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Design of Smooth Aluminum Bonded Sheaths in HV XLPE Cables Based on the Bending Performance Research

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ABSTRACT In China, recent ablation failures of water-blocking buffer layer occurred in high voltage (HV) cross-linked polyethylene (XLPE) cables with corrugated aluminum sheath have stimulated the product development of cables with smooth aluminum bonded sheath. Despite the many advantages, bending performance is one of the few weaknesses of smooth aluminum bonded sheath. In this paper, a three-dimensional model of a cable with smooth aluminum bonded sheath in a four-point bending test was set up, where the cohesive zone model was applied to simulate the mechanical behavior of the adhesive layer (bonding interface). The influence on the bending performance of the bonded sheath by the thickness of aluminum layer, the parameters of hot melt adhesive, the thickness and material parameters of outer jacket, as well as the cable specification was investigated, together with the stress distribution and damage analysis of the adhesive layer. Based on the research, the material selection and structural design of smooth aluminum bonded sheath were recommended for HV XLPE cables, including an additional requirement for the shear strength of hot melt adhesive besides those already in IEC and IEEE standards. Finally, a 110 kV XLPE cable with smooth aluminum bonded sheath was manufactured and type tested.

INDEX TERMS HV XLPE cable, smooth aluminum bonded sheath, bending performance, bonding interface, hot melt adhesive.

I. INTRODUCTION

In the past few decades, high voltage (HV) cables insulated with cross-linked polyethylene (XLPE) have been widely applied in urban power grids around the world [1], [2]. The metal sheath is essential for a HV cable, providing it with radial water-tightness, short-circuit current path and mechanical protection. For XLPE land cable, metal sheaths are mainly made of aluminum, while copper, lead, stainless steel, and other metals are only used in some special occasions, such as in the case of vibration and corrosion [3]–[5]. Meanwhile, the metal sheath can be corrugated or smooth.

HV XLPE cables with smooth and plastic-coated aluminum bonded sheath, labelled as combined design (CD) and separate design (SD) in CIGRE TB 446, are widely used in Europe, the Middle East, and America. For CD, the aluminum sheath is usually thick enough to carry the short circuit current. While for SD, the aluminum foil thinner than 0.5 mm is used as a radial-moisture barrier, and supplementary metal wires are needed to fulfill the short circuit requirement. According to the prediction of CIGRE WG, the increase of the market share of cables with bonded sheath will be a global trend [3].

HV XLPE cables with corrugated aluminum sheath are extensively used in China, Australia, Japan and other countries because of the excellent mechanical performance. In recent years however, the ablation failures of water-blocking buffer layer occurred in cables with corrugated aluminum sheath have been reported repeatedly, which poses a serious threat to the reliability of transmission line [6], [7]. Although the research on ablation of buffer layer has not been concluded, the poor electrical contact between the metal sheath and insulation screen is thought to be one of the main causes of the failure.

Due to the compact structure of smooth aluminum bonded sheath, the radial heat dissipation is improved, the poor

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contact issue is avoided, and the cable outer diameter is decreased, which provides both technical and economic advantages over the corrugated aluminum sheath [3], [4]. Although the poorer mechanical performance has once limited the application of smooth aluminum bonded sheath in China, the development of production technology and the improvement of installation condition have made a good time for product development.

Despite the wide application of XLPE cables with smooth aluminum bonded sheath, only a few manufacturers master the technical details of design and production due to the strict confidentiality. Introductions about SD cables can be found in IEEE standards, CIGRE TB and literatures, while few about CD cables. The only thing known is that the key procedure in the production of a CD cable is to use a qualified adhesive to bond the metal sheath and plastic outer jacket of proper dimensions, so as to improve the bending performance [3], [4], [8]–[10]. If not, when the cable is bent during production, transportation, and installation, the smooth aluminum layer may wrinkle, craze, and squeeze inward to damage the XLPE insulation, which will cause the degradation of water tightness and corrosion resistance, and finally lead to the premature breakdown of the cable. In order to support the product development and engineering application of HV XLPE cables with smooth aluminum bonded sheath in China, it is essential to carry out a comprehensive and systematic study on bending performance of the bonded sheath, which can also provide reference solutions for other countries with similar demand.

In this paper, by using a finite element software, a three-dimensional simulation model was set up for a cable with smooth aluminum bonded sheath in a four-point bending test, where the cohesive zone model (CZM) was adopted to simulate the mechanical behavior of the adhesive layer. Based on that, the effects of the bonding adhesive, the smooth aluminum, the outer jacket, and the cable specification on the bending performance were discussed, and suggestions on material selection and dimension design of the bonded sheath were proposed. Furthermore, the mechanical strength requirements of the bonding interface were determined after the stress and damage analysis of the adhesive layer, which improved the selection strategy of hot melt adhesive with additional requirements on the shear strength, the softening temperature and aging performance. Finally, a 110 kV XLPE cable with smooth aluminum bonded sheath was designed, produced, and successfully type-tested.

