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A Study of the Effect of Additional Magnesium (Mg) on Erosion-Corrosion Resistance and Bending Strength in Aluminum A383 Alloy

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Abstract

In this study, evaluating the erosion-corrosion resistance and mechanical properties, especially the bending strength of aluminum alloy A383 with variations in the addition of 4%, 6%, and 9% magnesium was investigated with variations in velocity (45l/h, 60l/h, and 75l/h), and angle variations (30º, 40º, and 50º) using 12% sodium hypochlorite solution. The test equipment used is an injection diaphragm pump in the recirculation system for 4 hours per sample. The results showed that the erosion-corrosion resistance of A383 alloy is proportional with the increase of magnesium addition to the alloy maximum weight loss occurs at an impact angle of 30° with a velocity of 75 l/h. The degradation of decreased slightly with increasing the impact angle and decreasing velocity. Analysis of the erosion-corrosion mechanism shows that the corrosion process dominates material damage rather than erosion. The results of the bending test showed that the highest strength is A383 9% Mg which is 366.09 MPa, and the lowest bending strength is A383 material without magnesium addition which is 261.80 MPa. From these results it can be concluded that the addition of elemental magnesium (Mg) to aluminum alloys can reduce porosity and increase the amount of Mg_2Si precipitates formed during aging, these deposits strengthen the aluminum matrix by suppressing the atomic lattice making dislocation movements difficult thereby increasing strength and resistance corrosion.

Keywords: Erossion-corrosion; corrosion rate; Magnesium; bending strength

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1. Introduction

Corrosion is an event of damage or destruction to the material due to chemical reactions in the surrounding environment. Corrosion is the degradation experienced by attacks on metal materials due to oxidation-reduction reactions between metals and their environment [1]. One form of corrosion that we often encounter in an industry is erosion corrosion.

Erosion-corrosion is common in oil and gas processing plants where there are interactions between solid particles, corrosive liquids, and target materials [2]. The combination of corrosion and erosion, called erosional corrosion, accelerates the rate of material inefficiency, causing major problems in engineering components such as pumps, valves, agitators, condensers and heat exchanger tubes, gasoline supply equipment, and pipelines that come into contact with aqueous sludge during operation and can be exposed to erosion corrosion degradation [3]. During the erosion-corrosion phenomenon, the observed weight loss is greater than the sum of the weight loss due to pure corrosion and pure erosion that occurs separately [4].

Various studies have been conducted to find out what factors influence this phenomenon. This phenomenon occurs at high flow velocities where the material wears out due to the fast fluid flow which favors corrosion and is exacerbated by high temperatures and abrasive particles which cause wear [5, 6, 7] , while the impact angle is also a very large factor. in the erosion-corrosion behavior of brass and the highest erosion-corrosion rate was obtained at an impact angle with a low value compared to an impact angle with a medium or high value [8]. Other studies have been carried out to understand the influence of the erosion-corrosion behavior of materials for ductile materials. It has been shown that erosion corrosion has a maximum rate at low-impact angles [9, 10]. The combination of the two can result in the material being damaged due to the erosion-corrosion process. However, corrosion erosion can occur quickly due to the presence of fluid in the form of sodium hypochlorite.

Sodium hypochlorite solution is a strong oxidizer with a corrosive oxidation reaction, coupled with the flow velocity of the solution so that the phenomenon of erosion-corrosion occurs. Fluid in the form of sodium hypochlorite is used to immobilize microorganisms consisting of bacteria, archaea, fungi, algae, and protozoa

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so that they do not nest and damage equipment with the desired concentration. Hypochlorous acid is an alkaline solution divided into hydrochloric acid (HCl) and oxygen (O) [11]. The oxygen atom is a very strong oxidizing agent. The formation of corrosion products is influenced by many factors, one of which is the fluid factor in the form of sodium hypochlorite which is a very strong oxidizing agent [12].

Equipment commonly used in modern industries such as aerospace equipment, and rail transit rooms use aluminum material which is a very light type of non-ferrous metal. However, the technology for supplying aluminum alloy materials as a whole still needs to be improved [13]. The strength of pure aluminum metal is not as good as other metals, but to increase the strength of aluminum metal it is combined with other elements such as Cu, Si, Mg, Zn, Mn, and Ni. These aluminum alloys are commonly called aluminum alloys [14].

