Journal of King Saud University – Science 33 (2021) 101547

Contents lists available at ScienceDirect

Journal of King Saud University – Science

journal homepage: www.sciencedirect.com

Original article

A study on the optimization of residual stress distribution in the polyethylene and polyketone double layer pipes

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ARTICLE INFO

Article history:
Received 30 December 2020
Revised 1 July 2021
Accepted 11 July 2021
Available online 21 July 2021

Keywords:
Finite element analysis
Stress contour
Wall thickness
Deformation
Displacement

ABSTRACT

Pipes are generally used in the variety of industries such as water purification, automobiles and air ventilation and so on which is commonly made from various materials like stainless steel, plastic and iron. Recently, plastic and copper pipes were widely used in the water industries due to their higher corrosive resistivity and durability. However, the mechanical defects are the major problem in the usage of the plastic pipes. The plastic pipe wall thickness and stress distribution are key components for the plastic deformation in the pipe. Among them, the residual hoop stress is the mainly affects the life time of the pipe. The present study investigates the effect of the inner and outer wall thickness on the pipe defects is explored by finite element analysis. As a result of observation, a discontinuity of stress is observed at the PK/PE interface of the double-multiple pipe due to the void value, and it is judged that the PK pipe has superior tensile strength due to its high mechanical strength and excellent physical properties such as yield stress and stiffness compared to PE pipe. It is judged that the conditions in the real environment can be analyzed by verifying the peeling phenomenon due to thermal fatigue due to different coefficients of thermal expansion between the heterogeneous resins and observing the peeling phenomenon due to local stress concentration due to the thickness non-uniformity of the bonding interface of the heterogeneous resins. The simulation and experimental results confirmed PK pipe has superior tensile strength due to its high mechanical strength and excellent physical properties such as yield stress and stiffness compared to PE pipe.

Capsule: This work investigates the residual stress distribution in the polyethylene and polyketone double layer pipe.

1. Introduction

The usage of the pipes has been greatly increased in the industries process such as marine, automobiles, aviation, air conditioning, and water purification industry (Wang et al., 2019; Wagner et al., 2017; Yen and Shou, 2015; Hachem and Schleiss, 2011). The various materials such as aluminium, steel, iron, polyvinyl chloride and copper pipes are being used in many industries (Yang and Lee, 2020). Among them the polyvinyl chloride material based pipes are mainly being used in various industry and cultivation process due to its low cost, light weight and high corrosive resistivity (Kajikawa et al., 2018; Karakouzian et al., 2019). In recent years, the many shapes of the pipe like long tube, bending tubes and long type elbow have been developed based on their application purpose . However, the poor tensile nature of the polymer pipe can easily damage and failure happens with the external loads (Poduška et al., 2014; Gupta et al., 2009). Li et al. reported that the maximum deformation or damage occurs at the bending

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Peer review under responsibility of King Saud University.

Production and hosting by Elsevier

https://doi.org/10.1016/j.jksus.2021.101547
1018-3647/

region (Li et al., 2017). Although the sustainable load of the fluid can make thermal expansions which leads to the sudden displacement, excess stresses in the pipe wall. Hence, the optimization and analysis of the limit of the fluid load, pressure, stress and strain distribution in the pipe wall is highly desirable in order to enhance the pipe durability (Christo Michael et al., 2012; Shi et al., 2013).

