Evaluation of impact properties of butt-fusion-jointed medium-density polyethylene pipes for gas distribution

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High-speed tensile and Charpy impact tests were conducted on fusion-joined specimens to clarify the impact properties of medium-density polyethylene pipes for gas distribution. Comparison of the impact energy of substrates with those of butt fusion joints reveals that the impact energy differs with resin grades, and that, in all cases, the impact energy of the fusion joints is lower than that of the substrates. The effects of fusion conditions and combination of different grades of resins on fusion strength are also discussed.

(Keywords: butt fusion; substrate; Charpy impact test; energy absorption; high-speed tensile test; polyethylene)

INTRODUCTION

Medium-density polyethylene (MDPE) pipes for gas distribution are often joined by using butt fusion, and the integrity of pipe systems depends upon the strength of these joints. In practical uses, it is recommended that the butt fusion joints hold the same strength as a pipe substrate. In these circumstances, there are two approaches for evaluating the fusion strength of MDPE pipes. One is to estimate the long-term performance under service conditions. For this purpose, stress rupture tests at elevated temperatures or fluctuating internal-pressure loading tests have been conducted. Furthermore, tensile creep tests and tensile fatigue tests for specimens cut out from a pipe have been conducted concurrently. The second approach is to examine the short-term performance by tensile tests or impact tests. Although many methods have been reported to evaluate the fusion joint strength, some of them are not sensitive enough to measure the loss of integrity of fusion zones. In this report the short-term performance of fusion joints is studied by two impact tests to establish a reliable evaluation of pipe system integrity.

EXPERIMENTAL

Materials, pipes and fusion joining

As shown in *Table 1*, pipes of five grades of polyethylene (PE) for gas distribution were used in this study. To check the properties of the materials, pellets were moulded into a sheet of 2 mm thickness according to JIS (Japanese Industrial Standard) K6760. The pellets were melted at 190°C for 6 min, and then pressed at 8.9 MPa for 5 min. Cooling was done at a rate of 20–30°C min^{-1}. Three pipes (PE-D, PE-E and PE-F) were 50 or 75 mm (2 or 3 inch) in diameter, with standard dimension ratio $SDR = 11$, specified in JIS K6774, and the outer two (PE-A and PE-H) were 75 mm (3 inch) in diameter, $SDR = 11$, specified in ASTM D-2513.

The standard fusion conditions for Japanese pipes of a butt fusion type are shown in *Table 2*. Heating time and joining time were changed with pipe diameter. The contacting surface of a pipe end with the heater face of a fusion machine was held evenly throughout the pressure heating process, and then a melted layer was usually produced by a heat soak except for zero pressure. After the heater was quickly removed in less than 5 s, the surfaces of the ends of the pipes were held under a certain pressure and then cooled for at least 180 s after the applied pressure had been removed. For the fusion of pipes PE-A and PE-H, the heater temperatures were 170 and 260°C respectively, as recommended by the manufacturers. The other conditions for 75 mm diameter pipes are listed in *Table 2*[1].

Test specimens and test conditions

Figure 1 shows the shapes of test specimens for a high-speed tensile test and a Charpy impact test. The specimens for the former test were cut longitudinally from a pipe into two types of dumbbells. The thickness of type A was 2 or 4 mm and of type B was 4 mm. Both specimens were cut out and processed from the middle of the pipe section, so that the fusion interface would be located at their centres. The type A specimens, which had a parallel region in the dumbbell shape, were used for the investigation of a stress–elongation curve. The type B specimens, which had a gentle curve to concentrate the stress at the fusion interface, were used to cause a failure there. A specimen of 2 mm thickness of type A was also cut out from the pressed sheet. The Charpy impact test specimens were also chosen from types A and B, and processed so that the fusion interface would be located at the centres of these specimens. The fusion interfaces of the above specimens were notched into U and V shapes, respectively. The type B specimens were a new type, which is specified in JIS K6774 in 1989.

