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INVESTIGATION OF CORROSION RATE OF AISI 316L STAINLESS STEEL IN MALAYSIAN TROPICAL FRUIT JUICE ENVIRONMENT USING FACTORIAL EXPERIMENTAL DESIGN

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BACHELOR OF MANUFACTURING ENGINEERING TECHNOLOGY (PROCESS AND TECHNOLOGY) WITH HONOURS

2023

Faculty of Mechanical and Manufacturing Engineering Technology

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A thesis submitted
in fulfillment of the requirements for the degree of
Bachelor of Manufacturing Engineering Technology (Process and Technology) with Honours

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Mechanical and Manufacturing Engineering Technology

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2023

DECLARATION

I declare that this Choose an item. entitled "Investigation of Corrosion Rate of AISI 316L Stainless Steel In Malaysian Tropical Fruit Juice Environment Using Factorial Experimental Design" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :

Name : Nazirah Aqilah Binti Yunadi

Date : 20/01/2023

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APPROVAL

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the Bachelor of Manufacturing Engineering Technology (Process and Technology) with Honours.

Signature :

Supervisor Name : Dr. Yusliza Binti Yusuf

Date : 20 Jan. 2023

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DEDICATION

I would like to dedicate my work to my beloved father, Mr. Yunadi Bin Yusak and my precious mother, Mrs. Masnom Binti Abu, who have been a greater supporter and provided moral, emotional, spiritual and financial support and also strength when I wanted to give up. I'd also like to thanks to my beloved fiance, Yusra Fitri Bin Yusoff and all my friends for your helpful advice and encouragement throughout this study.

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ABSTRACT

316L stainless steel is commonly used in kitchen utensils. This is due to its outstanding mechanical properties and great corrosion resistance. However, it is critical to keep a careful focus on what happens when stainless steel items are used, especially since those ingredients are often chosen by the population for their daily diet. Malaysians regularly consume fruits as juice or as a culinary element. As a result, it is critical to examine the effect of corrosion resistance on 316L stainless steel kitchen utensils in Malaysian common fruit juice medium. Over a 40-days period, measurements will be performed at 8-days intervals to explore the influence of corrosion resistance quality of 316L stainless steel on chosen Malaysian tropical juices (lime, tamarind, and pineapple) by using weight-loss technique. To design the experiment and analyse the results, the experimental design (DOE) and analysis of variance (ANOVA) methods were utilised. In order to pick the optimal material, it is necessary to analyse the influence of each variable and its interaction on stainless steel corrosion. The highest corrosion rate is 0.4775mmpy observed in tamarind juice, followed by lime juice and the lowest corrosion rate is 0.0075mmpy in pineapple juice. Moreover, Corrosion rates differ depending on time and environment. Where, the corrosion rates are highest during the first week of the experiment and gradually decrease as the experiment progresses. The generalised model equation was obtained to predict the corrosion rate of stainless steel in a similar environment.

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ABSTRAK

Keluli tahan karat 316L biasanya digunakan dalam peralatan dapur. Ini disebabkan oleh sifat mekanikalnya yang luar biasa dan rintangan kakisan yang hebat. Walau bagaimanapun, adalah penting untuk mengekalkan tumpuan yang teliti pada perkara yang berlaku apabila barangan keluli tahan karat digunakan, terutamanya kerana bahan-bahan tersebut sering dipilih oleh penduduk untuk diet harian mereka. Rakyat Malaysia kerap mengambil buah-buahan sebagai jus atau sebagai unsur masakan. Akibatnya, adalah penting untuk mengkaji kesan rintangan kakisan pada peralatan dapur keluli tahan karat 316L dalam medium jus buah-buahan biasa di Malaysia. Dalam tempoh 40 hari, pengukuran akan dilakukan pada selang 8 hari untuk meneroka pengaruh kualiti rintangan kakisan keluli tahan karat 316L pada jus tropika Malaysia terpilih (limau, asam jawa dan nanas) dengan menggunakan teknik penurunan berat badan. Untuk mereka bentuk eksperimen dan menganalisis keputusan, kaedah reka bentuk eksperimen (DOE) dan analisis varians (ANOVA) telah digunakan. Untuk memilih bahan yang optimum, adalah perlu untuk menganalisis pengaruh setiap pembolehubah dan interaksinya terhadap kakisan keluli tahan karat. Kadar kakisan tertinggi ialah 0.4775mmpy diperhatikan dalam jus asam jawa, diikuti oleh jus limau nipis dan kadar korosin terendah ialah 0.0075mmpy dalam jus nanas. Selain itu, kadar Kakisan berbeza bergantung pada masa dan persekitaran. Di mana, kadar kakisan adalah paling tinggi semasa minggu pertama percubaan dan secara beransur-ansur berkurangan apabila percubaan berjalan. Persamaan model umum diperolehi untuk meramalkan kadar kakisan keluli tahan karat dalam persekitaran yang serupa.

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In the name of Allah, the Most Merciful and Gracious

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Last but not least, I want to express my heartfelt gratitude to my beloved parents for their unending support, love, and prayers. My heartfelt gratitude also goes to my family for their understanding and patience. Finally, I'd like to express my appreciation to everyone who helped, supported, and inspired me to proceed my studies.

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LIST OF SYMBOLS AND ABBREVIATIONS

ρ - Density
ANOVA - Analysis of Variance
AISI - American Iron and Steel Institute
AS - Artificial Sliva
A - Expossure Area
ASTM - American Society for Testing and Material
BCC - Body Centered Cubic Crystal Structure
C - Carbon
Cr - Chromium
Cu - Copper
CO_2 - Carbon Dioxide
Cb - Columbium
DOE - Design of Experiment
Fe - Iron
GDP - Gross Domestic Product
H - Hydrogen
H^+ - Hydrogen ion
k - Corrosion rate unit conversion
Mn - Manganese
Mo - Molybdenum
mm - Milimter
mmpy - Milimter Per Year
N - Nitrogen
Ni - Nickel
Nb - Niobium
PH - Precipitation of harrdenable alloy
pH - Potential of Hydrogen
P - Phosphorus
Ra - Roughness average

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Rq - Root mean square
Rz - Different between highest peak and deapest valley
S - Sulfur
SCC - Stress Corrosion Cracking
Se - Selenium
Si - Silicon
SEM - Scanning Electron Microscope
t - Immersion time
Ta - Tantalum
Ti - Titanium
TXRF - Total Reflection X-ray Fluoresence
UNS - Unified Numbering System
USA - United State
w - Weight loss of sample

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Stainless steels are a class of iron-based alloys containing different elements, such as nickel, chromium, molybdenum, nitrogen, manganese, etc. Stainless steels especially 316L type have high corrosion resistance and greater mechanical properties that make it suitable to use in food industries (Zaffora et al., 2021). Stainless steels 316L types are widely used for utensils such as commercial cookers, cutleries and process equipment of fruit juice due to their characteristics which are food flavour protection and easy to clean with minimum maintenance (Subbaiah & Rao, 2012).

Even though, stainless steels are suitable in food industry or use as utensils, it also can be highly aggressive in the acidity environment which can lead to corrosion phenomena. The longer stainless steels immerse in acidic media can lead to passive corrosion. Corrosion of stainless steel will release ions or metal particle which possibly risk for the user’s health (Zaffora et al., 2021).

In addition, in food industries the production process can be extremely corrosive to the equipment materials that lead to the release of metals as ions, particles, or complexes that can affect the final quality of the product. As a consequence, selecting equipment materials is critical to ensure that the food or drinks are not contaminate. It is important to have standard conditions in which testing stainless steel in contact with the intended foods (Zaffora et al., 2021). Therefore, 316L stainless steels are suitable to be used in food

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industries due to low carbon and high nickel and chromium content (Subbaiah & Rao, 2012). The elements such as nickel and molybdenum have a strong influence on formability and increased corrosion resistance of austenitic stainless steel. Nickel is used to create the austenitic structure and also responsible for its toughness and strength at high and low temperature. Nickel also significantly improves oxidation and corrosion resistance. (Subbaiah & Rao, 2012).

Malaysia is known as a tropical country which produce million tons of different variety of tropical fruits every year and Malaysian tend to consume by drink as juice (Salleh, 2010). The corrosive properties of the fruits juice such as pineapple and orang, which are commonly consumed by the world population whether fresh or processed, have been examined. This study will concentrate on the influence of corrosion resistance qualities of 316L stainless steel on selected Malaysian tropical juices, and it will employ a factorial experimental design approach to further refine the experiment.

1.2 Problem Statement

Corrosion is a type of reaction of material with the environment. Corrosion will begins at the surface of a material and occurs due to the spontaneous tendency of a material to return to their thermodynamic stable state (Ahmad et al., 2012). Corrosion is a problem in a lot of industries and is even a greater challenge in the food processing industries, where in addition to the loss of production time for maintenance and risk of equipment failure, there exists the additional risk of product contamination by corrosion products which may result in food poisoning (Ofoegbu et al., 2011).

Stainless steels especially 316L stainless steels are suitable as a kitchen utensil due to present of nickel which greatly improves resistance to oxidation and resistance (Subbaiah & Rao, 2012). However, stainless steels also can be highly aggressive when it exposed to the environment with the presences of chloride ions and the acidic environment can lead to corrosion phenomena. Longer immersion in acidic media can lead stainless steels to passive corrosion. (Zaffora et al., 2021).

Malaysia is well known as a tropical country which has variety of tropical fruits such as this eight major fruits given more emphasized for domestic as well as for export markets which are pineapple, papaya, watermelon, starfruit, banana, citrus, mangosteen and durian (Salleh, 2010). Malaysian often consume the fruits as juice or as cookery ingredients. However, there has been little research on the corrosion resistance properties of 316L stainless steel, which is accessible as cooking utensils and dining accessories in Malaysia, towards such tropical fruits. Thus, the purpose of this study is to investigate the corrosion resistance properties of 316L stainless steel in Malaysian tropical fruit juice.

1.3 Research Objective

The aim of this study is to investigate the corrosion rate of AISI 316L stainless steel in Malaysian tropical fruit juice environment by using factorial experimental design (DOE). Specifically, the objectives are as follows:

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i) To design the experimental matrix for single replicate factorial design with factor such as media and duration for corrosion analysis.

ii) To examine the corrosion rate of AISI 316L stainless steel in various Malaysian tropical fruit juices media by using weight loss technique.

iii) To analyse the corrosion rate of AISI 316L Stainless steel in various Malaysian tropical fruit juice media by using ANOVA method.

1.4 Scope of Research

The scope of this research are as follows:

The experiment was set up in the material science laboratory UTeM where AISI 316L stainless steel specimen with thickness 0.9 mm was used. The raw material will undergo surface roughness testing before cut to 75 same size sample (50mm x 20mm) by using laser cutting machine. The prepared samples were stored in desiccator to avoid atmospheric corrosion. To start the experiment, each sample was rinsed with three pumps of distilled water before drying process which by using dry clean cloth. Three (3) Malaysian tropical fruits that used for this experiment were commonly consumed by Malaysian citizen, either as juice or in cooking process which directly contact to the kitchen utensils namely pineapple, lime and tamarind. Those tropical fruits were obtained from the local supermarket. The pineapple was blended by using blender and filtered to get the juice. For tamarind, it is made into juice by adding tap water and then filtered. For lime, the limes are squeezed and filtered to get the juice only. All of the juices were filtered by using cloth filter to make it fibre free. Then each of the juice were measured to 1500 ml and collected in the glass container as the media for the experiment. The corrosion rate of AISI 316L stainless steel in various Malaysian tropical fruit juices was determine by using weight loss technique. Each of the specimen is weighed using the same digital scales each time the weighing process is performed. It is necessary to use the same balance during the experiment as each balance may be calibrated differently. The exposure periods were a total of 40 days with measurements taken at an interval of 8 days, respectively. Minitab software was used to do the analysis of variance (ANOVA) on the effect of different media on the corrosion rate of 316L Stainless Steel.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

At the early use of stainless steel, there were limited to a few applications such as cutlery, gun barrels, nitric acid tanks, etc. As manufacturers began to use it for a wider range of applications as different compositions were created, which made stainless steels highly corrosion resistant even at elevated temperatures, and gave it high strength. Stainless steels are now increasingly popular and a part of everyone's lives, as well as being used in a wider range of industries (Dexam, 2019; Subbaiah & Rao, 2012) Stainless steel utensils and equipment, such as commercial cookers, pasteurizers, transfer bins, milk, soft drink, and fruit juice processing equipment, and other specialist equipment, play an important role in our daily life. Besides, restaurants, public kitchens, schools, local health clinics, and other establishments use stainless steel goods to improve hygienic elements of service (Ivy Ho, 2018; Kinnek Knowledge Team, 2018; Subbaiah & Rao, 2012).

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Stainless steels contain between about 16% – 25% chromium, and they can also contain nitrogen in solution, both of which contribute to their high corrosion resistance. Nickel also helps to stabilize their austenitic structure. Therefore, stainless steels have been used even more widely in many industries (McGuire, 2001). Their high corrosion resistance and their superior mechanical properties make stainless steels suitable materials especially for food industries (Zaffora et al., 2021). Moreover, because of the presence of chlorides ions in varying concentrations and the acidity of the foodstuffs, the normal working environment for stainless steels in the food industry could be highly aggressive, potentially leading to corrosion events. In acidic conditions with no halides in solution, corrosion mechanism predicts protective passive film breakdown with generalized (uniform) corrosion practically regardless of stainless steels grade (Zaffora et al., 2021).

However, Corrosion of metals and their alloys when exposed to the action of acids in industrial processes are recognized as major contributions to infrastructure deterioration. In the food industry, these consequences are very important. Food substances, like other organic and inorganic substances, are becoming increasingly corrosive, resulting in considerable degradation of equipment materials and the maintenance or replacement of items that have been lost or contaminated as a result of corrosion reactions (Oladele & Okoro, 2011).

2.2 Stainless Steel

Stainless steels are made from some of basic elements found in the earth’s crust such as iron ore, chromium, silicon, nickel, carbon, nitrogen, and manganese (Subbaiah & Rao, 2012). Stainless steel is an iron alloy with at least 10.5% of chromium. Chromium element produces a thin layer of oxide on the surface of the steel identified as the passive layer to avoids the surface from corroding further and allows it to heal when the oxygen is presence. When the chromium content increasing it will gives an increased to corrosion resistance (Yahia, 2016). Stainless steel also contains different proportions of silicon, carbon and manganese. Other elements, such as molybdenum and nickel, may be added to provide additional benefits including enhanced formability and corrosion resistance (Yahia, 2016). Stainless steels are categorized into five basic types according to their metallurgical structure. They are martensitic stainless steels, precipitation hardening stainless steels,

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duplex stainless steel, austenitic stainless steel and ferritic stainless steel. Figure 2.1 shows the classification of stainless Steels.

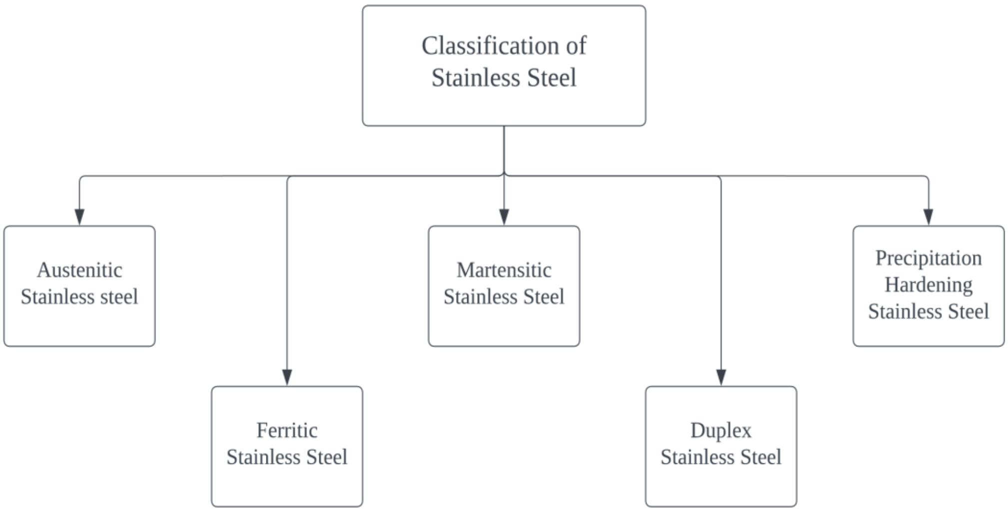

Figure 2.1 Classification of Stainless Steel

Moreover, stainless steel has a high corrosion resistance due to the creation of a very thin (1 - 3 nm) chromium oxide or hydroxide-rich passive coating, whose composition, thickness, and protective function can change with time and the environment to which the steel is exposed. Stainless steel is a good material for the food industry because of its great corrosion resistance and superior mechanical qualities (Zaffora et al., 2021).

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2.2.1 Types and Classification of Stainless Steel

Stainless steels can be divided into five classification. Four are based on the characteristic microstructures which are ferrite stainless steels, austenitic stainless steels, duplex stainless steels and martensitic stainless steels. The fifth is the precipitation hardenable (PH) alloy, which is based on the type of heat treatment used rather than microstructure. All stainless steels have high resistance to corrosion which improves with high Chromium content. Addition of Nickel and Molybdenum raises corrosion resistance making stainless suitable for more aggressive environments (Y. A. E. Ahmed, 2014).

Each alloying element has a significant impact on the properties of the steel. The combined effect of all alloying elements and, to a lesser extent, impurities determines the property profile of a steel grade. Table 2.1 lists the stainless steel grades that are commonly referred to by registered trademark designations (Moore, 2013).

Table 2.1 Stainless steel grades registered trademark (Moore, 2013)

Type	Clasisication	Registered trademark.
Austenitic stainless steel	301, 301L, 301LN	High strength for roll formed structural componenet
	302HQ	Low work hardening rate grade for cold heading fasteners
	303, 303Se	Free-machining bar grades
	304, 304L, 304H	Standard 18/8 grades
	310, 310S, 310H	High temperature resistance grades
	316, 316L, 316H	Improved resistance to pitting corrosion in chloride environments
	321, 321H, 347	Stabilised grades for heavy section welding and high temperature application
	253MA (S30815)	High temperature resistance grades
	904L	High resistance to general corrosion, pitting and stress corrosion craking
Ferritic stainless steel	AtlasCR12	Utility steel resistance to wet abrasion and mild corrosion
	AtlasCR12Ti	Utility steel resistance to wet abrasion and mild corrosion – weld stabilised
	409	Automotive exhaust grade – weld stabilised
	430, 430F	Resistant to mildly corrosive environment

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	F18S / 439	Resistant to mildly corrosive environment – weld stabilised
	F20S	A ferritic alternative to grade 304/304L – weld stabilised
	S18MS / 444	A ferritic alternative to grade 316/316L – weld stabilised
Duplex stainless steel	2101	Lean duplex – economical alternative to 304 and 316
	2304	Duplex alternative to grade 316
	2205	Standard duplex stainless steel – high resistance to pitting and stress corrosion
	2507	Super duplex with very high resistance to pitting and stress corrosion
	2507Cu	Super duplex with very high resistance to pitting and stress corrosion
Martensitic stainless steel	410	Standard martensitic grade for low-duty hardened application
	416	Free-machining bar grade
	420	Higher hardness martensitic grade for cultury, cutting tool and dies
	431	High hardness and toughness grade, primarily for shafting
	440A, 440B, 440C	Very high hardness grades used in cutting tools
Precipitation hardening stainless steel	630	(17-4PH) High strength shafting grade

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Ferritic stainless steels (Figure 2.2) are type of stainless steels 400 series which are straight-chromium stainless steels that contain approximately 14 and 27 percent chromium and very little carbon (typically less than 0.10 percent). At normal temperature, the steels' crystalline structure is ferritic (BCC = body centered cubic crystal structure). These alloys purposely low in nickel contents, because nickel makes the steels austenitic (Yahia, 2016). Ferritic steels are better suited for general and high-temperature corrosion applications than for high-strength applications. Ferritic steels are chosen for their stress corrosion cracking resistance. High-chromium steels with molybdenum additives can withstand harsh environments like sea water. The ferritic stainless steels are the lower-cost stainless steels, because they contain less alloys, and do not contain nickel (nickel is more expensive than chromium) (Yahia, 2016). Ferritic stainless steels are magnetic, have good ductility and resistance to corrosion and oxidation. Type 430 is the general-purpose stainless steel in ferritic group (Garlick, 2015).