Till now, numerous experimental and theoretical simulation studies were carried out to minimize the pipe defects for the pipe bending whereas the ratcheting behaviours of the straight pipe lines are quite limited (Vishnuvardhan et al., 2013; Rezaei et al., 2015; Kodikara et al., 2017). Recently, Williams et al. investigates the stress distribution on the polyethylene pipe materials and stated that the axial and hoop stresses are present in the out layer of the pipe whereas the tensile stresses are present in inner wall of the pipe (Xu et al., 2017; Williams et al., 1981; Areias et al., 2014; Areias et al., 2014; Areias et al., 2016; Areias and Rabczuk, 2017). The plastic pipe wall thickness and stress distribution are key components for the plastic deformation in the pipe (Chen and Chen, 2016; Wu et al., 2014). Among them, the residual hoop stress is the mainly affects the life time of the pipe (Wang, 2017). The present study investigates the effect of the inner and outer wall thickness on the pipe defects is explored by finite element analysis (Zhang et al., 2018; Vazouras et al., 2010). In addition, the residual hoop stress and strain in the tube, wall thickness change and the radial displacement of the pipe were also investigated. This paper mainly, focused on the optimization of the residual stresses distribution in the polyethylene and polyketone in the pipe wall. In addition, the basic parameters such as displacement, radial stress were optimized. Furthermore, the effect of the polymer materials on the crack growth were also investigated.

2. Product specification

2.1. Geometry and material characteristics

The double layer straight pipe specimen shown in Fig. 1. The double layer straight pipe specimen used for finite element analysis. The outer layer pipe was composed by polyethylene with 7 mm wall thickness whereas the inner layer pipe was made of polyketone with 3 mm wall thickness and both pipes are inserted with zero gap resulting the overall thickness and diameter of the double layer specimen 10 mm and 110 mm respectively. In this experiment, the radial stress in the pipe at constant internal pressure can be expressed as the following equation, and the hoop stress is expressed as in the following equation.

$$\sigma_r = -P \tag{1}$$

$$\sigma_h = \mathrm{P(D - t)/2t} \tag{2}$$

2.2. Finite element analysis method

To find out the stress due to internal pressure, straight pipes were used, and both ends were modelled as open types, and the finite element analysis of PK/PE pipes was performed by GT-STRUDL, a general-purpose program (Khademi-Zahedi, 2019; Chen et al., 2013). Modelled to be the same as the actual specimen dimensions as shown in Fig. 1 by applying the average of the measured thickness of each test specimen. The modulus of elasticity of the finite element analysis model is 2.25 GPa obtained from the tensile strength test, and the dimensions and mechanical properties applied to the finite element analysis model are the same as the piping specifications in 1–1 2). Two types of internal pressure conditions were considered, 1.0 MPa and 5 MPa, and two types of actual PK test specimens were averaged and the average PK and PE properties were applied. Radial stress and Hoop stress are measured along the thickness (10 mm) from the inside of the double pipe under each internal pressure condition. The geometric shape of the cylindrical shell element can be expressed using the node coordinates of the neutral plane and a vector (thickness) perpendicular to the neutral plane by separating the neutral plane from the three-dimensional hexahedral finite element. It can be displayed using two coordinates of the lower point, and the coordinates (x, y, z) of an arbitrary point inside the element are obtained from the shape function N and the node coordinates.

3. Results & discussion

The radial stress and hoop stress were measured at constant internal pressure and the obtained results are shown in Fig. 2. From Fig. 2b it can be seen that at the internal pressure condition of 1.0 MPa, the radial stress is reduced as the distance from the force applied point to the surface direction decreases, and the sudden change in slope at the point of 3 mm is 100 μm when modelling between PK and PE pipe. The dimensions of local inside wall thinning of the PE/PK pipes were changed. Due to result in stress concentration and accumulation plastic strain, brought about the structural discontinuity. In addition, in the case of hoop stress, the tensile force of PK is about 8 MPa and PE is about 3 MPa.

As a consequences of the internal pressure of 1.0 MPa, the displacement contour was observed in the PE/PK pipe and the obtained results are shown in Fig. 3. In the internal pressure condition of 1.0 MPa, the displacement value for stress is proportional to the radius as the radius r increases, and the radial displacement value increases almost constant for PK and PE pipes.

