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Long-range inspection of a pipe with a bend using microwaves

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Abstract. This study evaluated the effect of bends on the long-range nondestructive testing inspection of pipe surfaces based on microwaves propagating inside the pipe. Three-dimensional finite element simulations were conducted to reveal electromagnetic fields at bends with a diameter of 23 mm and various radii of curvature when microwaves were emitted into a pipe in the TM_{01} mode that had been mainly used in earlier studies. The simulations revealed that the effect of the bend on the microwaves is not significant when the ratio of curvature is larger than approximately 2, whereas in general a bend reflects a part of microwaves and causes non-TM_{01} modes. Subsequent experimental verifications, which used a pipe with a total length of approximately 4 m and a 90-degree or 180-degree bend, confirmed clear reflections due to artificial wall thinning in spite of the presence of the bend.

Keywords: electromagnetic nondestructive evaluation, wall thinning, pipe degradation, time of flight, electromagnetic wave, finite element simulation

1. Introduction

An efficient periodical inspection of pipes is an important issue to reduce the cost necessary for the maintenance of large structures such as plants because usually pipes suffer from various degradations although they play an important role [1]. To address this issue, a nondestructive testing method using microwaves, which detects degradations appearing on the inner surfaces of a pipe based on how microwaves propagate inside the pipe, has been proposed[2-4]. Results reported have confirmed that the method provided clear signals due to wall thinning[4-6], cracks[7], biofilm[8], and water leakage[9,10]. A recent study has reported that it was possible to detect a full circumferential artificial wall thinning situated more than 20 m away from a probe attached at an end of a pipe to emit microwaves[11].

In contrast, most of studies have evaluated the method using straight pipes, and only limited number of studies have discussed the applicability of microwaves to the inspection of pipes with bends. Jones et al. has investigated the effect of bends on the propagation of microwave quantitatively [10]; they used microwave propagating in the TEM mode that cannot be used to inspect the inner surface of a single pipe that are commonly used industries. Abbasi et al. attempted to detect a flaw at a bend; the signal-to-noise ratio they reported was not clear[12]. Because bends are commonly and frequently used in piping systems, it is important to reveal the effect of bends on the method to discuss the practical applicability of the method.

On the basis of the background above, this study evaluated the applicability of the method to the inspection of the inner surface of pipes with a bend. Three-dimensional finite element simulations were conducted to evaluate the effect of a bend on the propagation of microwaves. Subsequent experiments were performed to demonstrate the applicability of the method to the inspection of a pipe with a bend.

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2. Numerical simulations

Figure 1 illustrates the configuration of the three-dimensional finite element simulations. It should be noted that it is difficult to perform numerical simulations to evaluate signals directly comparable to the ones obtained by subsequent experimental. This is because such simulations, three-dimensional finite element simulations modeling a pipe longer than 4 m, need huge computational resource. Instead, the simulations in this study evaluated how microwaves propagating in the TM_{01} mode were transformed or reflected by a 90 degree bend with a curvature radius of r. because earlier studies have demonstrated that propagating microwaves in a pipe dominantly in a single mode is essential for the method[6,7]. The diameter of the pipe and the bend was 23 mm, which are decided on the basis of the availability of specimens in subsequent experimental verifications. A perfectly matching layer, which absorbs all microwaves, was situated behind the bend to simulate an infinitely long pipe; the pipe walls were modeled as a perfect conductor. The numerical simulations were conducted using commercial finite element software, COMSOL Multiphysics and its RF module (v.5.2a). The governing equation of the simulation was

$$\mathrm{rot}(\mathrm{rot}\boldsymbol{E})-\varepsilon_0\mu_0\omega^2\boldsymbol{E}=0,$$

where $\boldsymbol{E}$, ε_0, μ_0, and ω are electric field, permittivity and permeability of vacuum, and angular frequency, respectively. The simulations were conducted in the frequency domain with a step of 1 GHz, and quadratic tetrahedral elements were used to discretize the equation.

Figure 2 presents results of simulations. The lines show the energies of microwaves reaching the perfectly matching layer in each mode. The sum of the energies is almost unity, which implies little reflection at a bend. When the ratio of curvature is as small as two, a part of the microwaves tends to be transformed into TE modes, which indicates that a bend with a small ratio of curvature makes signals due to a flaw behind the bend unclear.

