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A systematic review on corrosive-wear of automotive components materials

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ABSTRACT

The choice of automotive component material plays an important role to avoid corrosive-wear problem that encountered in moving and static parts due to fuels used in the engine. Biofuel or biodiesel has become increasingly common and significant alternative to traditional petroleum fuels in recent years. However, biodiesel has more corrosive properties compared to other fuels. Therefore, this paper reviews the effects of biodiesel fuel on corrosive-wear of the engine component materials that come in contact with biodiesel and its blend. This study was performed as a review of previous research and examined the corrosive-wear behavior of automotive components materials. The effect of biodiesel on corrosive-wear behavior has also been highlighted. Based on the previous research it can be said that corrosion resistance can keep in the desired range with the use of suitable material under biodiesel condition. The copper material is prone to corrosion against biodiesel, while stainless steel materials have high corrosion resistance. Furthermore, this study provides a way forward with corrosive-wear model design for biodiesel behavior in contact with different materials.

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1.0 INTRODUCTION

Corrosive-wear is a phenomenon of material removal from a material surface within wet or dry environment and is characterized by pitting in generally. In the literature, the term tribo-corrosion also refers to corrosive-wear. For particular material, corrosive-wear rate is always higher than the sum of corrosion rate and wear rate (Yang et al., 1994). In diesel engine, operating temperature, heat load and extended oil drain intervals deteriorate the fuel causing material removal due to corrosion to the engine component materials (Jie et al., 2018). Besides, the mechanical effects such as friction and wear can cause failure of the material at long operating time period (Nuraliza et al., 2016). In addition to the mechanical effects, corrosion by the reason of chemical or electrochemical effects causes deformation of the materials that come into contact with fuel. Acidic oxygen, sulfur and water in diesel fuel enhance the aging process that trigger corrosion (Abramek et al., 2015), (Perez, 2004). For the reduction of the corrosion, ultra-low sulfur diesel (ULSD) and low sulfur diesel (LSD) type fuels were introduced, and research indicated that ULSD combustion produces lower rates of carbon dioxide, sulfur and nitrogen oxides emissions (Lim et al., 2007). This positive approach provides positive impacts and continues to increase the use of such diesel fuel. However, this approach to the traditional petroleum fuels did not cast a veil over the damage of the environment. Furthermore, the rapid depletion of oil resources has increased interest in new and clean fuels.

The experience of the oil crisis has turned eyes to possible patches of alternative diesel fuel production with the name of "biodiesel" for the first time. However, with the frightening level of carbon emissions in the world and air pollution, biodiesel now came to the forefront. Biodiesel is a long chain fatty acid mono alkyl ester derived from vegetable oils using alcohol and catalyst (Jamal et al., 2019), (Folayan et al., 2019). Biodiesel has good lubrication properties than low sulfur petro diesel (Hamdan et al., 2018). However, being a clean energy, it has attracted a lot of attention in recent years as the traditional oil resources will begin to run out in the near future. Researchers are aware of this and have realized that the direction of research in this area should continue through renewable and future-oriented fuels. Furthermore, energy is the most important investment area when considering the country's economies and growth indices. The most demanding of energy is first the industrial sector and then the transport sector and occupying 30% of the total energy produced. In the transport sector, almost all energy is provided from fossil oil (97.6%). However, the reduced lifespan of fossil fuels and the environmental problems resulting from their use have accelerated research for alternative biodiesel (Mishra and Goswami, 2018). The emission of gas from biodiesel is also important consideration. Previous studies (Menichetti and Otto, 2009), (Beer at al., 2007) have examined greenhouse gas emission and fossil energy improvement in detail according to different oil groups. The results postulated that biofuels have changed their emissions along with the oil sources from which they are produced. On the contrary of diesel fuels, it has no net CO_2 emissions. Also, it releases less carbon monoxide, zero particulate matter, sulphur, smoke and hydrocarbons (Atabani et al., 2012), (Reddy et al., 2016). In the same patch, tribological issues on biodiesel drew attention for many years as various forms of surface problems may occur in presence of biodiesel (Maleque and Abdulmumin, 2014). The hygroscopic nature and oxidation of biodiesel might damage metal components of the automotive engine (Sazzad et al., 2016). Therefore, biodiesel has negative effect and impact especially on corrosion and wear behavior (together known as corrosive-wear) caused by their interaction with metals. Corrosion caused by contact of metals with biodiesel both reduces the life of metal parts and worsens the fuel properties which in turn negatively affects engine performance (Maleque et al., 2015). The main challenge of the automotive manufacturer is to overcome the damage of mechanical components engine that come into contact with the fuel typically, fuel tank, filter, fuel pumps and injector those exhibited corrosion-prone behavior (Hoang et al., 2019). The chemical compositions that biodiesel contains have an effect on corrosion. For example, the lack of sulfur in biodiesel is an important advantage, which guides to the reduction of corrosion in fuel containers (Hoang et al., 2019). Besides, sulfuric acid is one of the catalysts frequently used in biodiesel production and provides to biodiesel fuel corrosive properties (Aysu et al., 2016). The corrosive property of the fuel is directly related to the presence of dissolved oxygen in biodiesel and can cause corrosion of metal elements (Zuleta et al., 2012).