An Instron model type 1331 was used in the high-speed

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Table 1 Basic properties of resins

Resin symbol	Density (g cm^{-3})	*MFR* (g/10 min)	Weight-average molecular weight	Type of branch	Test of material	Test of pipe
PE-A	0.936	1.20	8×10^4	Ethyl	No	Yes
PE-D	0.935	0.21	12×10^4	Butyl	No	Yes
PE-E	0.935	0.21	14×10^4	Isobutyl	Yes	Yes
PE-F	0.935	0.20	15×10^4	Ethyl	No	Yes
PE-H	0.957	0.001	36×10^{4a}	Butyl	No	Yes

[a]Viscometric-average molecular weight

Table 2 Fusion procedure (stages 1–5) and heating conditions (butt fusion, at heating temperature of 210 ± 10°C)

Diameter (mm)	1 Pressure heating time (s)	2 Heating time (s)	3 Heater removal (s)	4 Joining time (s)	5 Cooling time (s)
50	17	40	5 or less	40 or more	180 or more
75	17	60	5 or less	60 or more	180 or more
Applied pressure ($\times 10^5$ Pa)	0 → 1.23	0.1	0	1.23	0

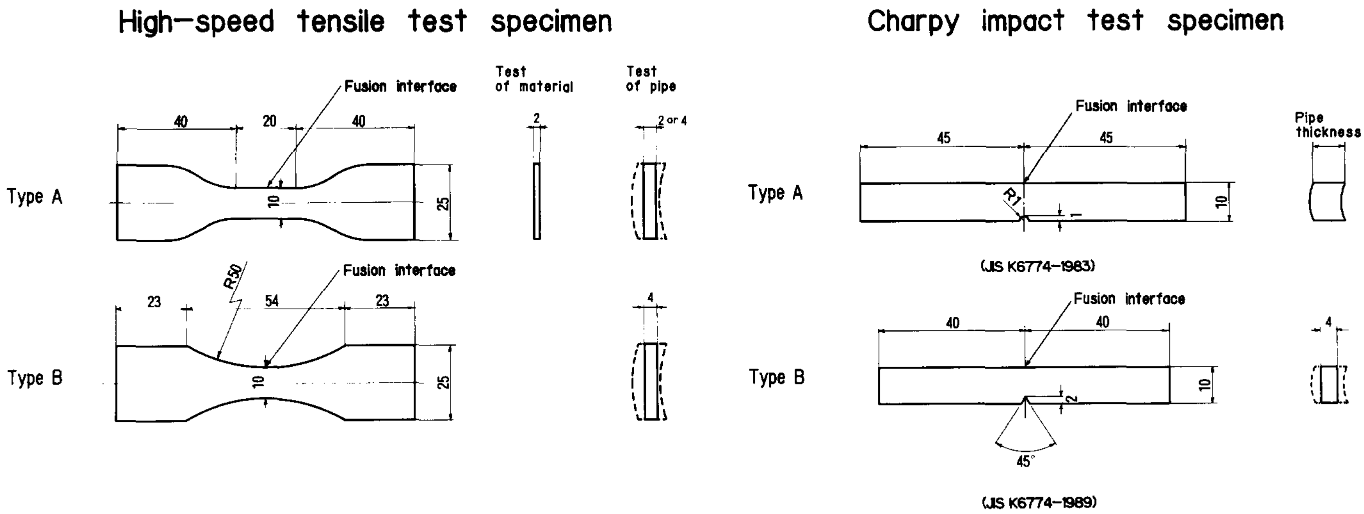

Figure 1 Shape of test specimens for the high-speed tensile test and the Charpy impact test

tensile tests. A Kistler force link having quicker response was used in load detection, and the tensile span length was established to keep the tensile speed uniform. In the Charpy impact tests, equipment made by Ueshima Seisakusho for measuring 2–15 J was used. All the test specimens were kept at 23 ± 2°C and in 50% r.h. for one week or more before measurement.

EXPERIMENTAL RESULTS AND DISCUSSION

Stress–elongation curves

The stress–elongation curves resulting from the high-speed tensile tests conducted on non-fusion-joined and fusion-joined specimens were obtained as shown in *Figure 2*. When an impact force is applied to a viscoelastic substance such as polyethylene, plastic deformation occurs after instantaneous and retarded elastic deformation. Generally, plastic deformation energy accounts for most of the total energy absorbed during fracture because elastic deformation strain energy is negligible. The tensile impact stress and stress at failure for the fusion joint and substrate are apparently quite different. The substrate shows the occurrence of necking, as in the conventional tensile test. For the fusion-joined specimens, the stress–elongation patterns in the conventional static tensile tests were nearly the same as those in non-fusion joints. However, in the high-speed tensile test, the plastic deformation energy in the fusion joint was much smaller than that in the non-fusion joint, although the impact stress was approximately equal to that of the substrate. This result may indicate that recrystallization of melted resin or crystal orientation occurred in the fusion interface. Deformation to failure was unlikely to occur when the tensile speed becomes high enough. *Table 3* shows the results of a tensile test using test specimens that were the same as those for the high-speed tensile