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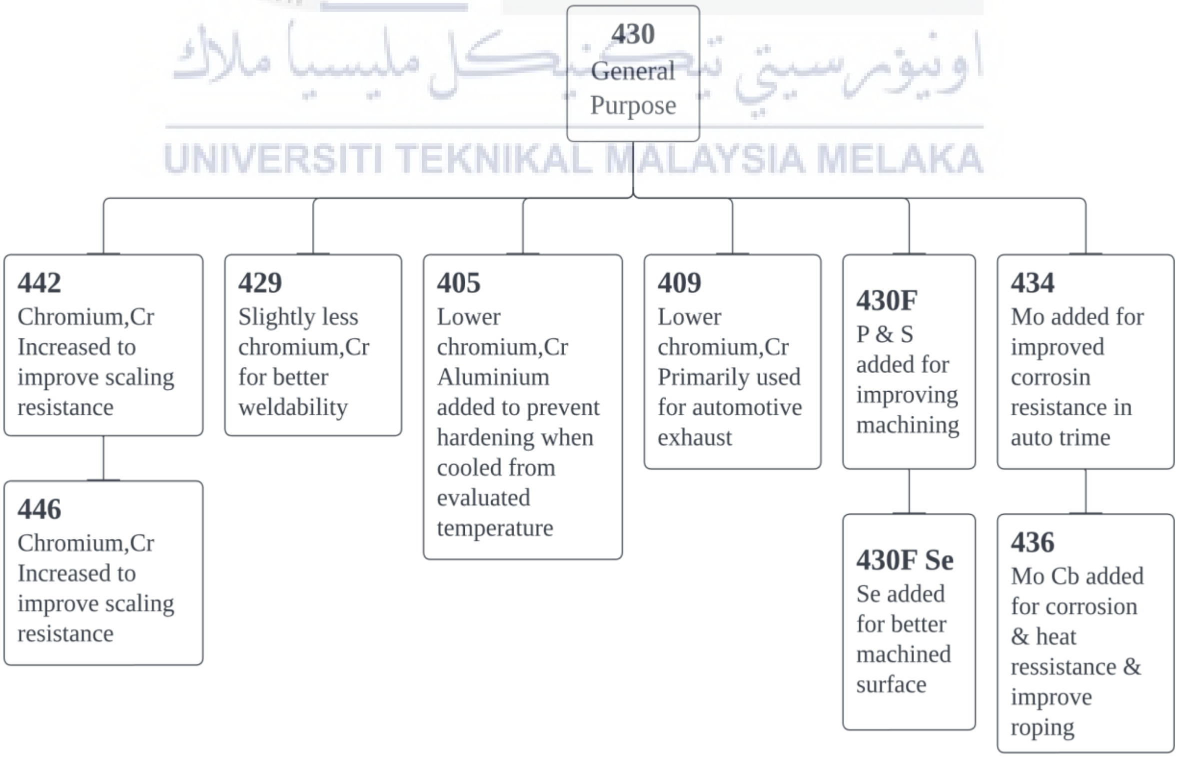

Figure 2.2 Families of Ferritic Stainless Steel

Austenitic stainless steels are metallic non-magnetic allotrope of iron with an alloying element, commonly known as gamma phase iron (Subbaiah & Rao, 2012). Austenitic stainless steels containing chromium and nickel are known as 300 series types while the alloy that containing chromium, nickel and manganese known as 200 series type(Garlick, 2015). When alpha iron (ferrite) is heated from 912°C to 1,394°C, it undergoes a phase transition from body-centered cubic to face-centered cubic, resulting in gamma iron, commonly known as austenite (Subbaiah & Rao, 2012).

Austenitic stainless steels contain chromium and nickel to stabilize the austenitic microstructure. Because of their stable austenitic microstructure, austenitic stainless steels have great formability, weldability, ductility, excellent toughness even at cryogenic temperatures, and a non-magnetic characteristic (Subbaiah & Rao, 2012). There are 30 compositional variations in the standard austenitic stainless steels, and a summary of the family relationships is shown in Figure 2.3 (Yahia, 2016). Type 304 also frequently known as 18-8 stainless steel is the most widely used alloy in austenitic group. Type 304 has a nominal composition of 18% of chromium and 8% of nickel (Garlick, 2015).

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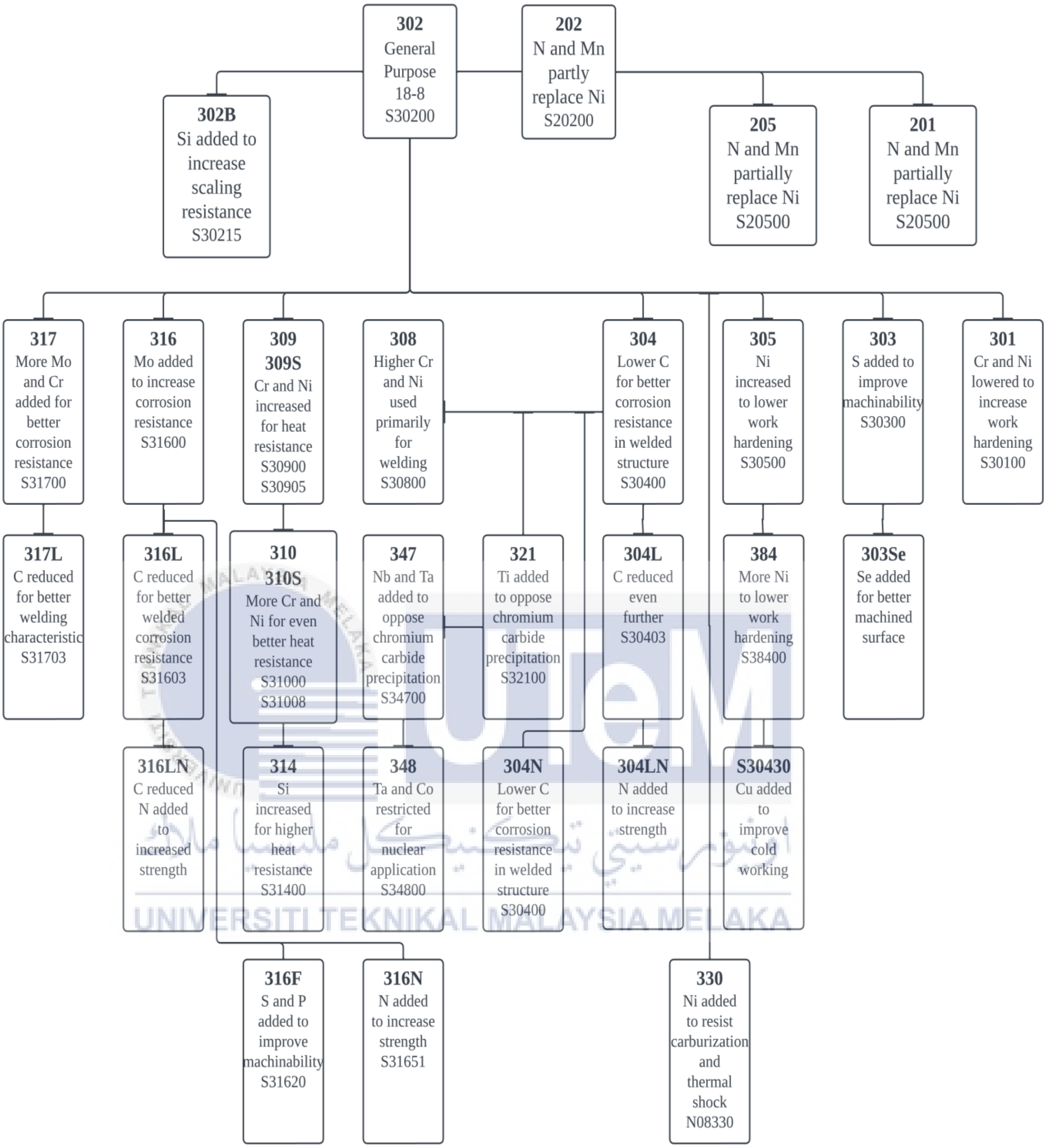

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Figure 2.3 Austenitic Stainless Steel Families

Duplex stainless steels are alloys with an annealed structure that contains roughly the same amount of austenitic and ferrite. Although not officially defined, it is generally accepted that the lesser phase will represent for at least 30% of the total volume (Garlick, 2015). Duplex stainless steels contain high amount of chromium (18% -28%) and moderate amount of nickel (4.5% – 8%) as compared to austenitic steels as major alloying elements (Y. A. E. Ahmed, 2014). The microstructure of these steels is roughly 50 % ferritic and % austenitic. They may have more strength than ferritic and austenitic steels, but less toughness than austenitic stainless steels (Yahia, 2016). The original alloy of duplex is AISI-329 (7-Mo) contains Cr, Mo, and sufficient Ni to provide the desired balance of both ferrite and austenite. More recent versions like 7-Mo Plus (S32950), Ferralium (S32550), and 2205 (S31803) alloys contain Nickel and exhibit different ferrite/austenite balances (Y. A. E. Ahmed, 2014).

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Martensitic stainless steels are straight-chromium 400 series types (Figure 2.4) that are harden-able by heat treatment (Garlick, 2015). They contain 12% Chromium and a moderate Carbon content. These stainless steels have good ductility and toughness, which decrease, as its strength increases (Y. A. E. Ahmed, 2014; Eric Partington, 2006). Martensitic stainless steels are resist corrosion in mild environment (Garlick, 2015). Application of martensitic stainless steels are usually in cutlery, aerospace, and general engineering applications (Y. A. E. Ahmed, 2014). Some of these stainless steels can be heat treated to tensile strengths exceeding 200,000 psi (1379MPa). Type 410 is the common type used in the martensitic group.

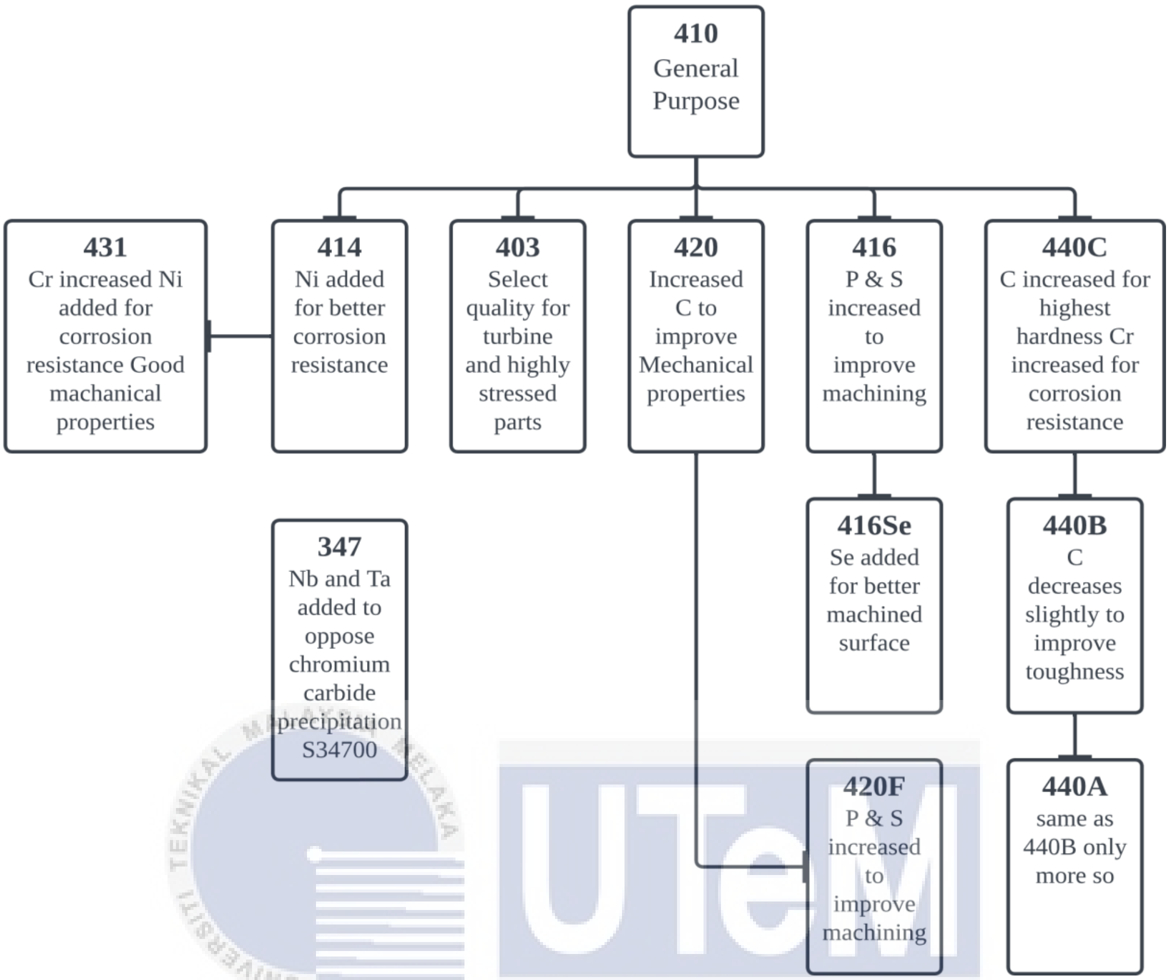

Figure 2.4 Families of Martensitic Stainless Steel

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Precipitation hardening (PH) stainless steels contain chromium and nickel as major alloying elements so it’s called as chromium-nickel types. By adding components like copper, niobium, and aluminium to the steel, it can develop extremely high strength. Coherent alloy precipitates are tend to formed by these elements (Yahia, 2016). They can hardened by solution threating and aging to high strength (Garlick, 2015). The most well-known PH- alloy is the martensitic Custom 630. It contains Chromium, Cr and Nickel, Ni, as do all PH stainless steels, with Copper, Cu for age hardening and Niobium, Nb for stabilizing carbon (Y. A. E. Ahmed, 2014).

2.2.2 Austenitic Stainless Steel

Austenite is a metallic non-magnetic allotrope of iron with an alloying element, commonly known as gamma phase iron. When alpha iron (ferrite) is heated from 912°C to 1,394°C, it undergoes a phase transition from body-centered cubic to face-centered cubic, resulting in gamma iron, commonly known as austenite (Subbaiah & Rao, 2012). At room temperature, austenitic stainless steels exhibit an austenite microstructure which called as face cantered cubic crystal structure (FCC). A popular austenitic stainless steel such as 304 type also called as 18/8 stainless steel because it contains nominally 18% chromium, Cr and 8% nickel, Ni (Yahia, 2016).

Austenitic stainless steels are all primarily chromium-nickel alloys. The chromium content ranges from 15% - 24%, while the nickel content ranges from 3% - 22%. The total chromium and nickel content in these steels is at least 23%. (Yahia, 2016). Because of their stable austenitic microstructure, austenitic stainless steels have good formability, weldability, ductility, excellent toughness even at cryogenic temperatures, and a non-magnetic property. Because of the high percentage of chromium and nickel content, it is also the most corrosion resistant of all grades. As a result, austenitic stainless steels have become the most popular and widely used of all Stainless Steel groups today (Subbaiah & Rao, 2012).

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Austenitic stainless steels are derived from the 200 and 300 series general-purpose alloys. The type 302 subtypes are chromium-nickel stainless steels, series 300, with specific compositional variations to impart specific properties. Better weldability, increased strength, increased heat resistance, improved corrosion resistance, and improved machinability, for example, resulted in type 304 with improved weldability and a lower tendency toward carbide precipitation by lowering the carbon content to 0.08% maximum. The 300 series is the most widely used grade worldwide, based on the classic 18% chromium and 8% nickel stainless steel. Nickel is used to form the austenite structure, which accounts for its high toughness (impact strength) and strength at both high and low temperatures. Nickel also greatly improves resistance to oxidation and corrosion (Subbaiah & Rao, 2012).

There are also 'L' and 'H' sub-grades in the 300 series grades. The 'L' type grades are designed to be more corrosion resistant. The letter 'L' denotes low carbon, as in 304L and 316L, which are both around 0.03% carbon. This is only used for welding. The 'H' grade contains between 0.04% - 0.10% carbon. It is recommended when the material will be exposed to high temperatures. The most commonly used grade is 304 which has a 18% chromium content and 8% of nickel content. The most common grade after type 304 is 316, which is the standard molybdenum-bearing grade among austenitic stainless steels (Subbaiah & Rao, 2012). Molybdenum in grade 316 provides better overall corrosion resistance than molybdenum in grade 304, with higher resistance to pitting and crevice corrosion in chloride environments (Yahia, 2016). It has a chromium content ranging from 16% -18% and a nickel content ranging from 11% - 14%.

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Chemical processing, food and dairy processing, beverage processing, aircraft manufacturing, nuclear reprocessing plant construction, household appliances, and other industries use the 300 series grades (Subbaiah & Rao, 2012). Grade 316L is a low carbon version of 316 that is resistant to sensitization (grain boundary carbide precipitation). As a result, it's commonly found in heavy gauge welded components (over about 6mm). The price difference between 316 and 316L stainless steel is usually negligible. The austenitic structure also provides these grades with exceptional toughness, even at cryogenic temperatures

(Yahia, 2016). Stainless steel 316 also corresponds to the following standard designations and specifications (Table 2.2).

Table 2.2 Standard designation and specification of Stainless Steel 316 (Aalco, 2022)

Euronorm	UNS	BS	En	Grade
1.4401	S31600	316S31	58H	316
1.4404	S31603	316S11	-	316L
-	S30609	316S51	-	316H
1.4571	-	320S31	-	316Ti

The type 202 of chromium-nickel-manganese stainless steels is limited to only two types, series 200, and was designed to replace nickel, a costly alloying element, with nitrogen and manganese. (Yahia, 2016). The 200 series comes in several grades, including 201, 202, and 205. The most durable grades are 201 and 202, which contain 3.5% - 6.0% nickel, compared to 8.0% - 10.5% nickel in type 304, the most widely used 300 series grades, as shown in Table 2.3. Other 200 series grades, such as Type 205, use as little as 1% to 1.75 percent nickel. The 200 series has a lower material cost than the 300 series, has better formability (ductility), is stronger and harder due to more nitrogen and manganese, and has a 30% higher yield strength than 304 grade and non-magnetic stainless steels. (Subbaiah & Rao, 2012).

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Table 2.3 Registered grades of 200 series chemical composition (Subbaiah & Rao, 2012)

Grade		*Chemical composition (wt%)*			
AISI	*UNS*	*Cr*	*Ni*	*Mn*	*N*
304	S30400	18.0 – 20.0	8.0 – 10.5	2.0 max	0.10 max
201	S20100	16.0 – 18.0	3.5 – 5.5	5.5 – 7.5	0.25 max
201	S20200	17.0 – 19.0	4.0 – 6.0	7.5 – 10.0	0.25 max
205	S20400	16.5 – 18.0	1.0 – 1.75	14.0 – 15.5	0.32 – 0.40

The 200 series grades are very popular in China and Southeast Asia. The 200 series austenitic stainless steels were developed in the early 1930s. Because of the rise in nickel prices in the 1950s, its use increased (Subbaiah & Rao, 2012). This steel family is now widely produced and consumed in Asia. Because of their lower corrosion resistance, 200 series stainless steels have a narrower range of applications than 300 series steels. It should not be used in chemical environments, but it has found its way into many household items (Bell, 2020). These can be found in deep drawn kitchen equipment, liquid gas storage vessels, trailer frames, industrial strapping, railway rolling stock, furniture, bins, coal handling equipment, and other application (Subbaiah & Rao, 2012).

2.2.3 Application of Stainless Steel 316 in Food Industries

Austenitic stainless steels are widely used in a variety of industries due to their excellent mechanical properties and corrosion resistance. Initially, stainless steels were only used in gun barrels, cutlery, and nitric acid tanks. As the industry discovered the full potential of these corrosion resistant alloys, new compositions were developed to fulfil the needs for greater corrosion resistance, higher strength levels, different fabrication characteristics, and resistance to elevated temperatures. (Y. A. E. Ahmed**,** 2014**).**

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The 300 series grades have a wide range of applications, including chemical processing equipment, food and dairy equipment, beverage equipment, aircraft equipment, nuclear reprocessing plants, household appliances, and so on (Subbaiah & Rao, 2012). Stainless steels of type 316 were originally designed for use in paper mills. However, due to their superior properties, such as those listed below, 316 stainless steels are commonly used in a variety of industries (Aalco, 2022):

- Food processing equipment

- Brewery equipment
- Chemical and petrochemical equipment
- Laboratory benches & equipment
- Coastal architectural paneling
- Coastal balustrading
- Boat fittings
- Chemical transportation containers
- Heat exchangers
- Mining screens
- Nuts and bolts
- Springs
- Medical implants

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Furthermore, the addition of molybdenum to stainless steel 316 improves general corrosion and chloride pitting resistance. It also has increased creep, stress-to-rupture, and tensile strength at high temperatures up to 120°F (38°C). AISI 316L is a technologically important stainless steel that is widely used in a variety of industries due to its high temperature corrosion resistance (Buscail et al., 2008; Sandmeyer, 2014). Furthermore, 316 or 316L stainless steels are resistant to pitting corrosion in phosphoric and acetic acid. In the food and pharmaceutical processing industries, stainless steel is used to handle heated organic and fatty acids in order to prevent product contamination. Stainless steels 316 or 316L are particularly resistant to high levels of chloride or sulphur dioxide in the operating environment, making them ideal for sulfur-containing applications such as those found in the pulp and paper industry. Stainless steels 316 are also suitable for the storage of white wines, salty foods, and aggressive media such as the pectin used in jam-making. (Ofoegbu et al., 2011; Sandmeyer, 2014).