Wear is the loss of material caused by the transfer of material from one surface to another surface or formation of wear parts. The wear caused by friction of engineering materials that come into contact with each other causes great economic losses during the use of various machines and equipment. Wear intensity, wear particle shape and wear surface roughness give important information about the quality of wear (Gür, 2006). The main types of wear are: Adhesive wear, abrasive wear, fatigue wear and corrosive wear.

Corrosive wear is a type of wear caused by contact of the material surface with a chemical substance. In the first stage, the contact surfaces react with the environment and reaction products are formed on the surface. In the second stage, friction of the reaction products occurs as a result of crack formation and/or abrasion in the area where the interaction occurs at the contact points of the materials. Razavizadeh et al., (1982), studied the oxidation behavior of aluminum alloys and concluded that corrosive wear is formed by a combined process of oxidation, deformation, and fracture to form layers on the metal surface. Factors that affect the wear is presented in Figure 1.

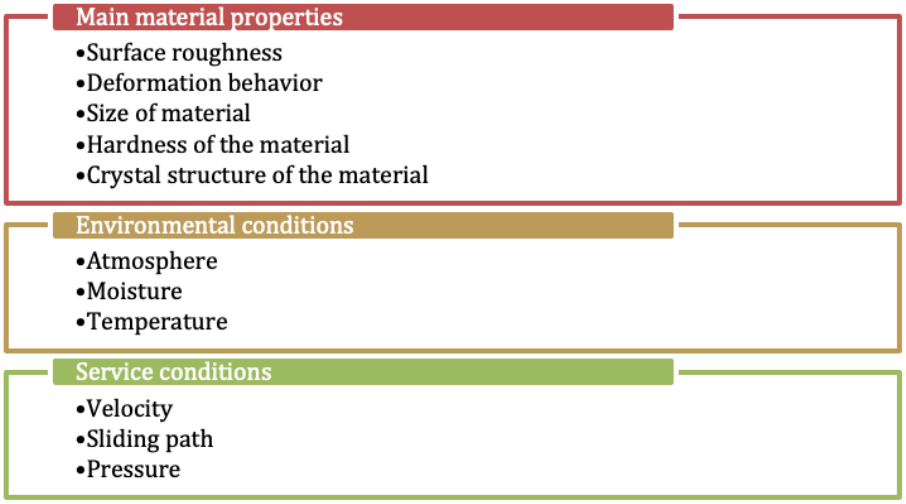

Figure 1: Factors that affect the wear.

2.0 EFFECT OF BIODIESEL ON CORROSIVE-WEAR

Biodiesel has particular importance for sustainability as it is derived from renewable resources. However, as mentioned in the previous section, corrosion and wear are the main disadvantages of biodiesel which can erode metal parts in vehicles and shorten the lifespan. Biodiesel fuels absorb more water than conventional petroleum diesels and also the electronegativity of oxygen causes corrosion and choking (Hoang et al., 2020). Besides, some of the properties of biodiesel such as dissolved water, free water and emulsified water accelerate oxidation of metallic materials (Suthisripok and Semsamran, 2018). During combustion process, the biodiesel contributes to the corrosive-wear of the engine component. This is due to the increasing acidity of the biodiesel as the acidic components disintegrate during the combustion process. It is also said that acid formation corrodes engine parts (Sriram and Kumar, 2011). The most well-known of the factors that causes corrosion is the oxidation effect induced by oxygen. Research shows that biodiesel's hygroscopic properties are greater than diesel. Therefore, biodiesel is more corrosive than diesel fuels (Belal and Maleque, 2013). Figure 2 shows the parameters that related to the corrosiveness of biodiesel. According to graph, it is clearly seen that, after biodiesel exposure, the formation of pits caused by corrosion attacks on metal is higher than diesel exposure. Besides, biodiesel's aggressive behavior on metals leads to curiosity about its effect on corrosive-wear.

The standards are aimed to prevent possible problems like corrosion and wear from the use of biodiesel in daily life. Moreover, safety and quality are important parameters for use of biodiesel. Therefore, the ANP (National Agency of Petroleum and Neutral Gas and Biofuels) established a standard to ensure safety and quality in all situations from fuel stations to vehicles fuel tanks. Besides, European standards have also been established to eliminate that may arise possible difference in working and environmental conditions. Standards are established taking into account many parameters such as density (specific mass), kinematic viscosity, flash point, sulfur content, copper strip corrosion, cetane number, cloud point, water content, maximum % mass of ethanol and methanol etc.