In the internal pressure condition of 5.0 MPa, as shown in Fig. 4, the radial stress decreases as the distance from the force application point to the surface direction decreases. Therefore, in the case

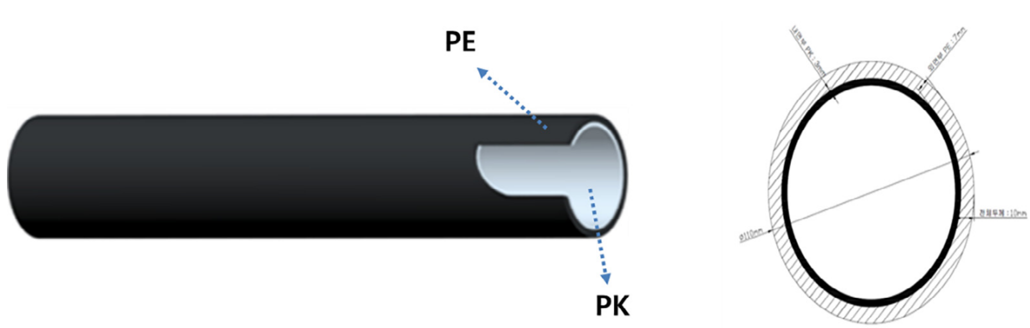


Fig. 1. Details of PE and PK double layer pipe.

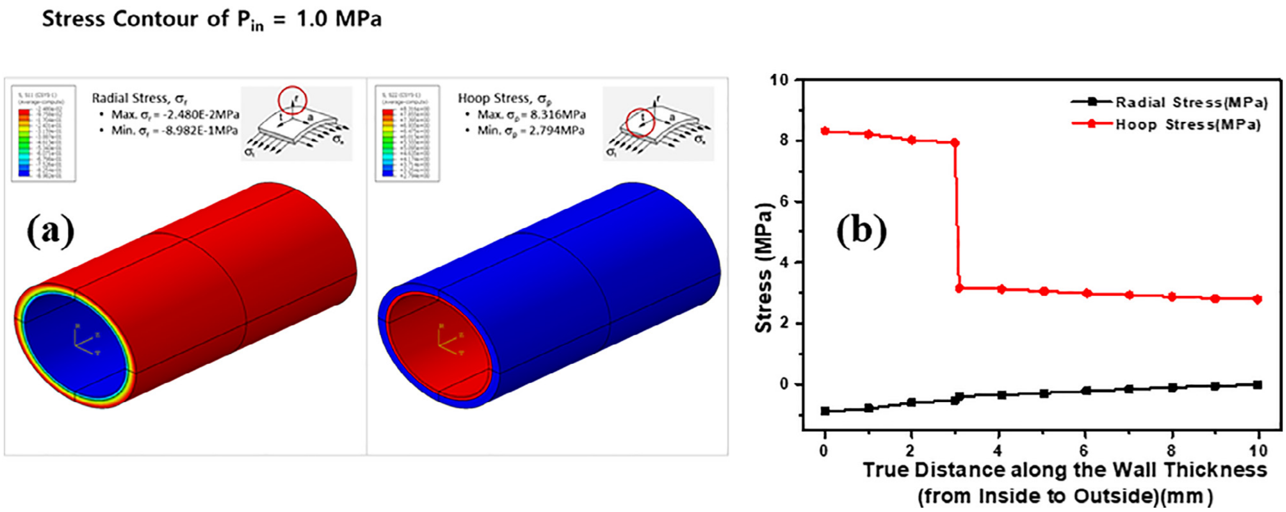


Fig. 2. Radial stress and hoop stress analysis of the PE and PK double layer pipe at internal pressure condition of 1.0 MPa.