Austenitic steel grades, such as AISI 304 and AISI 316, which contain 16%-20% Chromium and 8%-14% Nickel, are the most commonly used for food applications. Nickel alloying improves corrosion resistance, resulting in slower metal release kinetics (Dalipi et al., 2016). Stainless steel is commonly used in applications such as cookware, kitchen utensils, and cutlery. This is due to its durability, corrosion resistance, and lack of effect on food flavour when used for food storage or production. Foods with a high acidity level will not harm you due to your resistance level (McMullen, 2018).

2.2.4 Advantages and Limitation of Stainless Steel 316

Commercial cookers, pasteurisers, transfer bins, milk, soft drink, and fruit juice processing equipment, and other specialised equipment made of stainless steel play an important role in our daily activities. Stainless steel products, among other places, help to improve hygienic aspects of service in restaurants, public kitchens, schools, and local health centres (Subbaiah & Rao, 2012). Stainless steels are commonly thought to be safe for human health and are used in applications where safety and cleanliness are important, such as cookware, where all pots were washed with tap water and a common dishware detergent, simulating a home scenario (Guarneri et al., 2017).

Stainless steels offer numerous advantages, including ease of cleaning with little maintenance, good corrosion resistance, durability, economy, food flavour protection, and sanitary design. Another significant benefit of stainless steel is its environmental friendliness. It has a much longer life than mild steel and can be completely recycled.

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Because of its durability, stainless steel is commonly used in commercial kitchens and food processing plants. (Dexam, 2019; Ivy Ho, 2018; Kinnek Knowledge Team, 2018; Subbaiah & Rao, 2012):

- It can withstand shock and abrasive conditions in kitchens and food processing facilities.
- It is simple to clean and can withstand multiple washings with the various chemicals and detergents used to meet public health requirements.
- It is unaffected by alkalis and acids found in milk, cooked foods, vegetables, and dietary additives.

Austenitic stainless steels have good ductility and toughness at cryogenic temperatures, and cold working can significantly harden them. Work hardening and corrosion resistance are determined by the alloy content, which ranges from good to exceptional (Y. S. Ahmed, 2014). Type 316 contains slightly more nickel and 2-3% molybdenum than Type 304, making it more corrosion resistant, especially in chloride environments where pitting is a problem. Type 316 was developed for use in sulfite pulp mills due to its resistance to sulfuric acid compounds. However, it is now used in the process industries to handle a wide range of chemicals (Garlick, 2015).

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The unique composition of 316 stainless steel improves performance in a variety of areas. 316 stainless steel has excellent chloride resistance (St, 2021). Corrosive salts can be found in a wide range of locations around the country. In addition to coastal areas, sea sprays, and salt in rain water, many areas of the country that use de-icing salts on roadways have high chloride exposure. Salt-laden roadways in northern climates can produce even more salt deposits than coastal areas. De-icing salts are carried into the air by dust and road mist, allowing them to travel great distances from busy roads and deposit on nearby objects like buildings, external furniture, lamp poles, and so on (St, 2021).

Furthermore, due to the addition of molybdenum, stainless steels 316 have a high resistance to corrosive chemicals, including acetic, sulfuric, and sulphurous acids, as well as various industrial chemicals and solvents. These corrosive process chemicals are used in the production of a variety of products, including inks, textiles, photographic chemicals, paper, textiles, rubber, and bleaches. Furthermore, stainless steel 316 is more resistant to cracking and pitting. Because stainless steel 316 has a lower risk of stress corrosion cracking, better creep resistance, and better resistance to pitting and crevice corrosion (St, 2021). Besides, stainless steels 316 also have excellent cleanability and exceptional resistance to both high and low temperatures, making this stainless steel well suited for use in a variety of industries such as food processing, kitchen or restaurant, architecture, pharmaceutical or biopharmaceutical manufacture, ovens, heat exchangers, marine, and hospitals (Jornitz, 2019).

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Despite the fact that stainless steels have higher corrosion resistance and superior mechanical properties, making them suitable materials for food industries, there are a few limitations to using stainless steels. Stainless steels are constantly in contact with food in the food and beverage industries, which can cause corrosion on food processing equipment due to the acidic content of the food or beverages (Hamzat et al., 2020; Zaffora et al., 2021).

To reduce metal diffusion in foods, stainless steels are frequently coated with a surface coating. Indeed, if metal ions are not covered, they can diffuse into food, potentially harming human health if the total content exceeds the sanitary recommended exposure limits. Furthermore, in more concentrated solutions and at higher temperatures, stronger bases, such as sodium hydroxide, may exhibit some attack, cracking, or etching. Commercial purity caustic solutions may contain chlorides, which will amplify any attack and may cause pitting of both Type 316 and Type 304 steel (Dalipi et al., 2016; Garlick, 2015).

2.3 Corrosion Properties

The corrosion resistance of stainless steels is the single most important quality and the cause for their existence and widespread use. A brief introduction to corrosion phenomena is necessary before looking at the properties of the various stainless steels. Stainless steels, despite their appearance, can be prone to "rusting" and corrosion if improperly used (Leffler, 2020). Corrosion is the degradation, deterioration, or destruction of metals and alloys caused by chemical or electrochemical reactions with the environment. It's also a natural way to restore low-energy materials to their original state. Corrosion has a significant impact on the food processing industry, affecting production schedules, final product contamination, and safety concerns (Hamzat et al., 2020; Ogunleye & Adeyemi, 2011).

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In reality, rusting and corrosion are interchangeable terms. Corrosion is a destructive attack on metals caused by environmental reactions. Corrosion rate refers to how quickly they corrode over time. Some argue that the term should be limited to metals, but corrosion experts argue that non-metallic materials such as ceramics, plastics, rubber, and other non-metallic materials should also be included. Corrosion can refer to either the process or the damage that results from it (Yahia, 2016).

Corrosion has a significant impact in the food processing industry, affecting production scheduling, final product contamination, and safety concerns. Corrosion's devastating impact compels advanced countries such as the United States (USA) to spend $276 billion per year (3.1 percent of GDP) on direct corrosion costs. Food processing accounted for $2.1 billion (12 percent) of the $17.6 billion spent in the manufacturing and production industry. This emphasises the significance of corrosion research in the food processing industry (Hamzat et al., 2020).

2.3.1 Corrosion Principle

Corrosion is an electrochemical reaction composed of two half-cell reactions, anodic reaction and cathodic reaction. The anodic reaction emits electrons while the cathodic reaction absorbs them. Oxygen reduction (fast), hydrogen evolution from neutral water (slow), and hydrogen evolution from acid are the three most common cathodic reactions (fast). The corrosion event is the result of several elements interacting. Figure 2.5 depicts schematically the factors that influence material corrosive degradation (Brown, 2007; SABBAH, 2016)

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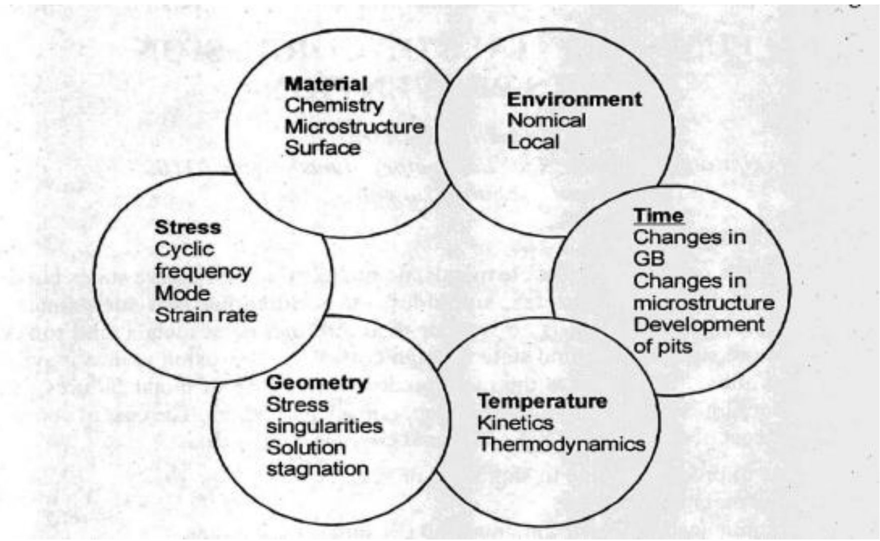

Figure 2.5 Factor influencing corrosive degradation of material

Electrochemistry is the study of the relationship between chemical change and electrical work. To investigate it, electrochemical cells, which are systems that use a redox reaction to produce or use electrical energy, are used. In an oxidation/reduction or redox reaction, free energy is always released or absorbed by the movement of electrons from one chemical species to another. In any redox process, oxidation involves the loss of electrons, whereas reduction involves the gain of electrons. An oxidising agent is the species that performs the oxidation and absorbs electrons from the species being oxidised. A reducing agent is the species that performs the reduction by donating electrons to the substance being reduced. (Brown, 2007). The corrosion cell can be represented as in Figure 2.6 below.

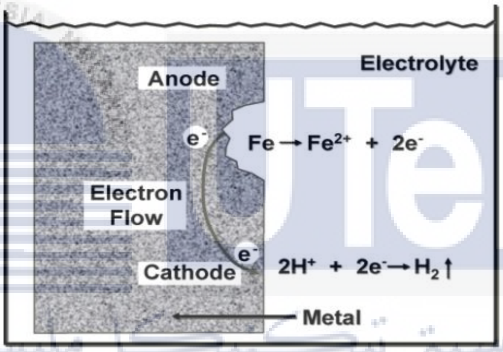

Figure 2.6 Schematic diagram of Corrosion Process (SABBAH, 2016)

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Furthermore, four conditions must be met before electrochemical corrosion can occur (Bushman, 2020). The removal of any of the four conditions listed below will stop corrosion:

- Something that corrodes must exist (the metal anode).
- A cathode must be present.
- A continuous conductive liquid path is required (electrolyte, usually condensate and salt or other contaminations).
- A conductor is required to carry electrons from the anode to the cathode. This conductor is typically formed by metal-to-metal contact, as in bolted or riveted joints.

2.3.2 Type of Corrosion

Corrosion is a chemical reaction that occurs when two metals come into contact. It is an electrochemical process with a limited application of electrochemistry. Because a metal's composition and structure influence its corrosion behaviour, metallurgy is an important topic in corrosion science (Kaneko, 2012). A corrosion phenomenon causes the corrosion form. Visual observation with the naked eye or magnification can be used to identify it. There are nine types of corrosion, which Uniform, Galvanic, Crevice, Pitting, Inter-granular, Leaching, Erosion-corrosion, Stress Corrosion Cracking, and Hydrogen Attack are all examples of corrosion processes (Kumaran & Baranidharan, 2021; Yahia, 2016) Corrosion can be classified according to how it manifests itself, with the appearance of the corroded metal serving as the foundation for this classification. A thorough examination of corroded test specimens or failed equipment can provide useful information for resolving a corrosion problem (Brown, 2007).

Uniform corrosion is defined as corrosive attack that occurs uniformly across the entire surface area or a significant portion of the total area. General thinning occurs until failure. These distinctions result in the formation of small corrosion cells, each with an anode and a cathode. Corrosion will continue until the metal is consumed or the rust film formed on the surface forms a barrier to the electrolyte. Furthermore, uniform corrosion is very easy to measure and predict, making catastrophic failures unusual (Yahia, 2016). If the steel does not contain enough of the elements that stabilise the passive film, uniform corrosion will occur. The steel is then exposed to an environment in which it cannot survive. The passive film deteriorates over the entire surface, exposing the steel to environmental damage (Leffler, 2020).

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Galvanic corrosion can occur if two dissimilar metals are electrically connected together and exposed to a corrosive environment (Figure 2.7). On the less noble metal, the corrosive attack increases, however it is reduced or prevented on the more noble metal, compared to the situation in which the materials are exposed to the same environment without galvanic coupling (Leffler, 2020). The risk of galvanic corrosion is most severe in sea water applications such as ship. Galvanic corrosion requires three conditions to occur (Hawkes, 2020) which are electrochemically different metals, such as copper and iron, must be present, the metals must be in electrical contact and the metals must be exposed to an electrolyte, such as water

Figure 2.7 Galvanic corrosion on mild steel welded to stainless steel and exposed to sea water

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Pitting corrosion is a type of corrosion that nearly everyone encounters on a daily basis. The electrochemical mechanism of corrosion in this corrosion cell is very similar to that of crevice corrosion (Yahia, 2016). Pitting corrosion is a complicated but critical thing that causes many of corrosion failures. It has been studied in detail for many years, yet crucial phenomena remain unclear. In pitting corrosion, the surface of the metal is attacked in small-localized areas. Organisms in water or breaks in a passive film can initiate corrosion. Pitting corrosion removes only a small amount of metal from the surface, but the effect is dramatic (Bushman, 2020).

Crevice corrosion happens in a specific region as well. This sort of corrosion is frequently related with a stagnant microenvironment, such as those seen in sculpture low points as in Figure 2.8 (Hawkes, 2020). In narrow, solution-containing cracks/crevice where the passive film is more easily eroded and destroyed, crevice corrosion occurs. This corrosion could be happened under washers, flanges, deposits, or fouling on the steel surface (Leffler, 2020). Besides, crevice corrosion can be caused by acidic environment or a lack of oxygen in a crevice. Consider a sheet of stainless steel that has been submerged in the ocean for an extended period of time, perhaps years. It was held in place by a bolt with a washer on it. Corrosion has developed beneath the washer. (Yahia, 2016). Chromium, molybdenum and nitrogen are the alloying elements that help to increase the resistance of stainless steels to both pitting and crevice corrosion. Resistance to localised corrosion in sea water requires 6% molybdenum or more (Leffler, 2020).

Figure 2.8 Repousse low point can form a micrienvironment in which cervice corrosion occers (Hawkes, 2020)

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For inter-granular corrosion, inter-granular corrosion is a type of electrochemical attack on metal grain boundaries. This is frequently caused by metal impurities, which are more common at grain boundaries. These boundaries are more prone to corrosion than the metal's actual crystal. Consider a stainless sheet that has been welded to another stainless sheet. A corrosive assault known as weld decay can be seen on both sides of the weld. Inter-granular corrosion causes this attack. That is, the attack is directed at the metallic grains that comprise the metal. When the metal is heated during the weld, chromium precipitates out of the heated grains and settles at the grain boundary, which separates the grains and is contaminated with impurities. The components of a chemical corrosion cell are the end result once more (Yahia, 2016). The precipitation of chromium carbides in the grain boundaries causes intergranular corrosion. Previously, this type of corrosion presented significant issues when welding austenitic stainless steels (Leffler, 2020).

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Next, selective leaching corrosion is a rapid corrosion caused by the selective leaching of an alloying element from the alloy matrix. Dezincification, or the selective leaching of zinc from the brass matrix, is the most frequent form of this type of corrosion. Brass is a zinc and copper alloy. Zinc is far more corrosive than copper. When exposed to a hostile environment, for example, zinc will corrode preferentially, draining zinc from the brass alloy and leaving behind a weak copper network. It appears to be powerful, but it has been badly weakened (Yahia, 2016).

Erosion corrosion is the combined action of corrosion and erosion caused by the rapid flow of any turbulent fluid on a metal surface. Pitting, which is commonly found on the inside surfaces of pipes, is the primary cause of turbulence. Erosion corrosion is frequent in pipelines, particularly around bends, elbows, and abrupt changes in pipe diameter, as well as locations where the fluid changes direction or the flow suddenly becomes turbulent. In turbulent conditions, the rate of erosion increases, which can cause leaks in tubes and pipelines. Poor craftsmanship might also lead to erosion corrosion. When burrs in the tubes are not removed during installation, they generate localised turbulence and disrupt the smooth flow of the fluid (Yahia, 2016).

Stress corrosion cracking (SCC) is characterized by the cracking of materials subjected to tensile stress as well as a corrosive environment. Aqueous solutions containing chlorides are the most common conditions that create stress corrosion cracking in stainless steels (Leffler, 2020). Stress corrosion cracking results from the conjoint action of three components: (1) a susceptible material; (2) a specific chemical species (environment) and (3) tensile stress. Lowering the amount of the tension is probably the greatest way to reduce or prevent stress corrosion (Yahia, 2016).

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Embrittlement corrosion occurs when a ductile material fails without localised yielding or shearing. More specifically, hydrogen embrittlement assumes numerous forms that are broadly comparable. This damage occurs at the cathode, which we tend to believe is corrosion-free, but it is not in this case. At the cathode, hydrogen ions are converted to hydrogen molecules. These atoms commonly combine to form hydrogen molecules. These molecules bubble away harmlessly as hydrogen gas (Yahia, 2016).

2.3.3 Corrosion Testing

Corrosion research has so far focused on laboratory methods and a few in situ corrosion initiatives using either synthetic or real flue gas. Laboratory methods, including electrochemical and immersion weight-loss procedures, have mostly served as screening tools for comparing corrosion rates under various situations (Pearson & Cousins, 2016)

Corrosion tests are used to investigate the waste form component release into solution during waste form degradation. It was discovered that corrosion processes are electrochemical in nature. These approaches are utilised for corrosion monitoring as well as laboratory techniques. One of the most important applications has been the instantaneous estimation of corrosion rate using polarisation resistance, with special emphasis on the relationship between mass loss and polarisation resistance, which cannot always be deduced from Tafel parameters because the constancy of electrochemical parameters with time cannot be assumed a priori (Genesca, 2016).

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2.3.3.1 Exposure Technique

An exposure test is used to determine the stability of a material when it is exposed to a chemical substance or environment. The test aids in identifying and resolving concerns about the material's durability and service life. An exposure test involves exposing a representative sample of the material to either standardised or non-standardized conditions. The exposure time could be several weeks or months, depending on the expected environmental conditions for the ultimate product. In order to qualify the usage of the material for the application, the conditions may be worst-case or standardised (Freeman & Janssen, 2020).

Some metals exist naturally in the metallic state and are stable under typical conditions (room temperature and fresh air), whereas others will tarnish and corrode quickly when exposed to air (Hawkes, 2020). Exposure tests, which are often performed for material selection and quality control, can be described by ASTM methods or proprietary methods and specifications (Freeman & Janssen, 2020).

2.3.3.2 Weight Loss Technique

Weight loss is one of the simplest, cheapest, and most extensively used methodologies for investigating corrosion rates. Many researchers have calculated the corrosion rate using an immersion test followed by a weight loss approach. The ASTM G31 standard specifies the mass loss experiment procedure. The ASTM G1 standard technique provides a general procedure to clean material samples (Thangarasu & Anand, 2019).

Weight loss corrosion measurements are straightforward and simple because they require only an accurate balance and no specialist equipment. Experiments are often carried out in line with a standard procedure. Weight-loss methods are slower than other techniques usually it takes more than one week, but multiple samples can be conducted at the same time (Pearson & Cousins, 2016).

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2.3.4 Corrosion Medium

Water can cause aqueous corrosion, which is the most common type of corrosion, because water is used for a variety of purposes, including drinking water, industrial duties such as waste transport, and heat exchangers. Water has a significant impact on material efficiency, so understanding its impact is critical for system control. Steels and iron-based alloys are the most commonly exposed materials to water, making them an excellent model for studying aqueous corrosion with a focus on the reaction of iron with water (Yahia, 2016).