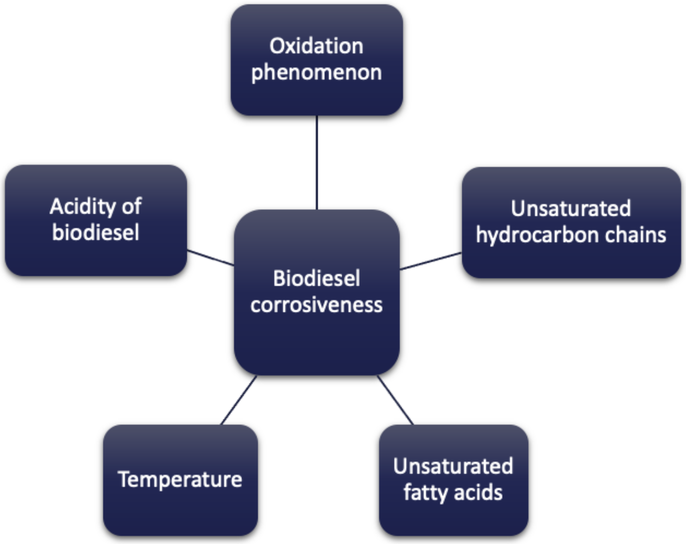

Figure 2: Biodiesel corrosiveness parameters.

Table 1: Quality standard of biodiesel for European and American Standards.

Parameters/Standards	**EN 14214**	**ANP (2007-2008)**
Flash point (minimum)	101 °C	100 °C
Sulphur content (maximum)	10 mg/kg	10 mg/kg
Acid value (maximum)	0.5 mgKOH/g	0.5 mgKOH/g
Ethanol and Methanol (maximum)	0.2 % of mass	0.2 % of mass
Water content (maximum)	500 mg/kg	380 mg/kg
Copper strip corrosion (maximum), (3hours)	1 (rate)	1 (rate)
Kinematic viscosity at 40 °C	3.5-5.0 kg/m^3	3-6 kg/m^3

Some of these parameters can trigger corrosion of the metal components. In example, corrosion can be accelerated with the increase of acid number. By the increasing of acidity, the degradation problems may occur in engine filters. Furthermore, the residual alcohol that presence in biodiesel can affect flash point and cetane number of biodiesels. Thus, it may cause corrosion of the metal parts (Munoz et al., 2012). Table 1 presents limitations of ANP and EN 14214 standards.

Many factors that affect corrosive wear phenomenon in engine components that come into contact with biodiesel are, auto-oxidation, unsaturated fatty acid (Lebedevas et al., 2013), (Gan and Ng, 2010) and unsaturated hydrocarbon chains (Fazal et al., 2011). In one study, the friction and wear characteristics of palm biodiesel using four-ball wear machine has been investigated and from the study, (Fazal et al., 2013) experimentation was conducted at 75 °C temperature and 600, 900, 1200 and 1500 rpm speeds with 4 different concentrated level of biodiesels (viz. B0, B10, B50, and B100). It was concluded that the friction and wear rate decreased with the increasing of biodiesel concentration.

The surface deformation of the metal's changes with the biodiesel blends ratio. However, it has been the subject of curiosity for years whether biodiesel produced from different sources is effective in corrosion and wear. In one of the studies, the tribo-corrosion and engine properties of biodiesel and diesel mixtures of Aegle Marmelos Correa was investigated (Thangarasu et al., 2019). In this study, diesel fuel and B10, B20, B60, B90 type mixtures/blends were used. As a result of the experiments, it was concluded that the B50 blend exhibited the lowest steady-state coefficient of friction.

The less corrosion effect was also observed from the same blend. However, it has been deduced that diesel fuel produces the lowest corrosion rate compared to other blends. This is because the removal of sulfur atoms that cause corrosion in diesel fuel to meet strict emission norms. On the other hand, the B100 produced more corrosion compared to diesel and B50. B10 and B20 produced more corrosion in all tested metals than diesel, B50 and B100 (Thangarasu et al., 2019). In another study, the corrosion behavior of copper-magnesium alloy, mild steel, aluminum and stainless steel were studied after exposing to a mixture of cooking oil methyl ester and commercial diesel using static immersion test method at room temperature for 965 hours whereby the biodiesel types were B0, B20, B40, B60, B80 and B100 (Fasogbon and Olagoke, 2016). Later, the same test was applied for 8 hours at temperatures of 40 °C, 60 °C, 80 °C and 100 °C. Consequently, it was observed that corrosion increases with increasing temperature in all biodiesel varieties. The highest corrosion rate was observed in biodiesel type B100, while the lowest corrosion rate was determined with B0. It has also been observed that copper-magnesium alloy has more corrosion than other metals. The characteristics of engine oil of B20 castor biodiesel and diesel fuel was evaluated using four stroke single cylinder diesel engine with tribological perspective (Arumugam and Sriram, 2012). At the end of the study, it was observed that B20 biodiesel showed higher concentration of copper in debris (112 ppm) compared to diesel fuel (73.9 ppm) those are mainly from the bushing and bearing wear. Hence, it is proven that biodiesel has more corrosive wear than diesel fuel. Moreover, castor biodiesel has higher oxidation value and is prone to corrosive-wear. Maleque et al., (2000) investigated the performance of palm oil methyl ester (5%) blended diesel fuel with tribological perspective with a steel-cast iron pair as the tribological experimentation set-up. At the end of the study, they found that the pits and corrosive-wear on the damaged surface were the dominant wear mode.