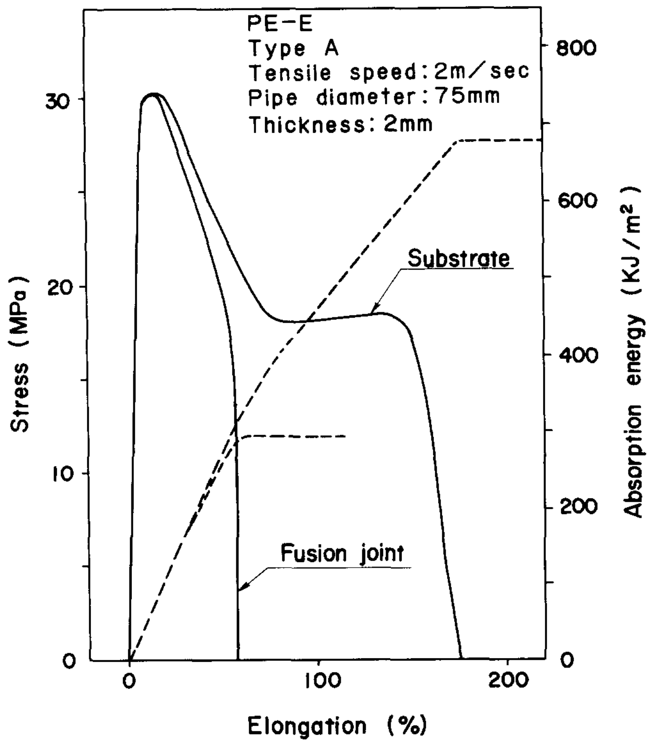

Figure 2 Stress–elongation curves

Table 3 Results of tensile tests (tensile speed, 200 mm min^{-1}; type A; pipe diameter, 75 mm; thickness, 2 mm; PE-D)

	Yield stress		Elongation at break	
	Mean value, $\bar{x}$ (MPa)	Standard deviation, σ (MPa)	Mean value, $\bar{x}$ (%)	Standard deviation, σ (%)
Substrate	23.0	0.15	723	19.7
Fusion joint	23.1	0.74	728	37.0

test at a tensile speed of 200 mm min^{-1}. Compared with the results of high-speed tensile tests, it is found that yield stress becomes smaller but elongation at break becomes much greater. The yield stress and elongation at break for the substrate and fusion joint in the tensile test are much alike[2,3]. The stress–elongation curve for high-speed tensile tests for specimens cut from a 2 mm thick pressed sheet for material evaluation were approximately equal to those for specimens cut from a 75 mm pipe shown in *Figure 1*.

Comparison of fusion-joined strength with substrate strength

Figure 3 shows a comparison of the absorbed energies of the substrate with those of fusion joints obtained from the high-speed tensile tests. Type B specimens with a 50 mm radius of curvature were used to break the fusion joints. Although absolute impact values of the substrate depend on resin grade, it is found in all cases that the impact values of a fusion joint are lower than those of the substrate.

In this figure, the 95% confidence limits were calculated from the following equation, considering the deviations of measurement values:

$$\text{confidence limit} = \pm t(n-1, 0.050)\sigma/\sqrt{n} \qquad (1)$$

where t = statistical profile, n = number of data and σ = standard deviation.

