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Damage Analysis of Cylinder Head Components on 3406C Industrial Diesel Engines using Fishbone Diagrams

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***Abstract* - Damage to diesel engine cylinder head components can cause crucial problems. This study describes the methods used to identify the causes of diesel engine cylinder head damage based on visual observations and interviews with technicians. The results of this study will provide a better understanding of the root causes that cause damage to the diesel engine cylinder head components used at PT. Pertamina Drilling Services Indonesia. This study provides an overview of effective repairs and maintenance to overcome these problems with the aim of increasing engine performance and extending component life.**

Keywords: Cylinder Head, Diesel Cachine, Fishbone Diagram.

I. INTRODUCTION

The development of oil drilling in Indonesia was first carried out by the Dutch in 1871 by Jan Reerink, in Majalengka. This activity was 12 years after the world's first oil drilling by Colonel Edwin Laurentine Drake and William Smith de Titusville (1859) in the state of Pennsylvania, United States of America. Furthermore, the oil exploration business in Indonesia was continued by another Dutchman named Aeilko Jans Zijker in the Langkat area, North Sumatra, which later in 1890 Zijker transferred his concession to Royal Dutch Petroleum (Zilfa Gita, 2016).

PT. Pertamina Drilling Services Indonesia (PDSI) is a company engaged in the field of exploration drilling services, exploitation, workover and well services for oil and gas, geothermal and integrated drilling solutions. For more than 10 years, PT PDSI has experience in the exploration sector and is competent as a provider providing services for drilling services and integrated solutions (Pertamina Drilling Service Indonesia, 2021).

Rig is a tool used to carry out the process of drilling (exploitation) of oil from the earth. Drilling rig is an installation of equipment for drilling into underground reservoirs to obtain water, oil or natural gas, or underground mineral deposits. Drilling rigs can be on land (on shore) and on the sea or offshore depending on the needs of their users.

The main components of the rig are divided into five parts. First, the hoisting system is a lifting system consisting of supporting structures such as substructures and drilling towers (derrick/mast), as well as hoisting equipment such as draw work, overhead tools (crown blocks, traveling blocks, hooks, elevators), and drilling lines. Second, the circulating system functions to circulate drilling mud through a series of drilling pipes and returns to the surface through the annulus using mud tanks, mud pumps, high pressure surface connections, drill strings, bits, and solid control equipment. Third, the rotating system is used to rotate the drill bit, put a load on the drill bit, and provide high pressure mud channels to the drill bit. Fourth, the BOP (blow out preventer) system consists of various valves installed at the wellhead and functions to prevent blowout and control well pressure. Finally, the power system is a system that provides energy for rig operations using generators driven by diesel engines. These components work together to support drilling activities and maintain the safety and efficiency of rig operations.

The diesel engine is an internal combustion engine which is ignited by spraying fuel into high pressure and temperature air. High pressure and high temperature fuel is produced from the compression process. There are several things that affect the performance of diesel engines, including the size of the compression ratio, the level of homogeneity of the fuel-air mixture, the characteristics of the fuel (including the cetane number), where the cetane number shows the ability of the fuel itself (Wharton, 1991).

Three things that will be discussed in this article are damage to the valve cylinder head, damage to the valve spring, and damage to the cylinder block. First, this article aims to determine the damage that occurs to the valve cylinder head. Valve cylinder head is an important component in the engine, and damage to this part can interfere with the overall

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performance of the engine. Research will be conducted to identify the type of damage that occurred and its causes. Furthermore, this article will discuss damage to the spring valve. Spring valve is a part that plays a role in regulating the flow of fuel and air in the engine. If the spring valve is damaged, it can cause problems with engine combustion and fuel efficiency. Research will be conducted to find the cause of the damage and propose solutions to fix it. Lastly, this article will also review damage to the cylinder block. Cylinder block is a component that acts as a container for other components in the cylinder head. Damage to the cylinder block can result in leaks, decreased engine power, or even fatal damage to the engine. Research will be conducted to evaluate the level of damage and determine the necessary corrective steps.

