

The corrugated metal gasket is still in the early stages of development. However, gasket contact flanges with a high surface roughness (more than $3.5\ \mu\text{m}$) leak and require a lot of force to tighten. A nickel or copper-coated corrugated metal gasket was designed. A water pressure test was used to measure leaks, and the results revealed that nickel or copper-covered gaskets performed better. The effect of high temperature has not been explored in this study, which only reveals high pressure. The goal of this study is to use copper and nickel coatings to improve the performance of corrugated metal gaskets. Copper or nickel infiltrates the pipe flange's rough surface, preventing leaking. The purpose of this study is to investigate the performance of a coated corrugated metal gasket in a boiler system, which has high temperature and pressure. Corrugated metal gaskets were formed using a cold forming process. The gasket material was SUS304, which is copper or nickel-plated through electroplating. The gasket was installed in a series of pipes in the boiler that flows water at high temperature and pressure. The water leak was trickling on white paper that had been placed beneath the gasket. Even small water leaks are detected on white paper. The thermal camera can detect vapor leaks. The results of the studies reveal that the coated corrugated metal gasket's performance was improved, as seen by the reduction in leakage. At the highest pressure of 7 bar and the lowest tightening force of 40 kN, neither gasket leaked. This result is different from standard corrugated metal gaskets, where at the same pressure and temperature, steam and water leaks are observed. Both copper and nickel-plating types can be used to coat corrugated metal gaskets made of SUS304.

Keywords: coating, nickel, copper, corrugated metal gaskets, performance, leakage, multilayered, boiler

IMPROVED PERFORMANCE OF CORRUGATED METAL GASKETS IN BOILER'S PIPING SYSTEM THROUGH MULTILAYERED COATING

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1. Introduction

Corrugated metal gaskets (CMG), which replace asbestos gaskets are still being developed. Gasket materials must withstand high temperatures, high pressures and corrosive chemicals. These gaskets are commonly used in the connection between pipes because of the limited length of the pipe or

because the pipe bends. At the pipe connection, there must be a flange and gasket. Bolts are used to tighten the gasket. The corrugated metal gasket consists of a flat section and 4 waves, namely 2 waves at the bottom and 2 waves at the top [1]. Corrugated metal gaskets are made to provide local high contact stress to reduce tightening forces and produce a spring effect that can reduce the effect of loosening bolts [1–4].

An optimum design of CMG using finite element method and Taguchi method sized according to 25 A standard has been developed in the previous study [2]. The optimum design was tested using the helium test. In the previous study, the influence of flange surface roughness towards leakages was investigated [3]. The surface roughness of the pipe flange greatly affects the leakage. The aforementioned studies, however, still have their weaknesses as they required high tightening force. It was also observed that for a flange with a high surface roughness (above 3.5 μm), helium leakage still occurred. To overcome the surface roughness problems while maintaining the spring stiffness of the gasket, the optimum design of laminated corrugated metal gasket using computer simulation was investigated [5]. The leakage performance of laminated corrugated metal gasket is better than in the previous corrugated metal gasket [3]. The researchers have modified the standard gasket by layering the outer part with a softer material [6, 7]. In addition to the primary metal gasket material, the outer part was coated with a layer of copper. However, it was quite difficult to manufacture the gasket with three layers of materials because copper cannot bond well with steel. Therefore, it is very important to do research on corrugated metal gaskets made of SUS304 coated with nickel or copper, which are tested for leaks at high temperatures and pressures.

2. Literature review and problem statement

Cold forming can be used to form gasket materials into corrugated metal gaskets. Giving the load and the amount of loading in accordance with the needs of the formation of the material can form CMG [4, 8].

The SUS304 CMG covered with copper using the finite element method was studied and the result revealed a modest decrease in contact stress and an increase in contact width [8]. The gasket leakage rate will be reduced if contact breadth is increased. However, experimental approaches have yet to confirm this idea of leakage testing. More research is needed to create a material that is softer than SUS304 but yet has the properties of being able to endure high temperatures and being corrosion resistant. Copper and nickel are two examples of such materials.

The surface roughness of the flange greatly determines the fluid leakage at the joint. Rough surfaces cause greater fluid leakage. The softer surface of the object can seal the surface roughness to prevent leakage [4].