One of the alloys and alloying elements used in this study is Alloy A383 with variations in the addition of Magnesium (Mg), in this case, alloy A383 is a cast aluminum alloy that is widely used because of its excellent material properties, namely high castability, high density. low yield, high productivity, low shrinkage rate, relatively high strength, good corrosion resistance, and good machinability due to higher silicon levels and lower copper levels [15]. Magnesium (Mg) enables good formability of aluminum alloys in the manufacture of components markedly increasing the strength of aluminum without reducing its ductility and good corrosion resistance [16, 17]. Aluminum alloys containing magnesium in the range of 4% to 10% have good corrosion resistance and mechanical properties [18].

Most of the previous studies have paid attention to the effect of impact angle and flow velocity on the erosion-corrosion behavior of the alloy. In this study, it was conducted to observe the effect of adding magnesium (Mg) to aluminum alloy A383 on erosion-corrosion resistance and mechanical strength, especially bending strength, tested using a closed circulation simulation installation tool. Later it will provide useful information about the corrosion behavior of alloys, which can help with material selection as a form of corrosion rate control in erosion-corrosion processes, namely how much influence the addition of magnesium to A383 alloy has in controlling corrosion rates in erosion-corrosion processes on its mechanical properties.

2. Research Methods

This research was conducted at the Mechanical Engineering Laboratory of Hasanuddin University and PT Datang DSSP Power Indonesia to obtain data on the effect of adding magnesium on the level of corrosion resistance and bending strength.

2.1. Specimen preparation

The materials used in this study were aluminum alloy A383 and aluminum alloy A383 with variations in Mg content of 4%, 6%, and 9% with the chemical composition in Table 1. Variations in the addition of magnesium.

Table 1. Chemical composition of the test material

Element	A383	A383 Mg4%	A383 Mg6%	A383 Mg9%
Si (%)	11.06	10.33	9.49	9.25
Fe (%)	0.83	0.74	0.78	0.76
Cu (%)	2.64	2.54	2.57	2.55
Mn (%)	0.22	0.25	0.21	0.21
Mg (%)	0	4	6	9
Ni (%)	0.07	0.072	0.079	0.063
Zn (%)	1.27	1.2	1.19	1.18
Ti (%)	0.04	0	0	0
Al (%)	Balance	Balance	Balance	Balance

Table 2. Chemical analysis of sodium hypochlorite

Parameter	Unit	Spec.	Value	Test Method
NaOCl	%	12 ± 2	13.35	ASTM D2022-16
Specific Gravity		Min 1.200	1.223	ASTM D891-18
NaOH	%	Max. 2.0	1.49	ASTM D 2022-16

The chemical composition of the materials listed in Table 1 was first tested, as a form of material verification before being tested using the Niton™ XL2 XRF Analyzer.

After the chemical composition test, the samples were cut into blocks with dimensions of 30x20x5 mm and coded. Before the simulation test, the specimen surface was cleaned according to the ASTM G-1 standard [19]. After cleaning, the specimens were weighed using a digital balance and then stored in a dry box.

2.2. Preparation of chemical solution

The chemical solution used in this study was a 12% sodium hypochlorite solution. Table 2 shows the Chemical of analysis of these solutions.

2.3. Erosion-corrosion testing

This type of research uses experiments that are useful to determine the value of the corrosion rate on the results of aluminum alloy A383 and by adding magnesium elements. Where the impact angle and flow velocity as variations are also the results of the effect of adding magnesium to the specimen.

Stages of the simulation test, the specimen was inserted into the simulation test tool using an injection diaphragm pump in Fig. 1 by installing the specimen on hubcap accompanied by a clamp made of polyethylene so that no metal material has direct contact with the specimen. Tighten the cap and position the specimen according to the desired impact angle. Turn on the simulation tool by pressing the power button to the ON position. Set the fluid speed on the rotameter and leave it for 4 hours so that the parameter conditions are reached.