Figure 4 shows the comparison of the Charpy impact energies of the substrate with those of the fusion joint. The results are similar to those obtained in the high-speed tensile test. It is also found that the fusion strength is lower than the substrate strength. Comparing the impact energies of the substrates among resin grades, PE-H (which is a high-molecular-weight resin) is the highest

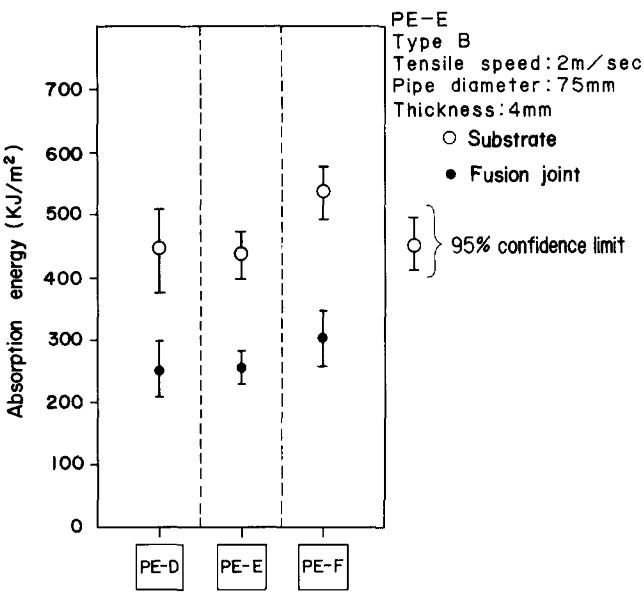

Figure 3 Comparison of fusion-joined strength with substrate strength in the high-speed tensile test

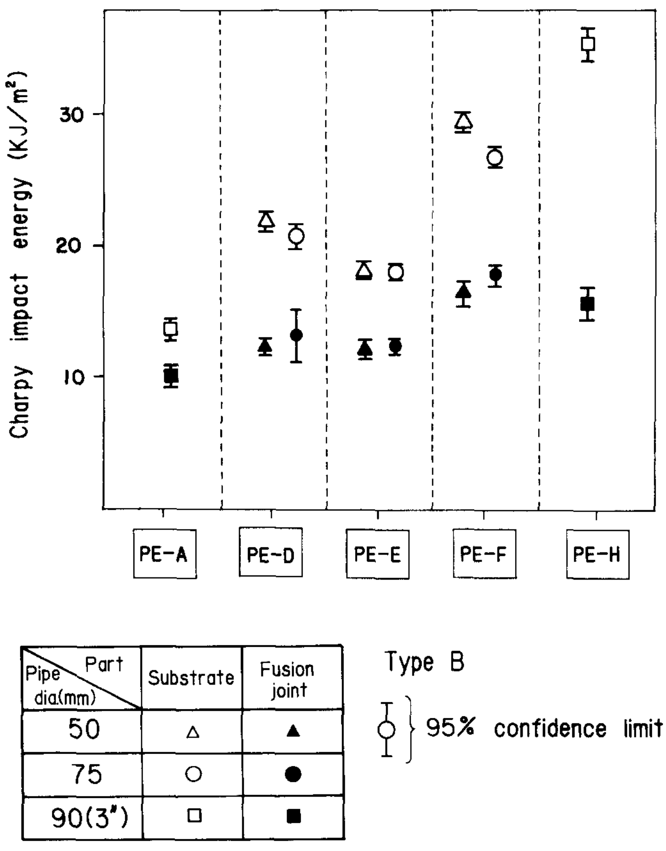

Figure 4 Comparison of fusion-joined strength with substrate strength in the Charpy impact test

and PE-A is the lowest. The reduction in the strength of fusion joints depends greatly on the grade of resin. The strength of PE-H of high-molecular-weight type in which the melt viscosity is relatively high decreases significantly by fusion joining compared with substrate strength. The reduction in fusion-joined strength is small in PE-A, whose melt flow rate (*MFR*) was high. The strengths of PE-D, PE-E and PE-F fusion joints are located between the above two resins. The rank of fusion-joined strength of the three resins agrees with that of the substrate strength, and the fusion strength was reduced to approximately 60% of the substrate strength.

Comparing the fusion strength of type B specimens cut from the middle of a pipe of 50 mm diameter (pipe thickness 6 mm) with that of those cut from the middle of a pipe of 75 mm diameter (pipe thickness 9 mm), no remarkable difference in impact values is found, although both heating and joining times were different. Although absolute impact values in the high-speed tensile test cannot generally be compared with those by the Charpy impact test because the shapes of test specimens were different, the latter showed lower values owing to small plastic deformation around a sharp notch.