The electrochemical corrosion of a Cr-C-coated steel sample when exposed to Ni and Cu was studied. At 0 V, corrosion resistance was detected electrochemically [9]. The corrosion behaviors of electroless Ni-Cu-O/n-TiN composite coatings were investigated [10]. They discovered that when the Cu amount in the coating grew, the corrosion current density decreased. According to both papers, copper or nickel coating reduces material corrosion. An AISI304 stainless steel coating experiment with nickel-coated copper used a time variable and a fixed electric current parameter to conduct [11]. The stainless-steel material was effectively copper coated, with the greatest results obtained at a current of 1.5 A and a time of 180 seconds. It was suggested that the copper bonded to the stainless steel be 26.50 μm thick.

Copper and nickel are materials that are resistant to temperature and chemicals. These materials are not easy to corrode under certain conditions, so they are suitable when used as a CMG coating [12, 13]. Both materials are softer than SUS304.

A corrugated metal gasket coated with nickel or copper was investigated. Leaks were measured using a water pressure test, the results showed an increase in the performance of nickel or copper-coated gaskets [4]. However, this study only shows high pressure, the effect of high temperature has not been studied.

3. The aim and objectives of this study

The aim of the study is to determine the performance of a coated corrugated metal gasket in a boiler system, which has high temperature and pressure.

To achieve this aim, the following objectives are accomplished:

- to form the gasket material for corrugated metal gaskets by cold forming;
- to carry out the electroplating process of copper and nickel;
- to investigate the performance of a copper-plated corrugated metal gasket in the boiler system;
- to investigate the performance of a nickel-plated corrugated metal gasket in the boiler system.

4. The study material and methods

4.1. Material

The underlying material of the gasket was SUS304 metal. This material is chemically robust, can withstand high temperatures, and has a high pressure resistance. According to [12, 13], the mechanical properties of SUS304, copper, and nickel are shown in Table 1.

Table 1

SUS304, copper, and nickel have different characteristics

Properties	Value		
	SUS304	Nickel	Copper
Yield strength	398.83 MPa	210 MPa	195 MPa
Young's modulus	210 GPa	170 GPa	115 GPa
Tangent Young's modulus	1900.53 MPa	1,200 MPa	1,150 MPa

From Table 1, it can be concluded that the mechanical properties of copper and nickel are both softer than in SUS304. The softer material is expected to fill the flange surface roughness and seal the leak.

4.2. Design of corrugated metal gaskets

The optimum design of corrugated metal gaskets used a Taguchi method. The design parameters were contact stress and contact width obtained from simulation analysis using MSC Marc software. The complete shape and dimensions of corrugated metal gaskets can be seen in Nurhadiyanto et al [2]. The next stage is to create dies for the forming process based on the results of this design.

4.3. Forming

The base material for the SUS304 gasket was shaped like a flat ring. The base material was 1.5 mm thick, with a 75 mm outer diameter and a 20 mm inner diameter. The gasket material is shown in Fig. 1 before it is cold molded. The gasket material must have no defects due to scratches when cutting the material. Cutting that does not cause scratches is to use

laser cutting. Gasket material scratches can occur when handling the material, placing it in a rough place, or rubbing against other materials. Material scratches occur on the bottom and top of the gasket material. In fact, that part will become the valleys and hills of CMG to prevent leakage. The part of the hill that is in contact with the flange. If there is a scratch on the hillside, it has the potential to cause leakage because it forms a radial path.

The outer and inner diameters of the gasket were cut to JISB2404 specifications [14]. According to the JISB2220

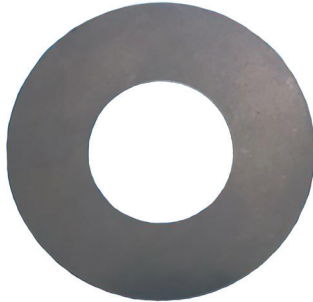


Fig. 1. Gasket base material

standard [15], the flanges were general-purpose flanges with a 10 K pressure rating. According to this specification, the flanges had a diameter of 25 A.

