High-density polyethylene (HDPE) pipe, well known as a type of thermoplastic pipe, is used instead of concrete and steel pipes for many applications, such as gas and fluid transfers, water/sewage drainages, and electrical and communication conduits (Refs. 1–3). The HDPE pipe shows many excellent properties, such as light weight, chemical resistance, and tolerance for decomposition (Ref. 4). Although HDPE pipe has been appropriate for underground applications, it also has high ductility and low stiffness, which causes an unstable shape when it receives highly compressive forces (Refs. 3, 4). Recently, the strength of HDPE pipe has been improved by methods such as increasing the wall thickness, spiral shape designs, and reinforcements such as fiberglass and ceramic, etc. (Refs. 3–5).

Steel-reinforced polyethylene (SRPE) corrugated pipe is a kind of sandwich composite consisting of HDPE and galvanized steel (Refs. 6, 7). The internal and external walls are covered by HDPE, and the center layer is reinforced with galvanized steel with V and U spiral shapes (Refs. 8, 9), as shown in Fig. 1. The SRPE has many advantages from the combined properties of HDPE and reinforced steel, such as high stiffness, high corrosion resistance, and better flexibility with steady structure (Refs. 8–10). As a result, there has been interest in using SRPE for underground applications such as drainage/sewage pipes and water storage tanks (Refs. 8–10). For fabrication and connection uses, SRPE is simple to weld at the HDPE joint by heating-fusion processes such as electrofusion belt, elastomeric seal, and heated tool welding (Refs. 11–14). However, these techniques are suitable for butt-joint welding on the outside of the pipe. It is difficult for completely welding on the inside of the pipe and other joints such as lap, corner, and T-shaped joints.

Extrusion welding is a thermal technique developed from hot gas/air welding for melting and joining thermoplastics and their composites (Refs. 14–18). The filler rod-based thermoplastic material is heated and extruded into a molten form at the joint area, which is welded after cooling. It also allows a large welding area with a single pass and good penetration (Refs. 19–20).
The travel speed and extruder speed were controlled at the controlled temperature of 190°–200°C during the welding. The SRPE pipes were prepared in a squared butt-joint configuration with a root opening of 5.0 mm and welded by manual extrusion with preheat. The modified extruder was welded in a single pass on the inside of the pipe from an overhead position with downhill progression.

After welding, the shape, dimension, and quality of the welds were inspected by visual testing (VT) according to American Welding Society (AWS) Standard G1.10M:2001, Guide for the Evaluation of Hot Gas, Hot Gas Extrusion, and Heated Tool Butt Thermoplastic Welds (Ref. 22). The inside welds were investigated by radiographic testing (RT) using a phosphor imaging plate (D7 class) and the exposure parameters of 20 kV, 2 mA, 40 s, and the FFD of 700 mm. The radiographic images were developed by a computed scanner. After that, the welded specimens were characterized by XRD using Cu-Kα as the radiation source (λ = 1.54 Å) and 2θ ranging from 10 to 40 deg with a scanning rate of 0.2 1/s. The crystallinity was determined from the integrated area of amorphous and crystalline as follows: %crystallinity (Xc) = Ac/(Ac + Aa), where Ac and Aa are the crystalline and amorphous areas, respectively (Refs. 23–25).

The crystalline thickness of the lamella was calculated by Scherrer equation as follows: τ = Kλ/βcosθ where τ is the mean size of the ordered (crystalline) domains, which may be smaller or equal to the grain size; K is a dimensionless shape factor, which has a typical value of 0.89; λ is the x-ray wavelength; and β is the line broadening at half the maximum intensity after subtracting the instrumental line broadening in radians. This quantity is also sometimes denoted as Δ(2θ); θ is the Bragg angle (Ref. 26).

Mechanical Testing

The tensile specimen was prepared from SRPE welded in the conditions of preheating and nonpreheating. The welded specimens were prepared as a rectangular strip with the dimensions of 25 × 150 × 10 mm (three samples were used per each condition), which was used to analyze the tensile strength of the weld (Ref. 20). The tensile strengths of the welded specimens were tested by UTM, and then the broken areas and types of fracture of the welded specimens were considered to determine the quality of the weld (Refs. 20, 27, 28).

For the stiffness test, the welded SRPE pipes were applied by a compression load at 5% deflection according to American Society for Testing Materials Standard F2435-15 (ASTM F2435-15) and Thai Industrial Standard 2764-2559 (TIS 2764-2559) for considering the strength of the welded SRPE (Refs. 8, 9). The pipe stiffness was calculated from the equation as follows: Stiffness = F/(L × ΔY), where F = compressive force (N), D = length of specimen (mm), and ΔY = changes in vertical deflection (mm) (Refs. 8, 9). Finally, the welded pipe was sealed at both ends and then filled with water into the lidded pipe for testing water leakage and hydrostatic pressure.