II. RESEARCH OBJECT

2.1 Cylinder Head Block

The cylinder head block is a component that acts as a container for other components in the cylinder head. Inside the cylinder head block, there are intake valves and exhaust valves which are controlled by a valve drive system, such as camshafts and rocker arms, according to the engine's working cycle. In addition, the cylinder head block also has space for ignition and cooling channels which are important for keeping the engine temperature within safe limits.

2.2 Valve

Diesel engine will not start if there is no valve. The function of the valve is to regulate the incoming and outgoing air as well as closing the hole when compression occurs. Valve on a diesel engine is a valve used to regulate the flow of air and fuel into the combustion chamber and remove exhaust gas from the engine. In diesel engines, there are two types of valves namely intake valve and exhaust valve. The intake valve opens to allow air into the combustion chamber as the piston descends on the intake stroke.

2.3 SpringValve

Spring Valve is a type of valve used in internal combustion engines. In gasoline or diesel engines, the Spring Valve regulates the flow of air or fuel into the combustion chamber and removes exhaust from the engine. Spring valve works by using a spring to open and close the valve according to the engine cycle.

When the engine is running, the valve is opened by the camshaft which moves the rocker arm to push the valve down so that air or fuel can enter the combustion chamber. Then, the spring on the valve will close the valve again after the desired phase is completed, so that the exhaust gas can be removed from the engine.

2.4 Fishbone Diagram

Fishbone diagram was introduced by Prof. Kaoru Ishikawa from Japan. He introduced this diagram as a method to show the cause and effect of a problem. Therefore this diagram can also be called Ishikawa's diagram (Ishikawa diagram). This is because Ishikawa shows causal factors and characteristics (M. B. Anthony, 2016). Problems can be solved by solving the problem into a number of categories and each category has causes that need to be explained through a brainstorming session. The principle used is brainstorming or brainstorming which is a method of discussion by obtaining creative opinions freely (Ishikawa, 1976). There are 6 affected factors that need to be considered in making a fishbone diagram, the human factor (man), the tool factor (machine), the method factor (method), the measurement factor (measurement), material and material factors (materials), and environmental factors (environment) shown in Image 1.

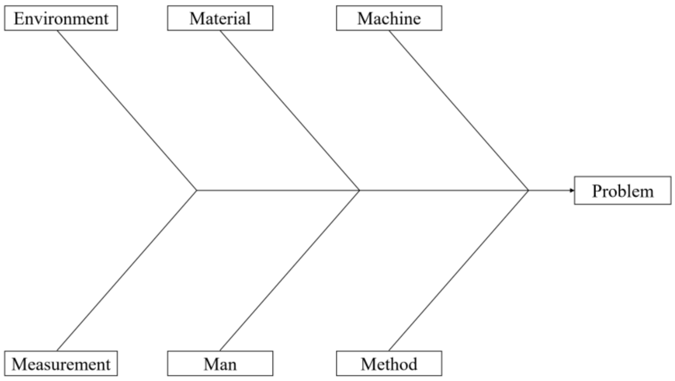

Figure 1: Fishbone diagram scheme

2.5 Problem Solving Method

The data obtained in this study were collected through various data collection methods. One of the methods used is the primary data collection method. This method involves direct surveys in the field to obtain data that corresponds to actual conditions. Primary data collection is done through interviews with engineers who have knowledge of machines and through direct observation of machines for observation. In addition, the method of collecting supporting data or secondary data is also used. This method involves using data from third party references related to the machine under study, such as data from brokers or other reference sources. This secondary data is used as a support and reference in obtaining information about the machine being studied.

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III. DATA AND ANALYSIS

3.1 Actual Data

The data obtained came from direct observation with the mentor engineer while checking damage to the diesel engine which was brought to the PT PDSI maintenance workshop. The following are the types of components and damage based on direct observation along with possible causes. The following is the assumption data for analyzing the causes of component damage shown in Table 1.