In other study, tribological performance of palm biodiesel (B10, B20, B50, and diesel fuel) at different temperature was studied by Haseeb et al., (2010). Four-ball wear machine was used, and experiment was carried out at fixed speed of 1200 rpm, fixed load of 40 kg, for 1 hour and at 4 specified temperatures such as 30 °C, 45 °C, 60 °C and 75 °C. The materials used in this study were, copper, brass, aluminum and cast iron. The study concluded that wear rate and surface deformation decrease with increasing biodiesel concentration. Also, worn surface deformation increases with the increasing of temperature. Besides, copper and copper-based alloys exhibited severe degradation when exposed to biodiesel and are not tribologically compatible. Metals may have different reactions to corrosion which may led to different lifespan either shorter or longer due to different level of corrosion-resistant and wear-resistant properties. In one study, the corrosion effect of rapeseed oil and methanol were examined on copper, mild carbon steel, aluminum and stainless steel (Hu et al., 2012). They mentioned that the effect of corrosion was clearly visible on copper and mild carbon steel surface. However, in the same note, they also highlighted that aluminum and stainless steel are more resistant to corrosion. Another study examined the corrosion behavior of different grades of stainless steel such as AISI 316L, AISI 904L, Sanicro 28 austenitic stainless steel, SAF 2205, SAF 2507 and SAF 2707 duplex stainless steels (Bellezze et al., 2018). During the experiment, a saturated solution of tartaric acid was used. This solution also contains a strong acid mixture of H_2SO_4 and HCl. Two different temperatures of 40 and 60 °C were considered, weight loss and corrosion were examined on the materials. At the end of the study, it is found that all duplex stainless steels were subjected to severe corrosion. The corrosion penetrates the material until mixture is separated leading to a high weight loss in stainless steels. In other study, the corrosion behavior of engine components made of metal when exposed to biodiesel was examined (Nguyen and Vu, 2019). In the first phase of the study, an analysis of the corrosion mechanisms of metals exposed to biodiesel was conducted. Static immersion testing was used as an experimental method. Then the level of corrosion of metal strips was measured and analyzed. Stainless steels appear to be resistant to pitting corrosion. It was observed that copper has the highest corrosion property, followed by aluminum, the material with the most corrosion property. It is also found that carbon steel has lower corrosion-resistance than stainless steel and higher corrosion-resistance than aluminum. Although many research works have been conducted on the issue of corrosive-wear of automotive engine components or component materials using various approaches as mentioned earlier, however, no research has been focused on the actual corrosive-wear phenomenon using a single dedicated approach to the corrosive-wear study. The information that provided however, is often inadequate for today's actual corrosive-wear measurement tasks. Therefore, research should come forward to the frontiers in corrosive-wear model design for biodiesel behavior in contact with automotive component materials.

3.0 AUTOMOTIVE COMPONENTS MATERIALS

Automotive mechanical components including engine are mostly metallic material components. Metal parts with high resistance to weather, climatic conditions, wind, fuel and lubricants are indispensable for automobiles. Metals such as soft carbon steel, copper, aluminum and stainless steel are generally used in diesel engines (Singh et al., 2012). These materials are used in generally including the route the fuel passes through in the vehicle. Fuels and lubricants come into contact with the following components: fuel pump, fuel injector, seals, filters, piston, bearing, piston rings, fuel liners, etc. Some copper alloy-based materials are also used for fuel pump, bearing and bushing (Chourasia et al., 2018). The factors such as load, speed, environment and biodiesel composition play a large role in corrosive wear (Ha et al., 2020). Therefore, material selection is essential and should be focused before designing an engine component. In addition, the lubricants that interact with materials play crucial role in moving parts (Zulkifli et al., 2014). In corrosive-wear, corrosion and wear are two independent mechanisms. When corrosion and wear happen separately, the state may be more serious than the combined effect of both. Therefore, the study of the corrosion and corrosive-wear behavior of metals or alloys used in these sections is also a notable and important issue that to be taken into consideration. In diesel engine, aluminum and aluminum-based alloys are usually used in engine blocks, piston components, and cylinder heads. Likewise, copper and copper-based alloys are used in fuel pump and injector components. Also, stainless steel is generally used in valve bodies, fuel filter and pump rings (Hoang et al., 2020). Besides, factors such as biodiesel composition and environment affect the level and modes of corrosion. Copper, aluminum and steel are among the materials commonly used in diesel engines (Nguyen and Vu, 2019), (Zhang et al., 2009). According to literature, some materials are considered to have little resistance to corrosion in biodiesel compared to others (Nguyen and Vu, 2019).