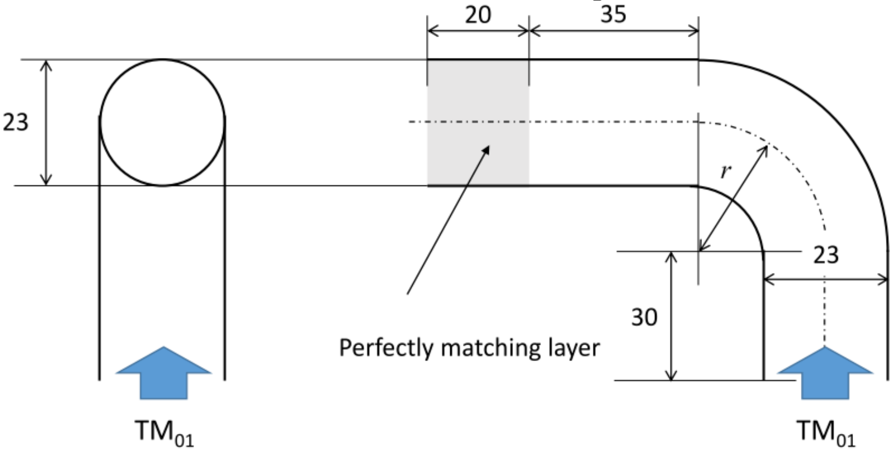
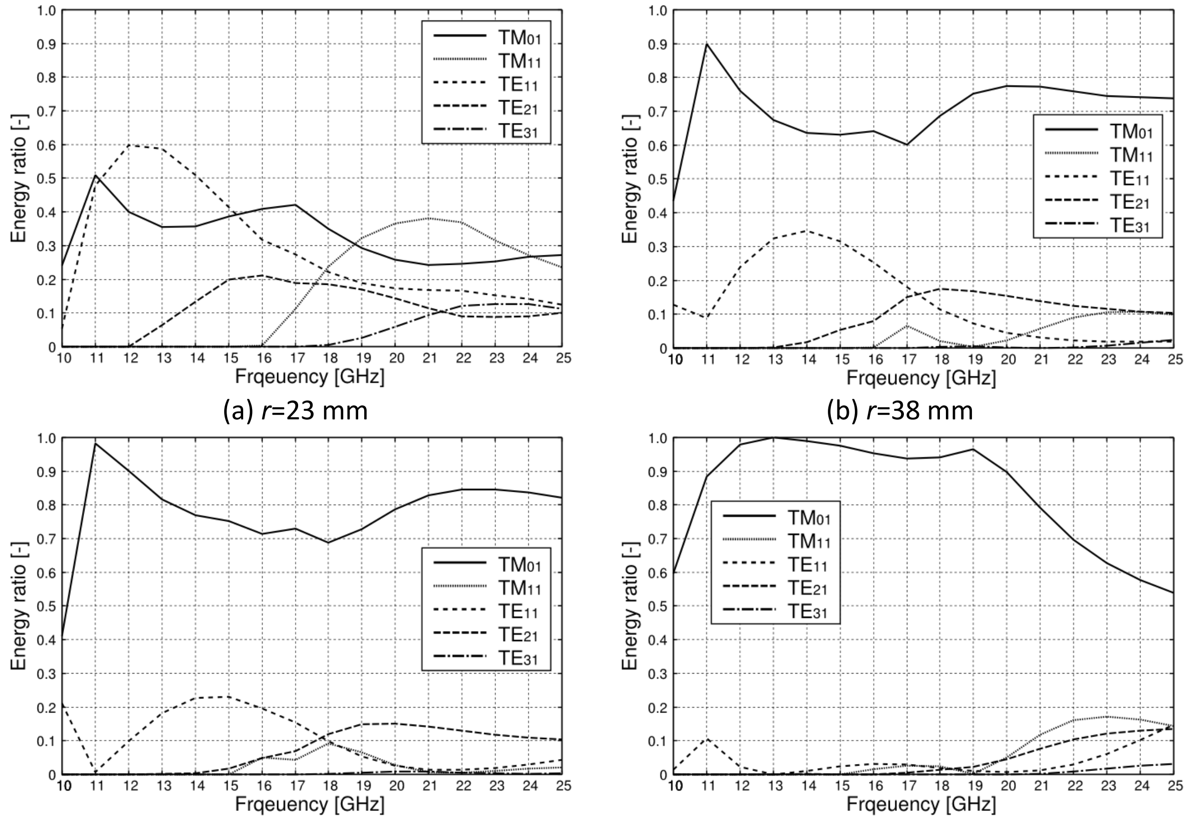