Table1: Damage data of cylinder head component

No	Component Name	Damage Type	Possible Causes of damage
1	Valve	Chipped, Burnt	soot accumulation, time belt error, overheating
2	Spring Valve	Broken	Error during installation.
3	Cylinder Head Block	Cracked	Overheating

3.2 Damage Analysis of Diesel Engine Component

Damage analysis on the overhaul of the 3406 diesel engine was carried out by observation and reconditioning of the diesel engine. Component replacement is carried out on all parts of the diesel engine that are affected by the damaged component to minimize further damage due to a domino effect.

3.2.1 Valve

The main function of the exhaust valve on the engine is to drain the burnt fuel from the engine and allow fresh fuel to enter the combustion chamber. This component plays a vital role in an internal combustion engine and care must be taken as damage to the valves can cause total damage to the engine. In the 3406 diesel engine, the engine valves are made of Austenitic Stainless Steel, one of the materials used. The value of the mechanical properties of Austenitic Stainless Steel can be found in Table 2.

Table 2: Mechanical properties of Austenitic Stainless Steel (Connor, 2013)

Mechanical Properties	Nilai
Tensile strength	515 MPa
Yield strength	205 MPa
Hardness	201 HB
Elongation at break	40 - 60%
Impact strength	100 J
Poisson's ratio	0.3
Elasticity Modulus	193 GPa

The valve in the cylinder head is a vital component of a diesel engine, this component gets a lot of pressure and load. Works by opening and closing up to 2500 times every minute under normal operating conditions. When one or more valves are damaged, the resulting consequences can be very significant, ranging from reduced engine power (power loss) and wasteful fuel consumption, to total engine failure. The two most common and frequently encountered types of valve failure are bent/damaged valves and burnt valves.

The most common valve failure is bending and cracking due to contact with the piston head. This happens because of the accumulation of soot in the combustion chamber so that the valve heads and piston heads meet or touch. The piston head has a higher hardness than the valve, using AISI 4140 material with a hardness level of 50-60 HRC. Therefore, if the valve is in contact with the piston head for a long time, it may cause damage to the valve. Contact between the valves and the piston head usually occurs due to engine synchronization errors, such as damage to the timing belt or improper belt installation. Bent valves can cause more serious engine problems, including damage to the cylinder head, pistons, and cylinder bores. One of the causes of bent valves is a worn or damaged timing belt (Nationwide Bearing Co. 2017). The timing belt is important in setting the exact time to open and close the intake and exhaust valves, which is also known as the valve timing diagram. This diagram is made based on the movement of the piston in the cylinder. The following is the condition of a broken valve shown in Figure 2.

Figure 2: Valve damage (perforated and broken)

Cracks can occur due to the collision of two different types of material. Materials that have a lower level of hardness will lose and become chipped. This happens because of the impact loading of the valve head with the piston head.

A common type of valve failure is burnt valve which is caused by a leak of combustion gas between the valve and valve seat. The hot gas burns the edge of the valve if the leak is not repaired. Austenitic stainless steel 304, which is commonly used in valve manufacture, has an operating temperature limit of around 870 degrees Celsius. The gas leak temperature in a Caterpillar 3406 diesel engine is 1300-2200

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degrees Fahrenheit, and if the valves are not properly sealed then the hot combustion gases can cause burning of the valve edges. This type of failure usually affects the exhaust valve and can damage the intake valve. (Southside, 2012). Figure 3 shows an example of damage to a burnt valve.

Figure 3: Burnt Valve

Burnt valve damage can cause problems in vehicle performance and fuel consumption. Symptoms such as unstable idle, reduced power, backfiring, and misfires are all signs of a burnt valve problem. If the vehicle shows these symptoms, it is advisable to check the condition of the engine thoroughly. Continuing to use the vehicle in those conditions with burnt valves could cause further damage to the engine and end up being more expensive to repair in the long run. (Baker, 2018).

3.2.2 Spring Valve

The damage that occurs to the cylinder head spring valve component is a broken spring (fracture). This can happen because of an error in installing the spring when installing the spring component on the valve stem, causing the pressure experienced by the spring to be uneven and making the spring work imperfect. The following Figure 4 shows a broken spring valve.