In a press machine, the corrugated gasket was cold manufactured with a compressive force of 1,100 kN. On the machine's base, the bottom die was first installed. The gasket base material was then applied to the top of the bottom die. The gasket base material was then connected to the upper die. After that, a force of 1,100 kN was applied to the upper die [16, 17].

4. 4. Electroplating

Following the formation of the corrugated metal gasket, separate layers of copper and nickel were applied. The thickness of the nickel or copper layer was varied, with 10 μm , 15 μm , and 20 μm being the most common. Taking this thickness is in accordance with previous research [4]. At that thickness, it was managed to reduce leakage by conducting the water pressure test. We will vary the thickness of the nickel layer to see if there is the most optimal thickness among these thicknesses. The prior study [18–20] demonstrated the electroplating coating technique.

4. 5. Leak measurement

Gasket leak test to determine the performance of CMGS, CPCMG, and NPCMG is carried out in the industry, especially in boilers. The leak test was carried out at Politeknik LPP Yogyakarta. The type of boiler is a TWA 300 kg/hours boiler with a maximum pressure of 7 bar as shown in Fig. 2.

The gasket is mounted on the flange and placed on the connection in the boiler as shown in Fig. 3. A more detailed picture of the gasket installation can be seen in Fig. 2. The gaskets tested were CMGS, CPCMG, and NPCMG. The flange used is made of SUS304 with a surface roughness of 3.5 μm . In the previous research [3], the flange with this roughness still leaks when using CMGS. This research is to see the increase in gasket performance after being given a nickel or copper coating.

Bolt tightening force is measured using digital torque. This tool can measure the tightening force of each bolt. There are 4 bolts used so that the tightening force is multiplied by 4.

The tightening forces used were 40 kN, 60 kN, 80 kN, 100 kN and 120 kN.

Steam leakage was measured using a Flir E4 thermal camera, see Fig. 4. This tool can detect steam leaks. Water leaks can be seen through visual observation [21–23]. Under the gasket and flange, white paper is put. If there is a leak, then the water will drip and fall on the white paper.



Fig. 2. Boiler type TWA 300 kg/hours



Fig. 3. Installation of the gasket on the flange in the boiler line



Fig. 4. Flir E4 thermal camera

The temperature of the fluid flowing in the flange of 270 $^{\circ}\text{C}$ was measured using a Krisbow KW06002718 digital thermometer. The maximum boiler pressure was 7 bar, while observations start from 3 bar, 5 bar, and 7 bar. The pressure can be seen on the panel on the boiler.

The first process was to install the gasket on the flange and then tighten it according to the tightening sequence. The boiler was turned on until it reaches its saturation point. Through the chimney temperature indicator, it can be seen that the saturation point shows a temperature of 270 °C. After that, the valve on the flange is opened in order to start the test. Because at a steam pressure of 3 bar there was still a little water, the test results are in the form of a water leak table and a steam leak table. Leakage measurements were carried out 3 times for the same type of gasket. A water leak dripped on white paper placed under the gasket. The smallest drops of water that fall on the paper will be visible on the paper. Therefore, water leaks can be detected on white paper.

5. Results of studying the performance of CMG in the boiler’s piping system

5.1. Cold forming

The formed gaskets were manufactured from corrugated metal gaskets with two circular pieces on the upper and lower sides. The gasket was once a flat disc made cold with a set of dies filled with specified loads. The die dimensions were calculated using the optimum dimension found using finite element and Taguchi methods, as published in the literature [2].

The material was then formed into corrugated shapes, which are known as Corrugated Metal Gaskets Standard (CMGS). The gasket after it has been manufactured is shown in Fig. 5. The forming process produces corrugated metal gaskets according to the optimum size.



Fig. 5. Corrugated metal gaskets standard

5.2. Electroplating

The electroplating process has resulted in copper and nickel plating on CMG. Nickel and copper plating thicknesses were 10 m, 15 m, and 20 m. Fig. 6 depicts the gaskets after they have been coated. The copper and nickel layers adhere perfectly to the CMG although there is no diffusion of nickel or copper with SUS304.



Fig. 6. Gaskets after the coating process: *a* – copper-coated gasket; *b* – nickel-coated gasket

Nickel coating has a better color and appearance because it does not change color. The copper layer changes color to become darker. Although the copper changes color, there is no corrosion that physically damages the copper layer.