Observation of fusion zone with a polarizing microscope

Figure 5 shows polarizing microphotographs of the fusion layers where melting and recrystallization occurred in the butt fusion process. Practically speaking, important factors in the control of fusion integrity are the heating temperature, heating time and applied pressure. The higher the heating temperature, and/or the longer the heating time, the wider the melted layer obtained. When the applied pressure is set higher, the melted resin flows into the inside and outside of the pipe to form large beads[4].

Fusion strength under various fusion conditions

Figure 6 shows the variation of Charpy impact values with change of heating conditions in a 75 mm diameter pipe. The Charpy impact values were obtained for the PE-D joints at various heating temperatures from 150 to 270°C and various heating times from 0 to 120 s. The impact values became lower when the heating temperature was below 170°C and the heating time was less than 30 s. The supply of an appropriate amount of energy was needed for good fusion. Regarding the applied pressure, it is important that a constant pressure should be applied to contact fully the ends of the two pipes. If the pressure is too high, impact values are likely to decrease since the crystalline structure of the fusion zones becomes continuous owing to the higher shear rate of melted resins than that of the substrate. The mean velocity V_m of a melted resin can be expressed as[5-7]:

$$V_m = \frac{8}{\pi} \frac{P_s L_0^2}{\eta_m d} \tag{2}$$

where P_s is the applied pressure, L_0 is the width of the melted layer, d is the pipe thickness and η_m is the mean nominal viscosity.

The relation between the mean velocity V_m and the Charpy impact value is shown in *Figure 7*. When the applied pressure is increased, the value of V_m increases and the melted resin flows in the radial direction. It results in a clear interface between the substrate and the fusion zone. If the value of V_m is small, diffusion and interpenetration of the melted flow to the fusion interface is less likely to occur. In this case, the impact strength decreases again.