II. DETAILS OF THE SIMULATION

A. SIMULATION MODEL OF THE CABLE

A 110 kV cable, with a conductor of nominal sectional area 800 mm^2 and a XLPE insulation of thickness 16 mm, was taken as the object. Except for the smooth aluminum bonded sheath (smooth aluminum, adhesive layer, and PE jacket), other components were designated with conventional dimensions. Because the research was focused on the mechanical behavior of the bonded sheath, the cable structure could be reasonably simplified to improve the calculation efficiency. The structures from the conductor to the insulation screen was simplified as a XLPE solid cylinder called XLPE cable core. Due to its great elasticity, the buffer layer inside the metal sheath was treated as a combination of an incompressible part and an air layer, and the incompressible part of 0.5 mm was incorporated into the XLPE cable core. The diagram and geometric parameters of the simulation model for the cable are listed in Table 1.

TABLE 1. Simulation model of the 110 kV XLPE cable with the smooth aluminum bonded sheath.

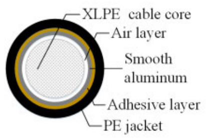
Structure	Thickness (mm)	Diameter (mm)	
XLPE cable core	-	73.0	
Air layer	1.5	76.0	
Smooth aluminum	2.0	80.0	
Adhesive layer	0.2	80.4	
PE jacket	5.0	90.4	

TABLE 2. Mechanical parameters of materials used in the simulation.

<table>
<tr><th colspan="4">Elastic parameters of XLPE, Al and PE</th></tr>
<tr><th>Material</th><th colspan="2">Elastic modulus (MPa)</th><th>Poisson's ratio</th></tr>
<tr><td>XLPE</td><td colspan="2">183</td><td>0.40</td></tr>
<tr><td>Al 1060</td><td colspan="2">68000</td><td>0.33</td></tr>
<tr><td>PE1</td><td colspan="2">877</td><td>0.42</td></tr>
<tr><td>PE2</td><td colspan="2">254</td><td>0.42</td></tr>
<tr><th colspan="4">Parameters of the adhesive in CZM (MPa)</th></tr>
<tr><th>Tensile modulus</th><th>Shear modulus</th><th>Normal strength</th><th>Shear strength</th></tr>
<tr><td>58.4</td><td>20.9</td><td>7.92</td><td>1.93</td></tr>
</table>

B. MATERIAL PARAMETERS

1) XLPE, ALUMINUM, AND POLYETHYLENE

The elastic modulus, Poisson's ratio, and the relationship between yield stress and plastic strain for each material need to be input for the mechanical simulation of the cable [5], [11]. Tensile tests on the dumbbell-shaped specimens of XLPE and two types of polyethylene (PE) (named PE1 and PE2 respectively) were carried out according to ISO 527, by using a CMT-4503 tensile test machine with the operation rate of 100 mm/min [12]. Unless otherwise specified, the outer jacket was made from PE1. PE2 was only used in the comparation with PE1 for the selection of jacket material. A tensile test on the dumbbell-shaped specimens of Al 1060 was carried out according to ISO 6892-1, by using an 858 MTS tensile test machine with the operation rate of 2 mm/min [13].

After the measurement, the elastic parameters of each material were obtained as shown in Table 2. Due to space limitation, the stress-strain relationship was not presented.

2) HOT MELT ADHESIVE

Adhesives are widely used in composite structures. As the weakest part of a composite structure, the bonding interface (adhesive layer) has become a research hotspot. CZM has been generally used to study the mechanical properties of epoxy adhesives in the composite structure of aircraft or automobile [14]–[16]. So far however, little research has been carried out on the hot melt adhesive used for bonded sheaths in cables except for some strength tests, and it is almost unknown about the stress state of the adhesive layer when the cable is bent.

In this paper, CZM is applied for the first time in the adhesive layer of smooth aluminum bonded sheath, whose mechanical response is defined by the bilinear traction-separation law. When the damage initiation criterion is satisfied, as given in (1), the interface begins to break:

$$\left(\frac{\langle t_\mathrm{n}\rangle}{t_\mathrm{n}^0}\right)^2+\left(\frac{t_\mathrm{s}}{t_\mathrm{s}^0}\right)^2+\left(\frac{t_\mathrm{t}}{t_\mathrm{t}^0}\right)^2=1 \tag{1}$$

where t_n, t_s and t_t are the normal and two shear stress components of the adhesive layer respectively, and t_n^0, t_s^0, t_t^0 are the strengths corresponding to above stress components. $< t_\mathrm{n} >$ indicates that a pure normal compressive stress cannot damage the interface. For the bonded sheath, no damage initiation of the adhesive layer is allowed in the engineering applications, so the accumulative damage, the sum of the three items on the left side of (1), must be less than 1.

The normal strength t_n^0 can be measured by a T-peel test according to the method specified in ASTM D1876 [17], the shear strength t_s^0 or t_t^0 can be obtained by a tensile lap-shear test according to ISO 4587 [18], and the tensile modulus can be measured by a tensile test according to ISO 527 [12]. Regarding the hot melt adhesive as an isotropic material, its shear modulus can be obtained by (2):

$$G=\frac{E}{2\left(1+\gamma\right)} \tag{2}$$

where G and E are the shear modulus and tensile modulus, and γ is the Poisson's ratio whose value is generally 0.4 for hot melt adhesive [19]. The material parameters of the adhesive in CZM are listed also in Table 2.