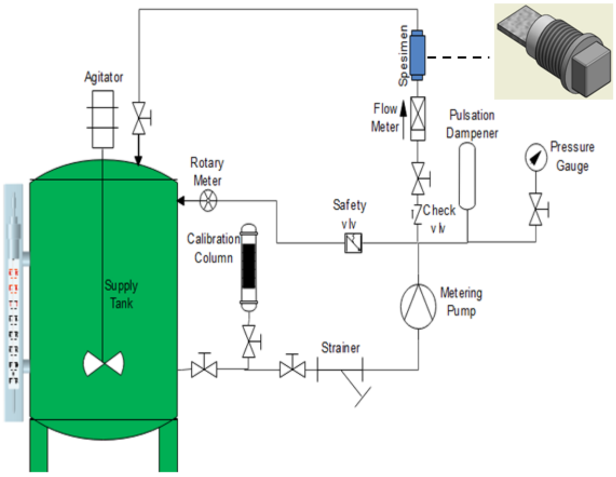


Figure 1. Test simulation design and tools

If the condition has been reached, wait until the exposure time was over. After the exposure time was complete, press the power STOP button, remove the sample from the tee joint, and clean it.

Erosion corrosion tests were carried out at flow rates of 45 l/h, 60 l/h, and 75 l/h. The erosion-corrosion test was carried out on a closed open circuit installation system. The erosion-corrosion rate was based on the impact angle that is impacted on the surface of the sample. To obtain the value of the erosion-corrosion rate, it was divided by several impact angles, where 30^0, 40^0, and 50^0 were the impact angles, as shown in Fig. 2. Examination of surface damage to the specimen due to erosion corrosion was observed in detail using a Digital Microscope 1600x macro photo.

2.4. Weight loss analysis

After the simulation test, the specimens were cleaned according to procedures in the ASTM G-1 standard [19]. Weight loss analysis was carried out by weighing the specimens before and after exposure. Method for determining the corrosion rate based on weight loss.

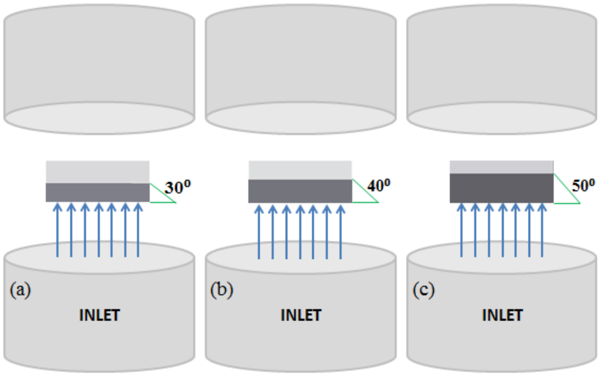


Figure 2. The effect of the impact angle that is impacted on the surface of the sample in the event a. 30^0; b. 40^0; and c. 50^0