Fig. 1 Numerical model

3. Experimental verification Environments

Figure 3 illustrates the experiments to confirm the results of the simulations. Two configurations are evaluated: pipe with a 90-degree bend and that with a 180-degree bend. Four straight pipes with a length of 1 m and an inner diameter of 23.0 mm were connected with flanges and a 90-degree, or 180-degree, bend. Figure 4 shows the 90-degree bend used in the experiments. The radius of curvature of the bend was 39.1 mm, which is the smallest among available bends for pipes with an inner diameter of 23.0 mm. The 180-degree bend was simulated by connecting two 90-degree bends sequentially. A short pipe with a length of 50 mm and an inner diameter of 23.0, 23.4, 24.0, or 25.0 mm was inserted at positions where are denoted with arrows in the figure to simulate pipe with no flaw, and full circumferential wall thinning with a depth of 0.2, 0.5, or 1.0 mm, respectively. The pipes, the flanges, and the bend were made of type 304 austenitic stainless steel. Microwaves generated by a network analyzer (Agilent Technologies, E8363B) propagated in a flexible cable (Junkosha, MWX051) in the TEM mode to be emitted into the pipe through a microwave probe attached at an end of the tube. The profile and the characteristics of the probe, which were evaluated by finite element simulations, are shown in Figs. 5(a) and (b), respectively. The measurements were conducted in the frequency domain at 1601 frequencies ranging from 10 to 18 GHz, because Fig. 5(b) reveals that this frequency range assures that microwaves propagate in TM_{01} mode in a pipe, with an average of 30 measurements. The measured signals were transformed using the inverse Fourier transform with the Kaiser window function (n=6) to obtain signals in the time domain to evaluate the reflections of the microwaves.

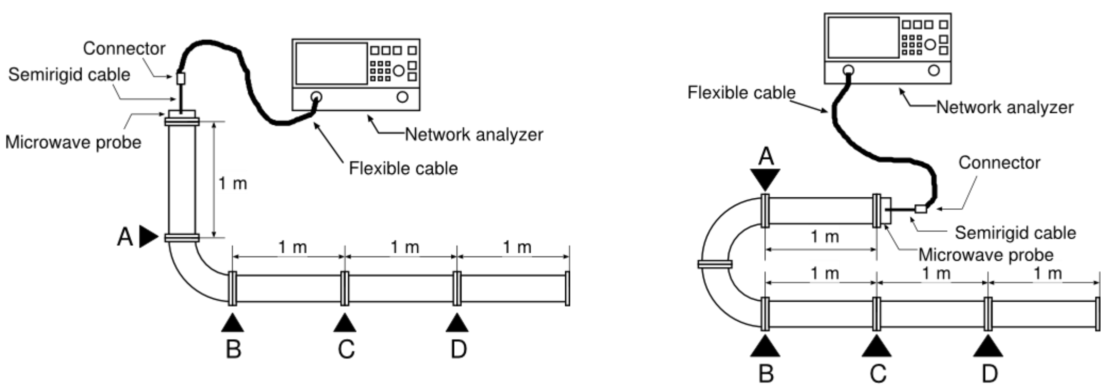
Figures 6 and 7 summarize the results of the experiments. Large signals near 0 ns are reflections at the probe; those after 35 ns are caused by the end of the pipe opposite to the probe. Although the results of the simulations predicted little reflection of microwave at a bend, the figure shows small reflections due to the bend around 10 ns. The most plausible reasons for this is misalignment of the attachment. Figure 6 confirms clear reflections due to the wall thinning especially with a depth of 0.5 and 1.0 mm. The amplitudes of the reflections due to the wall thinning with a depth of 0.2 mm is almost same with those due to the bend. It should be noted that the time of flight and the amplitudes of the reflections corresponds with the locations and the depths of the wall thinning, respectively. Comparing Figures 6 with 7 indicates that the 180-degree bend caused larger reflections than the 90-degree bend, and the pipe with the 180-degree bend provided less clear signals due to wall thinning. It should be noted, however, that clear reflection due to 1 mm wall thinning was confirmed even though the wall thinning was situated directly after the 180-degree bend.