C. FOUR-POINT BENDING TEST

Three-point and four-point bending test are commonly used to evaluate the bending performance of various structures. The former is easy to operate, but affected by the obvious indentation effect. Therefore, a four-point bending model was adopted to study the bending performance of the cable with smooth aluminum bonded sheath, as shown in Fig. 1. The cable was placed on two supports horizontally. When the two indenters moved down at the same time, the cable would bend. Between the two indenters, the cable was theoretically in the ideal bending state. Due to the symmetry, only a quarter of the cable needed to be modeled, as shown in the red dotted box in Fig. 1.

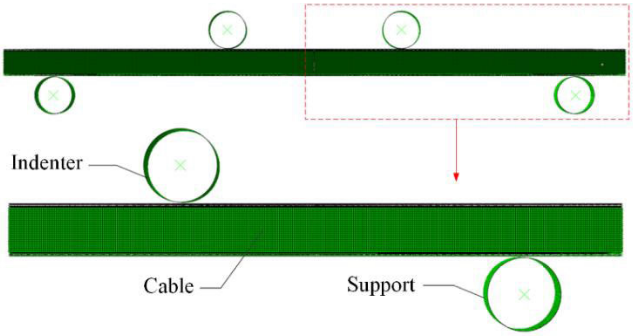


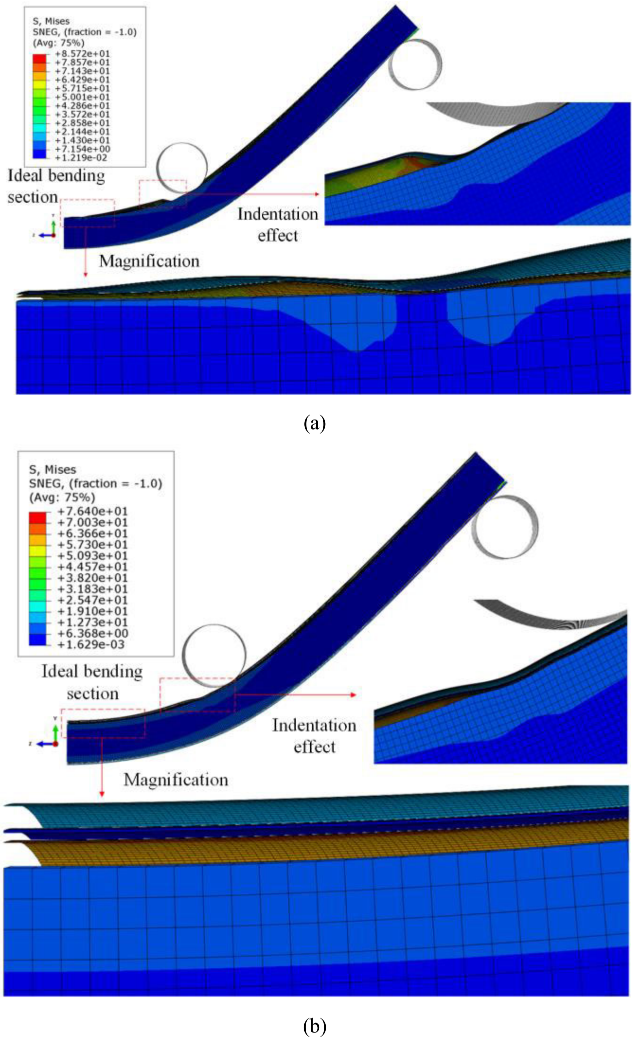
FIGURE 1. Simulation model of the cable in the four-point bending test.

The cable length was 2000 mm, the indenter distance was 560 mm, the support distance was 1680 mm, and the radius of both indenters and supports was 60 mm. The indenters and supports were meshed with rigid elements, the smooth aluminum and PE jacket were meshed with shell elements, the adhesive layer was meshed with cohesive elements, and the XLPE cable core was meshed with solid elements. Tie constraint was applied to the smooth aluminum, adhesive layer and PE jacket in order to form a bonded structure. For all unbonded interfaces, the coefficient of friction was set to 0.15. The supports were fixed. The indenters could move vertically down for 457 mm, which distance was determined under the assumption to wind the cable onto a drum with the radius of 1000 mm.

III. DIFFERENCE BETWEEN BENDING BEHAVIORS OF THE BONDED AND UNBONDED CABLE SHEATHS

In order to understand the wrinkling mechanism of the cable sheath, the simulation was first carried out on a cable with smooth aluminum unbonded sheath. When the cable was bent, the stress distribution was shown in Fig. 2(a). It could be seen that both the smooth aluminum and PE jacket wrinkled in the ideal bending section. Moreover, the local stress concentration in the XLPE cable core caused by the inward squeeze of the aluminum was a potential hazard to the insulation. The analysis showed that in this cable, the aluminum and PE jacket endured the bending force respectively. During cable bending, the aluminum on the compressive side could not resist the bending deformation due to insufficient stiffness, began to collapse inward, and squeezed the buffer layer. When it touched the XLPE cable core, the aluminum began to wrinkle, and then followed by the wrinkling of PE jacket.