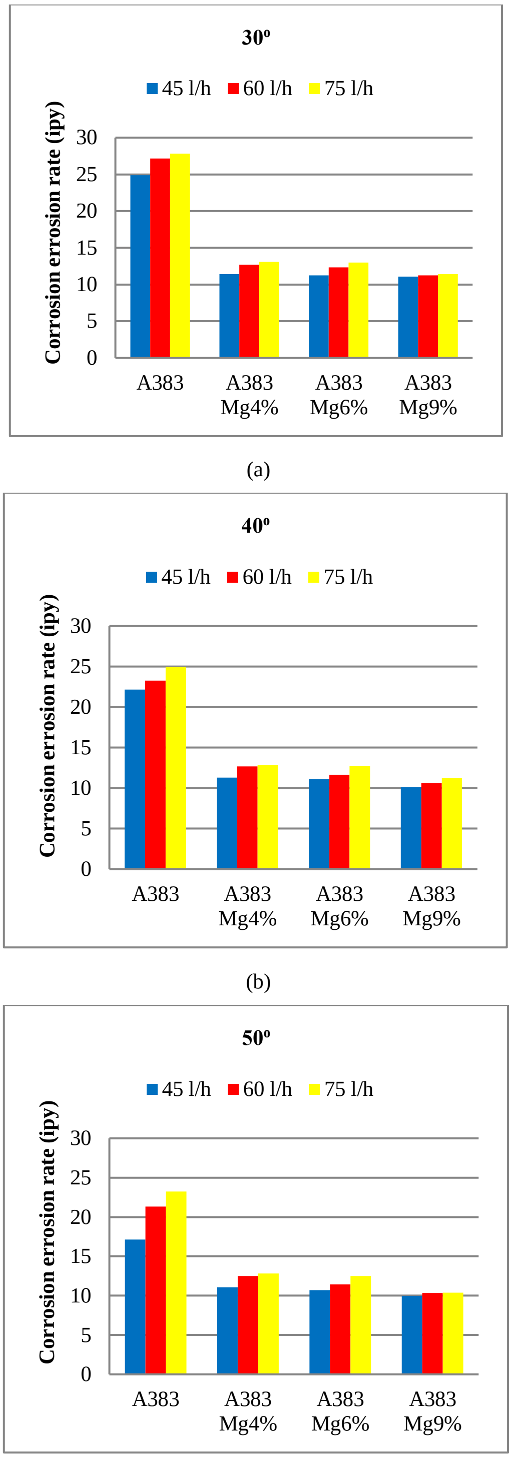
2.5. Bending test

Material testing was carried out to determine the bending strength of each test specimen. The bending test process was carried out according to ASTM D 790-03 [20] using a three-point bend using 4 samples with a support distance of 23 mm.

3. Results and Discussion

3.1. Corrosion test results with flow variations

Figure 3 shows the results of the simulation test as the corrosion rate vs. the test material specimens at impact angles of 30^0, 40^0, and 50^0 at different flow velocity variations; respectively 45 l/h, 60 l/h, and 75 l/h.

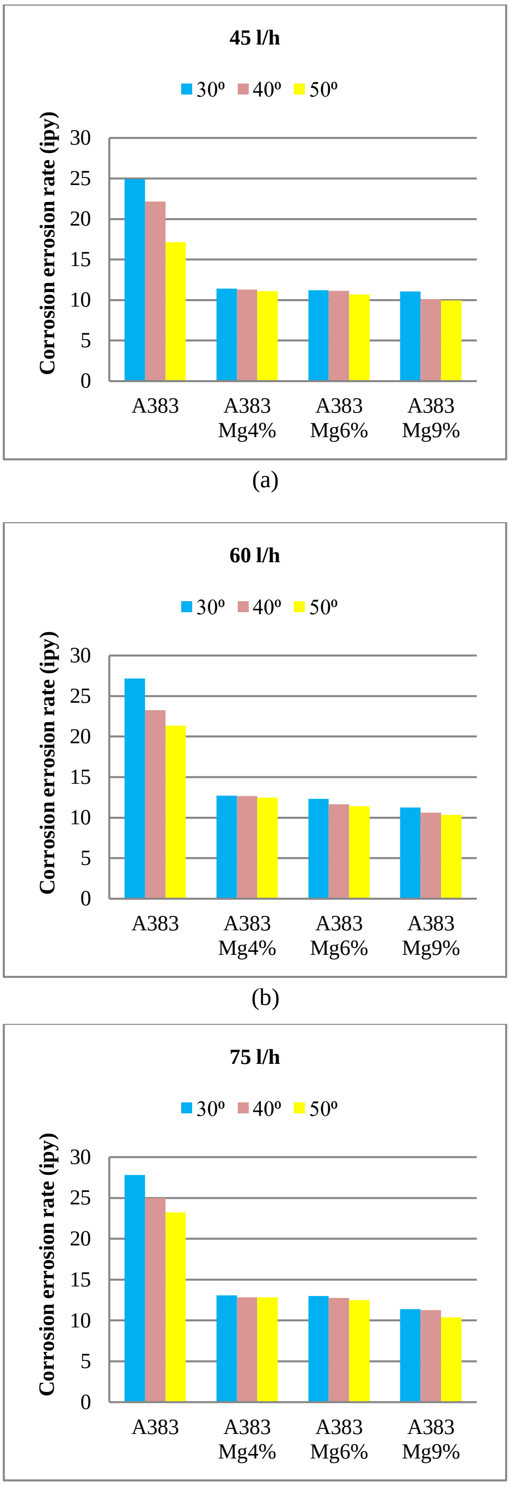


(a)

(b)

(c)

Figure 3. Corrosion rate due to variations in flow velocity at impact angles of (a) 30, (b) 40, and (c) 50



(a)

(b)

