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Detection and Comparison of Surface Defects in Pipe Welds

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ABSTRACT

At present, 24 nuclear power plants are in operation nationwide as the main power source responsible for about 27% of Korea's electricity, and five nuclear power plants are currently under construction. Issues of nuclear safety and reliability have always existed, but after the Fukushima accident, ensuring reliability has become an even more important issue for safety. Compared to other kinds of accidents, the initial response after a nuclear accident is more important than any other accident. Prior to accidents, it is important to be able to predict and judge the accident in advance for the sake of prevention. In this research, non-destructive inspection methods for existing pipe welds include radiographic, ultrasonic, magnetic particle practice , and liquid penetration testing. For this experiment, carbon steel pipes like that of the material used in nuclear pipes were adopted, and specimen welded to the flange (Flange) were manufactured. After testing, the weld specimen were not damaged through the infrared thermography (IRT) experiment. This study attempted to improve the safety of carbon steel pipes through a comparative analysis of finite element analysis.

Key Words : Carbon Steel Pipe(탄소강관), Weld Zone(용접부), FEM(유한요소법), IRT(적외선 열화상)

1. Introduction

By 2040, global energy demand is forecast to rise by approximately 28% from 2016, with power generation expected to rise by 59%. The nation's total energy consumption has increased by 1-3% annually since 2011. There are 24 operating nuclear power plants across Korea, which serve as the country’s main power source and are singularly responsible for about 27% of the nation’s electricity output. Moreover, five additional plants are under construction. The energy generated by a gram of completely fissionable uranium is equivalent to completely burning approximately three tons of coal and nine drums of oil. That is about three million times as much energy as coal. Nuclear power is the most efficient form of clean energy that can generate electricity by turning turbines with steam power, but it is significantly vulnerable to radiation.

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Although nuclear plants' reliability has been consistently improved, ensuring safety has become a critical issue after the Chernobyl and Fukushima nuclear accidents. The initial response to a nuclear accident is more important than any other accident response, and it is also more important to predict and evaluate an accident in advance so it can be prematurely prevented. It is impossible for materials and/or material structures to be complete or for them to have an infinite lifespan. Defects occur during machining and operation, in addition to in-house defects that affect the materials. In turn, these lead to shorter lifespans for the structures. Therefore, it is useful to check the presence of defects in the target material or structure through non-destructive testing and take countermeasures to prevent major accidents and damage, thereby enhancing nuclear plants' reliability.

Materials used for nuclear power plant piping are mainly carbon and stainless steel. In the areas where the two materials are bonded, enconels are used. Nuclear power plant piping has a total extension of about 100 Km with many penetrations, welds, and connections that are structurally vulnerable [1~2]. In particular, in the case of nuclear power plant safety-class piping, welds are the most vulnerable. Typically, there are approximately 3,000 to 5,000 such locations. The welded sections of the nuclear power plant piping have various characteristics, and as the general characteristics of the welds exhibit complex material behavior, such as Heat Affected Zone (HAZ), welds, parent metal parts and dissimilar metal welds, and defects are likely to occur, particularly in terms of fracture vulnerabilities [3]. The weldability of carbon steel pipes is affected by a number of factors, and research is being conducted on semi-automation and automation to identify the cause of these weld defects and improve weldability [4~5].

In contrast to destructive testing, non-destructive testing is a method that can be used to detect the presence, location, size, shape, and distribution of internal flaws (such as cracks, flacking, indentation, etc.) and external flaws or inclusions of materials, internal cracks, blow holes, and so on. Moreover, this method can determine the acceptance level of these flaws based on certain criteria.[6~8] Generally, non-destructive testing of welds is stipulated in KS B 0888 B for appearance testing, radiographic testing, and ultrasonic testing on the outside surface, as well as for magnetic particle practice testing or liquid penetration testing on the outside surface additionally [9~14]. Although this study does not apply the aforementioned criteria, the same carbon steel pipe material used in nuclear power plant piping was used to produce a test piece welded with a straight pipe and flange. The study's objective is to detect damages on this test piece of the welded section of the carbon steel pipe through Infrared Thermography Testing (IRT) and to enhance the pipe's safety through a finite element comparative analysis.

