CORROSION-WEAR SIMULATION OF AUTOMOTIVE ENGINE COMPONENT MATERIALS UNDER BIODIESEL

BY

SAFA YUSUF CETIN

A dissertation submitted in fulfilment of the requirement for the degree of Master of Science (Mechanical Engineering)

Kulliyyah of Engineering
International Islamic University Malaysia

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ABSTRACT

Biodiesel has become increasingly common and significant alternative to traditional petroleum fuel in recent years. However, biodiesel has some adverse effects such as susceptible to corrosion, oxidation and mixed wear to the engine components materials. Therefore, in this study, wear simulation of automotive engine component materials was done using computational fluid dynamics approach to develop to predict wear and corrosion behaviour of engine components materials and develop wear mechanism map. A pin-on-disc configuration was considered as a simulation model of wear under biodiesel whereby load was applied from pin to disc during the simulation process and corrosion behaviour was simulated using boundary box whereby biodiesel entered from the inlet section of the boundary box and left the system from the outlet section using three different types of steel materials. The relationship between wear rate, applied load and sliding velocity were simulated and discussed followed by the development of wear mechanism map. The corrosive and abrasive wear mixture were dominated for carbon steel and low-alloy steel. Stainless steel showed better wear-resistant behavior than other materials under biodiesel exposure. The individual wear map generated for the individual material is also discussed in the context of the wear mechanisms observed under biodiesel contact.

خلاصة البحث

أصبح وقود الديزل الحيوي بديلا شائعا ومهما بشكل متزايد لوقود البترول التقليدي في السنوات الأخيرة. ومع ذلك ، فإن وقود الديزل الحيوي له بعض الآثار الضارة مثل تعرضه للتآكل والأكسدة والتآكل المختلط لمواد مكونات المحرك. لذلك ، في هذه الدراسة ، تم إجراء محاكاة التآكل لمواد مكونات محرك السيارات باستخدام نهج ديناميكا الموائع الحسابية لتطوير التنبؤات بسلوك التآكلات لمواد مكونات المحرك وتطوير خريطة آلية التآكل. واعتبر تكوين دبوس (بُرغي)على القرص كنموذج محاكاة لإرتداء تحت وقود الديزل الحيوي حيث تم تطبيق الحمل من دبوس إلى القرص أثناء عملية المحاكاة وتم محاكاة سلوك التآكل باستخدام مربع الحدود حيث دخل وقود الديزل الحيوي من قسم مدخل مربع الحدود، وترك النظام من قسم منفذ باستخدام ثلاثة أنواع مختلفة من المواد الفولاذية. تم محاكاة العلاقة بين معدل التآكل والحمل المطبق وسرعة الانزلاق ومناقشتها متبوعا بتطوير خريطة آليّة التآكل. سيطر على خليط التآكل والكشط الكربوني والفولاذ الصلب منخفض السبائك. أظهر الفولاذ المقاوم للصدأ سلوكا أفضل مقاومة للاهتراء من المواد الأخرى تحت التعرض للديزل الحيوي. وتناقش أيضا خريطة التآكل الفردية التي تم إنشاؤها للمواد الفردية في سياق آليات التآكل التي لوحظت تحت اتصال وقود الديزل الحيوي.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Master of Science (Mechanical Engineering).

IR. DR. MASJUKI HJ. HASSAN
Emeritus Professor
Department of Mechanical Engineering
Kulliyyah of Engineering
International Islamic Universitiy Malaysia

Masjuki Haji Hassan
Supervisor

…………………………………..
Md. Abdul Maleque
Co-Supervisor

…………………………………..
Adib Hamdani Bin Rosli
Co-Supervisor

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Master of Science (Mechanical Engineering).

…………………………………..
Mohd Sultan Ibrahim
Internal Examiner

…………………………………..
Noor Azlina Hassan
External Examiner

This dissertation was submitted to the Department of Mechanical Engineering and is accepted as a fulfilment of the requirement for the degree of Master of Science (Mechanical Engineering).

…………………………………..
Fadly Jashi Darsivan
Head, Department of Mechanical Engineering

This dissertation was submitted to the Kulliyyah of Engineering and is accepted as a fulfilment of the requirement for the degree of Master of Science (Mechanical Engineering).