(c)

Figure 4. Corrosion rate due to variations in impact angle at flow velocities at (a) 45 l/h, (b) 60 l/h, and (c) 75 l/h

From Fig. 3a, it can be observed that the greater the flow velocity from each impact angle, the greater the erosion-corrosion rate produced. Aluminum A383, A383 Mg4%, A383 Mg6%, and A383 Mg9% at an angle of 30^0 with a flow rate of 75 l/h experienced specimen degradation due to erosion corrosion with the greatest value, whereas aluminum A383, A383 Mg4%, A383 Mg6 %, A383 Mg9% at an angle of 30^0 with a flow rate of 60 l/h experienced an increase, but the value of the increase in erosion-corrosion was not too large when compared to a flow rate of 75 l/h. While the aluminum material A383, A383 Mg4%, A383 Mg6%, and A383 Mg9% at an angle of 30^0 with a flow rate of 45 l/h has the lowest corrosion rate value. In this study, the same statement applies consistently in Figures 3b and 3c by placing the sample at an impact angle of 40^0 and 50^0 at various flow rates of 45 l/h, 60 l/h, and 75 l/h. The increase in the value of the corrosion rate is due to the velocity of the fluid flow. Judging from Fig. 3, the presence of Mg has a significant effect on decreasing the corrosion rate when Mg4% to Mg9% is added.

Table 3. Relationship between velocity, impact angle, and working pressure

Velocity (L/H)	Impact Angle (^{0})	Working Pressure (Bar)
45	30	1.87
60		1.95
75		1.98
45	40	1.85
60		1.91
75		1.94
45	50	1.79
60		1.83
75		1.87

3.2. *Corrosion test results with variations in impact angle*

Figure 4 shows the results of the simulation test as the corrosion rate vs. the test material specimens at flow velocities of 45 l/h, 60 l/h, and 75 l/h at different impact angle variations; 30^0, 40^0, and 50^0 respectively.

3.3. *Bending test results*

The bending test was carried out at the Hasanuddin University materials testing laboratory. This bending test uses the three-point bending method which uses 4 specimens as the test object. The dimensions of the specimen are measured, then the specimen is given a load in the middle of the specimen according to ASTM D 790-03 [20] until the specimen breaks. The results of the bending test on the A383 material and with the addition of Mg in the A383 material will produce a bending stress as shown in Fig. 5.

Figure 5 shows that the bending stress of A383 material is 261.80 MPa. For A383 material with a percentage of Mg 4% the bending stress is 282.81 MPa, then with a percentage of Mg 6% the bending stress is 361.48 MPa, and the highest bending stress value is obtained at the percentage of Mg 9% bending stress of 366.09 MPa. The test results show an increase in the average bending stress value for each additional amount of Mg compared to the raw material without the addition of Mg. It was concluded that the addition of magnesium element affects the value of the bending stress in aluminum A383 material, where the addition of up to 9% Mg increases the bending strength of a material.

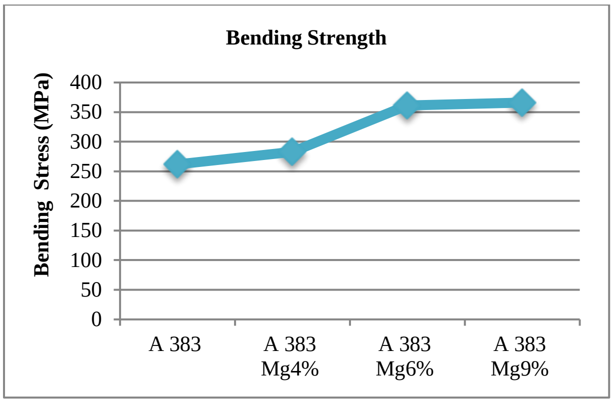


Figure 5. Bending tests on aluminum A383 and aluminum A383 with variations in the addition of Mg

3.4. *Effect of flow velocity on corrosion rate*

The weight loss at various flow velocities can be seen in Fig. 3. In general, it can be seen that the corrosion rate increases as the fluid flow velocity increases in the form of laminar flow. In corrosion processes that involve flow, of course, there is a force factor that is formed at the interface between the material and the solution which is known as the wall shear stress. This can result in grinding of the material which of course has an impact on the corrosion process of the material. This phenomenon occurs at high flow velocities where the material is subject to wear and tear due to the fast fluid flow which favors corrosion which causes wear on the material [5]. Where this velocity is a pattern of velocity changes between points adjacent to the specimen surface in the pipe caused by the frictional force exerted between adjacent layers of the flowing fluid and between the fluid and the specimen surface. The frictional force arises from the viscosity of the fluid [21].

