IMPROVING THE ABRASION RESISTANCE OF INSULATED WIRE USING COEXTRUSION TECHNOLOGY

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ABSTRACT

An experimental analysis is presented which shows that poor needle abrasion performance of thin wall insulated cables is largely due to a tearing mechanism which ultimately results in rapid wear. The data presented indicates that prolonging the onset of the tearing mechanism using coextrusion technology leads to significant improvement in abrasion performance. This is because of the superior fatigue crack growth performance of the skin layer. Even though the present study deals primarily with a high density polyethylene (HDPE) skin over a crosslinked polyethylene (XLPE) insulation, the coextrusion technology developed here is applicable to other wire and cable systems which exhibit poor abrasion performance.

An analysis is also described which demonstrates that needle abrasion performance and hence the mode of failure can be predicted from measurements of the compliance, tensile stress and fracture toughness of the resins. These parameters influence the size of the damage zone that results from contact between the test needle, the insulation and the wire.

1. INTRODUCTION

Many studies have been conducted on wire and cable abrasion, especially in the automotive and offshore oil industries. In the offshore industry, cables must resist damage from inspection tools as these are lowered into wells. In the automotive industry, resistance to abrasion is required mainly for handling purposes while cables are being installed or assembled into harnesses. In order to design against failure that directly or indirectly results from abrasion damage to wire insulation, it is important to understand the abrasion mechanism involved in each specific system. This normally involves various mechanical tests which attempt to simulate field conditions such as scraping of the cable against sharp objects. Two tests used for this are the needle and sandpaper abrasion tests.

Standard wire dimensions used in automotive under the hood applications consist of a 22 AWG wire with an XLPE insulation thickness of 16 mils (0.41 mm). Constructions such as these satisfy all the necessary United States automotive specifications where they have been successfully used for over 20 years. These specifications include sandpaper abrasion tests, where XLPE constructions meet all the required specifications. However, for certain foreign markets, abrasion performance is determined by use of the needle abrasion test, the requirements of which are not always satisfied by XLPE constructions.

In the present paper we are concerned with developing a system which satisfies needle abrasion requirements for an under the hood automotive application. While the needle abrasion performance of any given wire and cable system can be improved by increasing the insulation thickness, cost, weight and space limitations usually prevent such an approach. In the present paper, a study of needle abrasion mechanisms for XLPE and HDPE wires has been carried out in order to explore the possibility of developing a co-extruded system which offers improved needle abrasion performance for a given insulation thickness without sacrificing performance.

A procedure is also presented which can be used to predict the abrasion performance of cables made from any given polymeric material so long as some basic mechanical properties of the material are known.

2. EXPERIMENTAL

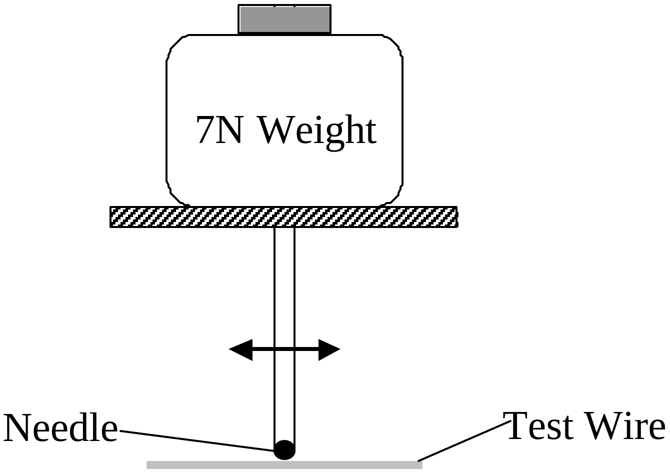
The generic materials involved in the present study are shown in Table 1. Both resins shown in the table are produced by Equistar Chemicals, LP and variations of these are used in telecommunications and automotive wire and cable applications. Sample A is a high density polyethylene resin, with low shrink back characteristics, developed for use as primary insulation for telephone singles. Sample B is a non-halogenated flame retardant crosslinked polyethylene compound formulated for use as insulation in low voltage automotive wire and cable. The XLPE sample contains an in-organic non-halogenated flame retardant filler. Both resins can be processed using conventional extruders, however, for Sample B, a continuous vulcanization tube is required. For Samples A and B, processing melt temperatures should be approximately 253 °C and 122 °C respectively.

