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INVESTIGATION ON THE THERMAL BUTTFUSION PERFORMANCE OF THE BURIED HIGH DENSITY POLYTHYLENE PIPING IN NUCLEAR POWER PLANT

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ABSTRACT

This paper presents the effect of fusion procedure on the fusion performance of the thermal butt fusion in the safety class III buried HDPE piping per various tests performed, including high speed tensile impact, free bend, blunt notched tensile, notched creep, and PENT tests. The suitability of fusion joints and qualification procedures was evaluated by comparing test results from the base material and butt-fusion joints. From the notched tensile test result, it was found that the fused joints have much lower toughness than the base material. It was also identified that the notched tensile test is more desirable than the high speed tensile impact and free bend tests presented in the ASME Code Case N-755-1 as a fusion qualification test method. In addition, with regard to the single low-pressure fusion joint performances, the procedure given by the ISO 21307 was determined to be better that the one specified in the Code Case N-755-1.

KEYWORDS

HDPE pipe, thermal butt fusion, fusion procedure, qualification procedure, fusion performance, high speed tensile test, free bend test, notched tensile test, notched tensile creep test, PENT test.

NOMENCLATURE

t	pipe thickness
P	internal pressure
R_m	mean pipe radius
σ_{hoop}	hoop stress
σ_{axial}	axial stress

ABBREVIATIONS

ASME	American Society of Mechanical Engineers
B&PV	boiler and pressure vessels
DLP	dual low-pressure
FPS	fusion procedure specification
HDPE	high density polyethylene
ISO	International Organization for Standardization
PE	polyethylene

PENT	Pennsylvania edge notch tensile
PPI	Plastic Pipe Institute
SHP	single high-pressure
SLP	single low-pressure
NRC	Nuclear Regulatory Commission

1. INTRODUCTION

Recently, HDPE (high density polyethylene) has been applied to the safety class III buried piping in service water and seawater systems of nuclear power plants because of its excellent corrosion resistance [1, 2] in particular, among other things. As a consequence, ASME B&PV Code Committee issued an ASME &PV Code Case N-755 for this purpose [3] and more recently a revised Code Case N-755-1 was published that includes the requirements for the design, manufacturing and installation of the safety class III buried HDPE piping of nuclear power plants [4]. In regard to the use of this code case for butt-fusion, the U.S. NRC has expressed some concerns relating to the fusion performance as well as its qualification procedures [5, 6]. To resolve these issues the work at the ASME B&PV Code Committee continues to this date.

At the present time the Code Case N-755-1 only allows thermal butt fusion for joining the safety class III buried HDPE piping. It provides a procedure for the SHP (single high-pressure) while the ISO 21307 [7] gives the description for SHP, SLP (single low-pressure) and DLP (dual low-pressure) procedures applied to the gas and water PE (polyethylene) pipes. In an attempt to develop a global standard compensating the difference between the standards, Beech et al. [8~10] investigated variations of short- and long-term performances of the HDPE fusion joints with three fusion procedures (SHP, SLP, DLP) via performing various short- and long-term performance tests. The performance tests showed that the DLP fusion joints had best short-term performance while the SHP fusion joints had worst long-term performance. Troughton [11], using conditions somewhat altered from the standard fusion procedure (WIS 4-32-08 [12]), showed that, of the three short-term tests including three-point bend test, tensile test using a dumb-bell specimen, and tensile test using a waisted specimen, only the waisted specimen tensile test was able to differentiate between fusions made under the different joining conditions. In addition, there was no correlation between results from short-term and long-term tests or between results from specimen and whole pipe tensile creep rupture tests. Although there were various kinds of test conducted, the test results did not show consistency among test methods and causes of the inconsistency were not explained enough. In summary, it is difficult to find the previous studies that have evaluated effect of the thermal butt fusion procedure, presented in the Code Case N-755-1, on the fusion performance considering actual biaxial stress state of the HDPE piping. Although there are a few studies related to suitability of the standard fusion and qualification procedures presented in the Code Case N-755-1, fully convincing conclusions were not drawn yet.

In this work, the butt-fusion procedure of the Code Case was revisited by further evaluating fusion joints prepared by both the Code Case N-755-1 and the ISO 21307 procedures. High speed tensile impact, free bend, notched tensile, notched creep, and PENT (Pennsylvania edge notch tensile) tests were utilized and their results presented to determine the suitability of the fusion and qualification procedures of the Code Case N-755-1.

