Failure analysis of aluminum alloys casting in four-wheels vehicle rims

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Abstract. The small industry of casting aluminum alloy produces four-wheeled motorized tire rims that have been used in various vehicles. However, in general, these products do not yet have the quality and safety guarantees required by SNI 1896: 2008. Failure analysis research must be conducted to examine the causes of failure. The research method is to compare the products of small industry with products made by local and imported products by analyzing test results. Observation on visual and penetrant test showed porosity at the center of the rim. Tensile strength was (111-145) MPa much lower than local and imported product (260-285) MPa. The impact value was (500-570) kg (rim broken) and this value was lower than the SNI requirement (936 kg). The content of iron element was (0.401-0.433)%, this content was higher than local and imported rim (0.120-0.135)%. This element will cause a tendency to form micro crack and reduce the strength of mechanical properties. Microstructure observation showed a dendritic structure, porosity, and AlFeSi phase resembles needles. It was concluded that the failure of this rim product is caused by the material and the casting process. Small industries should make efforts to know the casting defects aiming to minimize product failure.

1. Introduction
The products of decorative four-wheeled vehicle tire rims have been made by small industries of aluminum casting in Indonesia. However, these products do not have a guarantee of quality and safety for the driver, because it does not meet SNI standards after testing by The Center for Materials and Technical Products (Balai Besar Bahan dan Barang Teknik). Thus, the tire rim is said to be in poor quality or a failed product.

The vehicle’s tire rims product when being used and operated on the highway must be able to guarantee the safety of the driver. Tire rims which applied to the vehicles need to have a convincing quality of the product by conducting product research through tests [1]

To discover the product failure on the tire rim, a failure analysis research will be conducted on products that do not meet the SNI 1896: 2008 requirements. The Indonesian National Standard for vehicle tire rim products were on the category of M, N, and O. Rim category M for vehicles with at least four wheels constructed for the carriage of passengers, rim category N for vehicles with at least four wheels constructed for the carriage of goods and rim category O for trailer [2]. While the aluminum casting raw material for rims is regulated by other standards.

According to ASTM B 26 and ASTM B 179, the specifications of chemical composition of aluminum alloy castings, except for aerospace applications, are determined according to the appropriate chemical and spectrometer test methods. The addition of a small amount of modifier and purification element to the melting alloy from the melting furnace is permitted before casting. Pure metals, recycled materials,
and master alloys can also be used to make alloys as long as their chemical composition can be analyzed and adjusted to fit the requirements before pouring any casting. Casting products should only be repaired using approved processes such as welding, impregnation, peening, blending, soldering, and so on [1,3].

Aluminum is a mild and light metal which has silver appearance fades because of the thin oxidation that is formed when exposed to air. It also a non-toxic metal which is not pulled out by magnetic fields and has a strength of 49 Mpa to 700 Mpa. Aluminum alloying elements: Copper (Cu) to increase strength and hardness but reduce elongation by 4-6%; Zinc (Zn) increases tensile strength; Manganese (Mg) increases strength in high temperatures; Magnesium (Mg) increases strength and reduces ductility, corrosion resistance, and good weldability; Silicon (Si) increases hardness in heat treatment [3, 4].

Metal casting is the process of making a product by pouring hot molten metal into a box which has a hollowed mold model as demand and then waited until condensing in the mold to cool off. This solid part is known as a casting product. Castings must meet the mechanical properties associated with the ideal microstructure of the chemical composition of materials according to the material standards [5, 6, 7]. Casting is most often used to make complex shapes that will be difficult or uneconomic to be made by other methods. When the temperature drops below the melting point of the material, the solidification process begins [4, 8].

During the casting process, the rate of growth of defects is still possible. Therefore, it is important for the casting engineer to evaluate the possibility of defects caused by casting, identify the root cause of the casting failure, and take corrective action [10].

The biggest risk of casting failure is that the porosity on the surface in contact with the mold could be caused by the surface moisture of the mold, and the porosity of the core that occurs due to air trapped by the rapid cooling process [11].

Most of the casting defects are related to process parameters. Consequently, it is necessary to monitor the parameters of the casting process so that no defects will occur. This supervision is carried out by someone who must have knowledge of the effects of casting process parameters and their effects on defects. The appropriate identification of casting defects at an early stage is very important to take corrective action [12].

Possible failure castings, including releasing the mold core in a hurry; releasing excessive gas; low pouring temperature; inoculation of unbalanced material; core mold recovery; provision of transfer flow channels; gas supply; gas reduction; slow binder usage; binder reduction; use of coarse sand if necessary; reduction of gas speed and pressure [8].

Throughout metal solidification, some round or oval-shaped cavities could develop on the surface which associated with oxides. These oxides gather into bubbles in the mold cavity which will prevent the liquid metal from filling the space. This type of cavity or blowhole defect becomes a pinhole on the surface and core. Pinholes are very small holes. The core blowhole could only be seen after machining [9].