Figure 4: Spring valve damage

The springs used in diesel engines have certain specifications depending on the type of engine. The following Table 3 shows the dimensions of the 3406 diesel engine spring valve.

Table 3: Spring valve dimensions of 3406 Diesel Engine

Dimension	Unit (mm)
Free Length	62.74
Outer Diameter	31.75
Solid Length	40.64
Wire Diameter	4.877

After doing the calculations on the spring, the data is obtained as above. Meanwhile, the spring constant is k = 44.48 N/mm under normal conditions (good engine) spring valve, or the spring will be compressed by 11 mm at minimum and 22 mm at maximum (Zhi-Wei Yu, 2008). Based on these values, we can calculate the minimum and maximum loads of a spring using Hooke's Law equation in equation 1 below.

$$F = -k.\Delta x \qquad (1)$$

Where
F : The load experienced by the spring
K : Spring constant
Δx : Change in spring length

Calculation of the minimum and maximum loads with a value of k = 44.48 N/mm. For Δx = 11mm

$$F = -k.\Delta x$$

$$F = -(\,44.48\ \text{N/mm})(11\ mm)$$

$$F = 489{,}28\ N$$

So the minimum load is 489,28 N.

For Δx = 22mm

$$F = -k.\Delta x$$

$$F = -(\,44.48\ \text{N/mm})(22\ mm)$$

$$F = 978{,}56 N$$

So the maximum load is 978,56 N.

After calculating the maximum and minimum load ranges that will be accepted by the spring, the next step is to calculate the spring parameters to determine whether the load to be applied is safe or not. One of the parameters that need to be calculated is the shear stress amplitude (τ_a). Calculation of τ_a involves calculating the value of Fa based on the load applied to the spring, the free length of the spring, the diameter of the spring wire, and the number of turns of the spring. After the Fa value is obtained, τa can be calculated using a certain formula. Fa can be found by the following calculations.

$$F_a = \frac{(F_{max} - F_{min})}{2} = \frac{(978{,}56\ \text{N} - 489{,}28\ \text{N})}{2} = 240{,}14\ N \qquad (2)$$

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$$\tau_a = Kw \frac{8F_a D}{\pi d^2} \quad (3)$$

$$\tau_a = (1.28)\frac{8(240,14)(26,873)}{\pi(4.877)^2} = 184.43 \text{ MPa}$$

Table 4: Parameters to help calculate the safety factor on springs (AmesWeb, 2023)

Parameter	Value
Whal Factor [K_w]	1.28
Shear stress amplitude [τ_a]	184.43 MPa
Torsional rupture strength [S_{su}]	1029.39 MPa
Amplitude strength component for infinite life (Shot peened)(Zimmerli Data) [S_{sa_zim}]	242.51 MPa
Midrange strength component for infinite life (Shot peened)-(Zimmerli Data) [S_{sm_zim}]	827.02 MPa
Shear endurance limit according to Gerber (with Zimmerli Data) [S_{se}]	544.54 MPa
Shear stress amplitude limit (According to Gerber failure criteria) [S_{sa}]	251.65 MPa
Design factor for fatigue [n_f]	1.2

Based on the above calculations and several parameters obtained from data collection using the help of the spring parameter calculation application, Table 4 is obtained which contains the parameters used in calculating the safety factor of the spring valve.

The spring valve used in diesel engines uses chrome-vanadium material. From the data we have obtained through data search and calculation methods, we can calculate the factor of safety against fatigue [fos_f]of the spring when working normally by dividing the value of the shear stress amplitude limit (According to Gerber failure criteria) *[Ssa]*with the value of shear stress amplitude *[τ_a]*. The following is a calculation of the Factor of safety against fatigue [fos_f].

$$fos_f = \frac{S_{sa}}{\tau_a} (4)$$

$$fos_f = \frac{251.65 \text{ MPa}}{184.43 \text{ MPa}}$$

$$fos_f = 1.3$$

The spring has a factor of safety which is greater than the value of the factor of safety from the design when subjected to load (1.3 > 1.2). Therefore the spring can survive the work cycle according to the initial design of the machine.