…………………………………..
Sany Izan Ihsan
Dean, Kulliyyah of Engineering

DECLARATION

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

Safa Yusuf Cetin

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Firstly, it is my utmost pleasure to dedicate this work to my dear parents and my family, who granted me the gift of their unwavering belief in my ability to accomplish this goal: thank you for your support and patience.

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LIST OF SYMBOLS

ΔG	Change in Gibbs free energy
n	Transferred number of electrons
F	Faraday constant
E	Reduction potential
E^0	Formal potential
E_{cell}	Cell potential
R	Universal gas constant
T	Temperature in kelvin
Q	Quotient of reaction
z	Ion change
σ	Equivalent stress
V	Worn volume
k_0	Wear coefficient
F	Applied load
L	Sliding distance
H	Material hardness
G	Weight loss
γ	Material density
a	Thermal diffusivity
v	Velocity
r_0	Radius of the contact area

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Materials selection for automotive vehicle are important for the automotive industry. Automobile manufacturers focus on many parameters before manufacturing a car. Life, strength, usability, machinability, resistance to surface deformation and affordability are the important parameters for the selection of the materials. Furthermore, automotive engine component materials especially metallic materials with high resistance to corrosion, wear, weather and climatic conditions are indispensable for cars. Chemical and electrochemical reactions between metallic materials and their contact environment have a direct impact on the life and usability of metals. Furthermore, the combined effects of corrosion and wear make research in this field more important. Fuels which used in vehicles can cause surface failure. Corrosion and wear are the most common types of deformation in parts that come into contact with fuel. Besides, since fuels can cause wear, the materials used in the fuel sections in automobiles are also of great importance.

Biodiesel or biofuel is a renewable and clean energy that promising for the future. Producing from clean energy sources makes biodiesel attractive to use. However, despite its many positive properties, its corrosive behavior in contact with metals became biggest drawback of biodiesel. Biodiesel has a corrosion effect on metals due to its oxygen content and hygroscopic properties. Corrosion effect acts from the moment the fuel meets the tank to the combustion process in engine. That’s why, the process of selecting materials that come into contact with fuel is very important.

Nowadays, automobile industry manufacturers continue to work and innovate on many different types of metals. Metal parts can be corroded due to environmental effects. However, some of materials much more prone to corrosion than others. On the other hand, some of metals which are called as noble metals, more resistant to corrosion than others (viz. silver, platinum, gold, and palladium). Stainless steels are often used in many industrial applications including automotive. It is known to have high corrosion resistance. Moreover, it has many metallurgical advantages, such as excellent corrosion resistance, high mechanical properties, high ductility, good forming and heat resistance. Because of these properties, it is widely used in practices such as heat exchangers, tanks and ships for industrial processes such as food industry, chemical, pharmaceutical, paper etc. (Nguyen and Vu, 2019), (Gergely et al. 2018). In addition, it is very preferred in environments that can cause corrosion and wear. In studies, due to the presence of alloy chromium content (≤11 wt %), the formation of a chromium oxide-based passive film on the surface of stainless steel increases corrosion resistance (Solomon and Solomon, 2017).

Carbon steels are widely used in industrial applications due to their different physical properties and low cost. However, they can be corroded due to harsh environmental conditions which they are located (Guo et al. 2017). Carbon steels have high mechanical characteristics and low carbon ratio (up to 0.3%). These steels are easily found and inexpensive. They are highly preferred in industrial work, especially in applications containing acidic environment and in many areas such as petrochemical, pure oil processing (Abd El-Lateef and H. M., 2020). Carbon steel is classified according to the ratio of carbon content. They are categorized in three different ways;

- (<0.25% C) low carbon steels,

- (0.25-0.70% C) medium carbon steels,

- (0.70– 1.05% C) and high carbon steels.

The change in the percentage of carbon content allows different mechanical properties such as strength, ductility, hardness etc. (Dwivedi et al., 2017).