While for the cable with a bonded sheath, under the same bending condition, the stress distribution was shown in Fig. 2(b). As the smooth aluminum and PE jacket were bonded together by the hot melt adhesive, the effective thickness to withstand tangential compressive stress was increased, and the ability of the composite structure to resist bending deformation was enhanced [20]. That was why the smooth aluminum did not wrinkle and squeeze the inside XLPE cable core. In fact, even the indentation effect was obviously improved, as in Fig. 2(b).



(a)

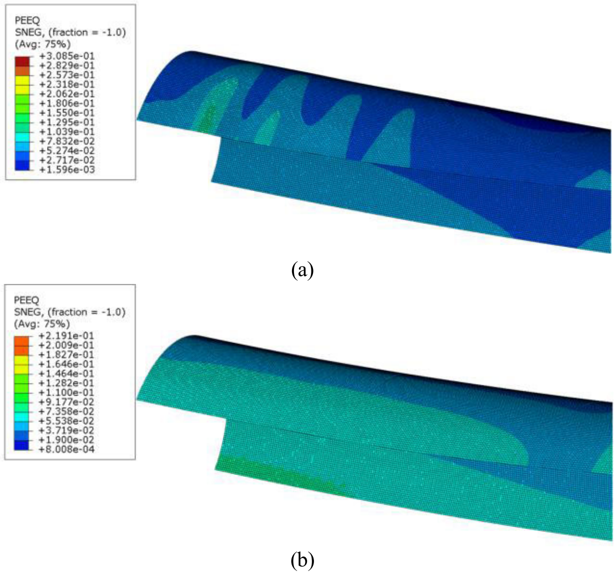
(b)

FIGURE 2. **The stress distribution of the cable with a smooth aluminum sheath: (a) unbonded, and (b) bonded.**

The equivalent plastic strain can be used to describe the deformation degree of the aluminum layer when the cable is bent [21]. Deformation degree of the aluminum layer was analyzed on the compressive side because it was more prone to damage than the tensile side under the specified bending radius. For the unbonded and bonded sheaths, the distributions of equivalent plastic strain of the aluminum layer were shown in Fig. 3.

For the unbonded sheath, the equivalent plastic strain of the aluminum was corrugated, with a maximum value of 0.118 at the top of the wrinkle. While for the bonded sheath, the distribution of equivalent plastic strain was quite even, with a maximum value of 0.073, 38.1 % lower than the former. In other words, the solid bonding could significantly reduce the plastic deformation of the aluminum layer and make the strain distribution even to avoid the wrinkling.

During the trial production, it was found that if the PE jacket was extruded after the asphalt had been coated on the aluminum instead of hot melt adhesive, the wrinkling of the jacket was observed when the cable was wound on the drum.



(a)

(b)

FIGURE 3. **The strain distribution on the smooth aluminum: (a) unbonded, and (b) bonded with the PE jacket.**

After the jacket was stripped, obvious wrinkles appeared on the compressive side of the smooth aluminum, as shown in Fig. 4. It confirmed the importance of solid bonding for the smooth aluminum bonded sheath.

IV. DESIGN OF SMOOTH ALUMINUM BONDED SHEATHS

According to IEEE Std 635, for a smooth aluminum sheathed cable with an external diameter <19 mm, 19-38 mm, or >38 mm, the bending radius shall not be less than 10, 12, and 15 times the external diameter of the cable respectively [22]. In IEEE Std 1142 it is recommended that the minimum bending radius of a HV cable with bonded sheath should be 8-16 times the cable diameter, depending on the cable diameter and insulation thickness [4]. This indicates not only the worse bending performance of the smooth bonded sheath compared with corrugated sheath, but also the influence of the cable dimension needing to be considered.

The structural design of HV XLPE cables with corrugated aluminum sheaths has been standardized in China. For example, the nominal thickness of aluminum sheath or plastic jacket is clearly specified for XLPE cables with different rated voltages and conductor cross sections. However, the influence of the material and dimensional parameters on the bending performance of smooth aluminum bonded sheath is not clear yet, so the applicability of such recommended parameters remains to be studied. Thus, the following research focused on the key design factors of smooth aluminum bonded sheaths.