When discussing the ionic content of an aqueous medium, the subject of how acidic or alkaline the solution is frequently raised. Simply put, this refers to the presence of an excess of hydrogen or hydroxyl ions. The hydrogen ion is acidic, whereas the OH^- ion is basic or alkaline. The other ionic portion of an acid or alkali given to water can improve conductivity or affect other properties of the liquid, but it has no effect on acidity. A higher pH indicates that there are less free hydrogen ions, and a change of one pH unit implies a tenfold change in hydrogen ion concentrations. Acidic compounds are those with a pH less than 7, whereas basic or alkaline substances have a pH equal to or greater than 7. A pH of 2 is very acidic, whereas a pH of 12 is very alkaline (Pierre, 2008).

When exposed to an aggressive media, stainless steel still suffers from localised corrosion. Many other metals are corroded by acidic environments, producing soluble salts and hydrogen gas as a result. Metal corrosion can happen in fresh water, seawater, salt solutions, and alkaline or basic media. In practically all of these environments, corrosion occurs only if dissolved oxygen is present (Pierre, 2008).

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2.3.5 Corrosion in Food Environment

Corrosion is a problem in many industries, but it is especially challenging in the food processing industries(Ofoegbu et al., 2011). Food substances, like other organic and inorganic elements, are becoming increasingly corrosive, resulting in significant degradation of equipment materials and to the risk of equipment failure and loss of production time for maintenance, there is the additional risk of product spoilage by corrosion products, which may result in food poisoning (Ofoegbu et al., 2011; Oladele & Okoro, 2011).

The most significant corrosion agents are organic acids found in foodstuff. The effects of these substances can be modified by processing ambient factors such as temperature, flow rate, food media viscosity, and the presence of stressors in the system. Due to their extremely complex compositions, precise examination of dietary ingredients is difficult (Ofoegbu et al., 2011).

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Fruit juice and beverages are frequently consumed by the worldwide community. However, people appear to neglect the complicated processing phases that occur prior to the final product. Crushing and squeezing raw fruit for juice extraction, batch preparation, pasteurisation, optional filtration, filling, and bottling are all part of this process. During these operations, metals or alloys are constantly in contact with the extracted juice. Because of the acidic content of the fruit, this causes corrosion of food processing equipment (Hamzat et al., 2020).

According to Sharma et al., (2018) investigated the effects of fruit juice and chloride ions on the corrosion behaviour of orthodontic arch-wire. For the experiment, 0.018inch (0.0472 cm) AISI 316L stainless steel was used. The fluid samples were prepared in a specific amount. The specimens were immersed in artificial saliva (AS) containing various fruit juices for approximately 24 hours, and another sample was placed in a separate fluid juice containing 1% NaCl in artificial saliva. The results show that the corrosion rate in artificial saliva increases significantly in the presence or absence of salt. When 1% NaCl was added to artificial saliva, pitting corrosion was observed. The most damaging to the surface are Solanum lycopersicum (Tomato) and Durio zibethinus (Amra) juice, followed by Prunus domestica Linn (Plum) juice. A scanning electron microscope (SEM) was used to examine the steel surface for blister formation.

The design of experiment module of a Minitab software was used by Hamzat et al., (2020) to analyse the corrosion effect of mild steel in a fruit juice environment. The coupon method was used to calculate the rate of corrosion in orange, pineapple, and cashew fluid over a 25-day period, with measurements taken every 5 days. Cashew fluid had the highest corrosion rate of 0.71mmpy, followed by pineapple fluid, and orange fluid had the lowest rate of 0.08mmpy. To predict the corrosion rate of mild steel in a similar environment, the generalised model equation was obtained.

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Oladele & Okoro, (2011) were using a weight loss technique to investigate the corrosion effect of mild steel in orange juice. For a total of 10 days, test specimens with known weights were immersed in the test media (orange juice with preservatives, natural orange juice, and water). Weight loss was measured every two days to determine the corrosion rate effect. Corrosion-aggressive substances were discovered to have a significant impact on equipment degradation and the maintenance or replacement of products lost or contaminated as a result of corrosion reactions. The results showed that the corrosiveness of sweet orange juice on mild steel was primarily determined by its acidity. The most corrosive orange juice was preservative-packed orange juice, followed by natural orange juice and water respectively.

Lodhi et al., (2018) used X-ray photoelectron spectroscopy (XPS) and electrochemical analysis to investigate the chemical composition and corrosion response of the passive oxide film formed on the additive manufactured 316L stainless steel in acidic regime (pH ≤ 3) and its comparison to wrought counterpart. In pH 1 and 3 electrolytes, XPS analysis revealed the formation of mono-layered and bi-layered passive oxide films. additive manufacturing specimens exhibited higher charge transfer resistance (50 times) and significantly lower corrosion current density (2 orders of magnitude) in aggressively acidic solution (pH 1) when compared to conventional wrought 316L stainless steel. In comparison, the additive manufactured 316L stainless steel has demonstrated significantly higher corrosion resistance in a highly acidic environment (pH ≤ 3), outperforming the conventional wrought material.

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Ofoegbu et al., (2011) investigate the corrosion of mild steel (uncoated), galvanised steel, and stainless steel (304L) was studied using the weight loss method over a 98-day period, with measurements taken at 14-day intervals in ground melon, cassava pulp, mashed palm fruit, tomato pulp, and black-eyed bean pulp. The presentation of the average corrosion rate and average specific weight loss of mild steel and galvanised steel in comparison to stainless steel allows for an easier assessment of the corrosion resistance of these substitute steels, which is expected to be of enormous benefit to local food and quality regulatory agencies as well as food processing equipment fabricators.

Dalipi et al., (2016) investigated a dependable procedure for recommending the preferential use of a material for food contact. Release tests using optimised parameters were carried out on six different stainless steels approved for food contact: AISI 420, AISI 430, AISI 202, AISI 303, AISI 304, and AISI 316. Total reflection X-ray fluorescence spectroscopy was used to determine the concentrations of Cr, Mn, and Ni in release test contact solutions. According to the results, AISI 202 and 430 release the least amount of Mn, Cr, and Ni. AISI 420, on the other hand, is the worst material, exceeding the limit set in the Italian regulation for all three metals of interest. One sample was chosen to examine the reproducibility of TXRF measurements taken in three different laboratories.

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Zaffora et al., (2021) are investigating corrosion in simulant media that mimics real-world operating conditions. The industrial and academic worlds have dedicated their efforts to improving analytical techniques in order to better understand the relationship between SSs microstructure and metal release, with the goal of standardising experimental conditions that accurately mimic food and drug production operating conditions. Future research will focus on the corrosion behaviour of various SS grades in increasingly complex environments, bringing them closer to real-world operating conditions in order to create safer and more efficient industrial manufacturing processes.

2.4 Design of Experiment (DOE)

The design of the experiment (DOE) and analysis of variance (ANOVA) may be a good technique to do this investigation by evaluating the effects of the factors and their interactions on the corrosion behaviour of materials, which is crucial in selecting the best materials (Gaber et al., 2020). The DOE method allows for a reduction in the number of experiments (Potentiodynamic polarisation) required to investigate the effect of various parameters on the passivity breakdown potential. DOE was used to generate a regression equation, which was then compared to laboratory data (Dastgerdi et al., 2019).

2.4.1 Factorial Design

A factorial experiment is one of the treatments in which all possible combinations of various levels of factors. Factorial experiments cover all possible combinations of numerous different sets of treatments or factors. They are the organization and arrangement of treatments inside various statistical designs. Thus, information on the responses to the many factors is gathered concurrently, as well as the impact of changes in the amount of each component on the responses to the others (Dafaallah, 2019).

There are various advantages to using a factorial experiment, which are as follows: Reduce cost, reduce time, and effort, Interaction detection and estimation, and the validity of the factorial experiment's conclusions under various experimental circumstances (Dafaallah, 2019).

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2.4.2 Analysis of Variance (ANOVA) technique

Analysis of Variance (ANOVA) is used to identify the design characteristics that have a substantial influence on the corrosion rate. Using the limited data at the time, it was presumed that the model characteristic was also applicable to longer-term trends for maximum and average pit depths. ANOVA is a decision tool for detecting variation in process parameters. ANOVA is a statistical technique for determining the best amount of variables for the verification of optimal design parameters through confirmation experiments.(Gaber et al., 2020).

ANOVAs are preferable in experimental designs that have a single dependent variable that is a measure of continuous parametric numerical data and several experimental groups in one or more independent variables. There are three common linear models for ANOVA which are fixed effects (Model 1), random effects (Model 2), and mixed effects (Model 3). The fixed effect model draws conclusions that are particular and valid only to the populations and treatments studied. The random effects model infers quantities of the factor that were not used in the study. The Fixed and Random effects are both present in the Mixed Effects model (Sawyer, 2009).

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The number of research publications centred on corrosion study in food processing industries suggests that it receives little attention (Hamzat et al., 2020). Corrosion, on the other hand, is a major issue in this industry. Aside from equipment failure and production downtime, there is also the risk of product contamination as a result of corrosion product, which can result in food poisoning and serious health concerns. According to the above research, no study has been conducted to investigate the corrosion rate of 316L stainless steel in pineapple juice, tamarind juice and lime juice at the same time.

2.5 Summary of Literature Review

Based on the reviews of stainless steel, stainless steel applications, corrosion types, corrosion testing, corrosion in food environments, factorial design, and analysis of variance (ANOVA), it is possible to conclude:

- Stainless steels are classified into five basic types according to their metallurgical structure (Y. S. Ahmed, 2014).
- Due to their superior corrosion resistance and anti-bacterial properties, 300 series stainless steels have been used in a variety of fields such as equipment in the chemical processing industry, food and dairy industry, beverage industries, aircraft industry, building nuclear reprocessing plants, household appliances, and so on (Subbaiah & Rao, 2012).
- Corrosion can also be defined as the degradation of a material as a result of its reaction to its environment. Corrosion occurs as a result of most metals' natural tendency to return to their natural state. Uniform, Galvanic, Crevice, Pitting, Inter-granular, Leaching, Erosion-Corrosion, Stress Corrosion Cracking, and Hydrogen Attack are the types of corrosion (Embrittlement) (Yahia, 2016).
- Laboratory methods, such as electrochemical and immersion weight-loss procedures, have primarily served as screening tools for comparing corrosion rates under different conditions (Pearson & Cousins, 2016)
- A good technique for conducting this investigation is the design of the experiment (DOE) and analysis of variance (ANOVA), which evaluates the effects of the factors and their interactions on the corrosion behaviour of materials (Gaber et al., 2020).

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CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter of the study describes the methodology of the study covering each activity including preparation of samples and mediums, corrosion testing, data collection and data analysis for results. The research approach used in this study is represented by the flowchart in Figure 3.1.

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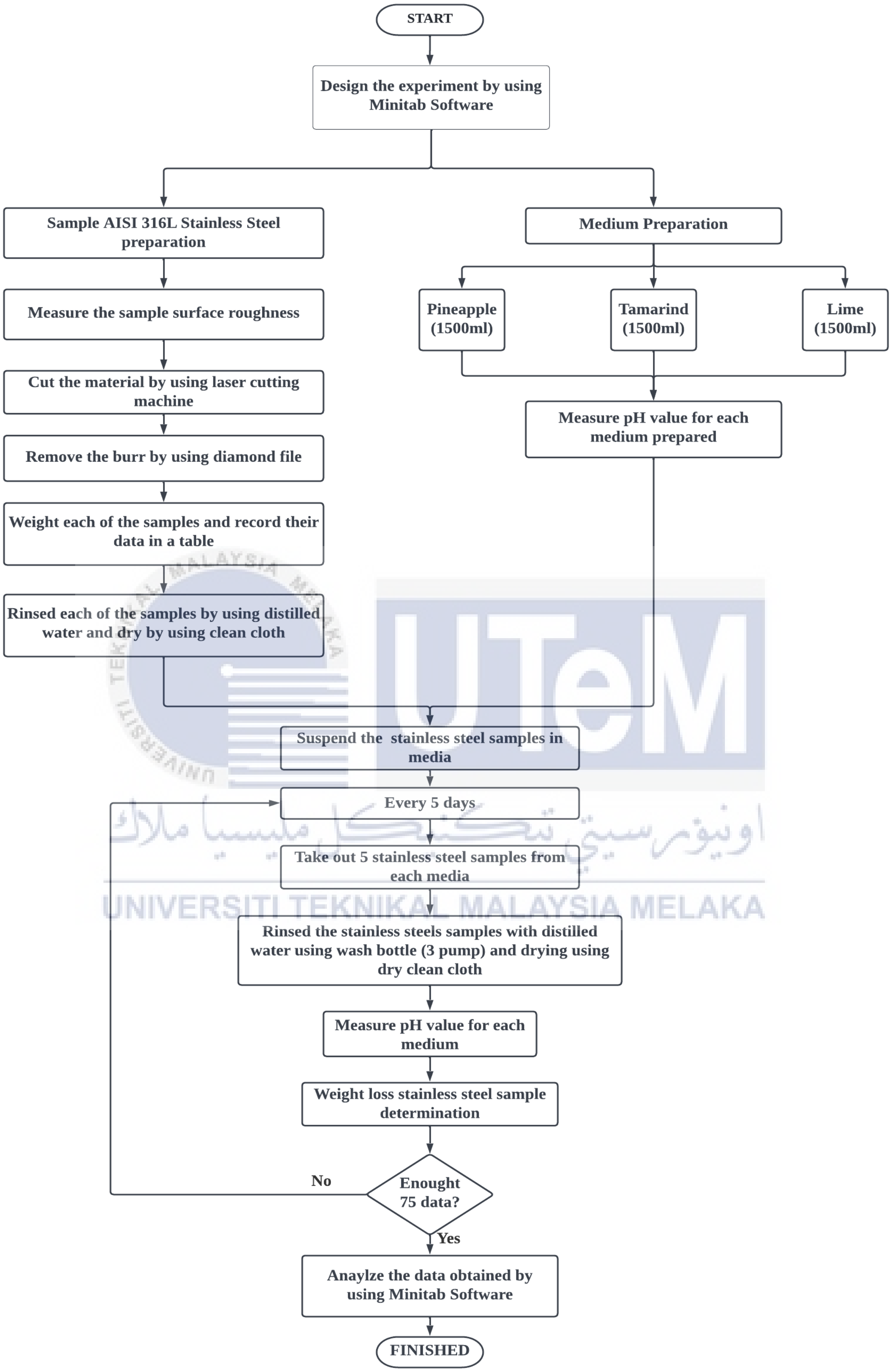

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Figure 3.1 Research flowchart

3.2 Preparation of Samples

According to the knowledge gained from reading, such comparison was done previously by Hamzat et al., (2020) and Oladele & Okoro, (2011). However, in Hamzat et al., (2020) case, comparison was done based on mild steel specimens in 25 days with interval 5 days. The comparison also uses two different sample thickness (1.0mm, 1.5mm) and different type of fruit juice (orange, pineapple, cashew).

Nevertheless, Oladele & Okoro, (2011) investigate the corrosion effect of mild steel on orange juice (orange juice with preservatives, natural orange juice and water) for a total exposure time of 10 days. The material used for this investigation is a mild steel alloy with a thickness of 1.0 mm. In addition, the specimens were surface-prepared using different grade emery paper, ethanol and water.

3.2.1 Preparation of AISI 316L Stainless Steel

The sample used in this study was AISI 316L stainless steel with thickness 0.9mm. The material as in Figure 3.2 was purchased from an external supplier, SCM Marketing shop, through the Lazada website.

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Figure 3.2 AISI 316L Stainless Steel

The raw material goes through surface roughness testing to measure the material surface finish at each end of plate by using a portable surface finish measuring machine Mitutoyo SJ-400 (Figure 3.3). This step is a must to determine the final result after corrosion test either surface roughness give some effect on corrosion rate or not.

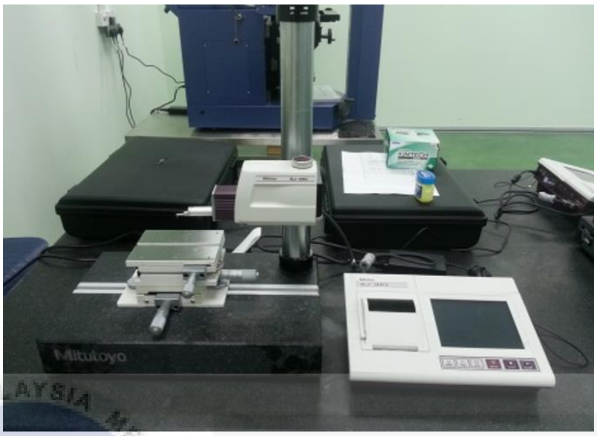

Figure 3.3 Surface Roughness Machine in Metrology Laboratory

Surface roughness testing will be performed to determine the texture of the sample's surface finish (Figure 3.4). A surface can never be perfectly smooth and will always have roughness and waviness as surface texture components. Roughness is an important factor in determining how a genuine stainless steel 316 product, such as a kitchen utensil, will react to the environment. Rough surfaces wear faster and have higher friction coefficients than smooth surfaces (Hassan, 2015).

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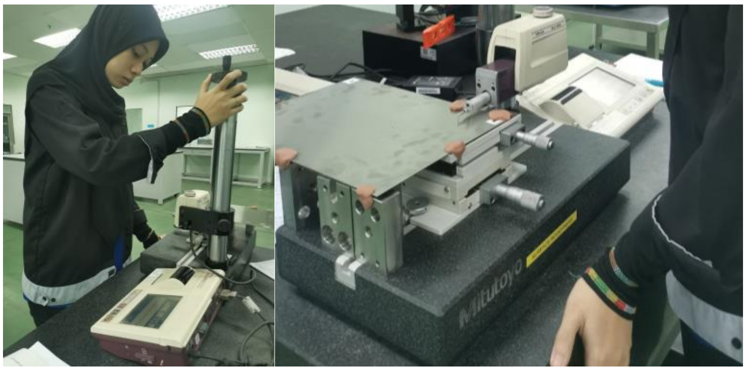

Figure 3.4 Surface roughness testing on raw material

Surface roughness is a measure of a product's technological quality and a significant factor in manufacturing cost. Roughness is a mechanical component's performance, where irregularities in the surface can result a good prediction for cracks or corrosion. In general, the literature for metallic materials shows that the higher the surface roughness, the higher the corrosion rate. Copper, nickel, aluminium, stainless steel, magnesium, and titanium alloys all showed this trend (Hassan, 2015; A. S. Toloei et al., 2015).

Several studies have been conducted to investigate various aspects of surface roughness in relation to corrosion rate and pitting corrosion. Barmatov et al., (2015) state th effect of fluid velocity on the corrosion rate of low carbon steel in 4 M hydrochloric acid in the presence of various concentrations of a film-forming corrosion inhibitor was investigated. It was demonstrated that the inhibitor's surface coverage is an important factor in controlling corrosion in both laminar and turbulent flow conditions. When the inhibitor film completely covers the metal surface, the corrosion rate increases slightly with increasing flow velocity, which is due to partial erosion of the inhibitor film at sufficiently high wall shear.

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The drawing sample with desired size has been drawn beforehand using Solidwork software as in Figure 3.5. then, the material will be cut into rectangular shape using a CO2 laser cutting machine (Figure 3.6). Figure 3.7 shows the samples condition after cutting process

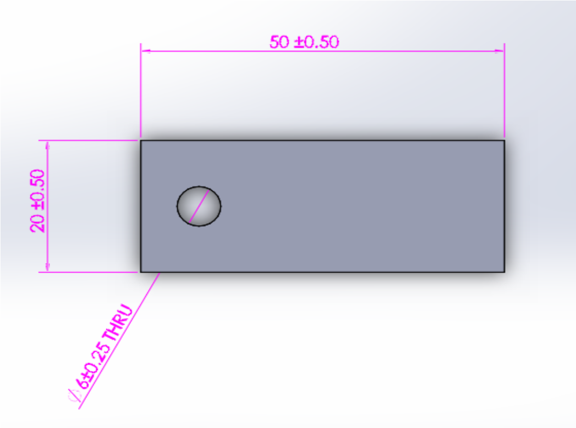

Figure 3.5 Solidwork sketching for desired sample size

Figure 3.6 CO$_2$ Laser cutting machine in Advanced Forming Technology Laboratory

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Figure 3.7 Samples condition after cutting process

3.3 Preparation of Media

3.3.1 Media Collection

Three (3) Malaysian tropical fruits that used for this experiment were commonly consumed by many people, either as juice or in cooking process which directly contact to the kitchen utensils. The fruits that has been selected are pineapple, lime and tamarind which can easily find at the local supermarket. Although supermarkets nowadays sell processed fruit juices, fresh fruit juices were chosen to be used in this experiment. Therefore, several processes are needed to extract the pure fruit juice from the fresh fruits. To produce juice from selected fruits, pineapple was blended by using fruit blender, tamarind was dissolved with tap water and lime was squeezed. All of the juices were filtered by using cloth filter to make it fibre free. Then each of the juice were measured to 1500 ml and collected in the glass container (Figure 3.8) as the media for the experiment.