Low alloy steel is the combination of various alloying elements such as Ni, Cr and Mo with %1 or less carbon steel (Ijiri and Yoshimura, 2018). Low alloy steels are mostly used for the production of pipes, automotive industry, railway lines, structural engineering plates and for many more applications. It preferred in automobile industry due to its high strength and corrosion resistance properties.

1.2 PROBLEM STATEMENT AND ITS SIGNIFICANCE

Biodiesel is constructed from hydrogen bonds with water, therefore it is more hygroscopic than diesel that is composed of hydrocarbons. The other chemical compositions or constituents of biodiesel such as dissolved water, free water and emulsified water accelerate oxidation of metallic materials. Therefore, corrosive behavior in contact with metals became biggest drawback of biodiesel. During combustion process, biodiesel contributes to the corrosive wear of the engine components. This is due to the increasing acidity of the biodiesel as the acidic components disintegrate during the combustion process. The most well-known of the factors that causes corrosion is the oxidation effect induced by oxygen. It is also believed that biodiesel's hygroscopic properties are greater than diesel which lead to more corrosive phenomenon than diesel fuels (Haseeb et al., 2011). Research on the tribocorrosion and engine properties of diesel fuel and diesel mixtures of Aegle Marmelos Correa (known as biodiesel) with B10, B20, B50, B60, B90 and B100 concluded that the lowest steady-state coefficient of friction was achieved with B50 amongst all biodiesel-diesel blends. On the other hand, the B100 provides satisfactory performance in the diesel engine with its effect of reducing NO, HC, CO and filter smoke emission. (Thangarasu et al., 2019). However, methyl ester in biodiesel also has an adverse effect on the degradation properties of biodiesel. A study on this subject was conducted on Karanja and coconut biodiesel (Jose and Anand, 2016) to compare the degradation properties. Karanja biodiesel has a higher unsaturated methyl ester content compared to coconut biodiesel. Therefore, they concluded that the degradation rate of Karanja biodiesel is higher than that of coconut biodiesel due to sulfur in biodiesel. The lack of sulfur in biodiesel contributes significantly to the reduction of corrosion in areas where the fuel is in contact or stored. Fuel used in automobiles comes into contact with many static and dynamic metal parts such as fuel tank, fuel pump, fuel filter, engine valve, piston, and cylinder liner etc. Accordingly, the interaction of corrosion and wear between metal and biodiesel fuel is an important subject of study.

The simulation studies to be carried out in this field are of great importance in order to predetermine the corrosive behaviour of biodiesel on metals and to make the appropriate material selection. This study contributes to automotive industry to make a decision about materials which are using for cars based on the findings from this study. Moreover, with the help of this study new simulative analysis added to the literature. Technological development on automobile industry improves day-by-day. Regarding this development, automakers wants to create high resistant, high strength, usable and affordable materials to use in automobile. Like mentioned from before sections, the interaction of corrosion and wear between metal and biodiesel fuel is an important subject of study. Therefore, development of maps for such processes are vital to represent the transitions between the corrosive-wear regimes as a function of wear and corrosive variables. The significance of the corrosive-wear and their maps is to find the materials with wide range of variables when expose to biodiesel. This study contributes to decision makers to make better selection for automobile materials during production and designing process.

1.3 RESEARCH OBJECTIVES

The main purpose of this research is simulate the automotive component material corrosion-wear behaviour using ANSYS software under biodiesel condition. The specific objectives of this study are:

1. To investigate wear behaviour of stainless steel, carbon steel and low-alloy steel, with biodiesel under different process variables to evaluate effects of load, sliding velocity and equivalent stress on wear phenomena.
2. To analyze corrosion phenomena of materials to find the susceptibility of corrosion in biodiesel.
3. To simulate a corrosive-wear map of three different materials for the safe use of biodiesel in automotive applications.