The tribo-corrosion properties development of the materials should satisfy the requirement of some applications such as pipe conveyor, biodiesel engines, marine energy devices (Maleque and Abdulmumin, 2014), (Lopez-Ortega et al., 2018), (Wang et al., 2015), (Wood et al., 2010), (Lopez-Ortega et al., 2018) as those area of applications showed high potential to corrosion and wear because of their often interaction with corrosive fluids and friction load (Muangtong et al., 2021). Following section describes the potential candidate materials those are used for mechanical parts of diesel engine. Figure 3 presents the sections where selected materials are used in automobiles.

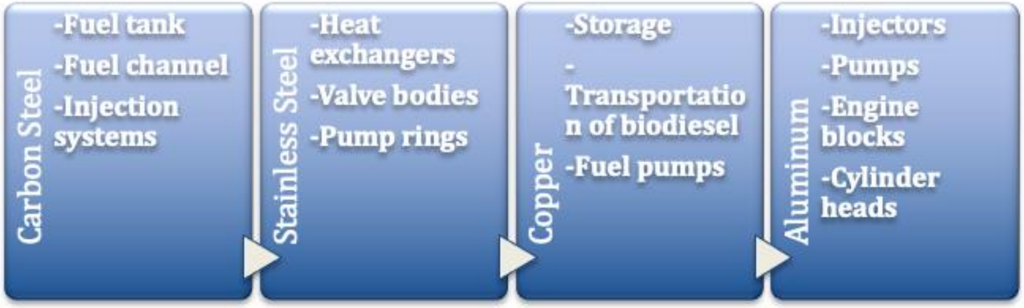

Figure 3: Materials and their areas of usage in automobiles.

3.1 Carbon Steel

Carbon steels are widely used in industrial applications due to their different physical properties and low cost. In diesel engines, many parts can be made of carbon steel. For instance, fuel channel, fuel tank, and injection system (Setiawan et al., 2017). 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%). 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.

Low carbon steels, contains up to 0.25% carbon. They are also known as soft steels, considering their mechanical properties. Low carbon steels cover a very large amount of world steel production. In particular, low carbon steels are preferred when producing flat products, steel rods and profiles used in construction industry. Low-carbon steels cannot be sufficiently hardened by heat treatment due to their low carbon content. However, surface hardening process such as cementation and nitration can harden surfaces.

Medium Carbon Steels are steels containing carbon between 0.25-0.70%. They have moderate mechanical properties depending on their amount of carbon. The biggest characteristic of steels in this group are that they can be sufficiently hardened by heat treatment. In particular, the machinery manufacturing industry prefers medium carbon steels. Their ability to machinability and plasticity is lower that low-carbon steels. The welding capabilities of the medium carbon steels are also low compared to low carbon steels. In addition, it is very important to pay special care in welding process of medium carbon steels. Because the uncontrolled thermal effects that may occur during welding may cause change in the structure of the steel.

High Carbon Steels contains more than 0.70% carbon. In normal condition, they have high strength and low ductility. They have high hardness due to their hardening with heat treatments. In this respect, they are corrosive resistant properties. Their ability to machinability and plasticity is lower than low and medium carbon steels. Welding capabilities are also low, and welding can be made with more specialized techniques. In general, high carbon steels are mainly used in tool production.

Setiawan et al., (2017) examined the characterization of carbon steel when exposed to biodiesel. The effect of contact time and temperature on corrosion was analyzed with 30 °C, 40 °C and 70 °C temperatures, with different time duration such as 30 days, 40 days and 50 days. The study concluded that corrosion of carbon steel increased at the same temperature from 30 days to 50 days. Thus, it can be seen that the corrosion rate of carbon steel tends to increase as the contact time increases. In addition, the highest corrosion rate was observed at 70 °C and by the end of the 50-days contact period. This is due to the tendency to oxidize biodiesel when storage for longer period of time. According to Baena and Calderon, (2020), after 3 months of interaction with biodiesel, carbon steel displayed approximately 0.0010 mm/year corrosion rate. Furthermore, it decreased 0.0005 mm/year after 6 months of exposure. Finally, after 12 months of interaction between carbon steel and biodiesel, it was observed that carbon steel showed 0.00024 mm/year corrosion rate. On the other hand, Sterpu et al., (2012), found that the corrosion rate of carbon steel was 0.000855 mm/year after 49 days of immersion period by sunflower oil biodiesel.

3.2 Stainless Steel

Stainless steels are often used in many industrial applications including automotive. It is known to have high corrosion resistance. Moreover, it has many other advantages in metallurgical, such as 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. (Hou et al., 2011), (Kurc et al., 2010). In addition, it is very preferred in environments that can cause corrosion and wear. 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). Stainless steel is an iron alloy that contains 10.5% or more of chromium and carbon of 1.2% or less, which as a result forming a self-repairing surface layer that provides corrosion resistance. Stainless steel takes its name from the fact that these steels do not face with stain, corrosion and rust like other steels. Stainless steel has a high resistance to corrosion and oxidation in many natural and artificial environment. However, it is very important to choose the right quality and type of stainless steel for each special application. Some of the main types of stainless steels can be listed as follows: Ferritic stainless steel, austenitic stainless steel, martensitic stainless steel, and ferritic – austenitic (duplex) stainless steel.