The phases of the process of making cast rim tires in small industries: heating the furnace to a temperature of 700°C to avoid moisture content; aluminum alloy scrap raw material put into the furnace; measurement of furnace temperature stability; pouring molten aluminum into casting mold; finishing the casting product by machining. Rim casting industry in Gresik is shown in figure 1.

This failure analysis research purposed as an input in solving problems in the small foundry industry to improve sustainable quality. The analysis of the failure of a product or engineering equipment can be carried out with four factors: material usage; product design; equipment operation or use during operation; and environmental conditions [13]. Failure analysis on rim products is carried out on raw materials and the product manufacturing process [14, 15].
Product testing is done in the form of visual, NDT, chemical composition, hardness, mechanical (impact), macrostructure, and microstructure. The results of the observation data will be analyzed as a statement of the causes of failure so as to improve the sustainability of the quality of the product [15].

2. Materials and methods

2.1 Materials

Five tire rim samples obtained by import (OEM) and local rim industries. The rim which is produced by small industry use raw materials from aluminum-ingots and aluminum scrap is given code EU, EO and YG. The identification of EU, EO, and YG rims are codes given by the rim manufacturer as production identification.

2.2 Methods

2.2.1 Casting Analysis. Casting failure analysis was directed at small industrial products. Visual observation method on the surface of tire rim castings by looking for possibilities of surface defects such as shrinkage of casting, porosity, and cracks. Smooth cavities that did not appear visually was checked using the Non Destructive Test (Penetrant Test) method. The penetration test was carried out by applying a penetrant liquid (usually the color is red) on the surface being tested. The liquid penetrant was left at sufficient time to seep into surface opening or defect. The excess penetrant fluid was then removed from the surface. The developer fluid was applied to draw the penetrant fluid to the surface (capillary action) to form a visible indication. The chemical composition of the rim was checked using a spectrometer analysis method. The specimens were taken from the rim and then subjected by an arc spark discharge at the spectrometer equipment. The intensity of emitted radiation caused by the arc spark was then analyzed by this apparatus to show the percentage of the chemical composition.

2.2.2 Tensile and Impact Test. Mechanical testing was done by performing tensile and impact tests and macrostructure observations on the cross section of castings after the impact test. The specimen for the tensile test was taken from the rim (not from extra material during casting). The specimen then subjected to a controlled tension at the tension testing machine 1,000 kg capacity until failure. The impact test was carried out on the rim that had been fitted with tires by dropping a load of 0.6W + 180 kg (W = maximum
load for the tire used) on a outer ring flange of the rim from a height of 320 meters at a certain rim angle. Fracture contours were observed with a magnifying lens. Microstructure observation used metallurgy microscope at 50 x magnification to observe porosity, 100 x magnification to observe micro-porosity, and 500 x magnification to observe micro-fissure and matrix structure of the sample.

3. Results and discussion

3.1. Observation of visual and NDT examination (penetrant test)

Through visual observations on the surface at the center of the rim wheels, the defect of cluster porosity appeared. The majority of porosity on the rim surface in the middle was porous castings, which appears that the holes were clustered as shown in figure 2. The porosity defects formed by gas trapped between the surface of the mold and molten metal related to the flow of liquid metal flowing through the mold exert thermomechanical pressure. Relatively large of compressive and shear forces occurred in the surface of mold will form a defect (porosity).

Irregular porosity was often difficult to diagnose because this defect generally occurred in various positions and was therefore very difficult to be associated with local causes. Porosity can also be trapped beneath the surface of the castings in combination with metal oxides, and can only be seen when machining.

3.2 Observation of mechanical test

Tensile testing of raw materials for imported sample rims resulted in higher tensile strength than local sample rims. However, EU, EO, and YG made from aluminum ingot and aluminum scrap raw materials produced a much lower tensile strength (table 1). Low tensile strength would cause a low impact value, and the hardness value of this rim (66 to 77) Hv10.

| Table 1. Mechanical test. |
|---------------------------|
| **Yield Strength, MPa**   | OEM Local | OEM Import | EU  | EO  | YG  |
| 255                      | 252       | 255        | 241 | 116 | 110 |
| 255                      | 255       | 255        | 241 | 116 | 110 |
| 266                      | 260       | 282        | 285 | 144 | 145 |
| Tensile Strength, MPa    | EU        | EO         | YG  |
| 255                      | 252       | 255        | 241 | 116 | 110 |
| 255                      | 255       | 255        | 241 | 116 | 110 |
| 266                      | 260       | 282        | 285 | 144 | 145 |
| 266                      | 260       | 282        | 285 | 144 | 145 |
| Elongation, %            | EU        | EO         | YG  |
| 3.7                      | 2.5       | 11.2       | 11.5| 0.8 | 0.9 |
| 3.7                      | 2.5       | 11.2       | 11.5| 0.8 | 0.9 |
| 2.5                      | 2.5       | 2.5        | 2.5| 2.5 | 2.5 |
| RA, %                    | EU        | EO         | YG  |
| 5.2                      | 0.7       | 16.7       | 13.7| 1.0 | 1.0 |
| 5.2                      | 0.7       | 16.7       | 13.7| 1.0 | 1.0 |
| 3.0                      | 3.0       | 3.0        | 3.0| 3.0 | 3.0 |

The impact tests carried out on the rims commonly used for mini bus vehicles with a minimum load stipulation of 936 kg according to SNI standards. Testing of small industrial rim products reached an impact load of 500 to 570 kg of broken rim as in Figure 2, the impact value was lower than that required by SNI standards.