A. THICKNESS OF THE SMOOTH ALUMINUM

With the thickness of PE jacket set to 0-5 mm, while other parameters the same as in Table 1, the deformation of smooth aluminum when the cable was bent was studied, and the

TABLE 3. **Effect of PE jacket thickness on the deformation of smooth aluminum bonded sheath.**

Thickness of PE jacket (mm)	Wrinkling of aluminum layer	Maximum equivalent plastic strain
0.0	Yes	0.211
1.0	Yes	0.088
2.0	Yes	0.082
3.0	Yes	0.080
4.0	No	0.075
5.0	No	0.073

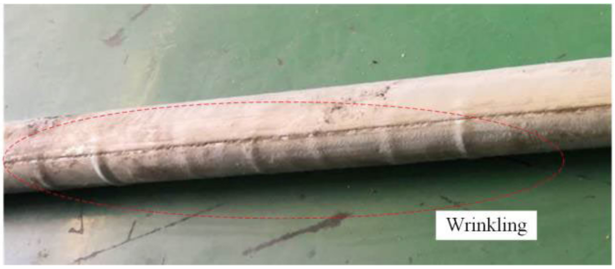
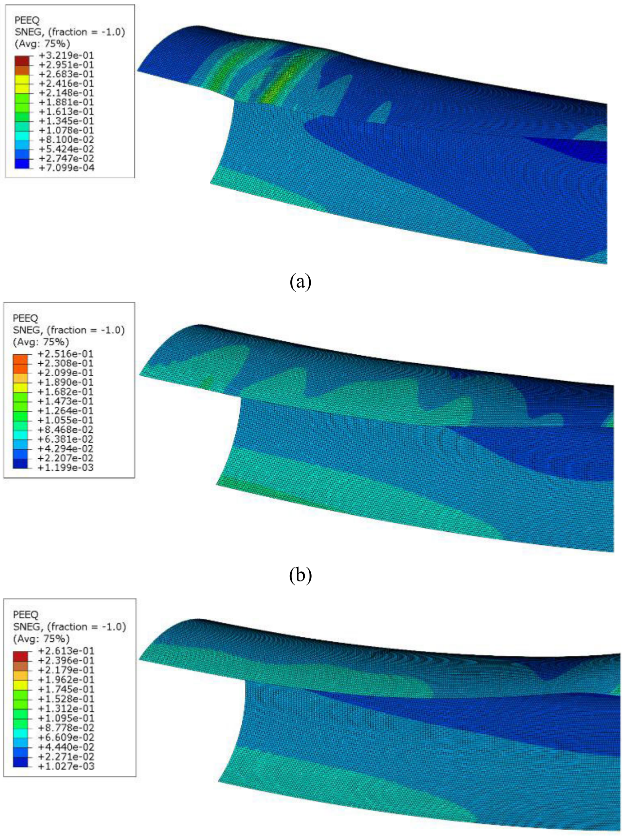


FIGURE 4. **Wrinkling of the smooth aluminum sheath unbonded.**



(a)

(b)

(c)

FIGURE 5. **Strain distributions of smooth aluminum layer when bonded to PE jacket of: (a) 0 mm, (b) 1 mm, and (c) 4 mm.**

results were shown in Table 3. It could be seen that with the increase of jacket thickness, the maximum equivalent plastic strain on the compressive side of aluminum layer decreased. Especially, when the jacket thickness increased from 0 to 1 mm, the strain decreased from 0.211 to 0.088, with a decline of about 60 %. Then, as the jacket thickness continued to increase, the decrease of strain gradually slowed down. In addition, when the jacket thickness was less than 4 mm, due to the insufficient bending stiffness of the bonded sheath, the wrinkling of aluminum sheath was observed in the simulation.

For the cables with the PE jacket of 0, 1, and 4 mm, the distributions of equivalent plastic strain of smooth aluminum layer in the ideal bending section were shown in Fig. 5. With the increase of PE jacket thickness, the strain distribution on the compressive side of the aluminum layer tended to be even, indicating a reduced risk of wrinkling, which was attributed to the higher bending resistance of the thicker bonded sheath. In the absence of PE jacket, the smooth aluminum was prone to wrinkle due to the insufficient thickness of itself, which could be seen apparently by the strain distribution in Fig. 5(a).

Two suggestions can be given from above analysis. Firstly, in cable manufacturing, the processing of smooth aluminum, the coating of hot melt adhesive and the extruding of PE jacket should be completed in a continuous production process, and semi-finished cables with only the smooth aluminum are not allowed to be wound on a drum for either storage or transportation. This is different from cables with corrugated aluminum sheaths. Secondly, since the bending resistance of the bonded sheath depends on the total thickness, a very thick aluminum layer is unnecessary. It is a reasonable way to design the aluminum thickness according to the requirement of short circuit capacity, and to fulfill the requirement of bending performance by extra thicken the outer jacket. The recommended thickness for corrugated aluminum in Chinese standards is 2.0-2.3 mm for 110 kV cables, 2.4-2.8 mm for 220 kV cables, and 2.9-3.3 mm for 500 kV cables [23]–[25]. These values can be adopted for smooth aluminum sheaths.

B. MATERIAL OF PE JACKET

The common materials used for non-metallic jackets are PE, polyvinyl chloride (PVC) and polypropylene (PP). In this paper, two types of PE were adopted as examples for comparison, which had different mechanical parameters as shown in Table 2. In this section, PE2 was used instead of PE1 as the jacket material, with other conditions unchanged, and the bending behavior of the 110 kV cable in Table 1 was simulated and analyzed. The results showed that when PE2 was used, although the aluminum layer did not wrinkle, the equivalent plastic strain was less evenly distributed, and the maximum strain was 0.085, 16.4 % higher than that in PE1 case. The reason was found to be the much lower elastic modulus of PE2, which was 254 MPa, only 29.0 % of PE1, and the lower maximum equivalent stress in the PE2 jacket, which was 13.5 MPa, 85 % of that in PE1. In conclusion, within the deformation range of the jacket caused by cable bending, the lower stiffness of PE2 resulted in the decreased bending

TABLE 4. Geometric parameters for simulation models of cables with different specifications.