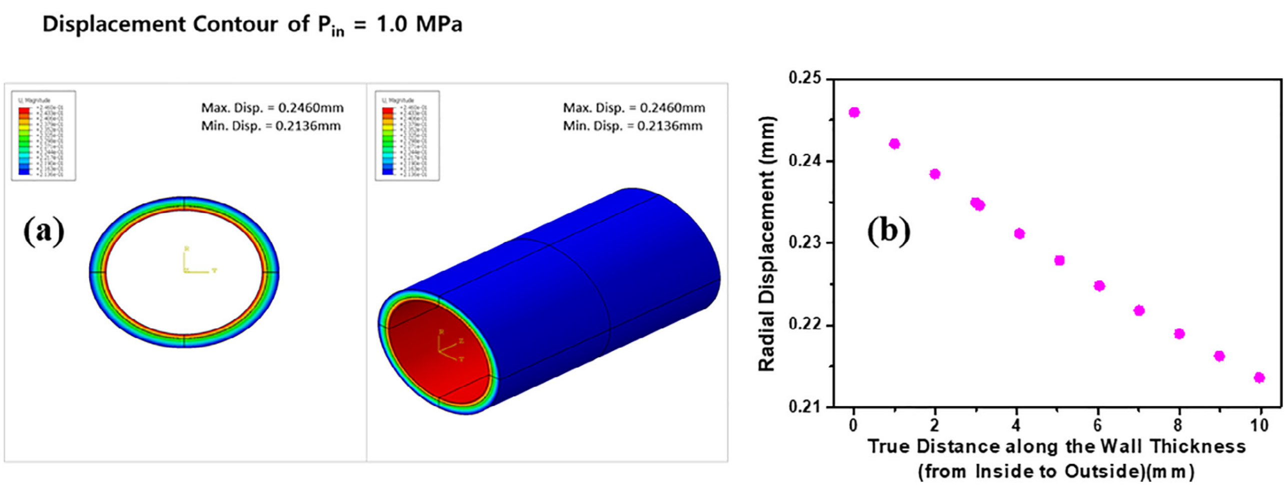


Fig. 3. Radial displacement of the PE and PK double layer pipe at internal pressure condition of 1.0 MPa.

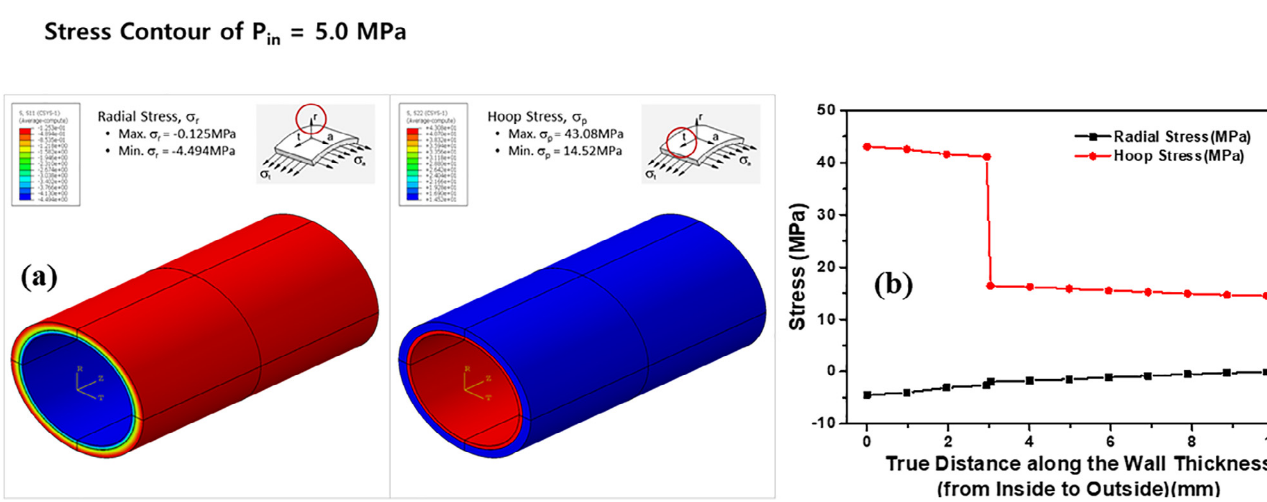


Fig. 4. Radial stress and hoop stress analysis of the PE and PK double layer pipe at internal pressure condition of 5.0 MPa.