The Caterpillar 3406 diesel engine has a service life before overhaul on the valve spring components of 12,000 working hours. However, often the spring is damaged, such as a broken spring, because the load exceeds the safety factor of the spring. Overload or overload can be caused by an error in installing the spring on the valve stem which results in uneven pressure and imperfect spring work. This reduces spring life to less than 12,000 working hours and adversely affects engine performance and incomplete combustion.

To solve this problem, an urgent repair is required when the engine suffers from a decrease in performance. This involves replacing springs during minor overhauls, to prevent a domino effect on other components that are still functioning normally and avoid major overhauls. In the drilling industry, machines work continuously so that a small disturbance can affect the entire drilling process. As a precautionary measure, there is usually a spare machine available which is used when there is a problem with the main machine.

3.2.3 Cylinder Head Block

The cylinder block is a fixed and integral part of the crank mechanism, which connects the engine cylinders. The cylinder block is made of cast iron more specifically gray cast iron. Gray cast iron – ASTM A48 class 40 has a material composition of 93% iron, 3% carbon, 2% silicon, 0.6% manganese, 0.15% sulfur and 0.1% phosphorus. The following are the properties of the basic materials for making cylinder blocks shown in Table 5.

Table 2: Mechanical Properties of Gray cast iron (Connor, 2023)

Properties	Value
Density	7150 kg/m^3
Ultimate Tensile Strength	395 MPa
Young's Modulus of Elasticity	124 GPa
Brinell Hardness	235 BHN
Melting Point	1260 °C
Thermal Conductivity	53 W/mK
Heat Capacity	460 J/g K

`All major engine components are mounted on or within the engine block. The top of the cylinder block is closed by the cylinder head, while the crankcase is attached to the bottom of the cylinder block. High precision is required in the installation of these components, including the cylinder bore to be able to withstand the pressure of the burning fuel mixture. A tight fit must be maintained between the cylinder bottom and the piston ring so that the piston ring can properly

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seal the combustible gases. Figure 5 shows damage to the cylinder head block.

Figure 5: Damage to the cylinder head block

Under normal conditions, diesel engines operate at temperatures of 104-111°C, where the value of the tensile strength of the material used does not change significantly (Costa, 2011). However, if the engine operates at abnormal temperatures, especially overheated temperatures, high pressure will be experienced on the cylinder head, cylinder liners and engine block. If the temperature is not controlled while operating, this can cause damage to the engine components, especially the cylinder block. This causes a decrease in the tensile strength of the material when the engine combustion chamber temperature increases, which is a factor affecting material fatigue. The tensile strength of materials, such as gray cast iron and other types of cast iron tends to decrease in the temperature range of 20-150°C (Costa, 2011).

As a result of a decrease in the tensile strength of the material, the material will experience fatigue more quickly and have an impact on damage. This is accelerated by the material environmental conditions which do exist at too high temperature conditions, causing excess pressure on these components. The damage that occurs to the cylinder block components is in the form of cracks in the cylinder block (Niaga Kita, 2019). Overheating of the engine can occur due to an error in the cooling system in a diesel engine. If the coolant ducts are not externally treated to keep them clean without obstruction in airflow along with not retaining coolant allowing internal blockage and tube blockage, overheating will result. If the engine continues to work under conditions of severe and excessive overheating it will cause cracks in the cylinder head block. This will result in engine performance and damage to other components. A cracked engine block can cause a variety of problems. Ultimately, because the circulation system that cools the engine is relatively fragile, a cracked engine block will cause coolant to leak out of the area where it is needed and overheat the engine. If not corrected, this will lead to engine failure which may result in the engine stopping operation. Cracked engine blocks can result in low engine compression, excessive engine smoke, and visible cracks in the engine block.

3.3 Fishbone Diagram Analysis

Damage analysis on the 3406 diesel engine overhaul was carried out by observation and reconditioning of the diesel engine. Component replacement is carried out on all parts of the diesel engine that are affected by the damaged component to minimize further damage due to a domino effect.