5.3. Leak measurement of CPCMG

Vapor leaks can be seen on the thermal camera. If a vapor leak occurs, an enlarged red hue will appear on the gasket. Fig. 7 shows a vapor leak measured using a thermal camera.

Thermal cameras can also measure non-leaks of the gasket. This designation can be seen on the green thermal camera. There is no red hue in the thermal camera designation. Fig. 8 shows non-leaks measured using a thermal camera.

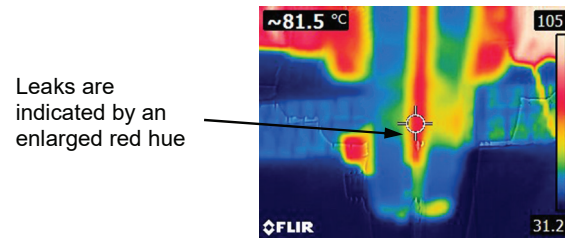


Fig. 7. Leaks shown by thermal camera

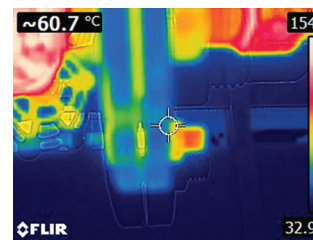


Fig. 8. Determination of non-leaks using a thermal camera

Before and after they are utilized to close the two flanges, both gaskets are inspected. This was a visual inspection that included a microstructure test. Previous researchers [18, 19] conducted the microstructure test and measured the results.

The leakage test findings for the CMGS, the 10 μm CPCMG, the 15 μm CPCMG, the 20 μm CPCMG, the 10 μm NPCMG, the 15 μm NPCMG, and the 20 μm NPCMG are compared. For CMGS, CPCMG, and NPCMG, Table 2 shows the results of a gasket leakage test using a thermal camera. The fluid passing through the flange has a temperature of 270 °C, and the boiler pressure ranges from 3 to 7 bar. The data was captured for 600 seconds. Axial forces of 40 kN, 60 kN, 80 kN, 100 kN, and 120 kN were applied to the bolts by tightening them. The torque imposed on the bolts is displayed on a digital torque wrench, and the axial forces can be estimated from the torque data using mathematical methods. Because there were four tightened bolts, the axial force is fourfold.

As mentioned in the method, the measurement of leakage on the same gasket is carried out 3 times. The three experiments yielded almost the same data; the difference was only in the leakage of water at a tightening force of 100 kN. The results of the CMGS leak test can be seen in Table 2. The data that we present here are the worst conditions of the three experiments.

With the same treatment with CMGS, CPCMG measurements were also carried out 3 times for each thickness. The data that we present here are 3 tables for each thickness. CPCMG leaks with a thickness of 10 μm can be seen in Table 3. CPCMG leaks with a thickness of 15 μm can be seen in Table 4. CPCMG leaks with a thickness of 20 μm can be seen in Table 5.

From Table 3, it can be seen that there is no leakage of either water or steam for CPCMG with a thickness of 10 μm . From the three trials, the results were the same. From the three experiments above, it can be concluded that the CPCMG mounted on a flange with a roughness of 3.5 μm did not have either water or steam leakage. These results indicate that CPCMG with a thickness of 10 μm is indeed suitable for use on flanges with high roughness, which is at least 3.5 μm .

From Table 4, it can be seen that there is no leakage of either water or steam for CPCMG with a thickness of 15 μm . From the three trials, the results were the same. From the three experiments, it can be concluded that the CPCMG mounted on a flange with a roughness of 3.5 μm did not have either water or steam leaks. These results indicate that CP-

CMG with a thickness of 15 μm is indeed suitable for use on flanges with high roughness, which is at least 3.5 μm .

Table 5 shows that there is no leakage of either water or steam for CPCMG with a thickness of 20 μm . From the three trials, the results were exactly the same. From the three experiments above, it can be concluded that the CPCMG mounted on a flange with a roughness of 3.5 μm did not have either water or steam leakage. These results indicate that CPCMG with a thickness of 20 μm is indeed suitable for use on flanges with high roughness, which is at least 3.5 μm .