2. THE STANDARD PROCEUDRES FOR FUSION JOINING OF PE PIPES

2.1 Standard thermal butt fusion procedures

Mandatory Appendix I in the Code Case N-755-1 prescribes requirements for a standard FPS (fusion procedure specification). The FPS, based on standard industry practice and testing as reported in the PPI's technical report [13], includes specified requirements for heater plate surface temperature, heater bead up size, heater plate removal time, fusion pressure, cool-down time under fusion pressure, etc.. The requirements for the thermal butt fusion in the Code Case N-755-1 are for SHP procedure.

Although there are several minor differences, the requirements for a standard FPS in the Code Case N-755-1 are similar with those of a SHP FPS in ISO 21307. The ISO 21307 presents three kinds of the standard FPSs (SLP, SHP and DLP) for thermal butt fusion joining of the PE pipes in gas and water distribution systems. The standard FPSs can be applied to both MDPE (medium density polyethylene) and HDPE pipes.

In the ISO 21307, the fusion pressure of the SHP fusion procedure is about three times higher than that of the SLP fusion procedure. The Code Case N-755-1 specifies the fusion pressure similar to that of the SHP procedure in the ISO 21307 but allows wider pressure range than the ISO 21307. Considering that the heater plate temperature and the fusion pressure are the most critical process variables in thermal butt fusion joining of HDPE pipes, it is worthy of notice that difference among the fusion pressures in the standards is about three times.

2.2 Standard qualification procedures for fusion joints

Both the Code Case N-755-1 and the ISO 21307 require the fusion performance tests as qualification for the butt fusion procedure. The Code Case N-755-1 requires high speed tensile impact tests using smooth specimen and elevated temperature sustained pressure tests in order to qualify the FPS and requires the free bend test in order to qualify each fusion machine operator. Meanwhile, the ISO 21307 recommends normal speed tensile tests using short length specimen, hydrostatic pressure tests and high speed tensile tests using smooth specimen as the quality control method for the fusion procedure.

3. FUSION PERFORMANCE TESTS

3.1 Fusion performance test methods

The study aimed to evaluate the effects of the SHP fusion procedure in the Code Case N-755-1 and the SLP fusion procedure in the ISO 21307 on the fusion performance. HDPE pipes were made of the PE 100 P600 resin of Korea Petrochemical Industry Company, Ltd. Using the HDPE pipes, total four kinds of the fusion joints were manufactured with different fusion pressure and heater plate temperature.

- Fusion Condition - 1 : SHP & low temperature (4.6±0.4bar & 208±3.0℃)
- Fusion Condition - 2 : SHP & high temperature (4.6±0.4bar & 230±3.0℃)
- Fusion Condition - 3 : SLP & low temperature (1.7±0.4bar & 208±3.0℃)
- Fusion Condition - 4 : SLP & high temperature (1.7±0.4bar & 230±3.0℃)

The SHP and the SLP fusion joinings were performed according to the requirements of the Code Case N-755-1 and the ISO 21307, respectively. Detailed fusion requirements are summarized in Table 1.
In accordance with the requirements in the Code Case N-755-1, the high speed tensile impact and free bend tests were performed as short-term fusion performance tests. In addition, considering the previous experiences [8~11], the blunt notched tensile tests were carried out as one of short-term fusion performance tests

Table 1. Specification of the thermal butt fused piping for tests – requirements of fusion variables

DN300, DR11 : OD 319.7 mm (12.59 inch), t 31.2 mm (1.228 inch) ID 257.3 mm, Cross section area 282.78 cm^2					
Variables		Condition 1[1)]	Condition 2[1)]	Condition 3[2)]	Condition 4[2)]
Heater plate temperature (℃)	T	208.0 (±3.0)	230.0 (±3.0)	208.0 (±3.0)	230.0 (±0.0)
Drag pressure (bar)	p_{drag}	-			
Initial bead-up pressure (bar)	p_1	p_3			
Initial bead-up size (mm)	d_1	-[3)]	-[3)]	≥ 3.23	≥ 3.23
Initial bead-up time (sec)	t_1	70[4)]	60[4)]	90[4)]	90[4)]
Bead size after heating (mm)	d_2	≥ 6.0	≥ 6.0	-[5)]	-[5)]
Heat soak time (sec)	t_2	328[6)]	200[6)]	≥ 328	≥ 328
Heat soak pressure (bar)	p_2	p_{drag}			
Heater plate removal time (sec)	t_3	≤ 5.0			
Fusion jointing pressure (bar)	$p_{int} = p_3 - p_{drag}$	4.6 (±0.4)	4.6 (±0.4)	1.7 (±0.4)	1.7 (±0.4)
Time to achieve interfacial pressure (sec)	t_4	≤ 12.9			
Cooling time in the machine under pressure (sec)	t_5	≥ 1080	≥ 1080	≥ 1860	≥ 1860
Cooling time out of the machine (sec)	t_6	-	-	≥ 1860	≥ 1860

