring thick sections, such as tubing hangers, and complex geometries. Issues such as quality variations due to production process and limits of performance still need to be addressed in a systematic manner for these materials.
6. As a combination of different materials to produce distinct properties from each individual components, composites are expected to fulfill the functionality of 1+1>2, e.g. flexible risers or flow lines in oil and gas industry.

7. The capability of aluminum alloys in offshore drilling processes is being explored by major aluminum producer as lighter weight alternatives to steel. However, there is a need to address the susceptibility to corrosion of proprietary aluminum alloys in sour and sweet environments and develop preventive coatings or other treatments.
8. Titanium alloys have been explored as light-weight, highly corrosion-resistant alternative to CRA, ideal for applications of drilling risers or high pressure heat exchangers. The data of titanium alloy are however still limited. Increased use of titanium alloy is dependent upon the scale of availability at reduced cost.

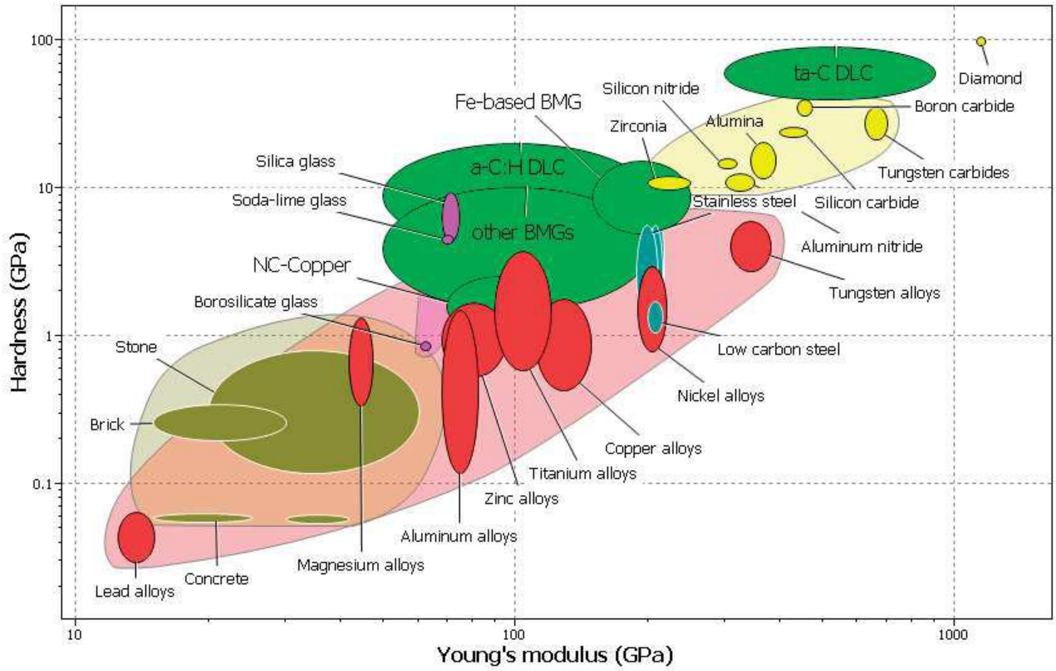

Figure 55 Hardness or yield strength is plotted against bulk elastic modulus for conventional metals, ceramics, and three types of advanced materials discussed in this section

Source: Safer, Smarter, and Greener, 2014

XII. CONCLUSION

In order to address the material challenges involved in the extraction of hydrocarbons from unconventional sources, high strength materials, such as LAS and PH-CRA, are required. The two main types of degradation that affect the alloys required for the safe and effective operation of sour, HPHT, and Arctic fields are localized corrosion and EAC. The performance of engineering alloys' macroscopic corrosion at the nano- and micro-scales can still be improved with more research. This paper compares three different types of advanced materials, DLC, BMG, and NC, to traditional metals and ceramics to highlight specific mechanical features of each type. It is desirable for the oil and gas industry that these new materials outperform more than traditional materials in terms of hardness or strength. High catalytic activity nanoparticles can operate as catalysts for chemical reactions upstream and high-performance inhibitors for upstream chemical reactions. The idea behind a smart coating is comparable to that of a chromate conversion coating, which was created with the ability to "smartly" heal or release a corrosion inhibitor from coating damage. Unique heat-treated strength and corrosion resistance are combined in precipitation hardenable CRA. For these materials, systematic solutions still need to be found for problems like performance limitations and quality inconsistencies caused by the manufacturing process. Major aluminum producers are investigating the potential of aluminum alloys in offshore drilling procedures as lighter weight alternatives to steel. The vulnerability of proprietary aluminum alloys to corrosion in sour and sweet environments must be addressed, and preventative coatings or other treatments must be developed. For applications like as drilling risers or high-pressure heat exchangers, titanium alloys have been investigated as a lightweight, highly corrosion-resistant alternative to CRA. However, there are currently only a few facts on titanium alloy.

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