1.4 RESEARCH METHODOLOGY

A planned work frame has been set up in order to achieve the objectives of this research. In addition, flowchart is shown in Figure 1.1. The fundamental research methodologies are:

i. Achieving to general knowledge about corrosion and wear effect of biodiesel on metallic materials.
ii. ANSYS/CFD based corrosion and wear simulation.
iii. Evaluation of stainless steel, carbon steel and low alloy steel behavior under exposure biodiesel.

iv. Corrosive wear map development

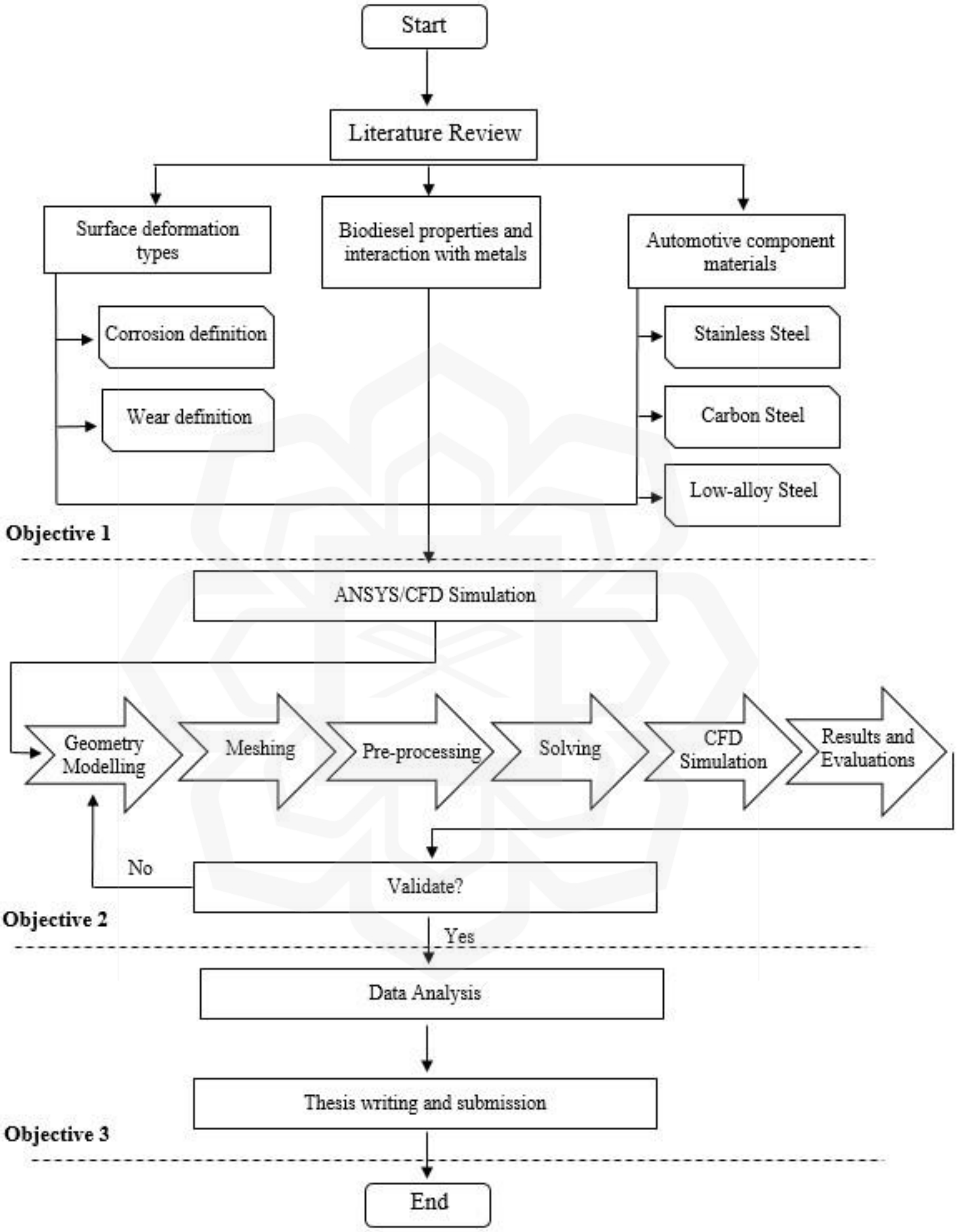

Fig. 1.1 Research process flow chart

1.5 RESEARCH SCOPE

The scope of this study covers the following areas:

- ANSYS based corrosion simulation and investigation of stainless steel, carbon steel and low-alloy steel with biodiesel under different process variables.
- Wear simulation of the selected materials with ANSYS.
- Characterization of the corrosion-wear phenomena in order to find the relationship between materials and biodiesel.
- Development of a wear map of the low-alloy steel, carbon steel and stainless steel for the safe use of biodiesel in automotive applications.