Ferritic type of stainless steels contains low carbon and between 12-18% Cr. Ferritic stainless steels provide moderate corrosion, and they cannot be easily shaped like austenitic steels. Apart from their magnetic properties, their strength cannot be increased with heat treatment.

An austenitic structure is obtained at room temperature when nickel is added to stainless steel. This provides the possibility of giving plastic forming to materials, high strength and good corrosion resistance. They have good weldability, and their impact resistance is good at low temperature.

If hardening is performed on austenitic stainless steels which have more than 0.1% Cr, the austenitic structure becomes martensitic structure. Martensitic stainless steels have high strength and hardness. However, their ductility is also relatively greater. They have moderate corrosion resistance and heat treatable. In addition, they have low weldability.

Ferritic-austenitic stainless steels coexist with both ferritic and austenitic structure at the same time. Since they keep these two structures together, they provide high strength, hardness and toughness properties at the same time. Moreover, they have very good wear resistance in corrosive environments. Also, they have good weldability and easy-to-shape properties.

By this time, many studies have been carried out on the corrosion behavior of biodiesel on stainless steels. Automobiles have stainless steel parts on fuel filter, valve bodies, pump ring, nozzle. Studies show that stainless steel are high resistant to corrosive effects caused by biodiesel. According to Fazal et al. (2010), biodiesel causes pitting corrosion on aluminum and copper while stainless steel is not affected. This is because of the electrical conductivity of stainless steels. In addition, it is emphasized that if a corrosion occurs in biodiesel-stainless steel, it may happen preferably galvanic corrosion. In a word, stainless steel is a resistant to pitting corrosion (Singh et al., 2012).

In a study, corrosion test of seven different types of stainless steel (six ferritic stainless steels and one austenitic stainless steel) with biodiesel were examined using half immersion test method whereby the biodiesel solution interacted with all material coupons at 95 °C temperature (Hiraide et al., 2019). At the end of the experiment, SUS436L and SUS444 showed satisfactory corrosion resistance under the most difficult conditions. There was no pitting corrosion on stainless steel samples except for 430LX steel. In addition, the same steels again showed excellent corrosion resistance in the fuel encapsulation experiment. Referring to Ahmmad et al., (2018), stainless steel showed approximately 0.0005 mm/year corrosion rate in presence of biodiesel for 2 months of period. In other flipside, according to Baena and Calderon, (2020), the corrosion rates of stainless steel that examined under exposure of biodiesel, displayed as 0.0001 mm/year and 0.00003 mm/year for 6 months and 12 months respectively.

Torres et al. (2020) studied the effect of biodiesel on 904L stainless steel. The work was carried out using a 904L stainless steel pipe whereby liquid biodiesel was flown through the pipe. It was observed that heavy corrosion was occurred in the areas where a mixture of biodiesel and acid water was passed through the stainless-steel pipe as shown in Figure 4 leading to the failure of stainless-steel pipe. Fig. 4a presents the failure of stainless-steel pipe right after the entry of the biodiesel and acid water mixture whereas, in other flipside (Fig. 4b) shows the failure after 29 months of operation with biodiesel and acid water in a spool.

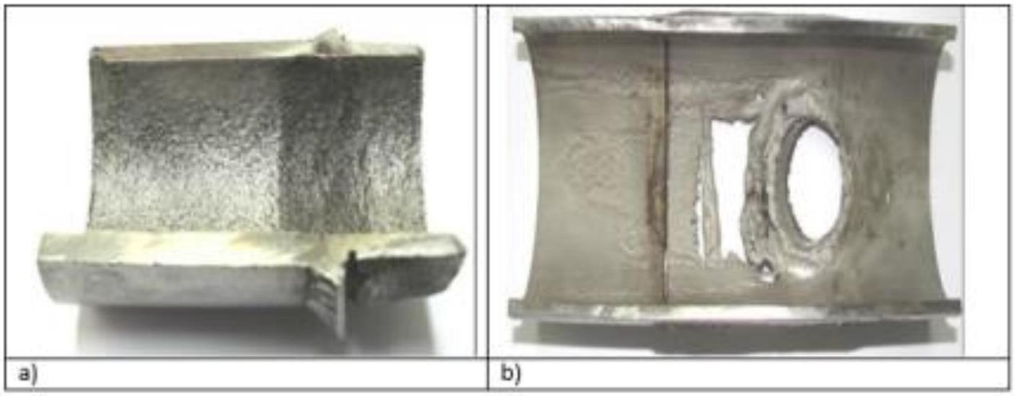

Figure 4: Corrosion of AISI 904L stainless steel (a) stainless steel pipe right after biodiesel-acid water mixture entry (b) spool of stainless steel after 29 months of operation.