Note 1) Mainly based on the Code Case N-755-1. Some items are based on the SHP condition in the ISO 21307.
2) Based on the SLP condition in the ISO 21307.
3) Only identification of 360^o bead formation by visual examination. There is no requirement for the initial bead-up size.
4) Based on the initial bead-up size requirements and preliminary test results, unified initial bead formation time is applied.
5) There is no requirement for the bead size after heating. Remove the heating plate based on the heat soak time.
6) Based on the requirements for the bead size after heating and preliminary test results, unified heat soak time is applied.

Table 2 presents an overall test matrix for four kinds of the fusion procedures of the HDPE pipes. The number of the high speed tensile impact and free bend test specimens was complied with the FPS qualification test requirement of the Code Case N-755-1 for each fusion joining condition. The free bend test was carried out for four kinds of the fusion joints with the different fusion conditions. The high speed tensile impact and notched tensile test were performed for the base material and the four fusion joints with three displacement rates (5mm/min, 50mm/min, 152mm/sec) under displacement control condition. Both the Code Case N-755-1 and the ISO 21307 require that the high speed tensile impact test shall be performed with the displacement rate of 152 mm/sec. The displacement rate of 5 mm/min is a requirement for the normal speed tensile test using a short specimen in the ISO 21307. The notched tensile creep test was performed for the base material and the four fusion joints in the air of 80℃ with the tensile stress of 8MPa on the basis of net-section area. The PENT test was carried out for the base material and the four fusion joints in the water of 80℃ with the tensile stress of 2.76MPa on the basis of net-section area. For reducing PENT test time, the test specimens were subject to alternate loading with the loading ratio of 0.1 and the frequency of 0.1Hz.

Table 2. Performance test matrix for HDPE butt fusion joints

Classification		Number of base material specimen	Number of fusion joint specimen			
			Fusion 1 (SHP - low temperature)	Fusion 2 (SHP - high temperature)	Fusion 3 (SLP - low temperature)	Fusion 4 (SLP - high temperature)
Qualification test by the Code Case N-755-1	Free bend test	-	4 1)	4 1)	4 1)	4 1)
	High speed tensile impact test (152 mm/sec)	-	12 2)	12 2)	12 2)	12 2)
Short-term performance test	Notched tensile test (152 mm/sec)	3	4 1)	4 1)	4 1)	4 1)
	Notched tensile test (50 mm/min)	2	2 3)	2 3)	2 3)	2 3)
	Notched tensile test (5 mm/min)	2	2 3)	2 3)	2 3)	2 3)
Long-term performance test	Notched tensile creep test	1	4 1)	4 1)	4 1)	4 1)
	PENT test	-	4 1)	4 1)	4 1)	4 1)

Note 1) Taken at intervals of circumference 90° for a joint
2) Taken at intervals of circumference 90° for three joints
3) Taken at intervals of circumference 180° for a joint

3.2 Fusion performance test results

3.2.1 High speed tensile impact and free bend tests

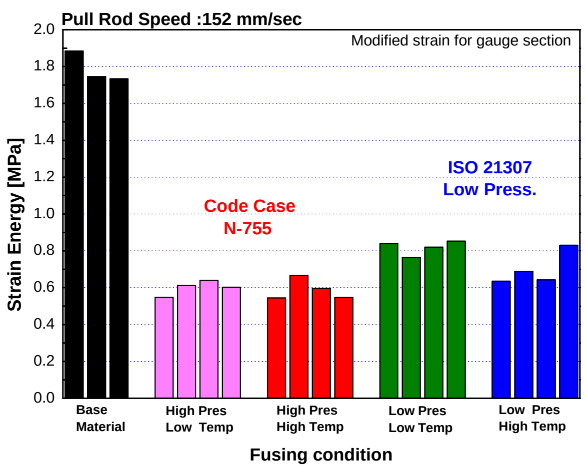
The acceptance criteria of the high speed tensile impact test in the Code Case N-755-1 are based on the failure mode of the test specimen. To be accepted, the failure mode shall not be brittle in the fusion interface. In this study, for all the fusion joint specimens, the failure modes were ductile fracture which occurred at fusion interfaces or base materials near the fusion joints. So, all the fusion joints meet the acceptance criteria of the high speed tensile impact test in the Code Case N-755-1.