1.6 THESIS ORGANISATION

The current thesis has been organized into five chapters.

Chapter One presents an introduction to give an overview of the research work including background of the study and the problem statement and its significance. In addition, research objective and research methodology section are also explained in this chapter.

Chapter Two presents the general and comprehensive literature survey about the biodiesel characteristics, corrosion behavior of the common automotive materials, corrosion and wear behavior of selected materials under biodiesel exposure. Furthermore, corrosion and wear phenomena were explained in detail in this chapter and results related to previous studies were discussed. Extensive literature research on corrosion prevention methods has been carried out. Moreover, studies in this field and the effects of protection of the material from the corrosive environment were evaluated.

Chapter Three exhibits detailed explanation of the research methodology. Specifically presents, wear and corrosion simulation parameters, designing and meshing of the simulation samples.

Chapter Four establishes the results and discussion of corrosion-wear simulation. Behavior of selected material were examined according to results of ANSYS simulation software. Finally, corrosion and wear behavior of the stainless steel, carbon steel and low alloy steel were explained based on simulation work results.

Chapter Five presents a collective conclusion, contribution of knowledge and recommendation for the further works.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

Automobiles are usually made of metal components. Due to environmental conditions, these components may have deformation on their surfaces. The two most common types of these surface deformations are corrosion and wear. Besides to shortening the life of metal parts, corrosion and wear can cause collapses and deterioration in structures. That is why corrosion and wear are vital factor for the metallic material. In recent years, interest in biodiesel has been increasing due to the need for renewable energy sources. Biodiesel, which is a strong alternative to traditional petroleum fuels, attracts attention with its environmentally friendly structure. Besides all these positive properties, the corrosive behavior of biodiesel make biodiesel unsuitable for the long-term usage. It is very important to investigate the behavior of stainless steel, carbon steel and low-alloy steels which are commonly used in automobiles when in contact with biodiesel.

2.2 CORROSION

Corrosion can be defined as deformation of metal parts due to chemical reactions between metal and its environment. This is one of the events that causes the damage to metallic materials over time. Because of the corrosion, bridges and buildings can collapse and pipelines can be damaged. Corrosion is an important factor to consider when making any design in which metal will be used. Because it directly concerns the safety of the structure and the life of the building. It is difficult to observe the effect of corrosion over short periods of time, but as the time increases, it is possible to see much more clearly the destruction caused by corrosion. (ECS., 2016)

Many of the metals that we use are found in nature, bound by sulphur or oxygen. Because this form is one of the most stable states of chemical compounds. In order to remove these compounds from this form and turn them “pure metal”, energy must be used at very high temperatures. Metal compounds with sulphur and oxide are stable and inactive but metals that are purified by high energy are much more dynamic. This metals try to return to their former stable state by releasing this energy in their structure. This is the main reason why the metals we use in our structure corrode and wear out. The predisposition of metals to corrosion varies from element to element. But in general the more active metals prone to corrosion. In order to determine in advance whether corrosion will occur voluntarily or not, it can take a help from the laws of thermodynamic. For this, Gibbs change in free energy must calculate. If the change in Gibbs free energy is less than zero, it can be said that the event can occur voluntarily. On the other hand, if it is greater than zero it can be said that the event cannot occur voluntarily. Since it is accepted the ground where corrosion occurs as an electrochemical cell, the Gibbs change in free energy expression is (Namazian and Zare, 2005):

$$\Delta G = -nFE_{cell} \qquad \text{Eq. 2.1}$$

Since the cell is not in standard conditions (0 °C, 1 atm), the cell potential must be calculated using Nernst equation (Gulaboski et al., 2002).

$$E = E^0 - \frac{RT}{zF} * lnQ \qquad \text{Eq. 2.2}$$

After calculating the cell potential using equation (2.2), Gibbs free energy change is found. Then it is possible to predict whether corrosion will occur or not. Corrosion is also divided into different types according to the way it occurs. Figure 2.1 shows various types of corrosion.