Looking at Table 3 the relationship between flow velocity and wall shear stress values, it can be seen that increasing speed will increase the value of wall shear stress. Increasing the value of the wall shear stress will certainly have an impact on the corrosion rate of the material, which will result in greater grinding of the surface, which in this case is a protective layer in the form of Al_2O_3. This of course will make the material exposed directly to the environment, and as a result, the corrosion rate will be even greater. According to Erosion corrosion can also be caused by very heavy fluids so it can erode the metal protective layer and cause metal corrosion.

3.5. *Effect of impact angle on corrosion rate*

Discussion regarding the influence of the impact angle on the corrosion rate can be done through the erosion phenomenon approach. In the destruction caused by erosion, there is a mechanism for removal degradation of material that occurs, namely through the process of cutting wear by shear stress. The maximum shear stress occurs at the small impact angle. Where the material will experience greater damage by this mechanism so the material will experience severe damage at a small impact angle [22].

Table 4. Relationship between wall shear stress values and flow velocity variations

Velocity (L/H)	0	45	60	75
Wall Shear Stress (N/m^2)	0	0.0016	0.0022	0.0027

Figure 4 shows that of all the types of materials used in the erosion-corrosion rate test, the rate of erosion increases as the impact angle decreases. This is following Table 3 the higher the flow velocity at a small impact angle, the greater the pressure generated due to the reduced cross-sectional area and gravity against the flow, resulting in large shear stress. Previous studies which argued that the impact angle is also a very large factor in erosion-corrosion behavior and the highest corrosion rate was obtained at the impact angle with a low value compared to the impact angle with a medium or high value [8, 10]. The highest corrosion rate is at an impact angle of 30^0, then at an impact angle of 40^0, while the lowest corrosion rate is at an impact angle of 50^0. This is because the difference between the erosion-corrosion rates at an impact angle of 30° and 50° can be caused by changes in the erosion mechanism. At an impact angle of 30° material loss through the cutting wear process is the dominant erosion mechanism caused by large shear stresses, whereas at an impact angle of 50° most of the material loss occurs through repeated deformation due to collisions of normal particles with smaller shear stresses.

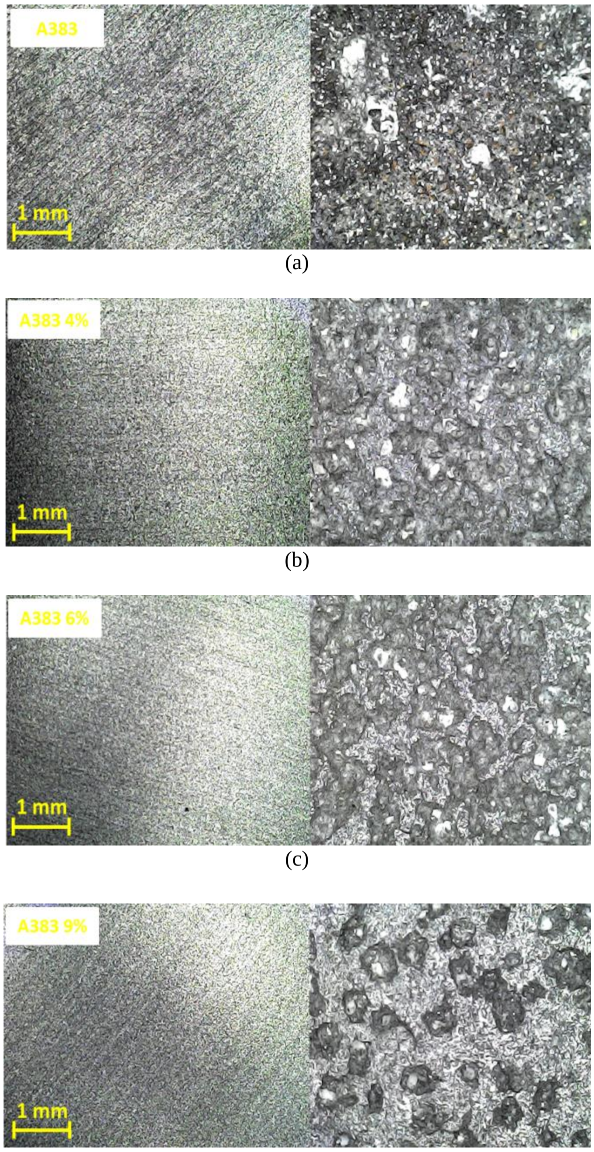
3.6. *Effect of adding magnesium (Mg) on alloy A383 on corrosion rate*