From the three thicknesses of the gaskets, it can be concluded that all of them are suitable as asbestos replacement gaskets. With these results, the authors suggest that CPCMG should be coated with copper with a thickness of 10 μm .

Table 2

CMGS leak test results

CMGS	Steam leak			Water leak		
	Boiler pressure (bar)					
Tightening force (kN)	3	5	7	3	5	7
40	Leaking	Leaking	Leaking	Leaking	Leaking	Leaking
60	Leaking	Leaking	Leaking	Leaking	Leaking	Leaking
80	Leaking	Leaking	Leaking	Leaking	Leaking	Leaking
100	Leaking	Leaking	Leaking	No leaking	No leaking	Leaking
120	No leaking	No leaking	Leaking	No leaking	No leaking	No leaking

Table 3

Leak test result of 10 μm CPCMG

10 μm CPCMG	Steam leak			Water leak		
	Boiler pressure (bar)					
Tightening force (kN)	3	5	7	3	5	7
40	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking
60	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking
80	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking
100	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking
120	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking

Table 4

Leak test result of 15 μm CPCMG

15 μm CPCMG	Steam leak			Water leak		
	Boiler pressure (bar)					
Tightening force (kN)	3	5	7	3	5	7
40	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking
60	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking
80	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking
100	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking
120	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking

Table 5

Leak test result of 20 μm CPCMG

20 μm CPCMG	Steam leak			Water leak		
	Boiler pressure (bar)					
Tightening force (kN)	3	5	7	3	5	7
40	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking
60	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking
80	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking
100	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking
120	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking

5. 4. Leak measurement of NPCMP

With the same treatment as CMGS, NPCMG measurements were also carried out 3 times for each thickness. The data we present here represent the worst conditions of the three experiments. NPCMG leaks with a thickness of 10 µm can be seen in Table 6. NPCMG leaks with a nickel thickness of 15 µm can be seen in Table 7. NPCMG leaks with a nickel thickness of 20 µm can be seen in Table 8.

Table 6 shows that there is no leakage of either water or steam for NPCMG with a thickness of 10 µm. From the three trials, the results were the same. From the three experiments above, it can be concluded that the NPCMG mounted on a flange with a roughness of 3.5 µm did not have either water or steam leaks. These results indicate that the 10 µm NPCMG is indeed suitable for use on flanges with high roughness, which is at least 3.5 µm.

Table 7 shows that there is no leakage of either water or steam for NPCMG with a thickness of 15 µm. From the three trials, the results were the same. From the three experiments above, it can be concluded that the NPCMG mounted on a flange with a roughness of 3.5 µm did not have either water or steam leaks. These results indicate that the NPCMG with a thickness of 15 µm is indeed suitable for use on flanges with high roughness, which is at least 3.5 µm.

Table 8 shows that there is no leakage of either water or steam for NPCMG with a thickness of 20 µm. From the three trials, the results were the same. From the three experiments above, it can be concluded that the NPCMG mounted on a flange with a roughness of 3.5 µm did not have either water or steam leaks. These results indicate that NPCMG with a thickness of 20 µm is indeed suitable for use on flanges with high roughness, which is at least 3.5 µm.

6. Discussion of studying the performance of CMG in the boiler’s piping system

The cold forming procedure followed was correct. This procedure yields a CMG with dimensions that are identical to the ideal design. The spring back effect did not occur because of the formation. The result is in line with the previous study [18, 19].

The electroplating procedure used was correct. This process produces a layer of copper or nickel as desired. CMG is a good surface for copper or nickel to attach to. After being utilized on the flange, the copper and nickel coatings on the CPCMG and NPCMG are not affected.