Figure 3.8 Glass container with capacity 2000ml

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A pineapple was chosen for this experiment because pineapple is one of the local fruits that popular among Malaysians and foreign tourists. However, most people tend to drink it as juice rather than to consume. The pineapple will be blended using a fruit blender and filtered to get the juice. The direct contact between steel on the blender and the fruit itself is likely to cause corrosion. Then the pineapple juice has been stored in glass container to avoid any corrosion between juice and container. Figure 3.9 shows the process to extract pineapple juice from fresh fruit.

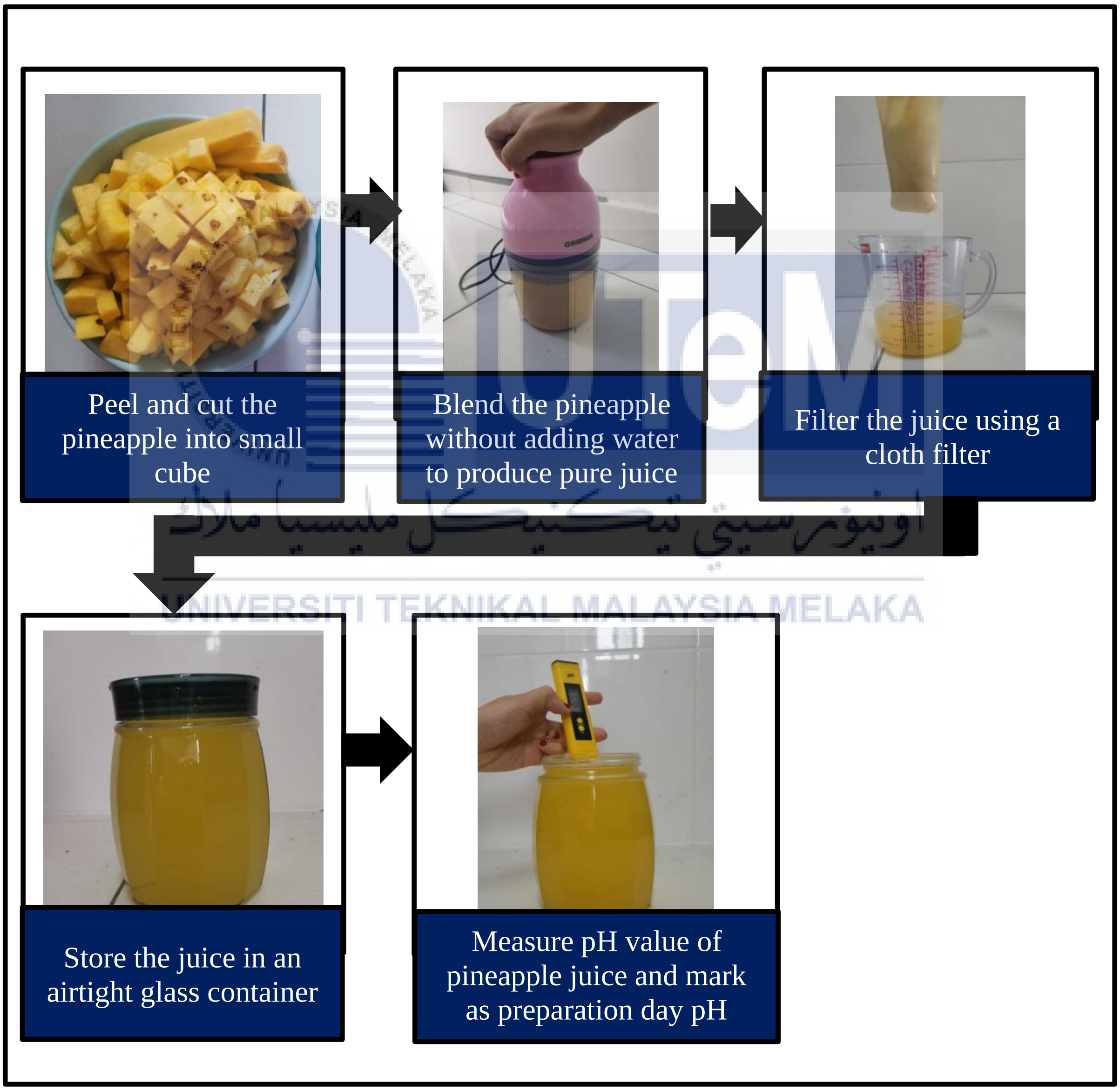

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Figure 3.9 Pineapple juice extraction process flow

For lime, the limes will be squeezed and filtered to get the juice only. Lime was chosen in this study because lime is widely used by Malaysians in cooking. The lime is cut by making direct contact between the knife and the lime. Kitchen knife is commonly made of stainless steels. As a result, lime was chosen to investigate the corrosion rate of lime on stainless steels. Figure 3.10 show the lime juice extraction process flow.

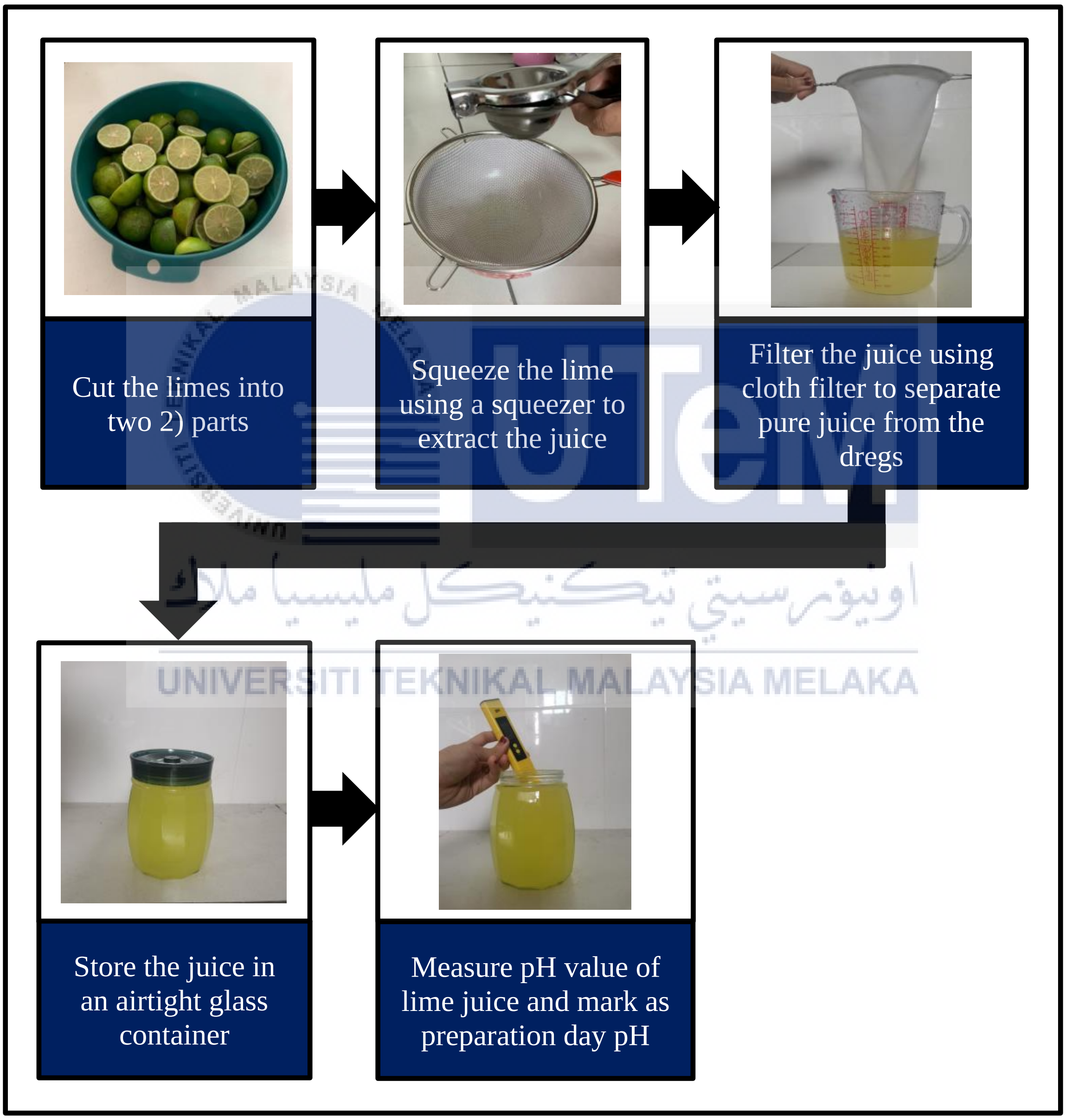

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Figure 3.10 Lime juice extraction process flow

For tamarind, it is made into juice by adding distilled water and then filtered. Tamarind juice has been chosen as one of the mediums to be studied because tamarind is widely used as an ingredient in various cuisines in Malaysia. Direct contact between tamarind and kitchen cookware such as pans and pots may also cause corrosion. Figure 3.11 show the tamarind juice extraction process flow.

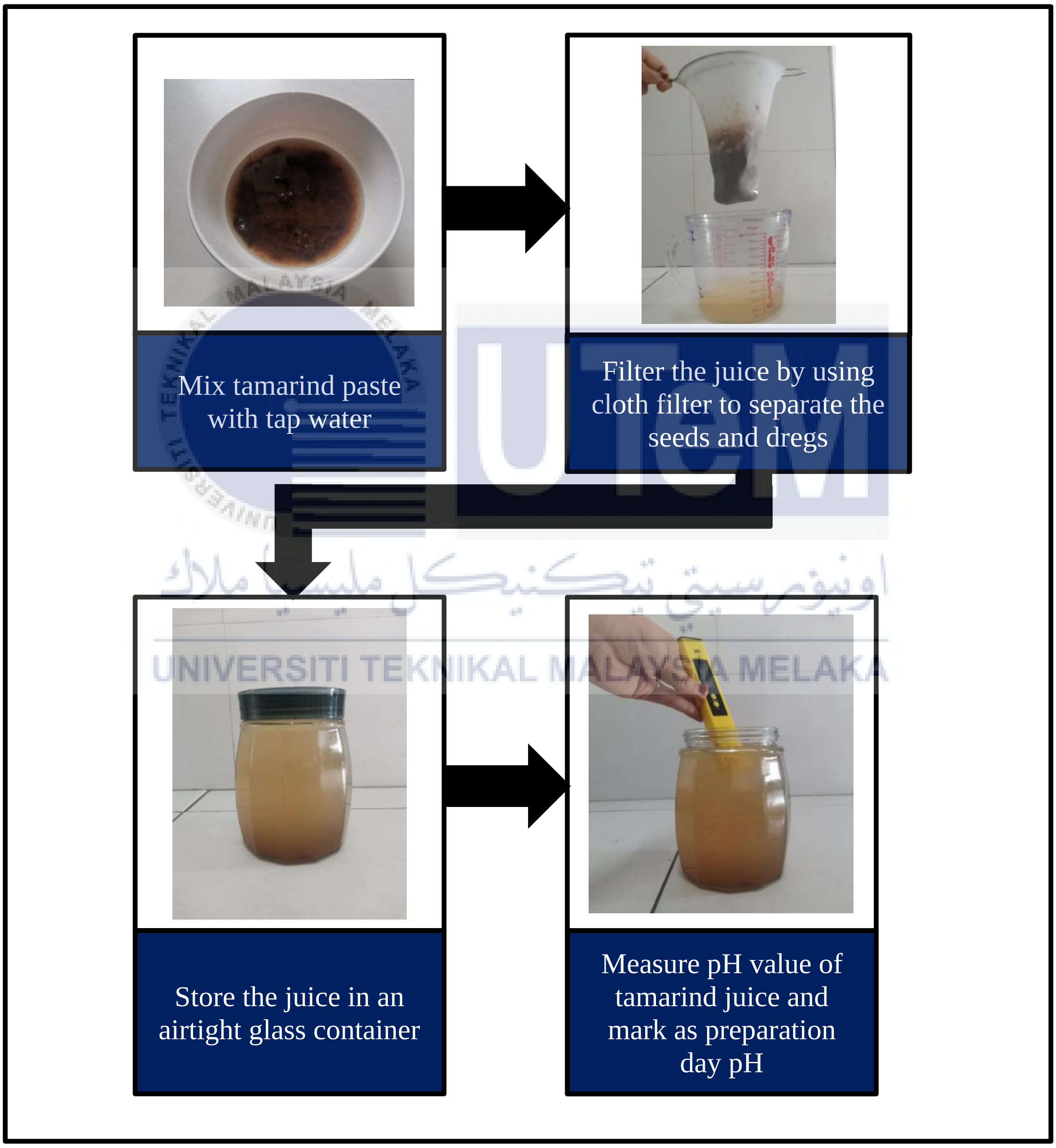

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Figure 3.11 Tamarind juice extraction process flow

3.4 Corrosion Test

The corrosion test will be conduct at material science laboratory (Factory 2) Faculty of Engineering technology (FTK), UTeM and the samples stored in a chemical storage cabinet (Figure 3.12). Corrosion tests were conducted for 40 days and data measurements were performed 5 times with an interval of 8 days.

Figure 3.12 Samples storage cabinate

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3.4.1 Initial Weight of AISI 316L Stainless Steel Samples

Following the cutting of the sample, each sample will be weighed to determine the average weight value using a high precision electronic scale. The weight of samples was taken without the thread. All data will be put in a table. All 75 samples will then be washed with three pumps of distilled water each and dried with a clean dry cloth. Finally, to avoid atmospheric corrosion, the manufactured samples will be stored in a desiccator chamber in the material testing laboratory until the corrosion tests are performed (Hamzat et al., 2020).

3.4.2 Suspended Stainless Steel Sample in the Medium

Each weighed sample will be tied to the thread which connect to the mouth of a glass container as in Figure 3.13. The sample will then be suspended in a glass container filled with pineapple juice, tamarind juice, and lime juice. To avoid the effects of displacement, the beaker is stationary. Make sure that every area of the sample is immersed and that there are no contact with the glass container's surface. The pH value of each medium for the first day will be recorded.

Figure 3.13 The condition of tied sample in the glass container

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Figure 3.14 shows the illustration of experimental setup while Figure 3.15 is the real experimental setup when AISI 316L Stainless Steels suspended and immersed in the medium for Day 1.

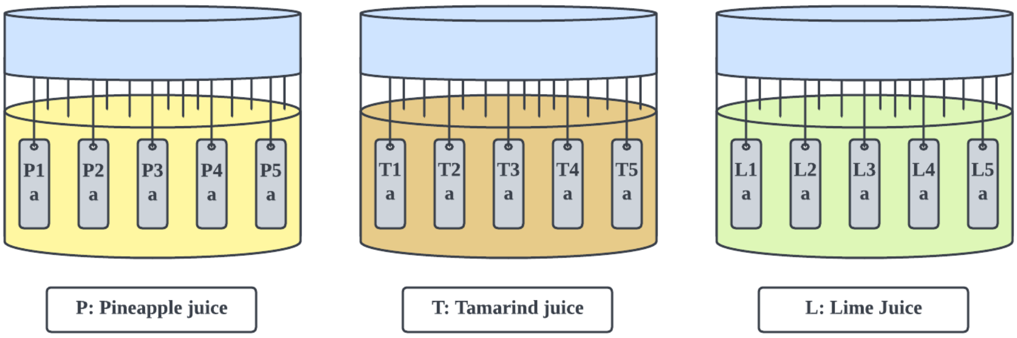

Figure 3.14 Experimental Setup illustration for Day 1

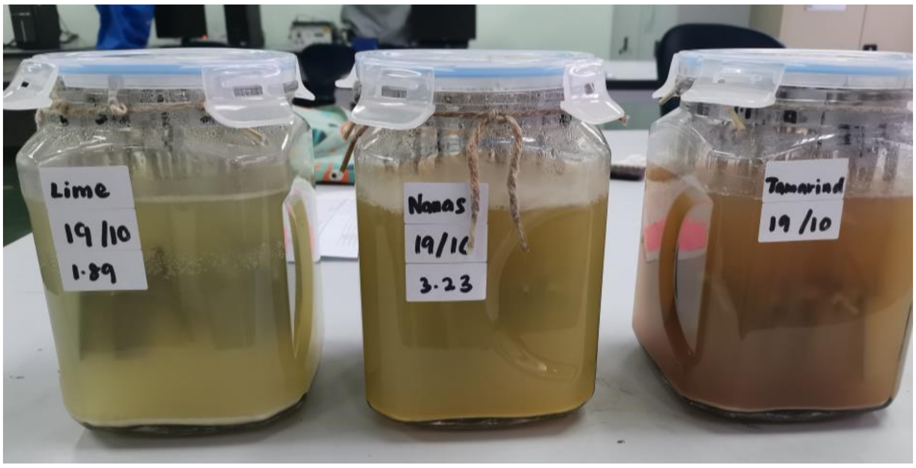

Figure 3.15 Real experimental setup for Day 1

3.4.3 Cleaning 316L Stainless Steel Samples for Weight Measurement

After 8 days, 5 sample will be taken out from each medium to calculate the weight loss. The pH of each medium will be measured using a digital pH metre. Before drying, each sample was gently rinsed with three pumps of distilled water as in figure 3.16. Distilled water is used to remove any pollutants and juice that have been adhered to the sample.

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Figure 3.16 Rinsing process after the sample is taken out of the media

The experimental setup illustration after the sample removed is shown in Figure 3.17 below. Figure 3.18 show the drying process of the samples using clean dry cloth before weighing process.

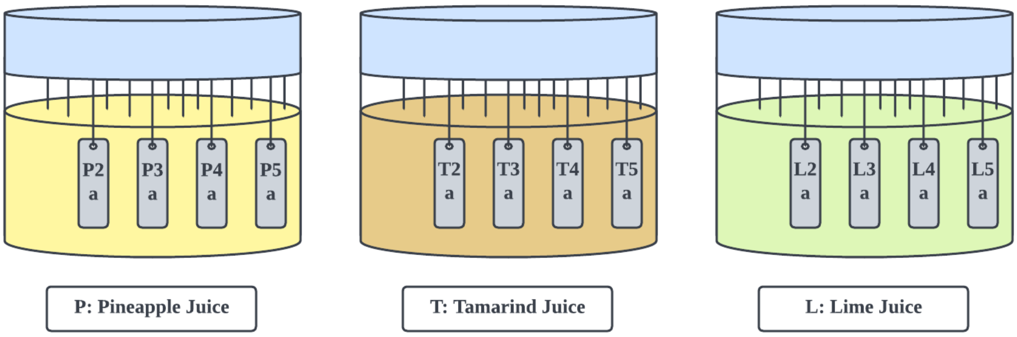

Figure 3.17 Experimental setup after samples taken from each medium

Figure 3.18 Samples drying process using a clean dry cloth

3.4.4 Weight Loss 316L Stainless Steel Sample Determination

The corrosion rate experiment is carried out in accordance with a standard procedure (ASTM G1-90, 1996). Even though weight-loss methods are slower than other techniques (currently more than a week), multiple samples can be run at the same time. This method calculates the average corrosion rate over a long period of time (40 days) (Pearson & Cousins, 2016).

The dried sample will be weighed, and the data will be recorded into a table. The weighing process is carried out on the same scales that were used to determine the initial weight of the sample. To achieve a more accurate average reading, the weighing process will be repeated five times for each sample. Figure 3.19 show a few samples of the weighing process performed on the corrosion test sample.

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Figure 3.19 Weighing process performed on the corrosion test sample

3.5 Analysis of Variance (ANOVA)

The following formula (Equation 3.1) will be used to compute the average corrosion rates of AISI 316L stainless steel in various types of Malaysian tropical fruit juice environments under study (Dastgerdi et al., 2019).

$$Corrosion\ Rate = \frac{W \ \times k}{A \times t \times \rho} \quad 3.1$$

Where corrosion rate of the specimen in millimetre per year (mmpy), W is the weight loss in milligram (mg), k is the corrosion rate unit conversion, equal $8.76 \ \times 10^4$ (Zainab & Ali, 2019), A is the exposed surface area of the specimens in (m^2), and t is the immersion time in (hours), and ρ is stainless steel 316L density (Azom, 2018; Hamzat et al., 2020; Sanni et al., 2018; Zainab & Ali, 2019).

The collected results will be entered into the software Minitab 19 for further examination of the experimental results. The variance analysis results will allow statistics to analyse the role of variables on the corrosion rate of stainless steel (Hamzat et al., 2020).