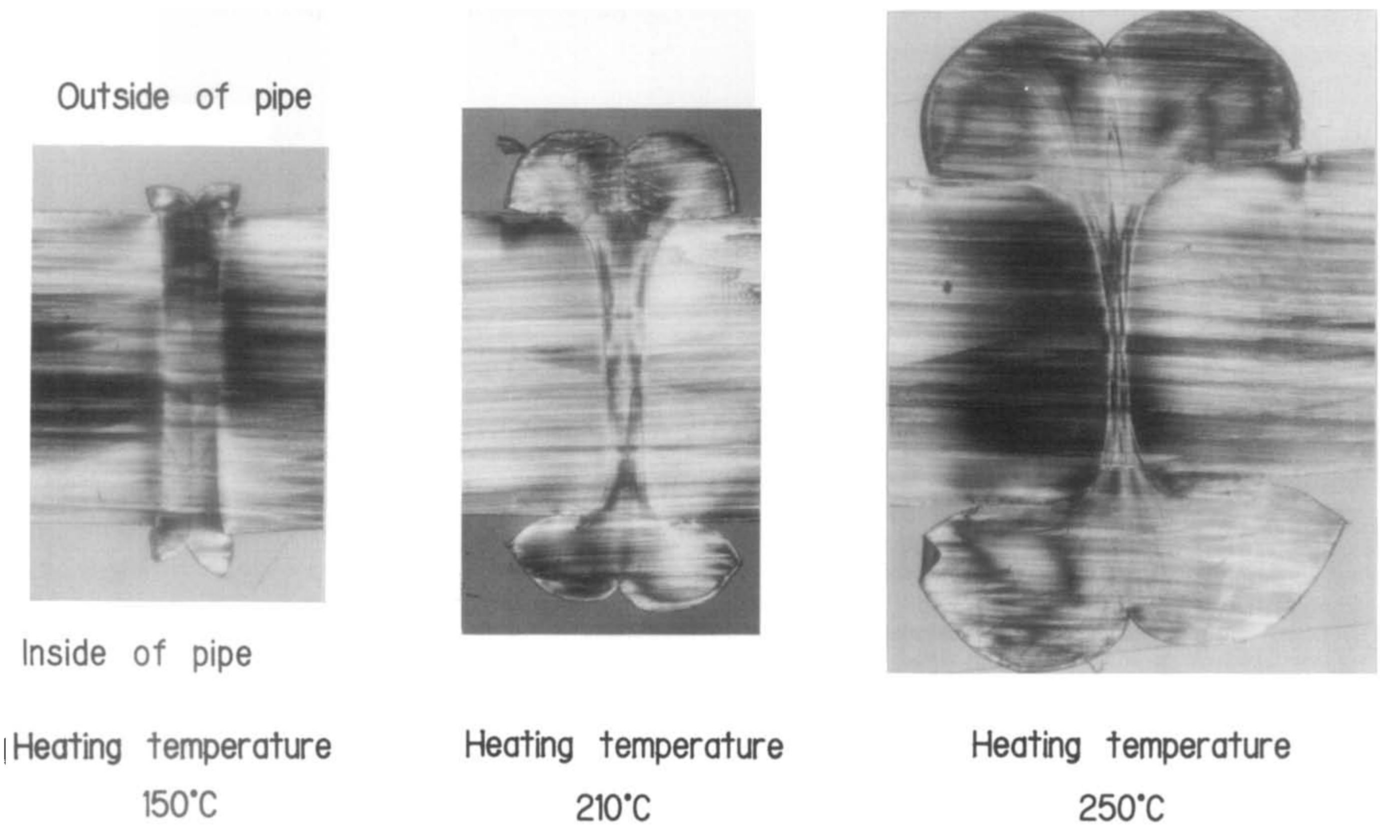

Figure 5 Polarizing microphotographs of a fusion zone

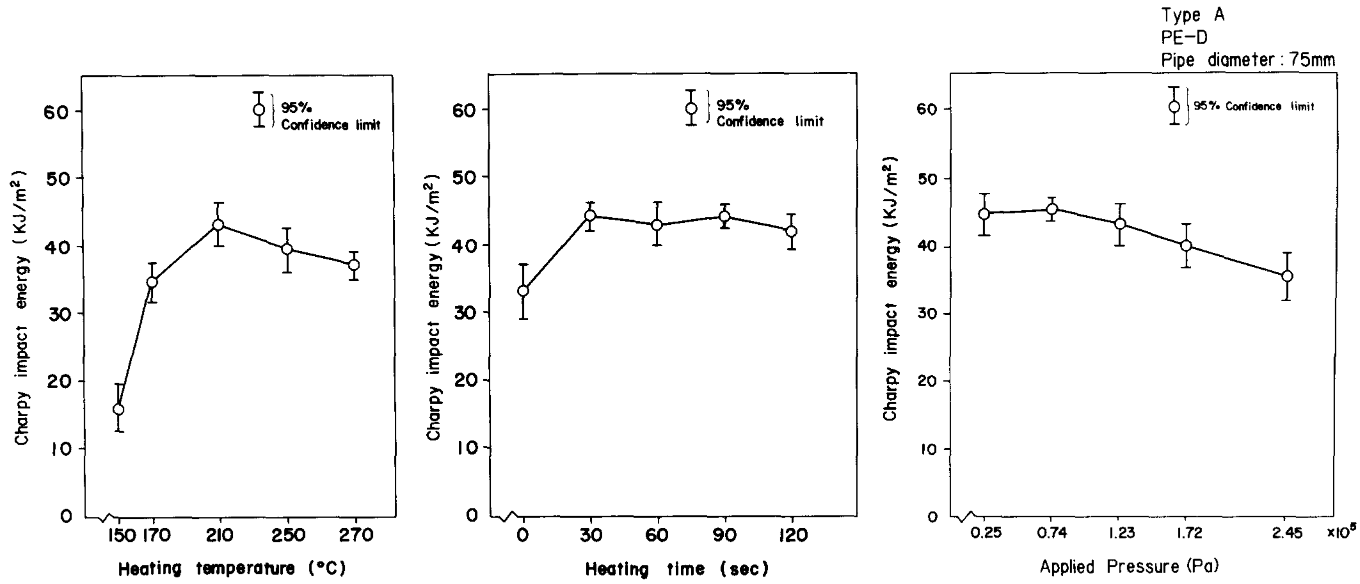

Figure 6 Fusion strength under various fusion conditions in the Charpy impact test