2. Experimental method

2.1 Test Piece Preparation

Carbon steel pipe materials, as used in nuclear power plant piping, were adopted to produce a test piece. The test piece was manufactured by welding a

Fig. 1 Carbon steel pipe flange specimen

straight pipe and flange to a 65mm diameter with a 3mm thickness. After welding, artificial defects were added by drilling and marked with a red circle. Since infrared thermography significantly affects the rate of radiation, black matte paint was applied to the test piece to reduce this rate. Fig. 1 represents a test piece bonded by welding the carbon steel straight pipe and flange.

2.2 Configuration of Experimental Device

For the experiment, a FLIR's T640 model infrared thermography camera was used with a 1kw of halogen lamp as a heat source to apply active inspection techniques. Table 1 presents the T640 model's specifications. Infrared thermography techniques are largely divided into two categories: active and passive. Active techniques, unlike conventional passive techniques, have a higher level of controllable energy without relying on a target-specific infrared dose. Thus, they measure and analyze the infrared energy emitted by the target body. Active inspection techniques have the advantage of being able to control the effects based on emissivity, angle of measurement, ambient temperature, shape, etc. of an object's surface. Therefore, the tester's expected data values can be obtained[15~18]. Subsequently, the commercial program ANSYS was used to perform the finite element analysis.

Table 1 Specifications of infrared thermography camera

Common Features	
IR Resolution	640*480 pixel
Temperature Range	-40℃ ~150℃, 100℃ ~650℃, 300℃ ~2,000℃
Thermal Sensitivity / NETD	40mK @ + 30℃
Zoom	1-8* continuous, digital zoom, including panning
Focus	Automatic (one shot) or manual
Data Communication Interfaces	USB-mini, USB-A, Bluetooth, Wi-Fi
Size(L*W*H)	143*195*95mm
Weight	1.3kg

3. Results and review of the experiment

3.1 Infrared Thermography Test of Carbon Steel Pipe

Infrared thermography was performed using a halogen lamp heat source with a 1 kw output on the welds of carbon steel pipes. Halogen lamps were used to irradiate the welded sections of the carbon steel pipe test piece in Fig. 1 for 35 seconds. As a result, it was confirmed that the artificial defect spot2, which had a relatively higher temperature than the surrounding area, featured a hotspot. The normal, non-defective parts of spot1 and spot3 had lower average temperatures than the defect areas; however, during the ongoing light survey of the halogen lamps, the temperature steadily increased. Hotspots on the welded sections enabled the identification of faulty locations as well as the presence of defects. Fig. 2 shows a thermographic image of the carbon steel pipe flange measuring the halogen lamps as a

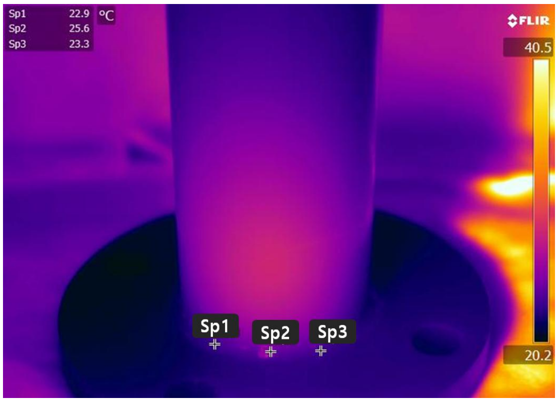

Fig. 2 Carbon steel pipe infrared thermal image

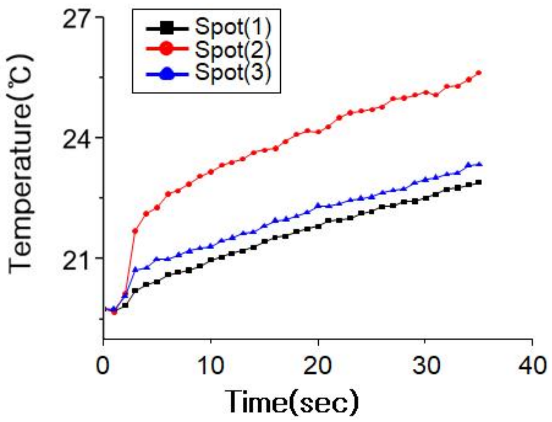

Fig. 3 Carbon steel pipe thermal image data

heat source. Fig. 3 features the data from Fig. 2, which was obtained during infrared thermographic imaging and reveals the temperature variation over time in this spot.

3.2 3D Design of Carbon Steel Pipe

In order to perform the analysis of the test piece of the carbon steel straight pipe materials and flange connections, first the 3D design was created using the commercial program CATIA. Fig. 4 shows the 3D modeling of the carbon steel pipe flange test piece through ANSYS.