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3.5.1 Capability Analysis

The purpose of measuring a process capability is to determine how well the process will meet specifications and the level of control required. Process capability also refers to the ability to implement machine, material, people, and methods to produce a product that consistently meets engineering specifications. Histograms, probability plots, and control charts are used in process capability analysis. The effective process monitoring analysis methods are control charts and process capability (Arzak et al., 2021).

Repeatability and capability analysis will be performed as the experiment is carried out under uniform experimental conditions (in terms of instrument/operator). A run chart (considered a type I gauge study) will be constructed for this purpose, and an analysis to evaluate precision and bias will be performed (Hamzat et al., 2020). The histogram and probability plot are used to test the data's normality. Capability indices can be used to evaluate process capability. Process capability indices evaluate a process's ability to meet the required engineering specifications (Arzak et al., 2021). Reference, tolerance, study variation, and percentage of tolerance are the design settings necessary to construct a run chart and other corresponding measures. These analyses will produce descriptive measures, bias, and capability indices (Hamzat et al., 2020).

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3.5.2 Model Adequacy

To validate the underlying assumptions in ANOVA, residual analysis was performed. The assumptions are that corrosion rate formula adequately describes the observations and that the error terms are normally and independently distributed with a mean of zero and an unknown but constant variance. These assumptions are abbreviated as $(0, \sigma^2)$ (Hamzat et al., 2020; Shalabh, n.d.).

3.5.3 Mathematical Model

Regression analysis was used to predict the value of a dependent variable (corrosion rate) based on any of the independent variables and to establish a linear relationship between them. This analysis' model equation can be used to calculate the corrosion rate of stainless steel for a similar condition with high accuracy (Hamzat et al., 2020).

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CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter results of the experiment as well as the analysis of variance. The discussion will mainly centre on corrosion tests on AISI 316L stainless steel in various types of Malaysian tropical fruit juice. However, the process before corrosion test were done such as surface roughness test and cutting process also discussed in this chapter due to the relationship that results in changes to the effects of corrosion tests.

4.2 Analysis of samples before corrosion test

4.2.1 Surface Roughness

Surface roughness is a measurement for a product's technological quality and a major contributor of manufacturing costs. Roughness affects how well a mechanical component works because surface irregularities can make cracks or corrosion more likely to occur. In comparison to smooth surfaces, rough surfaces typically wear faster and have higher coefficients of friction (Hassan, 2015). The result of eight (8) Ra readings from eight (8) different parts of the stainless steel plate before cutting process are shown in Table 4.1. The raw material obtained is in hairline finishing which may have smoother surface. With the typical average roughness obtained is between 0.1 and 0.5 mm. So, the result is a smooth, slightly to moderately reflective surface with good flatness control (Velling, 2019).

Table 4.1 Result of Surface Roughness Test before corrosion test

Part	Surface roughness, Ra (µm)
1 (P5e)	0.452
2 (T5e)	0.396
3 (L5e)	0.448
4 (P5d)	0.550
5 (T5d)	0.423
6 (L5d)	0.333
7 (P5c)	0.329
8 (P5c)	0.339
Average	**0.409**

4.2.2 Weight analysis of 316L Stainless Steel Samples

After the AISI 316L stainless steel sample was cut, the weighing process was performed for all 75 samples. The average initial weight, W_i have been recorded in Table 4.2 as initial value or benchmark value. The accuracy of the reading is very important because it will be used in the equation to obtain the value of the corrosion rate. To prevent the sample from being changed, the sample has been marked using a white sticker with the sample number written on it every time the weighing process is done. Figure 4.1 shows a few of the sample being weighed using a digital scale.

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Table 4.2 Initial weight of sample (Day 1)

Sample	Weight (mg)					Average Initial Weight, W_i (mg)
	a	b	c	d	e	
P1	6299.00	6286.00	6280.00	6283.00	6332.00	6296.00
P2	6292.00	6329.00	6263.00	6206.00	6327.00	6283.40
P3	6243.00	6173.00	6303.00	6236.00	6323.00	6255.60
P4	6236.00	6289.00	6294.00	6216.00	6311.00	6269.20
P5	6301.00	6355.00	6226.00	6256.00	6318.00	6291.20
T1	6290.00	6264.00	6294.00	6299.00	6305.00	6290.40
T2	6405.00	6295.00	6310.00	6309.00	6294.00	6322.60
T3	6354.00	6311.00	6297.00	6339.00	6331.00	6326.40
T4	6294.00	6317.00	6297.00	6333.00	6328.00	6313.80
T5	6284.00	6331.00	6302.00	6298.00	6286.00	6300.20
L1	6322.00	6274.00	6267.00	6517.00	6333.00	6342.60
L2	6323.00	6285.00	6294.00	6297.00	6314.00	6302.60
L3	6354.00	6330.00	6359.00	6483.00	6509.00	6407.00
L4	6312.00	6340.00	6306.00	6276.00	6551.00	6357.00
L5	6308.00	6295.00	6370.00	6297.00	6483.00	6350.60

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Figure 4.1 Sample weighed using digital scale

4.3 Analysis of samples after Corrosion Test

Corrosion tests were done by immersing stainless steel samples in three (3) different medium (Pineapple juice, tamarind juice, lime juice) for 40 days and data measurements were performed 5 times excluding immersion day with an interval of 8 days. Weight loss technique is used in this experimental study because of the technique is simple, which they require no specialized equipment other than an accurate balance.

The analysis also including, weight analysis of 316L stainless steel samples and the surface roughness of stainless steel after 40 days of immersion in medium. The comparison of surface roughness values before and after the corrosion test is also discussed to see if the surface of the sample becomes smoother or rougher.

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4.3.1 Weight analysis of 316L Stainless Steel samples

After an interval of 8 days, 5 samples from each medium will be taken out to be weighed for average final weight, W_f. The average weight will be used to calculate the weight loss and then the corrosion rate. The data have been recorded as in Table 4.3. The value of weight loss is calculated using equation 4.1 where the value of W_i is referred to in Table 4.2.

$$\text{Weight loss} = \text{Average Initial Weight, } W_i - \text{Average Final Weight, } W_f \qquad 4.1$$

Table 4.3 Weight of Sample after corrosion test

DAY	Sample	WEIGHT (mg)					Average Final Weight, W_f (mg)	Weight Loss, W (mg)
		a	b	c	d	e		
1 (8days)	P1	6289	6283	6277	6279	6324	6290.40	5.60
	T1	6283	6257	6288	6292	6300	6284.00	6.40
	L1	6314	6273	6259	6510	6326	6336.40	6.20
2 (16days)	P2	6283	6314	6256	6234	6319	6281.20	2.20
	T2	6403	6290	6305	6301	6289	6317.60	5.00
	L2	6315	6282	6290	6292	6307	6297.20	5.40
3 (24days)	P3	6239	6170	6299	6248	6314	6254.00	1.60
	T3	6349	6306	6291	6331	6328	6321.00	5.40
	L3	6349	6323	6355	6475	6501	6400.60	6.40
4 (32days)	P4	6233	6285	6288	6231	6307	6268.80	0.40
	T4	6286	6312	6287	6329	6324	6307.60	6.20
	L4	6307	6333	6301	6265	6542	6349.60	7.40
5 (40days)	P5	6293	6344	6223	6253	6310	6284.60	6.60
	T5	6277	6325	6294	6288	6279	6292.60	7.60
	L5	6303	6285	6360	6284	6472	6340.80	9.80

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4.3.2 Surface Roughness

Austenitic stainless steels, 316L, in recent decades, become one of the alloys that are increasingly used in civil engineering and building, as well as for specific architectural purposes. This is due to their good corrosion resistance, favourable mechanical properties, and reasonable price considering their excellent properties (Leban et al., 2014; Zaffora et al., 2021). Surface roughness of the metal surface has a significant impact on general corrosion, metastable pitting nucleation, and pitting potential (A. Toloei et al., 2013).

A. Toloei et al., (2013) and Leban et al., (2014) support the statement of when the lower the surface roughness values, the more the corrosion resistance. Table 4.4 is the surface roughness result after 40-days corrosion test for the same part as tested before corrosion test done.

Table 4.4 Surface roughness result after 40-days corrosion test

Sample	Surface Roughness, Ra (µm)
1 (P5e)	0.335
2 (T5e)	0.331
3 (L5e)	0.355
4 (P5d)	0.380
5 (T5d)	0.327
6 (L5d)	0.364
7 (P5c)	0.286
8 (P5c)	0.350
Average	**0.341**

The following table 4.5 shows a comparison of the surface roughness value of the same sample before and after the corrosion test was carried out which the average surface roughness value after corrosion test is lower compared to before corrosion test. Longer immersion in acidic media can result in stainless steel passivation with a different passive film composition than air-formed layers, resulting in reduced metal release over time (Zaffora et al., 2021).

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Table 4.5 Comparison of Surface Roughness value before and after corrosion test

Sample	Surface Roughness, Ra (µm)	
	Before corrosion test	After corrosion test
1 (P5e)	0.452	0.335
2 (T5e)	0.396	0.331
3 (L5e)	0.448	0.355
4 (P5d)	0.550	0.380
5 (T5d)	0.423	0.327
6 (L5d)	0.333	0.364
7 (P5c)	0.329	0.286
8 (P5c)	0.339	0.350
Average	**0.409**	**0.341**

4.4 Media pH analysis

Low pH acid waters accelerate corrosion by supplying hydrogen ions to the corrosion process. Fruit juices have been employed as corrosive media to study the corrosion rate of stainless steel in food media. Because of the evolution of hydrogen gas at low pH, steels are corrosive in fruit juice environments, which tends to eliminate the possibility of protective formation (Thangarasu & Anand, 2019). Zainab & Ali, (2019) has investigate the weight loss of stainless steel 316L due to corrosion rate at two different temperatures (25°C and 37°C) and pH levels (1,3, 6.3 and 7.4). It was discovered that as pH increased, weight loss decreased, which had an effect on corrosion rate, which decreased as pH increased.

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According to previous study from Dastgerdi et al., (2019), the design of experiment (DOE) method is used to assess the effects of environmental parameters (chloride, temperature, and pH) on pitting corrosion of AISI 304 L stainless steels. It conclude the passivity breakdown potential is strongly influenced by pH, temperature, and chloride concentration. Among all of these variables, temperature has the greatest impact, particularly in the 20°C-40°C range.

Other than that, Nik Masdek et al., (2021) have study on the effect of pH on the corrosion rate of 316L Stainless Steel, Nitinol and Ti-6Al-4V alloys have been investigated. An electrochemical method was applied to investigate the corrosion behaviour of these biomaterials under simulated biological condition. The potentiodynamic polarisation were performed in a Hank's solution with a pH value of 7.4 (neutral) and 5.2 (acidic). All materials corroded slightly faster in an acidic environment than in a neutral environment, with the exception of Nitinol, which corroded faster at pH 7.4 than at pH 5.2. This is due to the formation of an oxide layer on the surface of Nitinol, which increases corrosion resistance in harsh environments.

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Different pH value might influence the corrosion rate on stainless steel samples. Even though same medium was used from start to the end of the experiment, pH value might be fluctuated daily due to photosynthesis and respiration in the water. Therefore, pH value of the medium was taken on the same day as the corrosion data was taken. The pH value of each medium was taken on medium preparation day, experimental starting day(1-day), 1 (8-days), 2 (16-days), 3 (24-days), 4 (32-days), 5 (40-days).

4.4.1 Pineapple media pH analysis

The pH value of pineapple juice was taken and recorded as in Table 4.6 and Figure 4.3 is pH value of pineapple juice which interpreted in form of graph. Based on Figure 4.3 above, the highest pH value recorded for pineapple juice was on day 3 which is 3.66. On this day, the medium is less acidic compare to experimental start day which is 3.17. Overall, the pH reading value changes and shows an uneven trend.

Table 4.6 The pH value of pineapple juice

Day	pH Value
Preparation day	3.23
Experimental start day (1 day)	3.17
1 (8 days)	3.54
2 (16 days)	3.23
3 (24 days)	3.66
4 (32 days)	3.35
5 (40 days)	3.53

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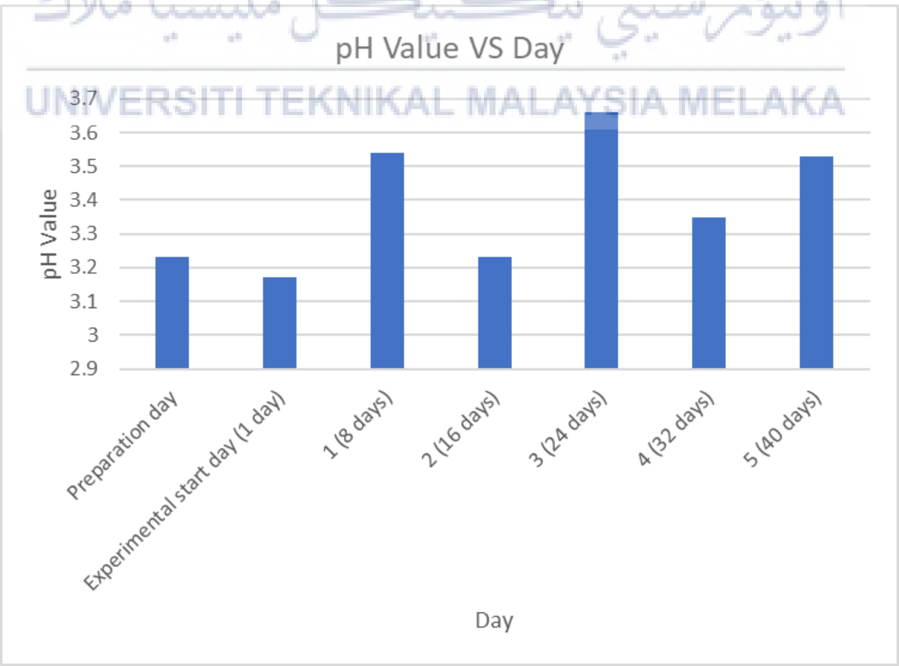

Figure 4.2 The Graph of pH value vs Day

4.4.2 Tamarind media pH analysis

The pH value of tamarind juice was taken and recorded as in Table 4.7 and Figure 4.4 is pH value of tamarind juice which interpreted in form of graph. Based on Figure 4.4 above, the highest pH value recorded for pineapple juice was on day 1 which is 2.73. On this day, tamarind juice medium is less acidic compare to day 2 which is 1.97. Overall, the pH value slightly changes day by day. From preparation day to day 1, the medium become less acidic which cause the pH value increasing. However, the value is dropped on day 2 and increasing again on day 3 before back down on days 4 and day 5.

Table 4.7 The pH value of tamarind juice

Day	pH Value
Preparation day	2.02
Experimental start day (1 day)	2.13
1 (8 days)	2.73
2 (16 days)	1.97
3 (24 days)	2.30
4 (32 days)	2.25
5 (40 days)	2.15

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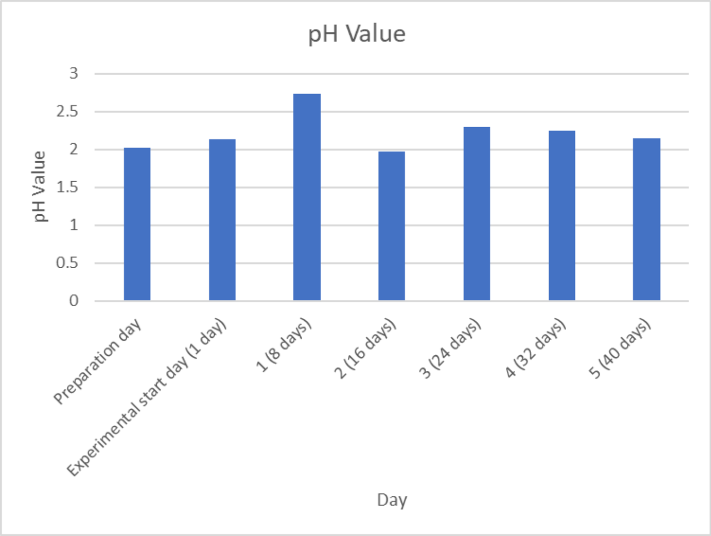

Figure 4.3 The Graph of pH value vs Day

4.4.3 Lime media pH analysis

The pH value of lime juice was taken and recorded as in Table 4.8 and Figure 4.4 is pH value of lime juice which interpreted in form of graph. Based on Figure 4.6 above, the highest pH value recorded for pineapple juice was on day 5 which is 2.87. The preparation day and day 2 have same pH value which is 1.89. From preparation day to day 1, the medium become less acidic which cause the pH value increasing. However, the value is dropped on day 2 and increasing again on day 3, day 4 and day 5.

Table 4.8 The pH value of tamarind juice

Day	pH Value
Preparation day	1.89
Experimental start day (1 day)	2.02
1 (8 days)	2.69
2 (16 days)	1.89
3 (24 days)	2.27
4 (32 days)	2.35
5 (40 days)	2.87

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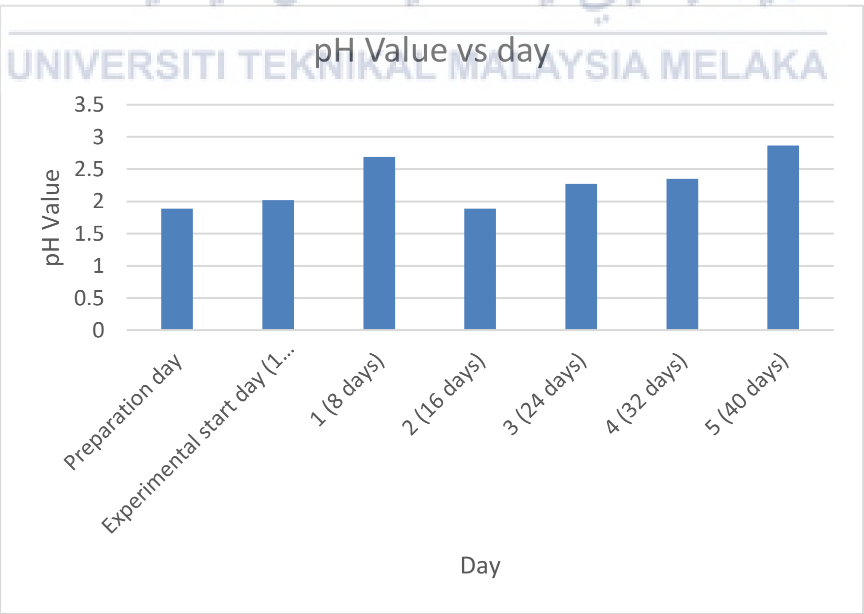

Figure 4.4 The Graph of pH value vs Day

4.5 Corrosion rate analysis using ANOVA method

Design of experiments (DOEs) and analysis of variables (ANOVA) were used to evaluate the effect of immersion time and different corrosive media (Malaysian Tropical Fruits juice) such as pineapple juice, tamarind juice, and lime juice at different time intervals on the corrosion rate of AISI 316L stainless steels.

The commercial software Minitab 19 will be used for detailed analysis of experimental results. The data obtained will be interpreted in several ways using this software, including capability analysis, model adequacy, and mathematical model. If there is a correlation between the dependent variable (corrosion rate) and the independent variable, the model is adequate. The data that will be obtained from analysis of variance (ANOVA) are;

- General factorial design result with model summary
- Descriptive Statistics of Corrosion Rates and Run chart with basic statistic table, bias and capability indices.
- Pareto Chart, Main Effect plot and Interaction plot between factors
- Residual plot

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4.5.1 Corrosion rate analysis based on factorial design

General Factorial Design is a statistical method for investigating significant parameters in an experiment. It is useful in experiment design where several factors and their interactions must be considered. This design has several advantages, including the smallest number of runs required to study k number of factors and all levels of factor combinations in a complete factorial experimental design. The general factorial design results are easily expressed in terms of the regression model (Hamzat et al., 2020).

This corrosion rate was calculated using equation 3.1, and the resulting data will be entered into the commercial software Minitab 21 for detailed analysis of the experimental results. Based on literature from Hamzat et al., (2020) and other corrosion experiment study, duration (days) and media (pineapple, tamarind, lime) were found as important parameter that affecting the corrosion rate of AISI 316L Stainless Steel and hence it was used as independent variables. The corrosion rate response can be obtained by using a general factorial design with different factor levels. Table 4.9 displays the design information for each parameter and its corresponding levels. There are two factors (A and B) at three and five levels, respectively, with a single replica completing the 15 experiments.