3.3 Copper

Copper has great thermal and electrical properties, good machinability and alloying ability. Because of all these specifications, it uses widely for the production process, storage, and transportation of biodiesel (Rocha et al., 2019). In one of the study, copper used for the investigation of corrosion behavior of biodiesel (palm) on copper. Room temperature (~25-27 °C) was selected as the experiment temperature. Static immersion test was performed with 5 different time periods such as 200, 300, 600, 1200, 2880 h. Study concluded that, the corrosion of copper increase with the immersion time. However, after a certain period of time, oxygenated compounds formed on the surface which reduces the rate of corrosion (Fazal et al., 2013). In other study, corrosion properties of pure copper and leaded bronze which are commonly used in fuel system mechanism in diesel engines were examined with biodiesel (B100) and B0 using static immersion test (Haseeb et al., 2010). Experiment was conducted for 840 h duration and at 60 ^{0}C temperature. After experimentation, it was found that corrosion rate of materials was higher for B100 biodiesel than B0. So, this proves that the biodiesel is more corrosive than diesel fuel. Moreover, it is indicated that fatty acids which caused by oxidation of biodiesel can increase the corrosion rate. Furthermore, the degradation of copper and leaded bronze increased with the increasing TAN number and free water.

Fazal et al., (2018), examined the behaviour of copper-based material for 2160 hours of exposure time period. The study conducted at room temperature (25 °C to 27 °C) by using biodiesel with additives of benzotriazole, butylated hydroxytoluene, tert-butylamine, and propyl gallate, pyrogallol. The corrosion rates for metals were calculated by the help of weight loss method. Herewith, the corrosion rate of carbon steel displayed 5.56 μm/y in biodiesel without additives. Besides, the blends of biodiesel BTA/B100, BHT/B100, TBA/B100, PG/100, PY/B100 showed 1.72 μm/y, 3.03 μm/y, 1.90 μm/y, 4.23 μm/y, 2.12 μm/y of corrosion rates respectively. According to the results, it can be highlighted that corrosion of metal sample decreased when additives used in biodiesel. Although pitting corrosion was observed on the surface of the copper samples, it remains safe from corrosion under biodiesel exposure.

3.4 Aluminum

Aluminum is a widely used material in automotive industry. The percentage of aluminum in the engine components includes, piston (100%), cylinder heads (70%), and engine blocks (19%). On the other hand, aluminum and its alloys are generally used in injectors and pumps (Bhardwaj et al., 2014). Díaz-Ballote et al. (2009) tested corrosion behavior of aluminum when exposed to a biodiesel. In this experiment which using electrochemical methods, the corrosion interaction between aluminum and biodiesel at different washing stages was examined. The process of corrosion took place like the exposure of aluminum to aqueous or ethanol alkali solution. Along with the initial wash, -600 mV was observed in the open circuit potential. This high negative value which caused by the reaction of aluminum-biodiesel, showed positive value in the next washes. The reason for this value to return to positive is $Al(OH)_3$ formation which is a passive layer formed on the material. Moreover, it has been reported that the purity of biodiesel influences the corrosion of aluminum.

According to previous studies, it has been found that copper and brass are the most affected materials under exposure of biodiesel in regard to corrosion. That is why, aluminum and stainless steel which are such alternative materials to copper, should be used instead of copper parts (Shehzad et al., 2021).

4.0 CORROSIVE-WEAR MODEL

A model of the corrosive-wear process is proposed to account for the behavior of biodiesel in automotive engine. Since, there is no systematic and integrated corrosive-wear testing device and tool available in order to predict this phenomenon under biodiesel condition, therefore, this model adequately can predict the outcome to a change in corrosive media and mechanical parameters. Recommendations are made to maximize the corrosive-wear resistant properties of the engine component materials when subjected to biodiesel interaction. The accuracy of the results in models can be affected from many parameters in systems which is created in laboratory environment. Therefore, model installation is extremely important to achieve reliable and accurate results. Figure 5 shows a proposed model of corrosive-wear testing system in the laboratory. Mechanical and chemical combine attack causes to accelerate loss of materials caused by the synergism between corrosion and wear which can be measured in presence of biodiesel. Hereby, the total material loss can be defined as $T= C_0 + W_0 + S$, where C_0 is free flow corrosion rate of solid, W_0 is material loss caused by the mechanical wear and S is the material loss caused by synergy of corrosion-wear (Maleque and Abdulmumin, 2014), (Chen at al., 2018).
The map development of corrosive-wear interaction requires:

(a) Measurement of wear rate (W_0) from corrosive-wear test, typically using disc-ball configuration system in the model.

(b) Integration of potentiodynamic with the test model and quantify corrosion rate (C_0).

(c) Determination of total material loss (T).

(d) Finally, determine the value of synergistic corrosion-wear (S).