The acceptance criteria of the free bend test in the Code Case N-755-1 are that the specimens shall not crack or fracture. No crack was found in all the fusion joint specimens. So, all the fusion joints meet the acceptance criteria of the free bend test in the Code Case N-755-1.

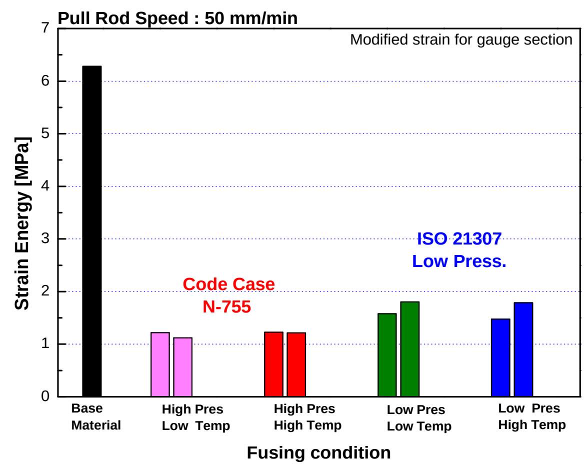
As a result, in the viewpoint of the short-term fusion performance, both the SHP and the SLP fusion procedures are acceptable to the safety class III buried piping of nuclear power plants according to Code Case N-755-1. From the test results, it was confirmed that short-term strengths of the HDPE butt fusion joint are not lower than those of the base material under uniaxial stress condition. However, these results cannot give an assurance that other kinds of short-term performances (for example, ductility, etc.) of the fusion joints are not worse than those of the base materials. For more investigation on the short-term performances, the blunt notched tensile test results need to be examined.

3.2.2 Blunt notched tensile tests

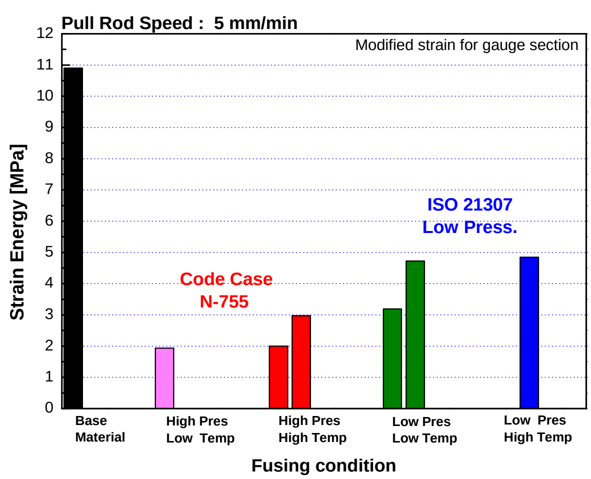
Figure 1 indicates variations of fracture strain energy for the base materials and four kinds of the fusion joints. From the figure, it is found that fracture strain energy of the fusion joint significantly decreases under all the displacement rates comparing with those of the base material. In general, the SHP fusion joints by the Code Case N-755-1 have lower fracture strain energy than the SLP fusion joints by the ISO 21307 as shown in Fig. 1. This tendency could not be indicated by the high speed tensile test using smooth specimen and the free bend test which are qualification tests of the Code Case N-755-1, as previously described in the Section 3.2.1.



(a) Displacement rate 152mm/sec



(b) Displacement rate 50mm/min



(c) Displacement rate 5mm/min

Fig. 1. Fracture strain energy vs. the fusion condition

Consequentially, the notched tensile test is more desirable than the high speed tensile impact and free bend tests presented in the Code Case N-755-1 as a fusion qualification test method. This finding is consistent with the Troughton's study result [12].

3.2.3 Blunt notched tensile creep and PENT tests

Variation of time-to-rupture vs. the fusion condition for the base material and the different fusion joints derived by the notched tensile creep test is presented in Fig. 2. From the figure, it is found that the time-to-rupture of the fusion joints show very large scatter within the same fusion condition. To minimize effect of the scattering, rupture time of each fusion condition was averaged excluding maximum and minimum values. On a basis of the average values, the rupture times of the fusion joints are about 41% shorter than those of the base material. The rupture times of the SLP fusion joints are about 11% longer than those of the SHP fusion joints.