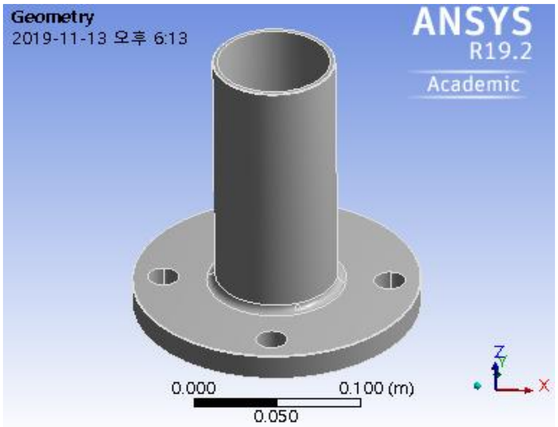

Fig. 4 Carbon steel pipe specimen 3D modeling

3.3 Finite Element Method (FEM) Analysis and Experiment Comparison

The FEM analytical program predicts temperature distribution and deformation and is capable of performing simulations. To conduct a thermal analysis of the carbon steel pipes, the commercial program ANSYS was used, and the mesh was set up with Nodes: 218,413 and Elements: 55,920. As with the experiment, the ambient temperature was set to 20°C, while the coefficient of heat transfer was $20\,W/m^{2}\cdot$℃ and the heat flux was $800\,W/m^{2}$. Fig. 5 shows a finite element analysis with the halogen

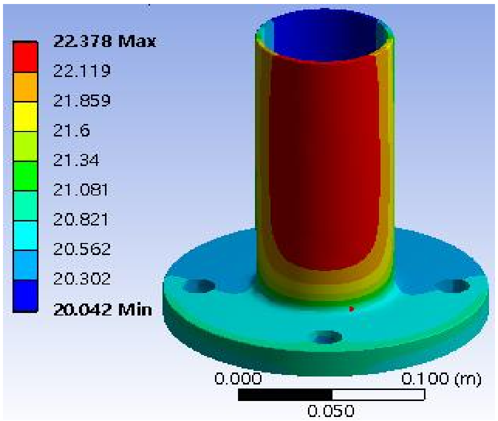

Fig. 5 Analysis of finite elements of carbon steel pipe

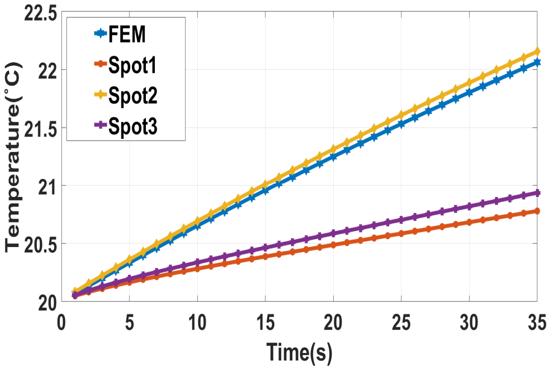

Fig. 6 Comparison of infrared thermal imaging experiment and FEM analysis

lamps applied to the carbon steel pipe flanges. There was a temperature differential of 2-3°C compared to the experimental value, but the overall temperature was found to be similar. Moreover, hotspots were found in areas where artificial defects were produced.

Fig. 6 presents a graph comparing the experimental value of the thermographic image of the carbon steel pipe flange welds with the finite element analysis. FEM represents the finite element analysis values while spot1, spot2, and spot3 represent the experimental thermographic imaging values. Observing the graph in Fig. 6, it is clear that the FEM values and spot2 where a hotspot occurred had a temperature of about 22°C, while spot1 and spot2 without any defects had a temperature of about 21°C.

4. Conclusion

In this study, a test piece was produced by creating artificial defects on pipes made of carbon steel, which is the material used in nuclear power plant piping. In order to improve the reliability of preventative defect identification in carbon steel pipes, research on comparative verification was conducted through the IRT technique—a type of non-destructive testing—and finite element analysis. The following conclusions were drawn.

1. We were able to detect a defect in the test piece of the carbon steel pipe welds by applying the active IRT technique.
2. The experimental values obtained from non-destructive testing using the active IRT technique and the values obtained through finite element analysis were found to be similar.
3. Although further studies will be required, this study verifies the possibility of detecting defects through finite element analysis. Thus, this is valuable information for enhancing the safety and reliability of nuclear power plant piping.

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