From this research process, it can be seen that variations in the addition of magnesium have a significant effect on the corrosion resistance of casting aluminum alloy A383, this can be seen in Fig. 3. The real effect of adding elemental magnesium is in the form of a decrease in the corrosion rate of aluminum alloys as the addition of magnesium increases. Aluminum alloys containing magnesium in the range of 4% to 10% have good corrosion resistance and mechanical properties [18]. With the addition of magnesium to the aluminum alloy, according to the provisions of the oxidation reaction, magnesium acts as a reducing agent and sodium hypochlorite as fluid as an oxidizing agent. Magnesium has non-cathodic corrosion potential and consequently, magnesium alloys can be used as anodes to provide corrosion protection to many other structural materials. Typical magnesium alloy anodes provide higher voltages than aluminum or zinc-based alloys [23]. The oxide film on magnesium can provide considerable protection to the alloy being exposed to atmospheric corrosion in rural, mostly industrial, and marine environments [23].

3.7. *Effect of bending strength on the addition of magnesium (Mg) on alloy A383*

The test data consistently show an increase in the stress value with variations in the addition of magnesium. The high magnesium content increases the amount of Mg_2Si precipitate formed during aging. These deposits strengthen the aluminum matrix by compressing the atomic lattice, making dislocation motion more difficult and thereby increasing strength [24]. The addition of Mg creates an intermetallic compound which improves its mechanical properties. The microstructure of the Al-Si alloy mainly consists of a primary phase (α-Al) and an Al-Si eutectic mixture, the amount of which leads to a dimicroeutectic depending on the amount of Si and the presence of Mg in the alloy inclines towards the formation of intermetallic compounds in the alloy microstructure. The intermetallic phase formed is Mg_2Si [25]. Research conducted by [14] argues that the greater addition of magnesium elements to the A383 smelting process is directly proportional to the increase in hardness and impact values based on the microstructure of the specimen, where the addition of 0.25% Mg elements indicates the formation of Si to Al has a different composition. denser and Si has a longer size and tends to be the same when compared to the microstructure with fewer variations in the addition of Mg.

Based on the graph of the increase in the average bending stress value in Fig. 5, it can be concluded that the addition of magnesium element affects the bending stress value in A383 aluminum material, where the addition of up to 9% Mg increases the bending strength of a material. This is also related to the grain size of aluminum, the smaller the grain size of aluminum, the closer the spacing between the grains so that it has the highest hardness and strength.



(a)

(b)

(c)

(d)

Figure 6. Before and after surface corrosion (a) A383 angle 40^0 velocity 60 l/h, (b) A383 Mg4% angle 40^0 flow rate 60 l/h, (c) A383 Mg6% angle 40^0 velocity 60 l/h , and (d) A383 Mg9% angle 40^0 velocity 60 l/h for 4 hours in flowing condition

3.8. Macro photo of corrosion on the surface of the specimen

Erosion corrosion on the plate surface through which fluid flows in the form of 12% sodium hypochlorite solution with an impact angle of 40^0 and a velocity of 60 l/h on aluminum material A383, A383 Mg4%, A383 Mg6%, A383 Mg9% in a simulation time of 4 hours for each sample as shown in Figure 3. The four materials were selected to represent a total of 36 samples based on the median value which consistently shows the same graphic between the effect of corrosion rate on variations in flow velocity and impact angle to compare the forms of corrosion experienced by each sample.