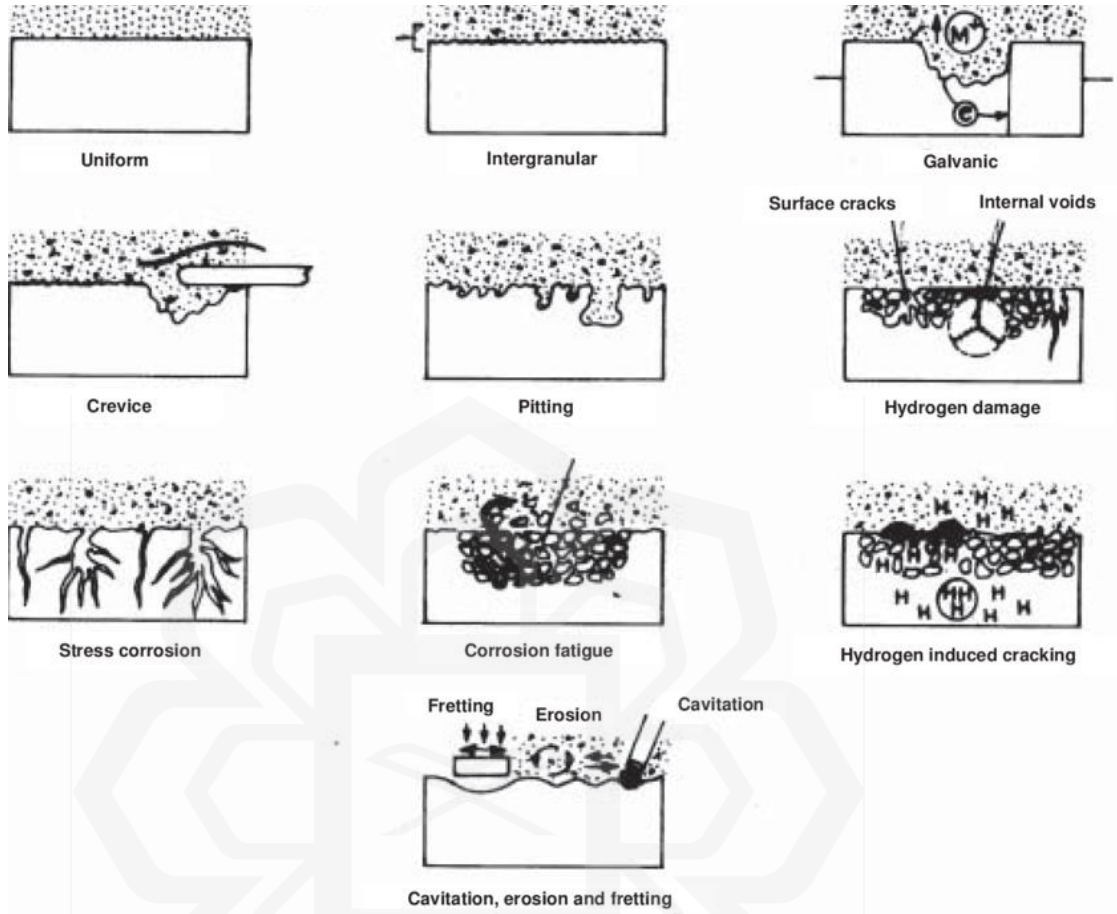

Fig. 2. 1 Various types of corrosion (Chaturvedi, 2009).

Uniform corrosion is a type of corrosion that occurs at the same rate in each region of the metal (Uniform Corrosion - NACE, 2016). Due to this type of corrosion is slightly easier to measure and predict that others, it rarely causes large-scale problems. If cavities occur from the metal surface due to corrosion, this is called pitting corrosion. This type of corrosion does not occur at the same speed in every area of the surface, unlike uniform corrosion. The anode and cathode are precisely separated from each other. Usually, when the surface protection layer is damaged or cracked, part of the metal becomes a cathode. It is very dangerous species as it has potential to completely pierce metal. According to Komariah et al. (2019) studied the behavior of carbon steel,