Structural dimensions (mm)	110×1600-2.0/2.3	220×2500-2.8	500×2500-3.3
Diameter of XLPE cable core	83.0	119.0	133.0
Thickness of air layer	1.5	3.0	3.5
Thickness of aluminum	2.0/2.3	2.8	3.3
Thickness of adhesive	0.2	0.2	0.2
Thickness of PE jacket	5.0	5.0	6.0

TABLE 5. Bending deformation of cables with different specifications.

Cable specification	Inner diameter of aluminum sheath (mm)	Wrinkling of aluminum sheath	Maximum equivalent plastic strain
110×800-2.0	76	No	0.073
110×1600-2.0/2.3	86	No	0.085/0.084
220×2500-2.8	125	No	0.103
500×2500-3.3	140	No	0.115

resistance of the bonded sheath, increased deformation of the aluminum layer, and poorer uniformity of strain distribution.

Based on above analysis, it is required that the elastic modulus of the jacket material should be no less than 800 MPa in order to ensure the bending resistance of the bonded sheath. Otherwise, it is necessary to design a thicker jacket, which may lead to the increased diameter and weight of the cable. Of course, the improvement of bending stiffness may increase the difficulty of cable installation, which should also be taken into consideration.

C. THICKNESS OF PE JACKET

According to Chinese standards, with the increase of the rated voltage and the conductor cross section, the thicknesses of corrugated aluminum sheath and outer jacket should be increased [23]–[25]. This shows the influence of the cable specification on the bending performance and thus on the thickness design of the sheath. XLPE cables of 110, 220, and 500 kV with the maximum conductor cross section in common use were chosen as the objects, and the dimensional parameters of the simulation models for them were shown in Table 4. The cables were labelled in the way of rated voltage × conductor cross sectional area-smooth aluminum thickness. For example, 110 × 1600-2.0/2.3 represented a 110 kV cable with a conductor of 1600 mm^2 and an aluminum layer of 2.0 (or 2.3) mm. For 220 and 500 kV cable with a conductor of 2500 mm^2, since the thermal expansion of XLPE insulation was more significant, the compressible thicknesses of the buffer layer was increased to 3.0 and 3.5 mm.

After the simulation on cables with different specifications, the deformation and maximum equivalent plastic strain of the aluminum sheaths under the same bending condition were obtained, as shown in Table 5, among which the cable of 110 × 800-2.0 was the one discussed in former sections.

It can be seen from Table 5 that for the 110 kV cable, when the inner diameter of aluminum sheath increased from 76 to 86 mm due to different conductor size, the maximum equivalent plastic strain of the aluminum increased significantly, which did not decrease obviously even when the thickness of aluminum layer increased from 2 to 2.3 mm. When the rated voltage increased from 110 to 500 kV and the conductor cross section increased from 800 to 2500 mm^2, the inner diameter of aluminum sheath was enlarged by 13.2, 64.5, and 84.2 %. Although the thickness of aluminum layer increased by 15, 40, and 65 %, from initial 2 mm to final 3.3mm, the maximum equivalent plastic strain still increased by 15.1, 41.1, and 57.5 %. This indicated that the enlargement of the inner diameter has a great impact on the bending deformation of the smooth aluminum sheath, which could not be offset completely by the thickening of the aluminum layer at the same rate of change.

According to the simulation results, the cables of 110 × 1600-2.0/2.3 and 500 × 2500-3.3 could meet the requirement of bending performance. However, for the cable of 220 × 2500-2.8 with an outer jacket of 5 mm, the equivalent plastic strain showed an uneven distribution which indicated a great risk of wrinkling. After increasing the jacket thickness to 6 mm, this situation was improved with the maximum equivalent plastic strain 7.8 % lower. In summary, for HV cables with large cross sections, the smooth aluminum may not be enough to offset the effect of the inner diameter enlargement, so a thicker outer jacket needs to be designed for a sufficient bending resistance of the bonded sheath.

It is suggested that for a cable with the bonded sheath, if the smooth aluminum is designed with the thickness value recommended in section A, the jacket thickness can be designed as follows: 4-5 mm for 110 kV cables, 5-6 mm for 220 kV cables, 6 mm and above for 500 kV cables.

D. REQUIREMENTS OF HOT MELT ADHESIVES

1) DAMAGE ANALYSIS OF THE ADHESIVE LAYER

The stress state of the adhesive layer in the bonded sheath of the bent cable can be used to determine the strength requirements of the bonding interface. When the adhesive layer is deformed, the internal stress can be divided into three components of the normal stress, circumferential shear stress and axial shear stress in the cylindrical coordinate system.