During the simulation process in a 12% sodium hypochlorite solution, there are bubbles on the metal surface. This indicates that the metal has been oxidized in the presence of a 12% sodium hypochlorite solution. Therefore, the longer the specimen flows with sodium hypochlorite solution, the more erosion will occur on the aluminum material. These white spots are caused because the surface layer of the metal has been oxidized in the presence of sodium hypochlorite solution which acts as an oxidizing agent and the metal as a reducing agent. The degradation experienced by the attack on metal materials is due to a reduction-oxidation reaction between the metal and its environment [1]. Corrosion products can cause the metal surface to become uneven, this causes the release of the film layer on the metal surface so that corrosion will occur at the anode which makes the metal hygroscopic.

Seen in Fig. 6 specimen Fig.6a on the A383 material the color changes to black with brown spots and there are more white spots, namely scale with a larger size, this occurs on the surface of the plate which experiences a focus of collision from a stream, which can cause corrosion. This corrosion is a form of uniform corrosion that occurs with equal intensity across exposed surfaces and often leaves a scale or deposit [26].

In specimen Fig. 6b the A383 Mg4% material is black in color and some cavities tend to be large and white spots which are less attached to the surface of the material when compared to specimen figure 6a which has many white spots. This will result in damage to the aluminum passivation layer or the aluminum passivation film will be released and will result in corrosion. The form of corrosion seen in Fig.6b is pitting corrosion.

Corrosion also appears as shown in Fig. 6c on the A383 Mg6% material, the color change from before simulation to after simulation looks much different, before simulation aluminum looks shiny and smooth, and after simulation aluminum changes color to black and rough accompanied by white spots and the surface is rough and creates cavities as shown in Fig. 6c, the same as in Fig. 6d, that is, in the material A383 Mg9%, corrosion damage to the material is characterized by a change in the color of the metal to black and a rough surface. Of all the material samples, erosion corrosion follows the impact angle. Where the material will experience greater damage by this mechanism so that the material will experience severe damage at a small impact angle [22].

The results of the micro photo in Fig.6 can be concluded in the form of a pattern of corrosion forms experienced by each sample. Where, for Fig.6a it forms a uniform corrosion pattern, while for Figures 6b, 6c, and 6d it forms a pitting corrosion pattern, this is evidenced by the average cavity size that occurs on each side of the metal. The corrosion products in Fig.6 show that the corrosion phenomenon was more dominant than the erosion phenomenon, this is because the flow velocity used during the test is quite small.

4. Conclusions

The flow rate of 75l/h produces the largest corrosion rate compared to the flow rates of 45l/h and 60l/h on the aluminum alloy materials A383, A383 Mg4%, A383 Mg6%, and A383 Mg9%. The increase in the value of the corrosion rate is due to the relationship between the value of the wall shear stress and the velocity of the fluid flow, so it can be seen that increasing the speed will increase the value of the wall shear stress. Erosion corrosion can be caused by frictional forces exerted between adjacent layers of the flowing fluid and between the fluid and the surface of the specimen, which can erode the metal protective layer and cause metal corrosion.

An impact angle of 30º produces the greatest corrosion rate compared to an impact angle of 40º and 50º for aluminum alloy materials A383, A383 Mg4%, A383 Mg6%, and A383 Mg9% loss of material through the cutting wear process by shear stress is the dominant erosion mechanism. The maximum shear stress occurs at the small impact angle. It was closely related between pressure increase and shear stress.

The real effect of adding elemental magnesium (Mg) is in the form of a decrease in the corrosion rate of aluminum alloys as the addition of magnesium (Mg) increases. With the addition of magnesium to the aluminum alloy, according to the provisions of the oxidation reaction, magnesium acts as a reducing agent and sodium hypochlorite as fluid as an oxidizing agent. In general, the corrosion rate of magnesium alloys is between that of aluminum and mild steel. In some cases, magnesium may have better resistance than some aluminum alloys.

The addition of magnesium element affects the value of bending stress on A383 aluminum material, where the addition of Mg4% to Mg9% increases the bending strength of a material.

The results of macro photos of the corrosion forms experienced by each sample form a uniform corrosion pattern and form a pitting corrosion pattern. Corrosion products show that the phenomenon of corrosion is more dominant than the phenomenon of erosion, this is because the flow velocity used during the test is quite small.

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