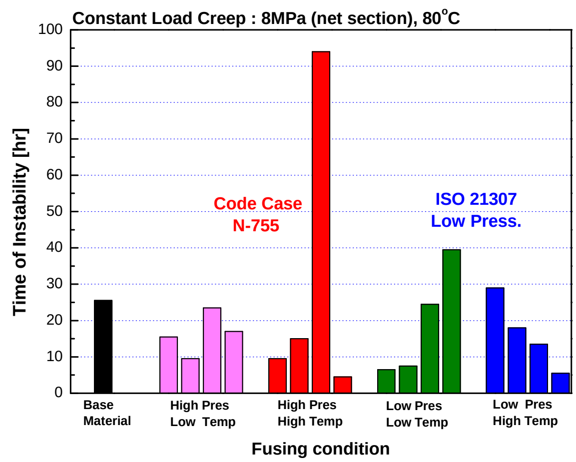


Fig. 2. Variation of time-to-rupture by the notched tensile creep tests vs. the fusion condition

Figure 3 shows variation of failure time vs. the fusion condition for the different fusion joints taken by the PENT test. As shown in the figure, the PENT test results show also significantly large scatter within the same fusion condition. On a basis of the average failure time, excluding maximum and minimum, the failure times of the SLP fusion joints are about 67% longer than those of the SHP fusion joints.

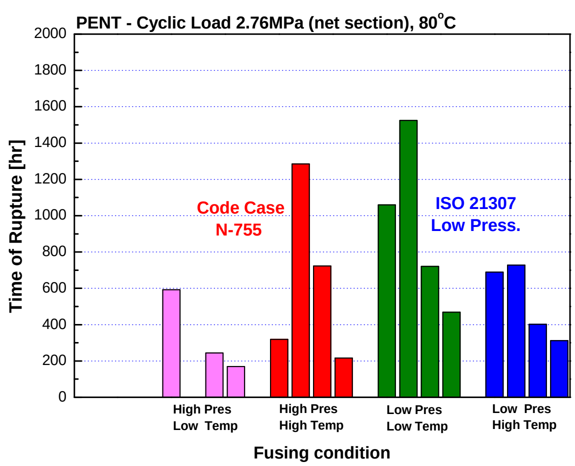


Fig. 3. Variation of failure time by the PENT tests vs. the fusion condition

3.2.4 Summary of the test results

All the test results conducted in this study were summarized in Fig. 4. Maximum and minimum values were excluded in this figure because of the large scatter mentioned previously. Considering both the short-term fusion performance test results by the notched tensile test and the long-term fusion performance test results by the notched tensile creep and PENT tests, it can be said that the SLP fusion joints by the ISO 21307 show better fusion performance than the SHP fusion joints by the Code Case N-755-1.

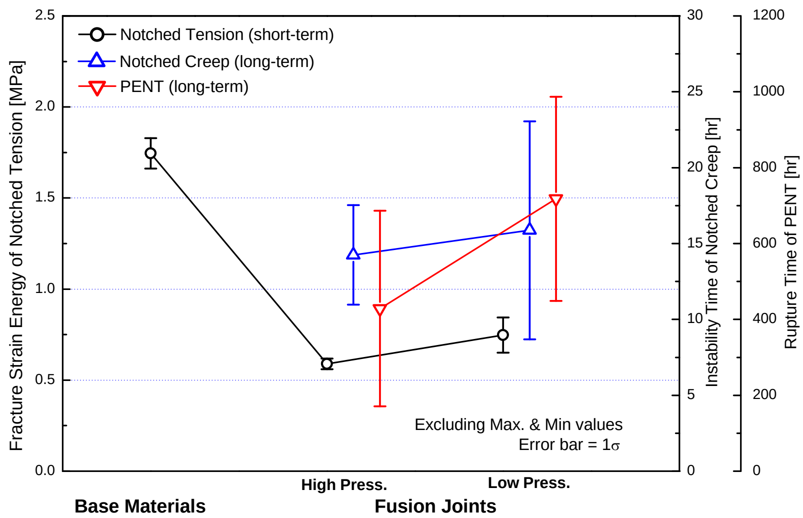


Fig. 4. Summary for the performance test results of the HDPE butt fusion joints

4. CONCLUSIONS

From the investigation on the thermal butt fusion performance of the safety class III buried HDPE piping in nuclear power plants, the following findings are derived:

- The SHP fusion joint by the Code Case N-755-1 and the SLP fusion joint by the ISO 21307 meet all the requirements of the high speed tensile impact and free bend tests, but the requirements have some limitation to qualify the fusion performance.
- In the notched tensile tests, the HDPE butt fusion joints have significantly lower ductility than the base material.
- The notched tensile test is more desirable than the high speed tensile impact and free bend tests presented in the Code Case N-755-1 as a fusion qualification test method.
- The SLP fusion joint by the ISO 21307 shows better fusion performance than the SHP fusion joints by the Code Case N-755-1.

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