Needle abrasion tests are carried out on a Tocksfors Verstads AB (TVAB) needle abrader with a needle diameter of 45 mils (1.14 mm), Figure 1. As shown in Figure 1, the longitudinal axis of the needle is perpendicular to that of the test wire. Testing is carried out by first clamping the test wire down, after which the needle oscillates back and forth over the insulation at a frequency of 60 Hz and an amplitude of 25.4 mm. The piano wire applies a 7 N load on the insulation as shown in Figure 1. The wire's resistance to abrasion is determined be the number of strokes that are needed before the wire insulation has been worn away. The equipment stops in this position automatically as there will be an electrical short circuit between the needle and the wire's conductor. Current requirements for the needle abrasion test call for greater than 200 strokes prior to failure.

Table 1. Mechanical properties of resins used in the present study.

	Resin	
Property	**Sample A**	**Sample B**
Density, g/cm3	0.943	1.4
Tensile Strength, MPa (psi)	21.7 (3150)	20.7 (3000)
Elongation, %	660	220
Stiffness, MPa (psi)	593 (86,000)	218 (31,600)
Compliance, MPa^{-1} (psi^{-1})	1.68×10^{-3} (1.16×10^{-5})	4.59×10^{-3} (3.16×10^{-5})

Figure 1. Schematic diagram of TVAB needle abrader.



All wires used in the current study were produced at line speeds of 1800 fpm on a commercial wire line. For the coextruded sample, a two step process was used which first involved running a 10 mil (0.25 mm) thick 22 AWG single layer XLPE construction on a continuous vulcanization line. The XLPE wire was then reeled and subsequently re-run in a second step where the 3 mil (0.08 mm) thick HDPE layer was extruded over it.

3. RESULTS AND DISCUSSION

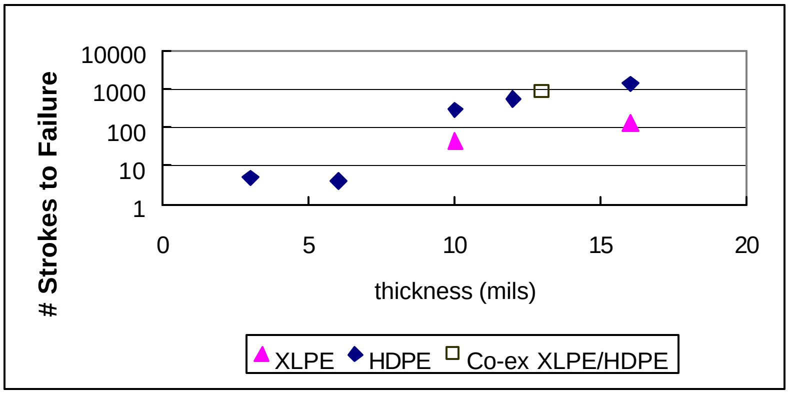
Needle abrasion results for wire samples made from XLPE, HDPE and a co-extruded construction of both are shown in Figure 2. The following interesting observations can be made from the results presented in Figure 2:

a) The 16 mil (0.41 mm) thick HDPE sample fails after 1363 strokes, far exceeding the requirement of 200 strokes. Therefore, for the same insulation thickness, HDPE exhibits far superior needle abrasion performance than the corresponding XLPE sample.

b) The co-extruded construction of 13 mil (0.33) overall insulation thickness fails after 843 strokes, satisfying the 200 stroke requirement; and in fact does so at a smaller insulation thickness. As mentioned in Section 2, the multi-layer construction consists of a 10 mil (0.25 mm) XLPE inner layer and a 3 mil (0.08 mm) thick HDPE outer layer. It is worth noting that a 10 mil (0.25 mm) thick XLPE sample fails after 45 strokes and a 3 mil (0.08 mm) HDPE sample fails after only 5 strokes. The combined system is therefore more effective than each of the individual constructions on their own.