Results and Discussion

Welding and Investigation

From visual inspection, the welded pipes from the preheat and nonpreheat conditions exhibited good welds and displayed complete joint penetration without defects and discontinuities at the surface — Fig. 3. The size of the width, convexity, and root of the weld were found to be approximately 32.0, 5.0, and 1.0 mm, respectively. The average...
sizes of the welded pipes were measured and summarized in Table 1 and were in the range according to TIS 2764-2559 and AWS G1.10M:2001 (Refs. 9, 22).

From the radiographic tests (Fig. 4), the x-ray images of welded specimens from the preheat and nonpreheat conditions showed the three contrast zones, such as dark black, black, and bright black, which were assigned as the areas of HDPE, steel-reinforced HDPE, and weld, respectively. The x-ray image of the preheated welded specimen (Fig. 4A) showed the complete weld without any defects observed along with the welded areas. For the x-ray image of specimens from the nonpreheat welding, it was found the HDPE and steel-reinforced HDPE zones had no defect and a smooth surface, but the welded area showed the discontinuities that formed inside the welded material as shown in Fig. 4B. These volumetric indicators inside the nonpreheated weld were assigned as a void that came from impurities such as moisture, as well as volatile and processing additives (including the immediate shrinkage of the weld). This caused the high cooling rate in nonpreheat welding and generated the void in the material at a high temperature. From the RT result, it indicated the preheated condition could eliminate these impurities and also soften the material during the welding process, which solved the problems of any defects inside the weld.

Phase components of the welded SRPE at the welded area and HDPE base were characterized by x-ray diffraction. The XRD patterns of the HDPE base and welds obtained from preheated and nonpreheated welding exhibited the diffraction peaks as shown in Fig. 5A–C, respectively.

The characteristic peaks of all specimens appeared at the 2θ of 21.4 and 23.7 deg corresponding to the diffraction planes of (110) and (200), respectively. These diffraction peaks agreed with the orthorhombic structure of HDPE as reported elsewhere (Refs. 23, 29). In addition, the XRD showed the broad peak at 2θ approximately 20 deg, which was typically assigned to the amorphous phase of HDPE. It confirmed that the structure of the HDPE base before and after welding consisted of the semicrystalline structure of both amorphous and crystalline phases. Moreover, it was found that the broad peak of the specimens after being welded was significantly changed into the more sharper shape, similar to the other crystalline peaks in the pattern. It indicated the hot extrusion welding changed the crystallinity and lamellar crystalline size of HDPE. Therefore, the amorphous characteristics and crystallinity of the welds, including the size of lamellar crystalline, were considered. The % crystallinity and lamellar crystalline size of the welded SRPE and HDPE base were calculated and summarized in Table 2.

From the crystallinity calculation results, it was found that the HDPE at the base showed lower crystallinity (64.65%) than that of the preheated (65.80%) and nonpreheated welds (70.15%). By the Scherrer equation, the calculated size of lamellar at the plane of (111) of the HDPE base, for both preheated and nonpreheated welds, were found to

<table>
<thead>
<tr>
<th>Welding Conditions</th>
<th>Inside Diameter (mm)</th>
<th>Outside Diameter (mm)</th>
<th>Pitch Range (mm)</th>
<th>Wall Thickness (mm)</th>
<th>Weld Size (mm)</th>
<th>Weld Defect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preheat</td>
<td>1201.0</td>
<td>1332.0</td>
<td>154.7</td>
<td>5.20</td>
<td>10.09</td>
<td>No defect</td>
</tr>
<tr>
<td>Nonpreheat</td>
<td>1201.1</td>
<td>1332.2</td>
<td>154.7</td>
<td>5.25</td>
<td>10.10</td>
<td>No defect</td>
</tr>
</tbody>
</table>
be 29.70, 28.72, and 24.30 nm, respectively. At the plane of (200), the crystallite size of the HDPE base, preheated and nonpreheated welds, was found to be 28.76, 27.45, and 22.94 nm, respectively. These results indicated the lamellar size of the weld was decreased after welding while the crystallinity was increased. The crystallinity and crystallite size of the nonpreheated weld was extremely changed from the HDPE base, which might indicate the welding process without preheating condition could not control the crystallinity and crystallite size of materials. In the case of the preheated weld, it was found that the crystallinity and crystallite size were close to those of the HDPE base, which might demonstrate that the preheated welding could control the crystal structure by reducing heat loss and the cooling rate during welding.