When the tensile modulus of the adhesive layer was set to 25, 58.4, 100, and 200 MPa respectively while other conditions remained unchanged, four-point bending simulations were carried out. The maximum values of the three stress components in the adhesive layer were obtained and listed in Table 6. The maximum value of each stress component increased slightly with the increase of tensile modulus. In addition, the circumferential shear stress was always significantly higher than the other two stresses, while the normal stress was the lowest.

The damage initiation criterion in CZM, equation (1), can be adopted to evaluate whether the bonding interface of the bent cable is damaged. After the values of accumulative

TABLE 6. Maximum values of the three stress components in the adhesive layer with different tensile modulus.

Tensile modulus (MPa)	Normal stress (MPa)	Circumferential shear stress (MPa)	Axial shear stress (MPa)
25.0	0.65	1.65	0.86
58.4	0.70	1.68	0.99
100.0	0.76	1.70	1.04
200.0	0.84	1.75	1.10

damage were calculated according to (1) at many positions of the adhesive layer (whose tensile modulus was 58.4 MPa), it was found that each one was less than 1. Meanwhile, the maximum accumulative damage appeared at the place where the circumferential shear stress was the largest, the normal stress was compressive, and the axial shear stress was only 13.1 % of the circumferential shear stress. Thus, although no damage occurred yet in the bonding interface when the cable was bent, the circumferential shear stress would be the dominant one to initiate the potential damage.

2) BOND STRENGTH OF THE ADHESIVE LAYER

Now different requirement can be found for the peel strength of the bonding interface in smooth aluminum bonded sheath, such as 1.5 N/mm in CIGRE TB 446, 1.75 N/mm in IEEE Std 1142, and 0.5 N/mm in IEC 60840 and IEC 62067, but none of specifications mentions the shear strength [3], [4], [26], [27]. In fact, however, the bond strength of adhesives was evaluated by cable manufactures through both the peel strength and shear strength [28], [29]. Moreover, the circumferential shear stress played a dominant role in the damage of the adhesive layer, as discussed in part 1), so it was necessary to supplement the requirement of shear strength.

For the peel strength of the adhesive, the value of 0.5 N/mm specified in IEC standards was used, which was converted to 2.5 MPa based on the thickness of 0.2 mm in this paper. This was much greater than the maximum normal stress in Table 6. For the shear strength, considering the maximum circumferential shear stress 1.75 MPa in Table 6, the value of 1.8 MPa was preliminarily selected. Then, the maximum accumulative damage in the adhesive layer with four different tensile moduli was calculated and the results were shown in Table 7. Since all the values of accumulative damage were less than 1, it meant no damage would occur in the adhesive layer of the cable under the specified bending radius.

By a safety margin of 10 %, the shear strength requirement was finally determined as 2.0 MPa. Since the tensile modulus was barely higher than 200 MPa, according to the results in Table 7, the requirement of the shear strength no less than 2.0 MPa and the peel strength no less than 0.5 N/mm would be appropriate for hot melt adhesive used in the bonded sheath. The test method of peel and shear strength was recommended in ASTM D1876 and ISO 4587 [17], [18].

TABLE 7. Maximum accumulative damage in the adhesive layer with specified parameters.

Peel strength (N/mm)			Shear strength (MPa)	
0.5			1.8	
Tensile modulus (MPa)	Normal stress (MPa)	Circumferential shear stress (MPa)	Axial shear stress (MPa)	Maximum accumulative Damage
25.0	-0.43	1.65	-0.01	0.84
58.4	-0.43	1.68	-0.22	0.89
100.0	-0.41	1.70	-0.05	0.89
200.0	-0.44	1.75	-0.08	0.95

TABLE 8. Effect of the tensile modulus of the hot melt adhesive on the bending deformation of the smooth aluminum sheath.

Tensile modulus (MPa)	Wrinkling of the bonded sheath	Maximum equivalent plastic strain
25.0	No	0.0731
58.4	No	0.0727
100.0	No	0.0721
200.0	No	0.0718

3) TENSILE MODULUS OF THE ADHESIVE LAYER

The effect of the tensile modulus of the hot melt adhesive on the bending deformation of smooth aluminum sheath was discussed below.

According to data in Table 8, when the tensile modulus of the adhesive increased from 25 to 200 MPa, the maximum equivalent plastic strain of the aluminum sheath decreased but with a very small range, no more than 2 %. The adhesive layer was thin, contributing little to the bending stiffness of the bonded sheath, and the bending resistance of the bonded sheath was mainly dominated by the smooth aluminum and outer jacket. Since it was a wide range of 25-200 MPa to most hot melt adhesives, there was no need to specify the requirement on the tensile modulus.

4) AGING PROPERTIES OF HOT MELT ADHESIVES

It is pointed out in IEEE Std 1142 that during the product development and test, the peel strength of the bonded sheath should be tested before and after aging (such as water, mechanical, and thermal cycles) to ensure the long-term reliability of the bonding interface [4].