This model also can provide quantitative information about tribocorrosion rate as it consists of mechanical and electrochemical combined system. The electrochemical setup shows corrosion rate with the help of three electrodes (reference electrode, working electrode, counter electrode). The mechanical part of the system shows corrosive-wear due to mechanical action. The total corrosive-wear finally can be calculated as;

$$W_{cw} = W_c + W_m + W_{in} \tag{1}$$

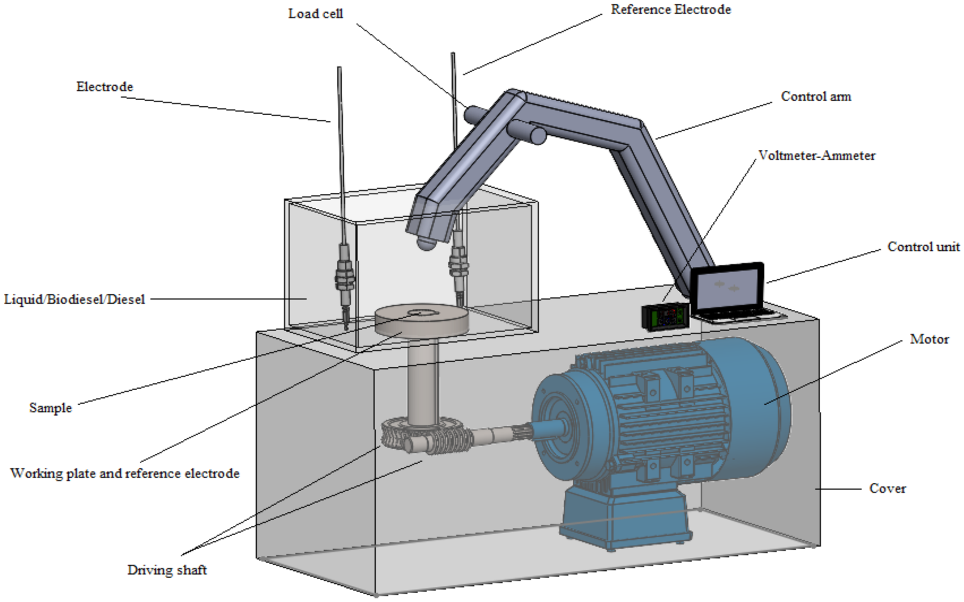

Figure 5: Model of corrosive-wear testing system.

Here, W_{in} can define as;

$$W_{in} = \Delta W_m + \Delta W_c \tag{2}$$

$$W_{cw} = W_c + W_m + (\Delta W_m + \Delta W_c) \tag{3}$$

Whereby, W_{cw} = total corrosive-wear, W_c = wear caused by corrosion, W_m = wear caused by mechanical action and W_{in} = wear caused by corrosion and mechanical action.

The corrosive-wear behaviour of two types of stainless steels such as AISI 316 and BJP316 steels in sea water environment are investigated with electrochemical evaluation by Wang L. et al. (2020). Electrochemical evaluation demonstrated that the corrosion of BJP316 was one order of magnitude higher than that of the AISI 316 in sea water. They also suggested the potential application of BJP316 in marine under corrosive environment. However, this current review highlighted the corrosive-wear behaviour of automotive component materials. Especially, the corrosive-wear effect of biodiesel which is clean and renewable fuel is emphasized. Regarding previous studies under different experimental conditions, a comprehensive review has been put forward. Besides, a new and easy-to-use wear model is proposed for further studies. In conjunction with the proposed model, it is aimed to reach high accuracy results and wieldy system setup for wear studies.

CONCLUSIONS AND WAY FORWARD

This study focused on the review of corrosive-wear of automotive components materials. Based on the systematic literature review it can be said that the contact of biodiesel with automotive components can cause corrosive-wear. Factors such as dissolved oxygen and free water in biodiesel can lead to severe corrosion. However, the corrosion rate can change with the change of biodiesel and materials type. It is possible to keep corrosion resistance in the desired range with the use of suitable material under biodiesel condition. The copper is prone to corrosion against biodiesel, while stainless steels have high corrosion resistance. Although many research have been done in order to assess the corrosive-wear behavior of different metal components used in automobiles but specific standard test method yet to develop. Therefore, research should come forward to the frontiers in corrosive-wear model design for biodiesel behavior in contact with automotive component materials. There is no systematic and integrated corrosive-wear testing device and tool available in order to predict this phenomenon under biodiesel condition, therefore, a model of corrosive-wear testing system has been proposed in this manuscript for the wear map development considering synergistic effect of corrosion and wear which can be measured in presence of biodiesel. Therefore, this study also provides a way forward with corrosive-wear model for different materials under biodiesel conditions. For the prevention from the corrosive-wear, the substances in biodiesel that cause to corrosion and wear should be eliminated or minimized. Also, surface coatings can be made that will allow metals to be less affected by corrosion and wear. Apart from all these, selecting the most resistant materials to corrosion and wear will significantly eliminate the problem.

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