**Mechanical Testing**

The tensile testing results of the welded specimens from preheating and nonpreheating were compared as shown in Fig. 6. The tensile strength (Fig. 6A) of the welded specimens from the preheated and nonpreheated conditions was found to be 46.04 and 31.01 MPa, respectively. The elongation at the break (Fig. 6B) of the welded specimens from welding with and without preheat was found to be 98.53 and 64.13%, respectively.

In addition, the types of failures (ductile and brittle ruptures) in the welded specimens after testing were considered for the weld quality of the joint (Refs. 20, 27, 28). The results showed the welded specimens from the preheated condition had good joint quality because they showed ductile ruptures after breaking at the base position of the test specimens, outside the welding area — Fig. 7A. It indicated preheat welding could control weld quality, crystallinity, and crystallite size of the weld. For the welding without the preheat condition, it was found that the specimens exhibited brittle ruptures and were broken at the welding area, which indicated the joint in the

**Table 2 — XRD Result of Welded Pipe**

<table>
<thead>
<tr>
<th>Specimens</th>
<th>2θ (deg)</th>
<th>Plane</th>
<th>Lamellar Crystallite Size (nm)</th>
<th>% Crystallinity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>21.4</td>
<td>(110)</td>
<td>29.70</td>
<td>64.65%</td>
</tr>
<tr>
<td></td>
<td>23.7</td>
<td>(200)</td>
<td></td>
<td>28.72</td>
</tr>
<tr>
<td>Preheated Weld</td>
<td>21.4</td>
<td>(110)</td>
<td>28.62</td>
<td>65.80%</td>
</tr>
<tr>
<td></td>
<td>23.7</td>
<td>(200)</td>
<td></td>
<td>27.45</td>
</tr>
<tr>
<td>Nonpreheated Weld</td>
<td>21.4</td>
<td>(110)</td>
<td>24.30</td>
<td>70.15%</td>
</tr>
<tr>
<td></td>
<td>23.7</td>
<td>(200)</td>
<td></td>
<td>22.94</td>
</tr>
</tbody>
</table>
nonpreheated specimens had poor quality as shown in Fig. 7B. This was due to the void that formed inside the weld, which decreased the strength of the welded specimens. From the compressive test (Table 3), the pipe specimens from welding, with and without preheat conditions, revealed stiffness of 0.41 MPa at the stress of 5% deflection according to ASTM F2412-15 and TIS 2764-2559 (Refs. 8, 9). Moreover, the test specimens were further tested at the high stress of 40% deflections, and it was found the welded specimens could stand without cracking at the weld and base areas. This could explain that the compressive force was dispersed by the strength of the reinforced steel; therefore, the weld and HDPE base received no damage.

For the water leak and hydrostatic pressure tests, the SRPE pipe welded at both cover lids was filled with water and kept for four weeks. The sealed tank showed no leakage at the weld and base material observed by water leakage testing. In addition, we found the welded SRPE pipe could endure hydrostatic pressure up to 0.18 MPa without any water leakage — Fig. 8. After testing by using the pressure over 0.18 MPa, it was found the water was able to leak out from the internal pipe wall near the reinforced steel. From these results, it might be concluded the welded SRPE pipe could be used for water drainage, sewage, water supply industrials, and nonpressure applications.

**Conclusions**

Steel-reinforced polyethylene (SRPE) corrugated pipe was welded by extrusion welding in preheated and nonpreheated conditions. From visual and radiographic inspections, the welded SRPE from the preheated condition exhibited...
ited a complete-joint-penetration weld without defects while that of the nonpreheated weld had a void formed inside. By X-ray diffraction (XRD) characterizations, the welds from preheated and nonpreheated conditions exhibited diffraction patterns that agreed with the orthorhombic structure. The crystallinity and crystallite size of the preheated weld was similar to unwelded high-density polyethylene (HDPE) while the nonpreheated weld was extremely changed. From the tensile results, the preheated weld specimens showed ductile ruptures at the HDPE base. In the case of the nonpreheated weld, the specimens showed brittle ruptures at the welding area because the void formed inside the weld. For compressive testing, superior results were presented due to the steel reinforcement. The preheated specimens could also endure the stress of 40% compression without cracking at the base and welding areas. Moreover, no leakage at the weld and the base was observed after water leakage and hydraulic pressure tests under a pressure of 0.18 MPa. From the overall results, it was clearly concluded that preheated welding was able to control the weld quality, crystallinity, crystallite size, and mechanical properties of the welded SRPE.

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