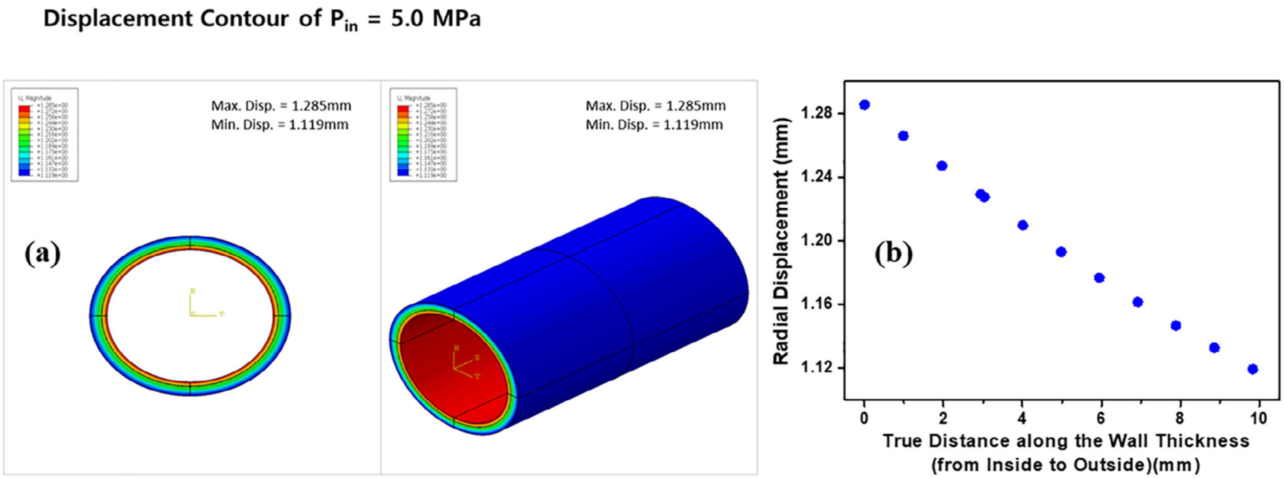