(a) *r*=23 mm (b) *r*=38 mm

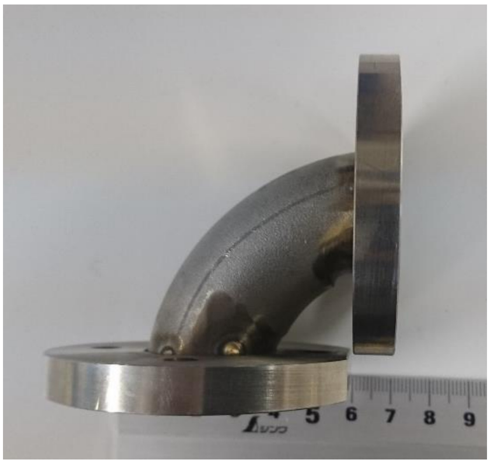
(c) *r*=46 mm (d) *r*=69 mm

Fig. 2 Transmission of microwaves

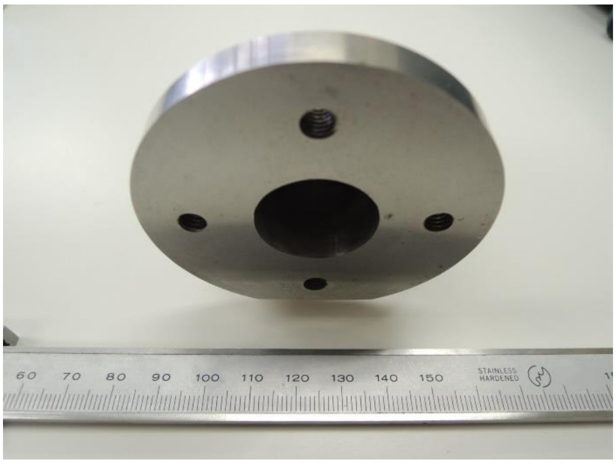


(a) 90-degree bend (b) 180-degree bend

Fig. 3 Experimental setup. Arrows denoted as A, B, C, and D indicate positions where the short pipe was inserted to simulate wall thinning