Table 6

Leak test result of 10 µm NPCMG

10 µm NPCMG	Steam leak			Water leak		
	Boiler pressure (bar)					
Tightening force (kN)	3	5	7	3	5	7
40	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking
60	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking
80	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking
100	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking
120	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking

Table 7

Leak test result of 15 µm NPCMG

15 µm NPCMG	Steam leak			Water leak		
	Boiler pressure (bar)					
Tightening force (kN)	3	5	7	3	5	7
40	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking
60	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking
80	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking
100	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking
120	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking

Table 8

Leak test result of 20 µm NPCMG

20 µm NPCMG	Steam leak			Water leak		
	Boiler pressure (bar)					
Tightening force (kN)	3	5	7	3	5	7
40	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking
60	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking
80	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking
100	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking
120	No leaking	No leaking	No leaking	No leaking	No leaking	No leaking

Table 2 shows the leakage of both water and steam for CMGS. Of the three trials, two of them had the same results, namely the first and third experiments. In the second experiment, the gasket was better because at a certain tightening force and boiler pressure there was no leakage. Steam leaks occur faster than water leaks. From the three experiments above, it can be concluded that the standard gasket installed on the flange with a roughness of 3.5 μm still has both water and steam leaks. Water leakage occurs at a tightening force up to 100 kN, pressure 7 bar, while steam leakage occurs at 120 kN, pressure 7 bar. These results indicate that the gasket is not suitable for use on flanges with high roughness, which is at least 3.5 μm . These results are in line with previous studies [3]. Despite being utilized at a temperature of 270 $^{\circ}\text{C}$ in the inner diameter, the gasket was unable to soften the SUS304 material, which remains rigid. This material has a melting point of 1.400–1.450 $^{\circ}\text{C}$ [12, 13]. The hardness of SUS304 material is insufficient to entirely conceal the flange's surface roughness [3, 4].

The three NPCMGs with a thickness of 10 μm , 15 μm , and 20 μm are suitable as gaskets to replace asbestos. All three gaskets have the same performance. With these results, the authors suggest using NPCMG with a thickness of 10 μm . This thickness of the nickel coating already has a nickel-like surface hardness. According to [24], layers with a thickness of less than 10 μm nevertheless have a mixed hardness between nickel and SUS304.

The gasket used for the leak test in this boiler uses CP-CMG with a thickness of 10 μm , 15 μm and 20 μm . Taking this thickness is in accordance with the experiment in [4]. At that thickness, it was managed to reduce leakage by conducting the water pressure test. We will vary the thickness of the copper layer to see if there is the most optimal thickness among these thicknesses.

There was no leakage in either the copper or nickel-plating types. This is because the coating material, such as copper or nickel, can hide the flange's surface roughness. Material made of copper or nickel is softer than SUS304. This substance seals the leak by filling the spaces created by the flange surface roughness. This is in accordance with previous research [4], which applied a leak measurement using a water pressure test.

Because it is the minimum thickness while still preventing leakage, a layer thickness of 10 μm is the ideal option. The coating material will be harder than SUS304 material if the thickness is less than that. The tougher the coating substance, the thinner the nickel or copper layer [24].

From both copper and nickel-plating types, both can be used to coat corrugated metal gaskets made of SUS304. We choose depending on the needs and availability of materials. However, judging by the appearance, nickel plating looks nicer and shiny. Copper plating looks dull, especially if it's been coated for a long time, it looks blackish.

Both NPCMG and CPCMG gaskets were not damaged after being used on flange joints. There was no peeling or cracking of the nickel or copper coating. The same results were obtained in previous studies [18, 19]. Bonding in the layer between SUS304 with nickel or copper does not occur compound. Although this bond is separate, but when in contact with the flange there is a pressure in the normal direction, so it does not damage the nickel or copper layer.

The limitations of this study include the use of a water leak meter by visually looking at the water dripping on paper and using a thermal camera to detect steam leaks. The leak gauge cannot measure the level of leakage, but only detects water and steam leaks. This CMG test is on a low-pressure boiler, in the future it will need to be tested on a high-pressure boiler, which is around 70 bar.

7. Conclusions

1. The result of forming gasket material becomes CMG as expected, i.e. the dimension of CMG according to the design result.
2. Coating result of both copper and nickel is as expected, i.e. there was no peeling or cracking before and after used.
3. CPCMG gaskets have very good performance, gaskets did not leak at a maximum pressure of 7 bar and the lowest tightening force of 40 kN.
4. NPCMG gaskets have very good performance, gaskets did not leak at a maximum pressure of 7 bar and the lowest tightening force of 40 kN.

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