3.3.1 Fishbone Valve Damage Diagram

Based on the results of the observations, analysis and brainstorming that have been carried out, it produces a fishbone diagram on the valve cylinder head component of the 3406 diesel engine which is shown in Figure 6.

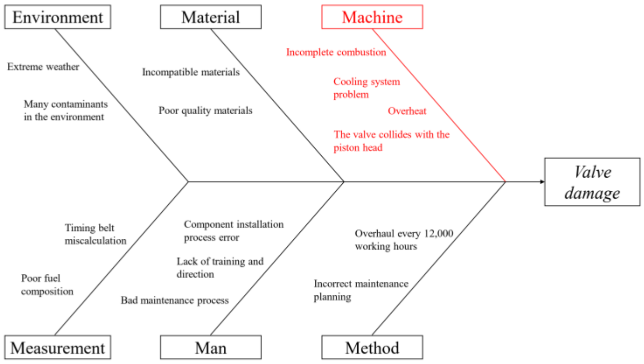

Figure 6: Fishbone diagram analysis for valve damage

In the results of the analysis using fishbone diagrams, it was found that there were 6 (six) factors that caused damage to the valve components in the cylinder head which consisted of method, machine, man, measurement, environment and material. In engine factors, incomplete combustion and problems with the cooling system can cause damage to the cylinder head valve components. Incomplete combustion results in excess soot buildup on the valves, while a faulty cooling system can cause engine temperatures to rise excessively. Both can affect valve performance and service life.

The damage that occurs to the valve is in the form of a puncture on the valve so that it makes the valve perforated. This can happen because of the collision between the valve and the piston head. Under normal conditions this does not happen. The collision occurs because there is an accumulation of soot left over from combustion in the valve head so that the distance or difference between the valve and the piston head which should have a distance and does not intersect ends up colliding, as a result the valve loses in terms of material strength and a puncture occurs in the valve.

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To overcome the engine factors, good care and maintenance is very important. This includes routine monitoring of engine performance, cleaning and maintenance of the combustion system, inspection of the cooling system, and replacement of damaged or worn components. By maintaining optimal combustion and a good cooling system, the risk of damage to valve components can be reduced and engine performance can be maintained properly.

3.3.2 Fishbone Diagram of Spring Valve Damage

Based on the results of the observations, analysis and brainstorming that have been carried out, the fishbone diagram for the spring valve cylinder head component of the 3406 diesel engine is shown in Figure 7.

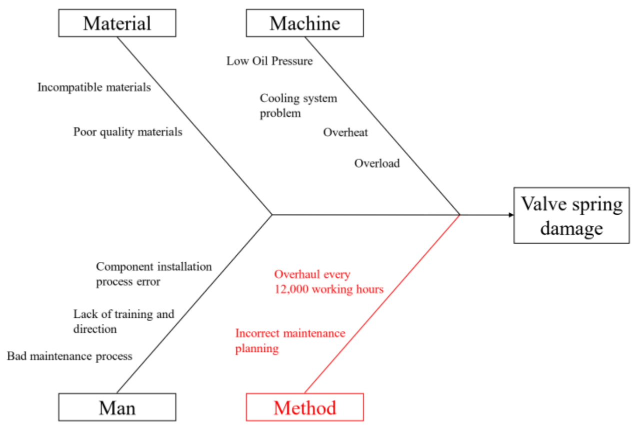

Figure 7: Fishbone diagram analysis for spring valve damage

The method factor is one of four factors that can cause damage to the valve spring in the cylinder head. This factor involves aspects related to the methods or procedures used in the care, maintenance, installation and operation of spring valves. Overhaul every 12,000 working hours which is the age limit of the spring valve. Spring valve has a recommended operational life limit, it is usually recommended to overhaul or replace at certain intervals, such as every 12,000 working hours. If the overhaul is not carried out according to the specified age limit, then there is a risk of damage to the spring valve due to wear and tear and material fatigue that is not repaired or replaced on time. Apart from having reached the wrong maintenance planning limit, improper maintenance planning can cause a lack of maintenance or excessive maintenance of the spring valve. If maintenance planning does not take into account the need for appropriate maintenance, such as cleaning, lubricating, or replacing damaged components, then the spring valve can wear or damage more quickly.