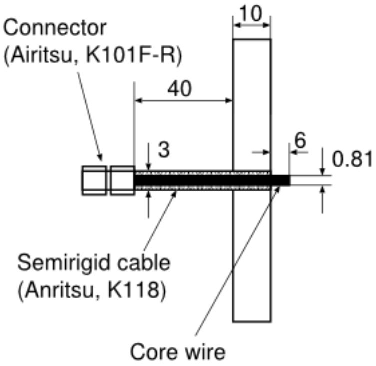


(a) side view

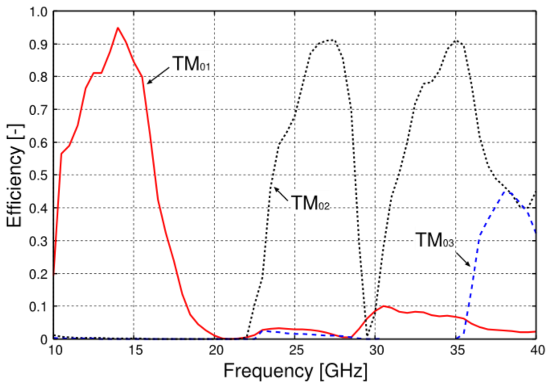


(b) front view

Fig. 4 The 90-degree bend used in the experiment

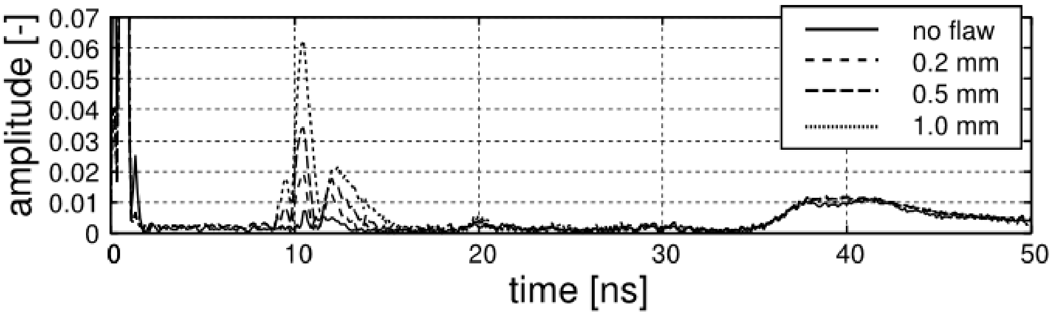


(a) Dimension

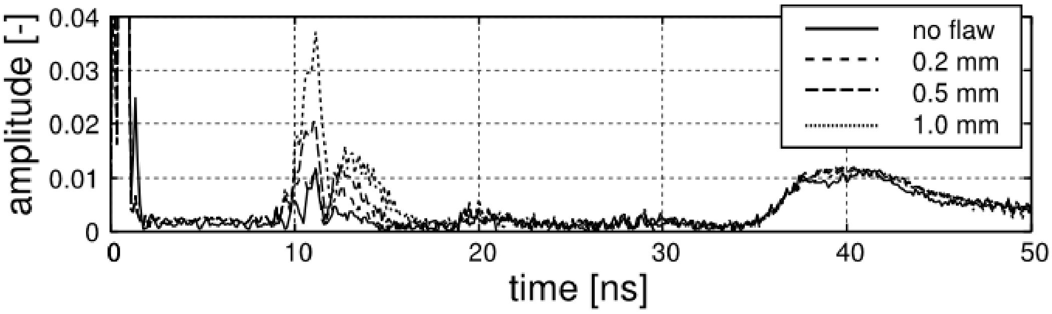


(b) Modes of microwaves the probe emits to a pipe

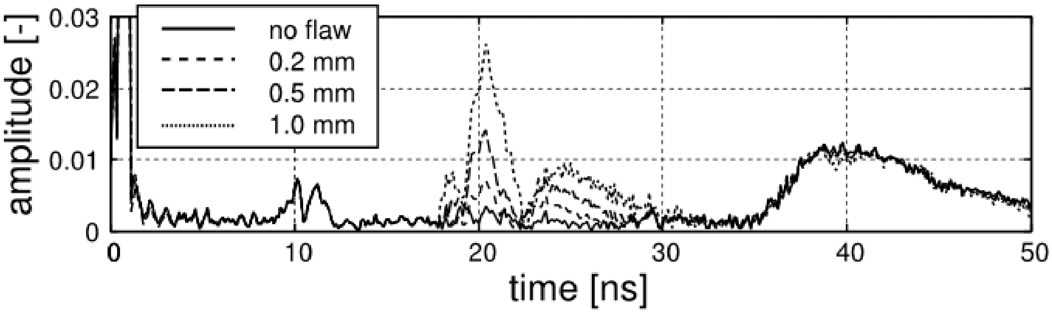
Fig. 5 Microwave probe used in this study