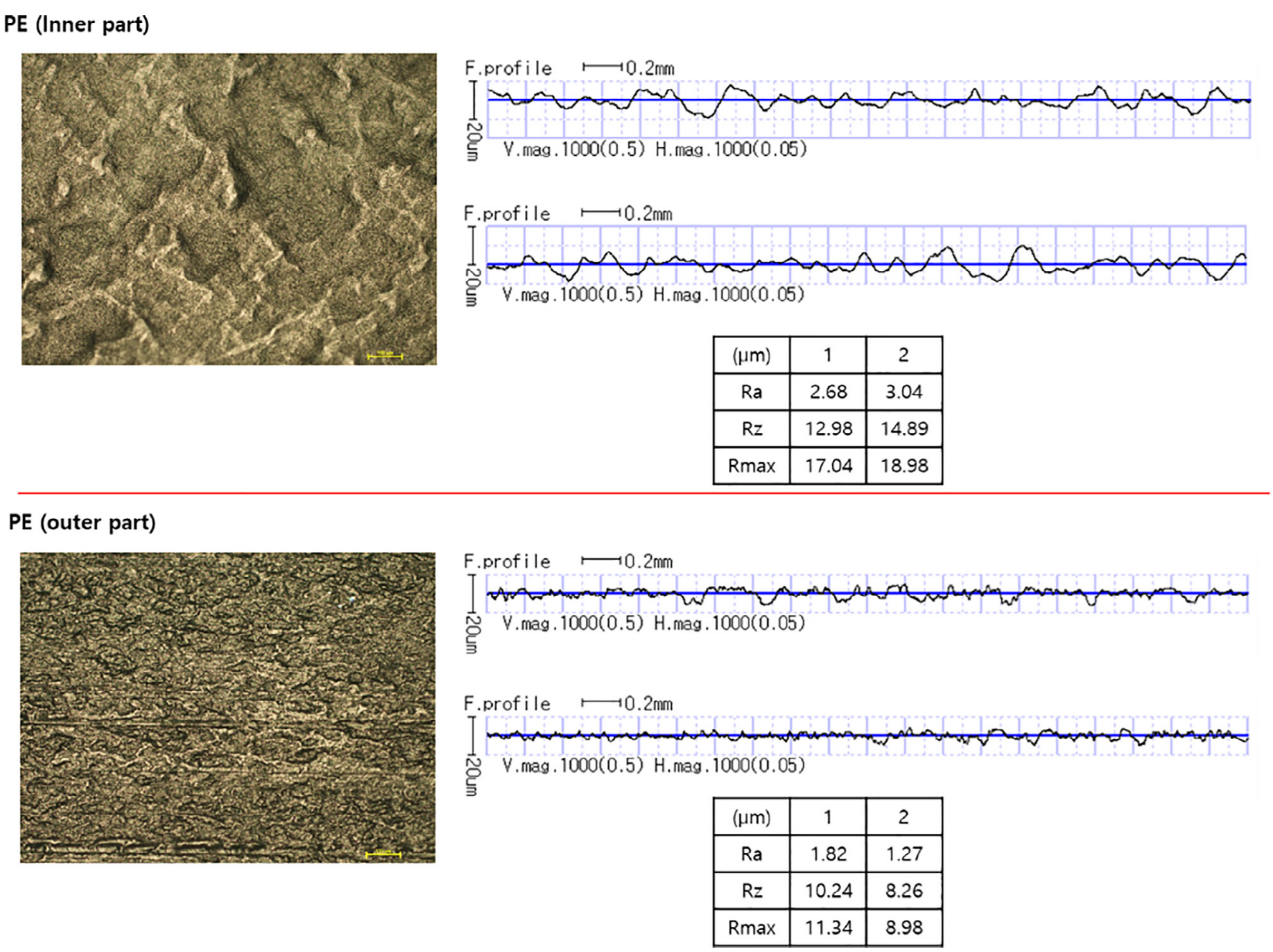