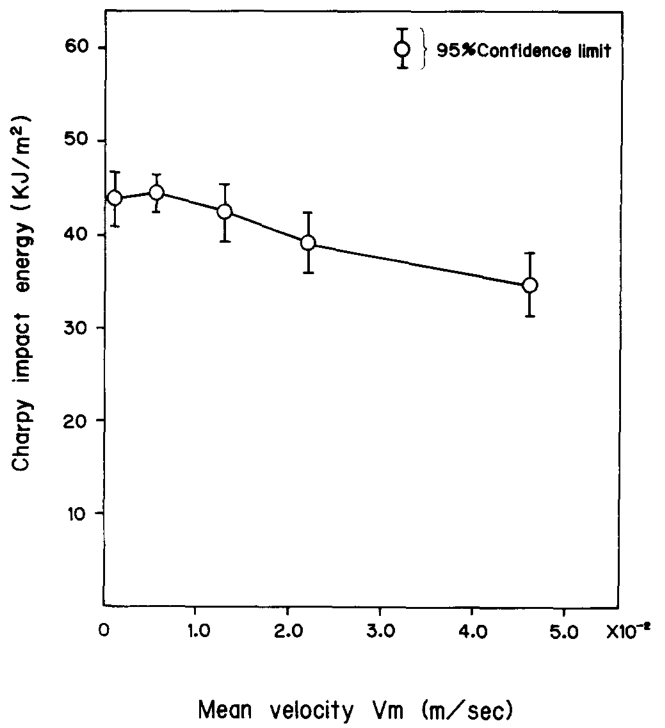

Figure 7 Relation between mean velocity and Charpy impact values

Material combination

As shown in *Table 1*, the molecular structure and the *MFR* of the resin grades used here are different. The effect on fusion strength of a combination of two different pipes from three resins has been investigated. As can be seen from *Figure 8*, when any two of the three resins were combined, the measured values as well as the 95% confidence limit for the combination of two different resins were located in the middle of those for the fusion strength of either resin[8]. According to observations of failed parts, crack initiation occurred at the tip of the U-shaped notch and propagated along the fusion interface.

CONCLUSIONS

The high-speed tensile test and the Charpy impact test were conducted on fusion-joined pipe specimens in order to evaluate the difference in impact properties of a polyethylene substrate and fusion joint. The changes in fusion strength obtained by varying the heating conditions and material combination were discussed. The fusion strength can be examined more closely by the high-speed tensile test or the Charpy impact test than by the conventional tensile test at lower tensile speeds[9–11]. Since the microstructure of fusion zones, such as degree of crystallinity and orientation, is different from that of the pipe substrate, sufficient plastic deformation before fracture does not seem to be able to occur when joints are subjected to impact loadings. The reduction in impact strength of a fusion joint was larger than that of the substrate.

The reduction in impact strength of fused joints depends on the resin grades. The fusion strength of PE-H having high molecular weight was greatly reduced. It may be due to the inferior flow of the melted resin at the fusion interface. It was revealed that the fusion strength was affected by the heating conditions[12–14]. For PE-D resin, impact strength decreased when the heating temperature was below 170°C, and/or the heating time was less than 30 s, and/or the applied pressure exceeded a certain value.

The values of impact strength for a combination of two different resins were located in the middle of those for the fusion strength of either resin.