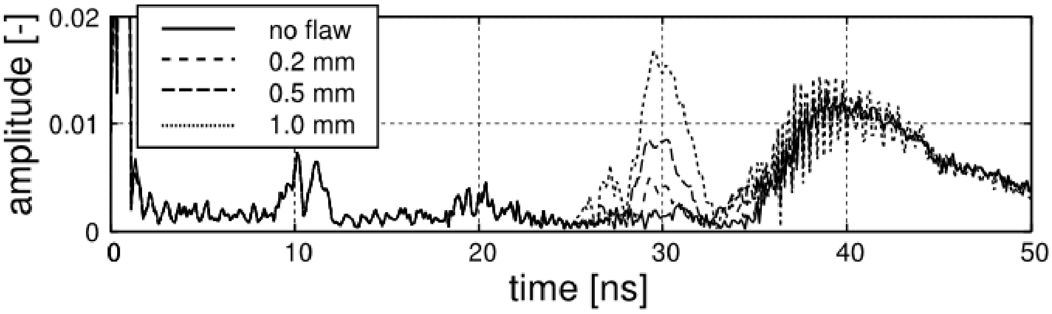
(a) Position A



(b) Position B

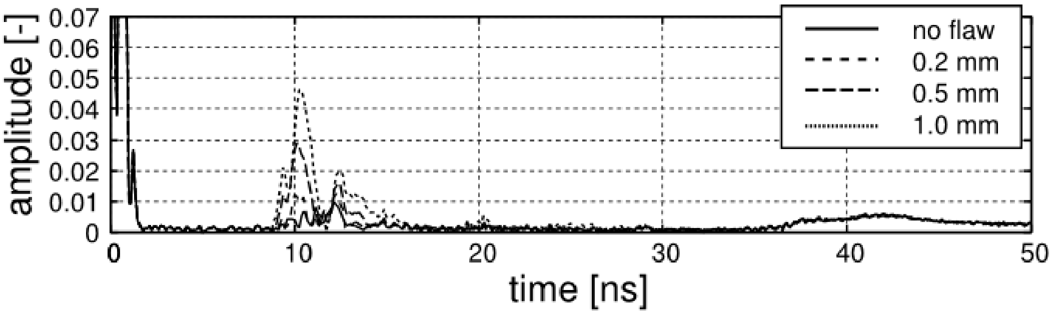


(c) Position C

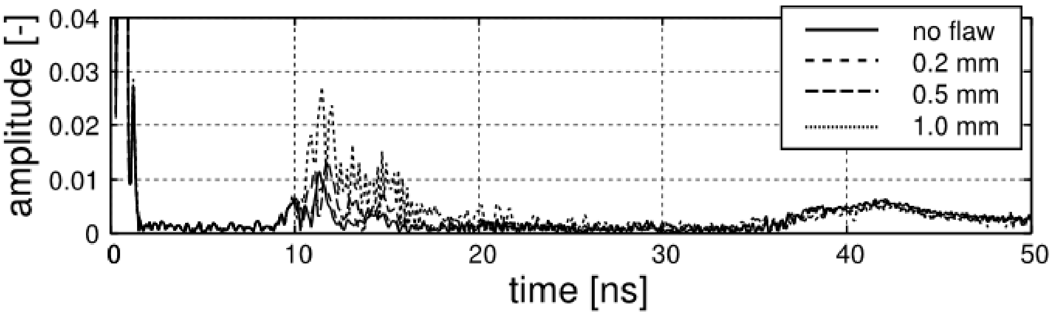


(d) Position D

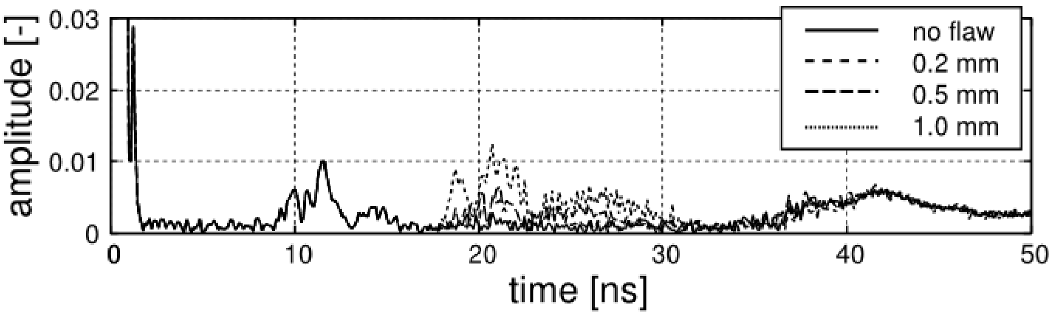
Fig. 6 Results of the experiments using the pipe with the 90-degree bend



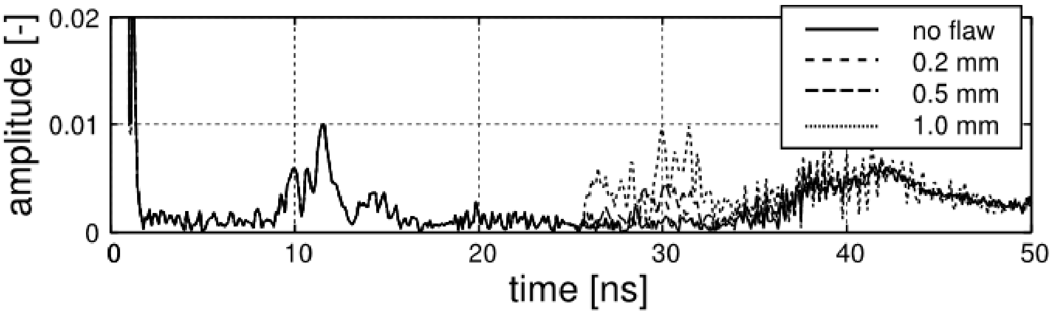
(a) Position A



(b) Position B



(c) Position C



(d) Position D

Fig. 7 Results of the experiments using the pipe with the 180-degree bend

4. Conclusion

This study has evaluated the applicability of a nondestructive testing method using a microwave to the long-range inspection of a pipe with a bend. Three-dimensional finite element simulations revealed that a bend with a large radius of curvature would not hamper the application. Subsequent experiments demonstrated that clear signals due to artificial wall thinning can be confirmed if microwaves propagate in a pipe solely in the TM_{01} mode.

Acknowledgements

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