Fig. 5. Radial displacement of the PE and PK double layer pipe at internal pressure condition of 5.0 MPa.

of hoop stress, the tensile force of PK is about 43 MPa and PE is about 17 MPa.

In addition, the displacement contour was observed at 5.0 MPa internal pressure and shown in Fig. 5. Similarly the dimensions of local inside wall thinning of the PE/PK pipes were changed at high internal pressure. The displacement value for stress in the internal pressure condition of 5.0 MPa is proportional to the radius as the radius r increases, and the radial displacement value increases almost constant for PK and PE pipes.

The roughness of the PE/PK pipe was analysed by microscope and results are shown in Fig. 6. PK pipe has superior roughness behavior than PE pipe, due to its high mechanical strength and superior tensile strength.

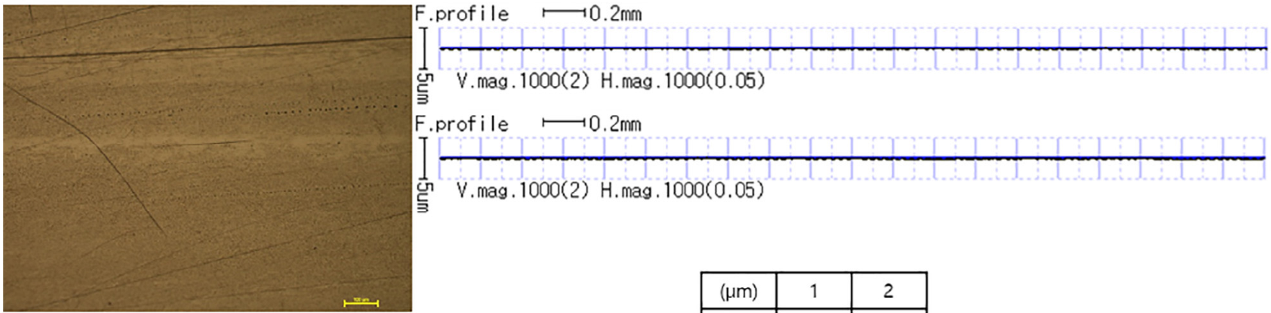


(μm)	1	2
Ra	2.68	3.04
Rz	12.98	14.89
Rmax	17.04	18.98

(μm)	1	2
Ra	1.82	1.27
Rz	10.24	8.26
Rmax	11.34	8.98

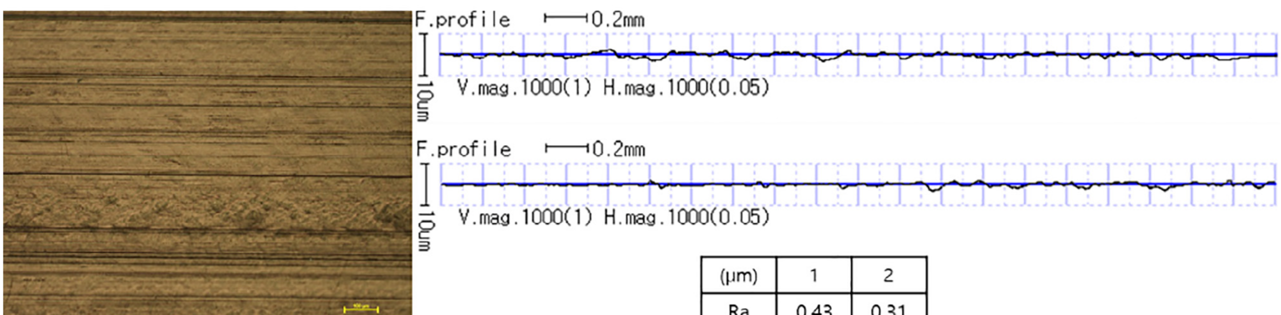
Fig. 6. Surface morphology and roughness profile of the PE and PK double layer pipe.

PK (inner part)



(μm)	1	2
Ra	0.03	0.03
Rz	0.25	0.27
Rmax	0.3	0.3

PK (outer part)



(μm)	1	2
Ra	0.43	0.31
Rz	2.3	2.17
Rmax	2.78	2.58

Fig. 6 (*continued*)

4. Conclusions

The above experimental results show the results of finite element analysis (FEM) according to Equations (1) and (2) for the amount of change in radial and circumferential stress while increasing the internal pressure under the conditions of 1 MPa and 5 MPa. As a result of observation, a discontinuity of stress is observed at the PK/PE interface of the double-multiple pipe due to the void value, and it is judged that the PK pipe has superior tensile strength due to its high mechanical strength and excellent physical properties such as yield stress and stiffness compared to PE pipe. Various wear environments are being further tested, and it is determined that long-term use environment (installation location, internal and external temperature/humidity) and service life setting should be considered. It is judged that the conditions in the real environment can be analyzed by verifying the peeling phenomenon due to thermal fatigue due to different coefficients of thermal expansion between the heterogeneous resins and observing the peeling phenomenon due to local stress concentration due to the thickness non-uniformity of the bonding interface of the heterogeneous resins.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This research was funded by Kumoh National Institute of Technology and This research was also supported by the Ministry of Trade, Industry & Energy (MOTIE), Korea Institute for Advancement of Technology (KIAT) through the Encouragement Program for The Industries of Economic Cooperation Region (P0002108). The authors also extend their appreciation to the Researchers supporting project number (RSP-2021/247), King Saud University, Riyadh, Saudi Arabia.

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