In maintaining performance and preventing damage to spring valves, it is important to follow proper maintenance methods, maintain the overhaul schedule according to the recommended age limits, carry out appropriate maintenance plans, and provide adequate training and guidance to operators or technicians who are responsible for maintenance spring valve.

3.3.3 Fishbone Cylinder Head Block Diagram

The fishbone diagram of the 3406 diesel engine cylinder head block components is shown in Figure 8.

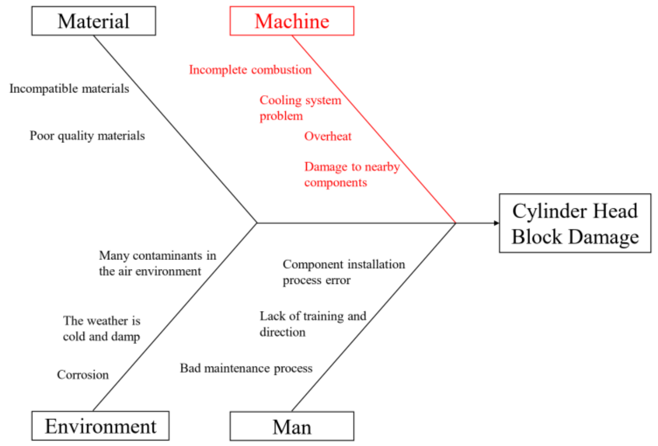

Figure 8: Fishbone diagram analysis for cylinder head block damage

Engine factor is one of the four main causes of damage to cylinder head components. A cooling system that is not functioning properly or problems with engine cooling components can cause an overheated condition in the engine. Overheating occurs when the engine temperature exceeds normal limits which can result in damage to the cylinder head. Excessive heat can affect the mechanical properties of the material, including changes in dimensions and a decrease in strength. This can cause deformation or cracking of the cylinder head, reducing the performance and service life of the component.

Incomplete combustion, the combustion process in the engine may experience disturbances, such as imperfections in the mixing of air and fuel or the presence of obstacles in the combustion process. Incomplete combustion can generate excess heat and increase pressure in the cylinder head. This can cause damage to components, including cracking or deformation of the cylinder head due to overpressure.

It is important to pay attention to and address these factors in maintaining engine performance and preventing damage to cylinder head components. This includes good maintenance, including monitoring of engine temperature and pressure, maintenance of an effective cooling system, meeting the need for adequate lubrication, and ensuring the workload of the machine does not exceed the set limits. Paying attention

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to these factors can reduce the risk of damage and extend the service life of cylinder head components.

IV. CONCLUSION

Damage to the valve can be in the form of abrasions that occur due to the accumulation of soot on the valve head as a result of which the valve head collides with the piston head. Other failures can be caused by several other factors such as bad materials, errors in the production process, environmental conditions, overload on the valve and lack of operator training on valve use and maintenance. Therefore, preventive and corrective measures can be taken by replacing or repairing damaged materials, providing operator training, improving machine and equipment maintenance, and modifying the production process to reduce the possibility of valve damage. Damage to the spring valve can be caused by several factors such as bad materials and errors in the production process. Damage to the spring valve in the form of a broken spring, this occurs due to an error in the installation so that the spring does not last long due to overload. Besides that, other causes can also occur due to the age of the spring which must be replaced (12,000 hours). Therefore, preventive and corrective measures can be taken by replacing or repairing damaged components, correcting improper operating processes, improving machine and equipment maintenance, and providing operator training on the use and maintenance of spring valves. Damage to the cylinder block can be caused by several factors such as bad material, errors in the lubrication system, bad environment, improper use which results in the condition of the cylinder head block being overheated. Therefore, preventive and corrective actions can be taken by repairing the lubrication system, increasing machine and equipment maintenance, and replacing or repairing damaged or worn out components.

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