Table 4.9 Design Information

Factor	**Factor Levels**	**Values**
A: Medium	3	Pineapple, Tamarind, Lime
B: Duration (Days)	5	1, 2, 3, 4, 5

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To avoid bias and obtain an accurate estimate of error, each experiment was conducted at random. The experimental matrix for the single-replicate general factorial design is shown in Table 4.10. The leftmost column displays the response (corrosion rate) for each of the experiment that has been run. All corrosion test parameter details are based on previous experiments obtained from articles and journals.

Table 4.10 General Factorial Design with two process parameters and response on AISI 316L Stainless Steel

Experiment Number	Media	Duration (Days)	Corrosion Rate (mmpy)
1	L	1	0.4552
2	P	5	0.1077
3	P	3	0.0400
4	L	3	0.1563
5	T	2	0.1856
6	P	1	0.4174
7	L	4	0.1366
8	T	4	0.1152
9	T	1	0.4775
10	L	5	0.1584
11	P	4	0.0075
12	P	2	0.0822
13	L	2	0.2010
14	T	5	0.1238
15	T	3	0.1335

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Since there are two factors at different levels are under consideration to perform this experiment, a single replicate or unreplicated factorial was found as desirable design for this analysis. There is no internal estimate of error or pure error occurs white use of single replicate design.

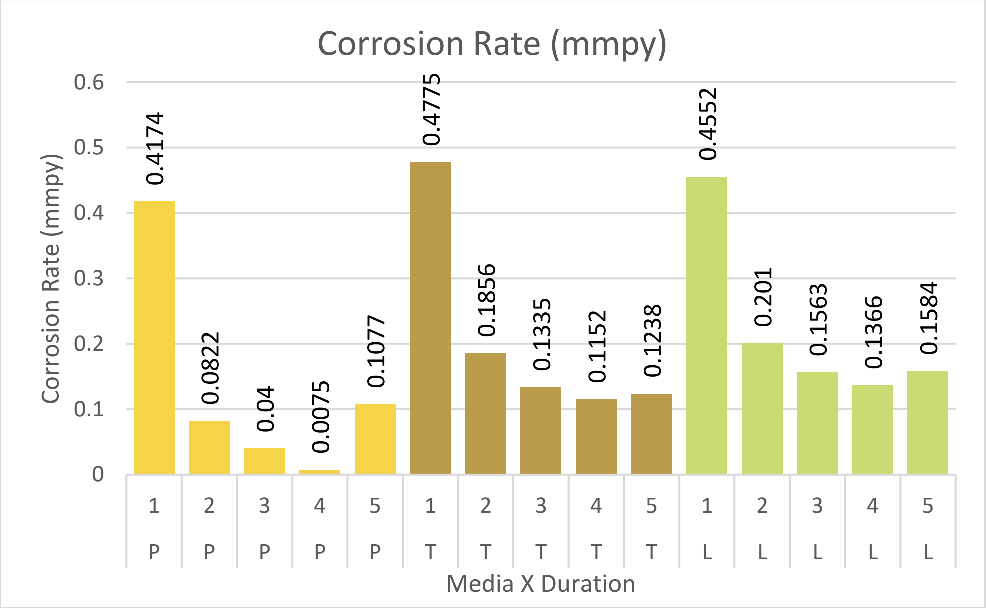

Figure 4.5 Corrosion Rate of Stainless steel in different media and immersion duration

From Figure 4.5 above, it shows that the highest corrosion rate is 0.4775mmpy, which obtained when 316L stainless steel was immersed in tamarind juice for immersion duration 1 (8 days). The lowest corrosion rate is obtained in pineapple juices for immersion time 4 (32 days) which is 0.0075mmpy. In addition, it can be seen that the corrosion rate at immersion duration 1 (8 days) for all three media, pineapple juice, tamarind juice and lime juice which are 0.4174mmpy, 0.4775mmpy and 0.4552mmpy, respectively.

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Table 4.11 Analysis of Variance (ANOVA) of general factorial design **(a)**

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	6	0.291981	0.048664	77.37	0.000
Linear	6	0.291981	0.048664	77.37	0.000
Medium	2	0.023674	0.011837	18.82	0.001
Duration (Days)	4	0.268307	0.067077	106.64	0.000
Error	8	0.005032	0.000629		
Total	14	0.297013			

(b) Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0250798	98.31%	97.04%	94.04%

The mean squares are combined to estimate the error. Table 4.11 (a) shown the analysis of variance result allows for a statistical analysis of the contributions of the variables on the corrosion rate of stainless steel with the corresponding F and P statistic. Since the P value for the model was less than 0.06, there was a statistical relation between the response (corrosion rate) and the selected variables at 95% confidence level. The adequacy of the model is good because there is a correlation between the dependent variable (corrosion rate) and the independent variable. This is proved in the R-sq value and R-sq(Adj) value in Table 4.11 (b) which are 98.31% and 97.04% respectively.

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To use model mathematical method, regression analysis was used to predict the value of a dependent variable (corrosion rate) based on the values of any independent variable and to establish a linear relationship between them, with factor A designated as a categorical predictor and factor B designated as a continuous predictor. The factor specification differs because factor A, unlike factor B, is not a numerical factor. The corrosion rate of stainless steel in three different media is represented by the regression equations 4.2 shown below.

$$\begin{aligned}\text{Corrosion Rate} = {} & 0.18653 - 0.05557\ \text{Medium\_P} + 0.02059\ \text{Medium\_T} \\ & + 0.03497\ \text{Medium\_L} \\ & + 0.2635\ \text{Duration (Days)\_1} - 0.0303\ \text{Duration (Days)\_2} \\ & - 0.0766\ \text{Duration (Days)\_3} - 0.1001\ \text{Duration (Days)\_4} \\ & - 0.0566\ \text{Duration (Days)\_5}\end{aligned} \tag{4.2}$$

4.5.2 Run Chart analysis

A run chart is a time-plotted line graph of data. Trends or patterns in the process can be discovered by collecting and charting data over time. Run charts is not describe if a process is stable because it does not use control limits. However, run chart is used to show how the process or experiment works. The run chart can be a useful tool early in a project or experiment because it reveals important information about a process before enough data collected to create reliable control limits (Walsh, 2015).

Table 4.12 Descriptive Statistics: Corrosion Rates

Variable	**N**	**Mean**	**SE Mean**	**StDev**	**CoefVar**	**Minimum**	**Maximum**
Corrosion Rate	15	0.1865	0.0376	0.1457	78.09	0.0075	0.4775

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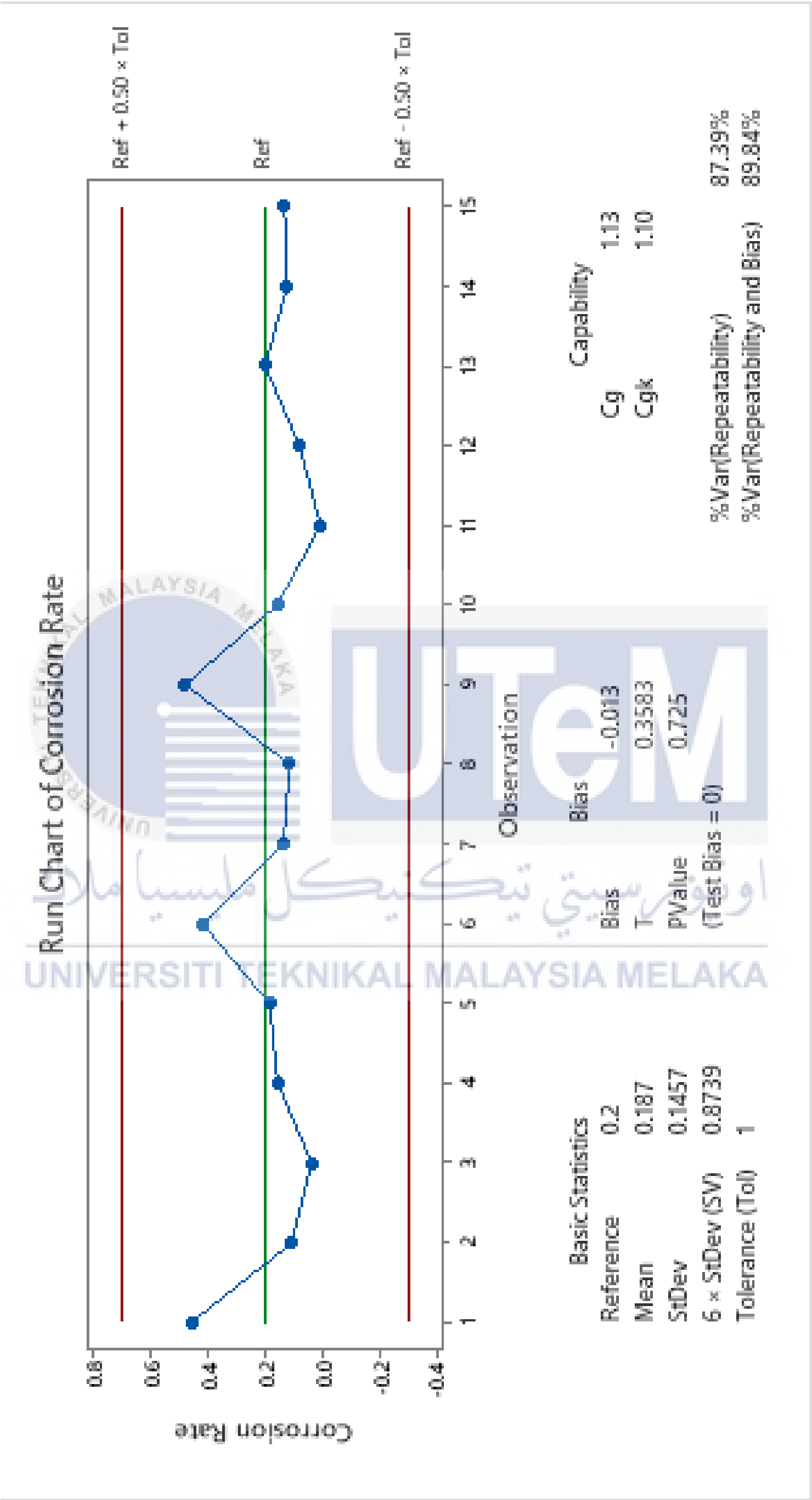
The various descriptive measures for corrosion rates of the experiment has been computed including mean, standard deviation, standard error, coefficient of variation (the variation relative to mean), minimum value and maximum values. Table 4.12 represent the descriptive measures for the experimental study.

From the analysis, descriptive measures reveal various aspect of data. Notably, the mean (0.1865) is a standard measure of the centre of the distribution of the data, standard deviation (0.1457) measurement of the average distance between each quantity and mean, standard error (0.0376) quantifies the accuracy of the estimator to estimate the parameter, coefficient of variation (78.09) tells us the ratio of the standard deviation to the mean (in percentage form), and minimum (0.0075) and maximum (0.4775) provide the range of the data. Descriptive statistics are useful for compressing large amounts of data into a few useful segments of data.



Basic Statistics

Reference	0.2
Mean	0.187
StDev	0.1457
6 × StDev (SV)	0.8739
Tolerance (Tol)	1

Bias

Bias	-0.013
T	0.3583
PValue (Test Bias = 0)	0.725

Capability

Cg	1.13
Cgk	1.10

%Var(Repeatability)	87.39%
%Var(Repeatability and Bias)	89.84%

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Figure 4.6 Run chart for experimental data

Figure 4.6 above shows the run chart of the corrosion rate for 316L Stainless Steel. This run chart was created using a type I gauge study, which aids in assessing the capability of a measurement process by combining the effects of bias and repeatability. It computes the amount of observed process variation caused by measurement system variation. The run chart has been constructed using the corresponding measurements as below:

i) Reference: 0.2 (to be around the centre)

ii) Tolerance: upper specification − lower specification = 1. (to capture the measurement variation within the tolerance bounds)

iii) Study variation: 6.0 (to estimate the variation in the measurements; the default choice is 6)

From the run chart above, the bias of the measurement system is indicated as -0.012. The resulting T value is 0.3583, and the corresponding P value is 0.725. Because the p-value is greater than 0.05, the null hypothesis, H_0, for the test bias = 0 is accepted. Besides, there are two capability indices has been considered in this analysis which are Cg and Cgk. The result is given as Cg = 1.13 and Cgk = 1.10 which both capability indices are less than the commonly used benchmark value of 1.33. Implying that, the measurement system for this experiment is insufficient and needs to be improved.

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4.5.3 Interaction Plot analysis

The identification of active and real effects is obtained with the help of Pareto and main effect plots (Antony, 2014). Figure 4.7 indicate that two factors A and B were found to be statistically significant at 5% significance level. A significance level also known as alpha or α means that there is a risk of a factor effect or interaction is significant when in fact it is not (Frost, 2017). The Pareto plots indicate that duration(days) is the active factor effect, followed by media.

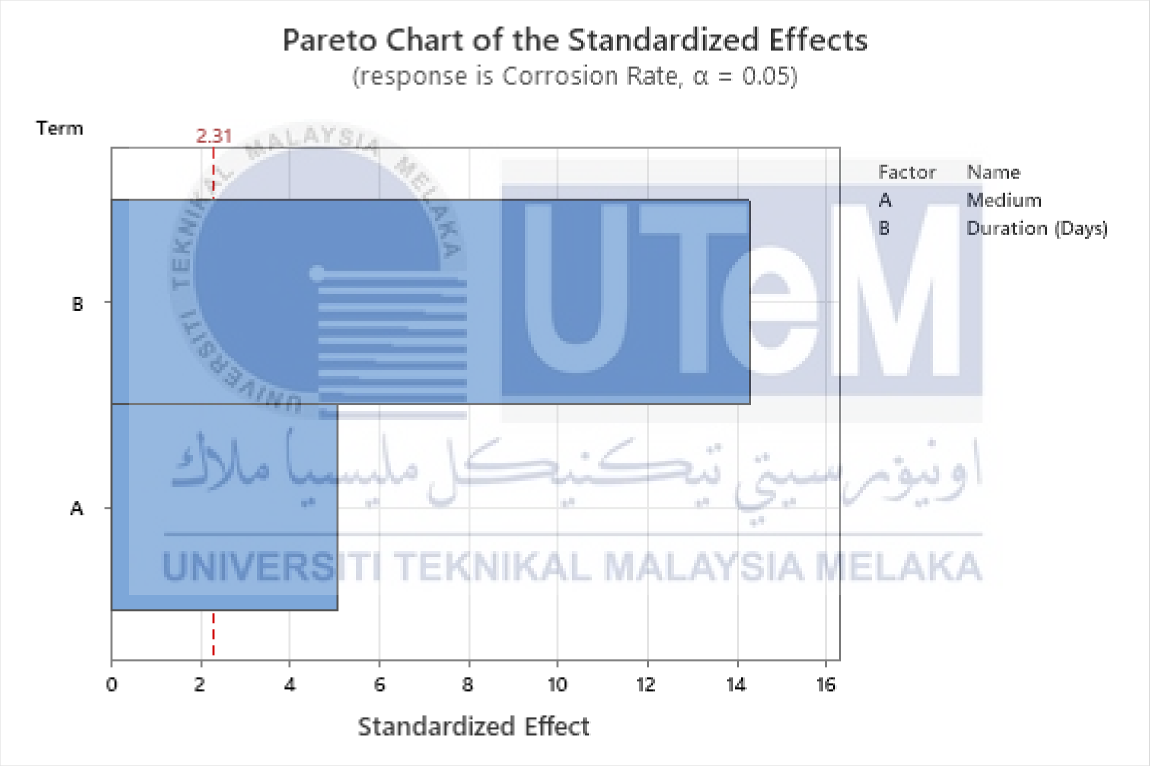

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Figure 4.7 Pareto chart of the Standardized Effects

The primary purpose of the main effects plot is to compare changes in the means in order to identify the most categorical variable that influences the response (Hessing, 2013). The means for each group within a categorical variable are displayed. According to this main effect plot (Figure 4.8), media L (lime juice), appears to be associated with the highest mean corrosion rate followed by tamarind juice. Figure 4.8 also illustrates that increasing the immersion days cause decreasing for mean of corrosion rate.

Different from main effects plot which illustrate the influence of each factor on the material under study (316L stainless steel), the interaction plot provides the effect of two or more process variables on the response (corrosion rate). Figure 4.9 shows the interaction effect of the means of corrosion rate between media (P, T, L) and duration (Days). Interaction between media and duration (days) was found to be significant since the lines are not parallel, and the slope of these variables is not horizontal. The changes in the mean response (corrosion rate) of 316L stainless steels in various media from low to high levels of process variable are dependent on the level of the second process variable. This demonstrates that the combination of immersion time and media (fruit juice) has a significant impact on the corrosion rate of 316L stainless steel.

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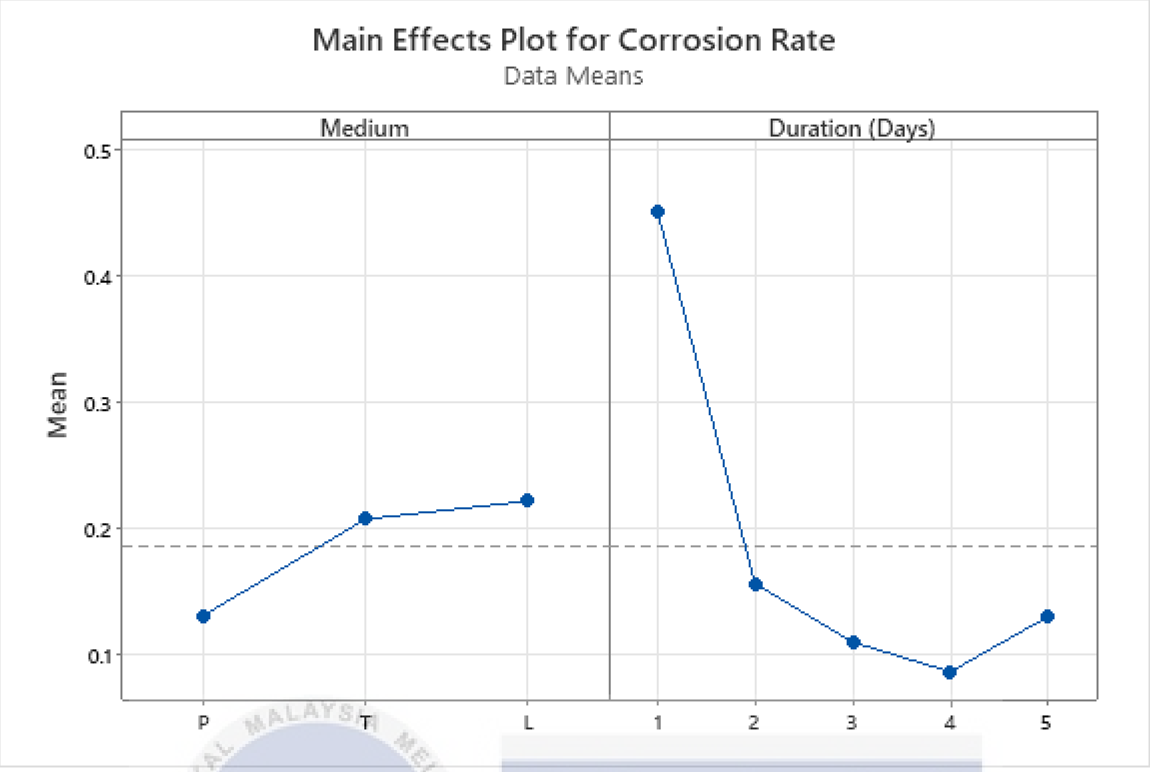

Figure 4.8 Main effect plots for corrosion rate means

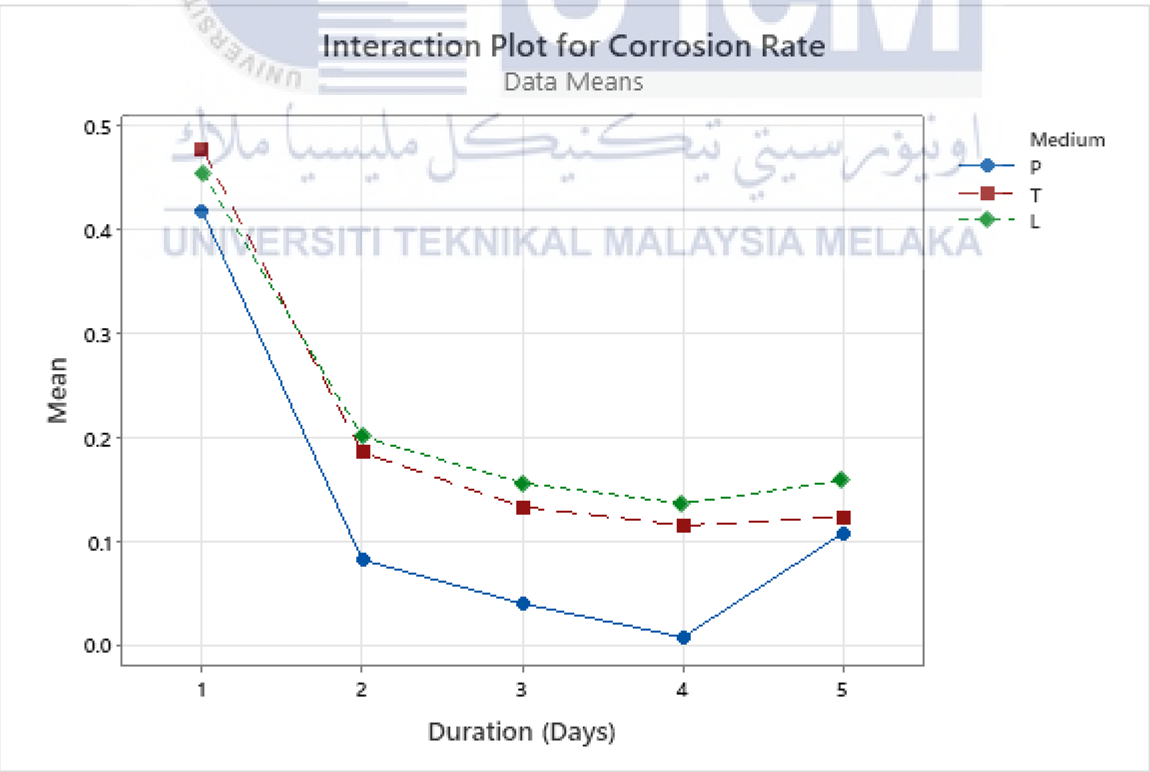

Figure 4.9 Interaction Plot for corrosion rate of 316L stainless steel

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4.5.4 Residual Plot

To validate the underlying assumptions in ANOVA, residual analysis was performed. The assumptions are that equation 3.1 adequately describes the observations and that the error terms are normally and independently distributed with a mean of zero and an unknown but constant variance. Figure 4.10 is a residual plot for corrosion rates of 316L stainless steel showing the accuracy of the model used. This plot contains nothing unusual because the residual is seen to be fairly distributed along the mean line and there is no possible outlier that reveals any non-normality in the distribution. Furthermore, the residual in time sequence plot is satisfactory because there is no positive correlation indicating a violation of the independence assumption, and finally, the residual versus fitted value plot shows a structureless pattern indicating that the constant variance assumption is met.