3.3 Observation of Chemical Composition

In the raw material for aluminum-ingot and scrap aluminum alloys, there was an iron content of 0.401-0.433% Fe (table 2), the Fe content was higher than the rim (imported and local). This element would tend to form micro cracks and grew the structure of needles of aluminum, iron, and silicon compounds. This would reduce the strength of mechanical properties (tensile and impact strength). The chemical
composition of the raw material for aluminum ingot alloys and aluminum scrap was not in accordance with ASTM B 26 for casting material for rim product.

3.4 Observation of Fractography
In the macroscopic fractography observation on the cross-sectional surfaces of broken pieces of rim product appeared of coarse grained (brittle), also cavities in the form of porosity defects found (Shown in Figure 3).

Table 2. Chemical composition.

| No | Elements      | IMPORT | LOCAL | P-EV | P-EO | P-YG |
|----|---------------|--------|-------|------|------|------|
| 1  | Silicon (Si)  | 7.46   | 7.12  | 7.18 | 7.23 | 7.33 |
| 2  | Manganese (Mn)| 0.0027 | 0.0049| 0.199| 0.216| 0.110|
| 3  | Chromium (Cr) | 0.0083 | 0.0020| 0.0116| 0.0127| 0.0100|
| 4  | Nickel (Ni)   | 0.0028 | 0.0043| 0.0195| 0.0149| 0.0173|
| 5  | Zinc (Zn)     | 0.0242 | 0.0147| 0.277 | 0.241 | 0.244 |
| 6  | Copper (Cu)   | 0.0077 | 0.0094| 1.71  | 1.54  | 0.116 |
| 7  | Lead (Pb)     | 0.0029 | 0.0013| 0.0175| 0.0122| 0.0164|
| 8  | Tin (Sn)      | 0.0034 | 0.0020| 0.0079| 0.0056| 0.0053|
| 9  | Iron (Fe)     | 0.120  | 0.135 | 0.432 | 0.433 | 0.401 |
| 10 | Magnesium (Mg)| 91.9   | 0.316 | 0.175 | 0.152 | 0.250 |
| 11 | Titanium (Ti) | 0.127  | 0.128 | 0.0433| 0.0427| 0.0444|
| 12 | Cadmium (Cd)  | 0.0013 | 0.0014| 0.0014| 0.0013| 0.0013|

Figure 3. Macroscopic cross section of impact test

3.5 Observation of microstructure
The microstructure of rims from local raw material (aluminum scrap) was in the form of a rough dendritic microstructure containing a sharp needle-shaped phase indication of ferrite. This element was compounded with aluminum and silica to form the FeSiAl compound. Micro cracks (micro fissure) near the porosity cavities was also found (Shown in figure 4).

Figure 4. Location of micro fissure and porosity

Through heat treatment, the imported product rim microstructure has a finer dendritic shape than the rim of a local product which has a coarse grain dendritic (figure 5). The microstructure of rim made
from aluminum-ingot and aluminum-scrap alloys was a coarse-grained dendritic, had a needle-shaped phase structure and porosity (figure 6).

![Figure 5. Rim microstructure](image1)

![Figure 6. Rim microstructure of aluminum ingot-aluminum scrap](image2)

**Figure 5.** Rim microstructure

**Figure 6.** Rim microstructure of aluminum ingot-aluminum scrap

### 4. Conclusion

Based on observations, the failure analysis of the four-wheeled vehicle tire rim was caused by the porosity on the surface and core materials. Micro fissure in the core of the castings made the value of low mechanical strength. In addition to micro fissures, the structure of ferrite compounds was in the form of AlFeSi compounds which indicated the presence of high Fe content.

To improve the quality of the rim to meet the SNI standard requirements, the local raw material (aluminum ingot-aluminum scrap) must have a low Fe content. To the local aluminum scrap raw
material, 99% aluminum (pure) must be added to achieve a balance of chemical alloys to meet the standard of raw material for aluminum casting. To avoid surface porosity, rim molds must meet the criteria for aluminum casting and degassing using nitrogen gas. For the stability of the microstructure, heat treatment tempering is required.

Defects such as porosity and shrinkage can be analyzed by casting computer simulations, as the most efficient and accurate method. The quality and results of casting can be improved efficiently by modifying such techniques as SQC DOE simulation in the shortest time possible and without conducting actual trials at the casting plant.

Efforts to analyze critical defects and possible corrective actions are recommended for casting producers to have knowledge of casting defects with the aim to minimizing the level of product rejection or failure.

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