In this paper, the aging properties of two hot melt adhesives were studied. The specimens were taken from two different trial samples of smooth aluminum bonded sheath, named Sample A and B, and the aging process was composed of 20 heating cycles. In each cycle, the specimens were heated to 80 °C, maintained for 8 hours, and then cooled down naturally for 16 hours. Finally, the peel and shear strength were measured for the specimens before and after aging.

For Sample A, the measured values of peel strength and shear strength were higher than 20 N/mm and 3 MPa respectively, no matter before and after aging. In fact, the bonding interface was so firm that the damage (both peeling and fracture) of the specimens during the test occurred in the PE

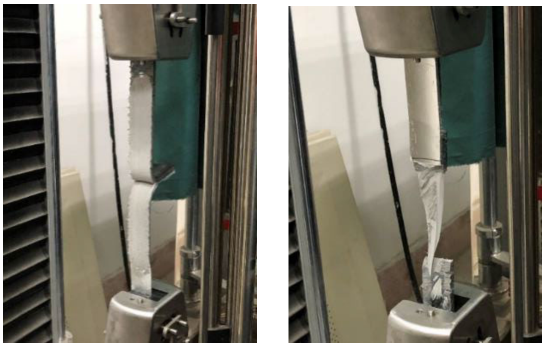


FIGURE 6. The damage of specimens taken from Sample A in: (a) peel strength test and (b) shear strength test.

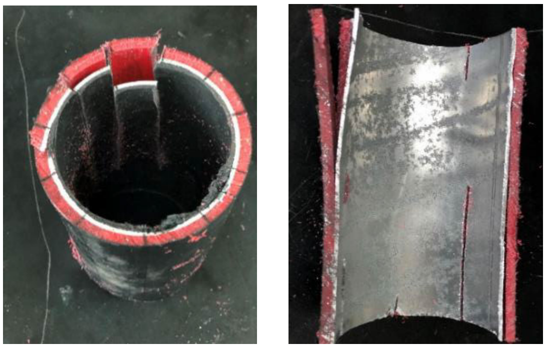


FIGURE 7. Interface delamination of Sample B after aging.

layer instead of the adhesive layer, as shown in Fig. 6. At the same time, no sign of performance degradation was observed in specimens after aging.

The situation was quite different for Sample B. The performance of original specimens was qualified. While after aging, delamination of bonding interface occurred during the cutting process of Sample B for specimen preparation, as shown in Fig. 7. This might be due to the low softening temperature of the adhesive or its property degradation during the thermal cycles, which caused the loss of the bonding ability to the interface. Obviously, this adhesive is not a good candidate for the bonded sheath.

Combining the test results above with the actual operation condition of HV XLPE cables, the first requirement suggested for the hot melt adhesive will be a softening temperature higher than 80 °C, which is the expected maximum temperature of the metal sheath when the conductor temperature is 90 °C for a full load cable [3]. Besides, the performance of the adhesive should be checked through a certain artificial aging scheme in the material selection stage. More importantly, it is recommended to perform inspection and testing on specimens taken from smooth aluminum bonded sheaths of cables after the type test or prequalification test.

V. PRODUCTION AND TYPE TEST OF THE CABLE

The geometric parameters in Table 1 have been testified for the applicability, so a 110 kV XLPE cable was produced based on them, with materials (XLPE, Al 1060, PE1, and the hot melt adhesive) as those listed in Table 2. When the cable was wound on the drum, the surface of the jacket was smooth and flat without any wrinkles, as shown in Fig. 8.

FIGURE 8. The 110 kV XLPE cable with smooth aluminum bonded sheath.

Then the cable was sent to be type tested according to the requirements of IEC 60840 [26]. During the mechanical pretreatment, the cable sample was wound on and off a test reel with a diameter of 3600 mm three times, with no wrinkling and delamination of the bonded sheath observed. Then the one-month test procedure, including thermal and electrical aging cycles, was conducted successfully. After the test, the cable was inspected for its integrity. The surface of the bonded sheath was smooth and flat, without any structural deformation or damage.

VI. CONCLUSION

In this paper, the bending performance of the cable with smooth aluminum bonded sheath was studied, and based on that, suggestions on material selection and parameter design of the bonded sheath were proposed.

An integral composite structure is formed by bonding the smooth aluminum with the outer jacket, which provides an enhanced bending resistance and prevents the wrinkling. The bending resistance depends on the total thickness of the bonded sheath, among which the thickness of aluminum can be designed by the short circuit capacity requirement, with the rest complemented by the outer jacket.

The elastic modulus of the outer jacket should be no less than 800 MPa, and the recommended thickness are as follows: 4-5 mm for 110 kV cables, 5-6 mm for 220 kV cables, and no less than 6 mm for 500 kV cables. For the cable with a higher rated voltage or a larger conductor cross section, the bending performance needs to be strengthened.

The requirements of the hot melt adhesive include the peel strength no less than 0.5 N/mm as specified in IEC standards, the shear strength no less than 2.0 MPa, and the softening temperature no less than 80 °C.

The validity of this study is basically verified by the production and type test of the 110 kV XLPE cable with smooth aluminum bonded sheath.

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