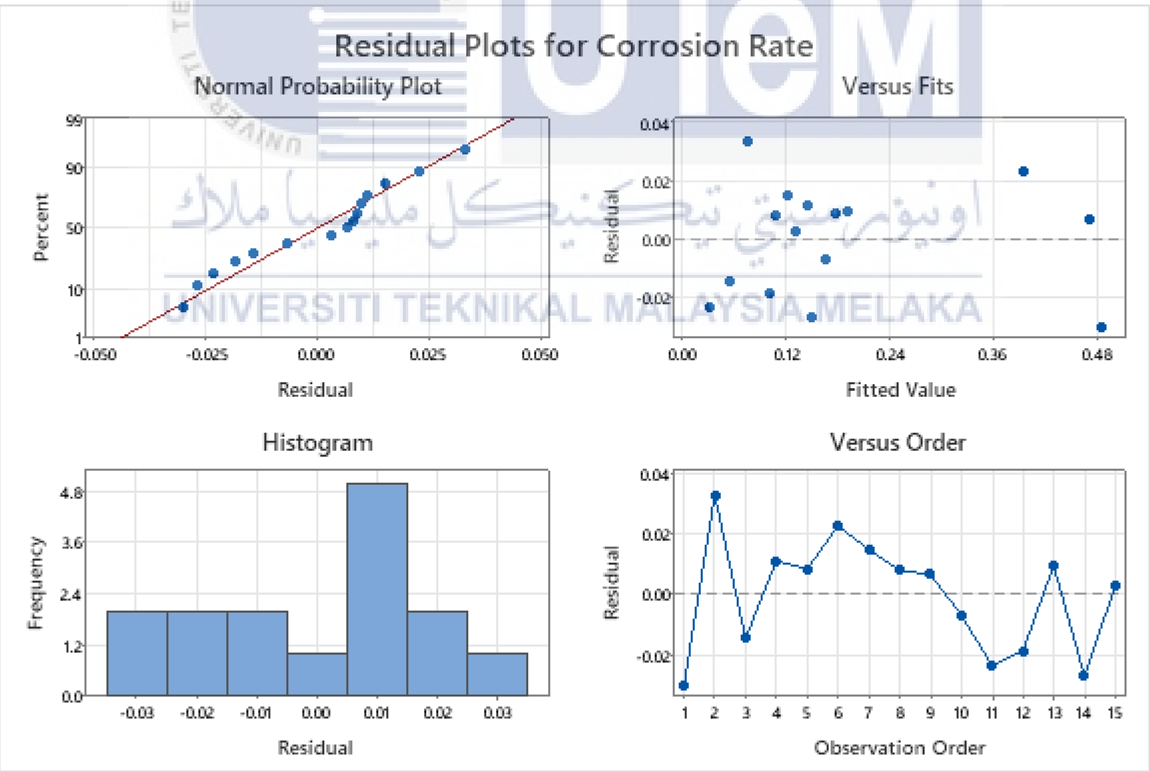

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Figure 4.10 Residual plot for corrosion rates of stainless steel

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The purpose of this study is to investigates the corrosion rate of AISI 316L stainless steel in Malaysian tropical fruit juice environment by using factorial experimental design (DOE). Specifically, the objective of this study is to design the experimental matrix for single replicate factorial design with factor such as media and duration for corrosion analysis.

- The experimental matrix for a single replicate factorial design completing the 15 experiments has been successfully designed by using 2 factors duration (days) and media (pineapple, tamarind and lime) as independent variables at three and five levels, respectively.

The second objective it to examine the corrosion rate of AISI 316L stainless steel in various Malaysian tropical fruit juices media by using weight loss technique.

- The highest corrosion rate is 0.4775mmpy, which obtained when 316L stainless steel was immersed in tamarind juice for immersion duration 1 (8 days).
- The lowest corrosion rate is obtained in pineapple juices for immersion time 4 (32 days) which is 0.0075mmpy.
- The corrosion rate in the first week of the experiment was high while it decreased towards the end of the experimental process.

Last but not least, the third objective for this study is to analyse the corrosion rate of AISI 316L Stainless steel in various Malaysian tropical fruit juice media by using ANOVA method.

- Analysis of variance results are successfully developed with the significant P-value.
- The regression equation was successfully developed from this analysis which can be used to calculate the corrosion rate of stainless steel for a similar condition with a very high accuracy (equation 4.2).
- The run chart of the corrosion rate for 316L Stainless Steel was successfully created by using a type I gauge.
- The residual versus fitted value plot shows a structureless pattern indicating that the constant variance assumption is met.

5.2 Recommendations

The current study reveals several areas that require future evaluation. Therefore, there are some recommendations for future research as below;

a) More research should be conducted in the future to increase knowledge on the corrosion situation on kitchen utensils with various independent variables such as corrosion rate at different media temperatures.

b) The experimental methods of corrosion experiments need to be improved by changing to electrochemical method which much faster than weight-loss method.

c) Investigations on other foods related to direct contact with foods such as milk (casein) which are widely manufactured in factories using metal-based machines.

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APPENDICES

APPENDIX A Measurement for each sample

Sample	Actual size without hole		Actual size with hole			
			Area, m^2		Volume, m^3	
	w	h	hole	area	hole	volume
P1 a	19.4	49.2	28.26	926.22	25.434	833.598
P1 b	19.4	49.2	28.26	926.22	25.434	833.598
P1 c	19.5	49.2	28.26	931.14	25.434	838.026
P1 d	19.4	49.5	28.26	932.04	25.434	838.836
P1 e	19.4	49.5	28.26	932.04	25.434	838.836
P2 a	19.5	49.6	28.26	938.94	25.434	845.046
P2 b	19.4	49.5	28.26	932.04	25.434	838.836
P2 c	19.4	49.5	28.26	932.04	25.434	838.836
P2 d	19.5	49.4	28.26	935.04	25.434	841.536
P2 e	19.5	49.5	28.26	936.99	25.434	843.291
P3 a	19.4	49.4	28.26	930.1	25.434	837.09
P3 b	19.4	49.4	28.26	930.1	25.434	837.09
P3 c	19.5	49.4	28.26	935.04	25.434	841.536
P3 d	19.5	49.5	28.26	936.99	25.434	843.291
P3 e	19.5	49.4	28.26	935.04	25.434	841.536
P4 a	19.5	49.5	28.26	936.99	25.434	843.291
P4 b	19.4	49.5	28.26	932.04	25.434	838.836
P4 c	19.4	49.4	28.26	930.1	25.434	837.09
P4 d	19.4	49.4	28.26	930.1	25.434	837.09
P4 e	19.4	49.3	28.26	928.16	25.434	835.344
P5 a	19.4	49.5	28.26	932.04	25.434	838.836
P5 b	19.6	49.5	28.26	941.94	25.434	847.746
P5 c	19.5	49.4	28.26	935.04	25.434	841.536
P5 d	19.3	49.4	28.26	925.16	25.434	832.644
P5 e	19.4	49.3	28.26	928.16	25.434	835.344
T1 a	19.3	49.4	28.26	925.16	25.434	832.644
T1 b	19.4	49.4	28.26	930.1	25.434	837.09
T1 c	19.4	49.3	28.26	928.16	25.434	835.344
T1 d	19.4	49.5	28.26	932.04	25.434	838.836
T1 e	19.4	49.4	28.26	930.1	25.434	837.09
T2 a	19.5	49.3	28.26	933.09	25.434	839.781
T2 b	19.3	49.4	28.26	925.16	25.434	832.644
T2 c	19.3	49.4	28.26	925.16	25.434	832.644
T2 d	19.3	49.3	28.26	923.23	25.434	830.907

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T2 e	19.3	49.3	28.26	923.23	25.434	830.907
T3 a	19.4	49.3	28.26	928.16	25.434	835.344
T3 b	19.3	49.3	28.26	923.23	25.434	830.907
T3 c	19.3	49.4	28.26	925.16	25.434	832.644
T3 d	19.4	49.3	28.26	928.16	25.434	835.344
T3 e	19.4	49.3	28.26	928.16	25.434	835.344
T4 a	19.3	49.2	28.26	921.3	25.434	829.17
T4 b	19.3	49.3	28.26	923.23	25.434	830.907
T4 c	19.3	49.4	28.26	925.16	25.434	832.644
T4 d	19.4	49.4	28.26	930.1	25.434	837.09
T4 e	19.4	49.3	28.26	928.16	25.434	835.344
T5 a	19.3	49.3	28.26	923.23	25.434	830.907
T5 b	19.5	49.4	28.26	935.04	25.434	841.536
T5 c	19.3	49.3	28.26	923.23	25.434	830.907
T5 d	19.3	49.3	28.26	923.23	25.434	830.907
T5 e	19.3	49.5	28.26	927.09	25.434	834.381
L1 a	19.3	49.3	28.26	923.23	25.434	830.907
L1 b	19.4	49.4	28.26	930.1	25.434	837.09
L1 c	19.3	49.3	28.26	923.23	25.434	830.907
L1 d	19.7	49.8	28.26	952.8	25.434	857.52
L1 e	19.4	49.4	28.26	930.1	25.434	837.09
T2 a	19.3	49.5	28.26	927.09	25.434	834.381
T2 b	19.3	49.5	28.26	927.09	25.434	834.381
T2 c	19.5	49.3	28.26	933.09	25.434	839.781
T2 d	19.4	49.5	28.26	932.04	25.434	838.836
T2 e	19.4	49.4	28.26	930.1	25.434	837.09
T3 a	19.4	49.3	28.26	928.16	25.434	835.344
T3 b	19.4	49.4	28.26	930.1	25.434	837.09
T3 c	19.5	49.4	28.26	935.04	25.434	841.536
T3 d	19.6	49.8	28.26	947.82	25.434	853.038
T3 e	19.6	49.9	28.26	949.78	25.434	854.802
T4 a	19.4	49.3	28.26	928.16	25.434	835.344
T4 b	19.4	49.3	28.26	928.16	25.434	835.344
T4 c	19.3	49.4	28.26	925.16	25.434	832.644
T4 d	19.3	49.5	28.26	927.09	25.434	834.381
T4 e	19.7	49.9	28.26	954.77	25.434	859.293
T5 a	19.3	49.3	28.26	923.23	25.434	830.907
T5 b	19.4	49.4	28.26	930.1	25.434	837.09
T5 c	19.4	49.4	28.26	930.1	25.434	837.09
T5 d	19.3	49.4	28.26	925.16	25.434	832.644
T5 e	19.6	49.8	28.26	947.82	25.434	853.038

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APPENDIX B Value obtained for each sample

Sample	Weight loss, mg	Exposure Area, m^2	Average Exposure Area, m^2	Weight Loss, mg	Volume, m^3	Density, mg/m^3	Average density, mg/m^3	Exposure time, h
P1 a	5.6	926.220	929.532	10	833.598	7.556	7.52594	168
P1 b		926.220		3	833.598	7.541		
P1 c		931.140		3	838.026	7.494		
P1 d		932.040		4	838.836	7.490		
P1 e		932.040		8	838.836	7.549		
P2 a	2.2	938.940	935.01	9	845.046	7.446	7.46688	336
P2 b		932.040		15	838.836	7.545		
P2 c		932.040		7	838.836	7.466		
P2 d		935.040		-28	841.536	7.375		
P2 e		936.990		8	843.291	7.503		
P3 a	1.6	930.100	933.454	4	837.09	7.458	7.44614	504
P3 b		930.100		3	837.09	7.374		
P3 c		935.040		4	841.536	7.490		
P3 d		936.990		-12	843.291	7.395		
P3 e		935.040		9	841.536	7.514		
P4 a	0.4	936.990	931.478	3	843.291	7.395	7.47835	672
P4 b		932.040		4	838.836	7.497		
P4 c		930.100		6	837.09	7.519		
P4 d		930.100		-15	837.09	7.426		
P4 e		928.160		4	835.344	7.555		
P5 a	6.6	932.040	932.468	8	838.836	7.512	7.49662	768
P5 b		941.940		11	847.746	7.398		
P5 c		935.040		3	841.536	7.398		
P5 d		925.160		3	832.644	7.513		
P5 e		928.160		8	835.344	7.563		
T1 a	6.4	925.160	929.112	7	832.644	7.554	7.52264	168
T1 b		930.100		7	837.09	7.483		
T1 c		928.160		6	835.344	7.535		
T1 d		932.040		7	838.836	7.509		
T1 e		930.100		5	837.09	7.532		
T2 a	5	933.090	925.974	2	839.781	7.627	7.58665	336
T2 b		925.160		5	832.644	7.560		
T2 c		925.160		5	832.644	7.578		
T2 d		923.230		8	830.907	7.593		
T2 e		923.230		5	830.907	7.575		

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T3 a	5.4	928.160	926.574	5	835.344	7.606	7.58636	504
T3 b		923.230		5	830.907	7.595		
T3 c		925.160		6	832.644	7.563		
T3 d		928.160		8	835.344	7.588		
T3 e		928.160		3	835.344	7.579		
T4 a	6.2	921.300	925.59	8	829.17	7.591	7.57935	672
T4 b		923.230		5	830.907	7.603		
T4 c		925.160		10	832.644	7.563		
T4 d		930.100		4	837.09	7.565		
T4 e		928.160		4	835.344	7.575		
T5 a	7.6	923.230	926.364	7	830.907	7.563	7.55677	768
T5 b		935.040		6	841.536	7.523		
T5 c		923.230		8	830.907	7.584		
T5 d		923.230		10	830.907	7.580		
T5 e		927.090		7	834.381	7.534		
L1 a	6.2	923.230	931.892	8	830.907	7.609	7.62075	168
L1 b		930.100		1	837.09	7.487		
L1 c		923.230		8	830.907	7.843		
L1 d		952.800		7	857.52	7.600		
L1 e		930.100		7	837.09	7.565		
T2 a	5.4	927.090	929.882	8	834.381	7.578	7.53101	336
T2 b		927.090		3	834.381	7.533		
T2 c		933.090		4	839.781	7.495		
T2 d		932.040		5	838.836	7.507		
T2 e		930.100		7	837.09	7.543		
T3 a	6.4	928.160	938.18	5	835.344	7.606	7.58786	504
T3 b		930.100		7	837.09	7.562		
T3 c		935.040		4	841.536	7.556		
T3 d		947.820		8	853.038	7.600		
T3 e		949.780		8	854.802	7.615		
T4 a	7.4	928.160	932.668	5	835.344	7.556	7.57295	672
T4 b		928.160		7	835.344	7.590		
T4 c		925.160		5	832.644	7.573		
T4 d		927.090		11	834.381	7.522		
T4 e		954.770		9	859.293	7.624		
T5 a	9.8	923.230	931.282	5	830.907	7.592	7.57681	768
T5 b		930.100		10	837.09	7.520		
T5 c		930.100		10	837.09	7.610		
T5 d		925.160		13	832.644	7.563		
T5 e		947.820		11	853.038	7.600		

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APPENDIX C Gantt Chart For PSM 1

Activity	Weeks														
PSM 1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
PSM 1 Briefing	🟩								MID SEM BREAK						
Registration and Selection of supervisor	🟩	🟩													
Registration of the title and submit into online system	🟩	🟩													
Confirmation of PSM Title	🟩	🟩													
Meeting with supervisor	🟩				🟩		🟩					🟩			
Chapter 1 expalination by supervisor	🟩														
Writing Chapter 1		🟩	🟩	🟩	🟩	🟩	🟩	🟩 ●		🟩	🟩	🟩	🟩	🟩	
Chapert 1 Consultation					🟩										
Correction on chapter 1 and submit to supervisor						🟩	🟩	🟩							
Chapter 2 explaination by supervisor							🟩								
Submision of TOC Chapter 2								🟩							
Writing Chapter 2										🟩	🟩	🟩	🟩	🟩	
Submision of TOC Chapter 3												🟩 ●			
Chapter 3 explaination by supervisor												🟩			
Writing Chapter 3												🟩	🟩	🟩 ●	
Writing Chapter 4														🟩	
Submit draft report on Chapter 2,3 and 4														🟩 ●	
Correction on Draft Report														🟩	
Submit finalize PSM 1 report to ePSM														🟩	
Preparation of slide and video presentation														●	🟩
Submition of slide and video presentation															🟩

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APPENDIX D Gantt Chart for PSM 2

Activity	Weeks													
PSM 2	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Revice previous study	🟩 🟪													
Meeting with supervisor	🟩 🟪													
Surface Roughness Test on Raw Material		🟩 🟪												
Preparation of Stainless Steel Sample			🟩 🟪											
Medium Preparation		🟪		🟩										
Corrosion Test				🟩 🟪	🟩 🟪	🟩 🟪	🟩 🟪	🟩 ● 🟪	🟪					
Data Measurement				🟪	🟩 🟪	🟩 🟪	🟩 🟪	🟩 ● 🟪	🟪					
Data Analysis using Minitab Software		🟪							🟩 🟪	🟩 🟪	🟩 🟪	🟩 ● 🟪	🟩 🟪	
Writing PSM 2 Report	🟩	🟩	🟩	🟩	🟩 🟪	🟩 🟪	🟩 🟪	🟩 🟪	🟩 🟪	🟩 🟪	🟩 🟪	🟩 🟪	🟩 🟪	
Submition PSM 2 Draft Report										🟩	🟩 🟪		🟩 ● 🟪	
Submision draft 4 page summary													🟩 🟪	
Submition Final PSM2 report, 4 pages summary, logbook													🟩 ● 🟪	
Sumbission MS Powerpoint Poster														🟩 🟪 ●

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Milestone for Gantt Chart PSM 1:

Description	Point	Week
Completion of introduction	M1	8
Completion of literature review	M2	12
Completion of Methodology	M3	14
Completion of preliminary result	M4	14
Completion of final report	M5	14

Milestone for Gantt Chart PSM 2:

Description	Point	Week
Completion of corrosion test	M1	8
Completion of data measurement	M2	12
Completion of data analysis	M3	14
Completion of writing draft report	M4	14
Completion of final report	M5	14

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