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REFERENCES

1 Nishimura, H., Shishido, T., Nakakura, M., Shibano, H. and Kitao, K. *J. Japan Soc. Polym. Process.* 1989, **1**, 447

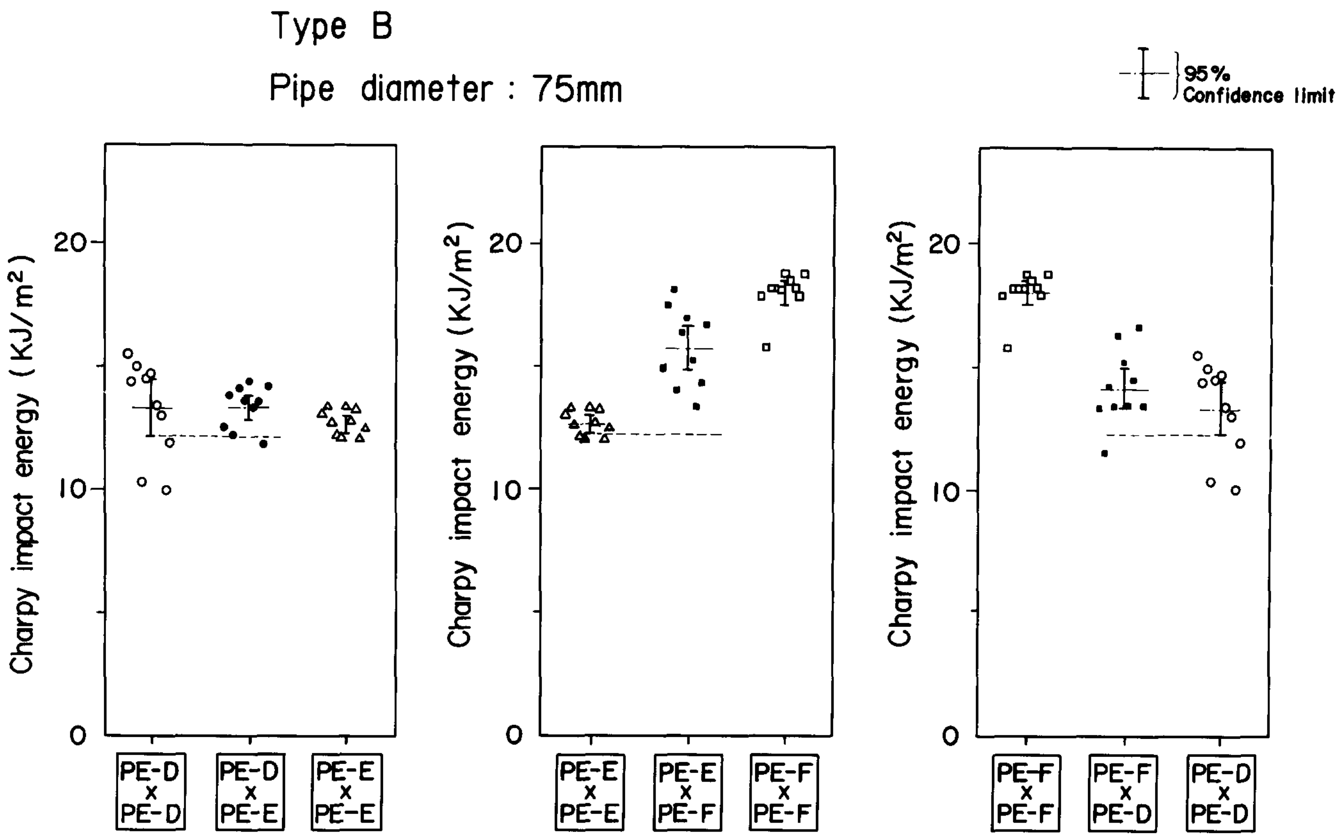

Figure 8 The effect of material combination on Charpy impact strength

2 DeCourcy, D. R. and Atkinson, J. R. *J. Mater. Sci.* 1977, **12**, 1535
3 Cowley, W. E. and Wylde, L. E. *Chem. Ind.* 1978, **3**, 371
4 Atkinson, J. R. and DeCourcy, D. R. *Plast. Rubber Process. Applic.* 1981, **1**, 287
5 Potente, H. *Kunststoffe* 1977, **67**, 98
6 Potente, H. and Cabler, K. *Plastverarbeiter* 1980, **31**, 203
7 Potente, H. and Keiter, J. International Institute of Welding, Doc. XVI-501/86, 1986
8 Kimata, A. *et al.* Proc. Tenth Plastic Fuel Gas Pipe, Symp., New Orleans, 1987, p. 127
9 Watson, M. N. Proc. Int. Conf. Plastics Pipes VII, Bath, 1988, p. 18
10 Pimputkar, S. M. Proc. Society of Plastic Engineers, 47th Annual Tech. Conf., New York, 1989, p. 3
11 Pimputkar, S. M. *et al.* 'Users' Guide on Butt Heat Fusion Joining of Polyethylene Gas Pipes', Topical Report, Sept. 1989
12 Potente, H. and Tappe, P. Proc. GERG-Workshop, 'Plastics Gas Distribution Systems', The Hague, 1984
13 Potente, H. and Tappe, P. *Mater. Design* 1985, **5**, 273
14 Bowman, J. and Parmar, R. *Polym. Eng. Sci.* 1989, **29**, 1406