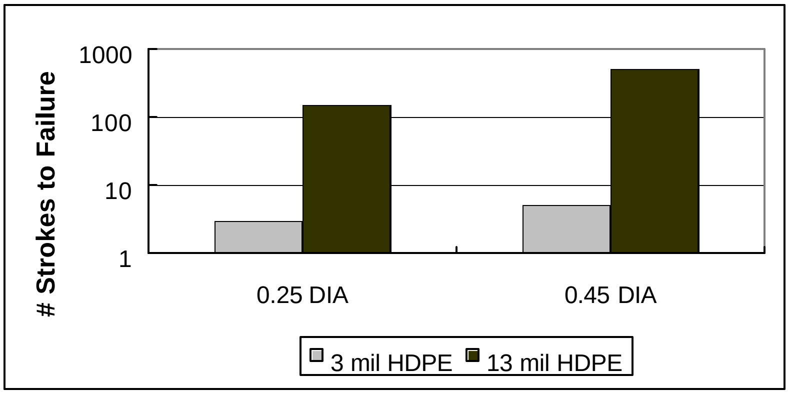
c) As expected, abrasion performance depends on insulation thickness, with the thinner wall thicknesses exhibiting inferior performance.

Figure 2. Needle abrasion performance of XLPE, HDPE and co-extruded XLPE/HDPE insulated wires.



An explanation for the superior performance of the 16 mil (0.41 mm) HDPE construction over the XLPE construction of the same insulation thickness in part lies in the difference in compliance between the two resins. As shown in Table 1, the HDPE resin is of lower compliance, suggesting that during testing, the needle penetrates further into the XLPE insulation since both are subjected to the same normal force of 7 N. Therefore, as the needle oscillates back and forth, it causes more damage in the insulation made from XLPE. By this token, using a needle of smaller diameter should exacerbate the resulting damage and speed up the rate of abrasion. Since the normal force will be the same for both needles, the higher stresses on the insulation from the thinner needle causes higher levels of strain, higher penetration into the insulation and therefore more damage. Data obtained for a thinner needle, showing the higher rate of abrasion are shown in Figure 3. The compliance of the wire therefore plays a significant role in the abrasion mechanism.

Figure 3. HDPE abrasion data for 0.25 (0.00635) and 0.45 (0.114) mil (mm) diameter needles



A further explanation for the superior performance of the HDPE insulation over that made from XLPE is evident from the abrasion mechanism associated with both. Scanning electron microscopy (SEM) photomicrographs of the abraded surfaces of a 16 mil (0.41 mm) XLPE sample and a HDPE sample of the same insulation thickness are shown in Figures 4 and 5.

The photomicrographs shown in Figures 4 and 5 are taken after 5 strokes in the needle abrasion test. As seen, both wires exhibit the typical ridge pattern associated with severe wear conditions in polymeric materials [1]. This is characterized by a series of ridges that develop at right angles to the sliding direction. As the needle oscillates back and forth over the insulation, abrasion proceeds mainly by crack propagation that occurs at the base of the ridge. During this process, fracture processes on the scale of microns take place, involving the detachment of relatively large particles from the ridge edges. In highly filled compounds, the detached particles tend to cause further wear by virtue of their abrasive characteristics [2].

Therefore materials that possess good resistance to crack propagation are likely to exhibit good needle abrasion. As a result, even though both XLPE and HDPE exhibit similar abrasion patterns (at least in the initial stages of the test), the superior fatigue crack growth performance of HDPE over the highly filled XLPE leads to the better needle abrasion performance.

SEM photomicrographs of the co-extruded sample is shown in Figure 6 after 5 strokes. Unlike the single layer constructions, the co-extruded sample exhibits no evident surface damage after 5 strokes. The use of the HDPE skin over the XLPE insulation therefore prolongs the onset of surface damage to the insulation leading to the observed improvement in abrasion performance. Although the mechanism that exists in the multi-layer constructions is not fully understood, it is thought to be related to the damage zone that exists at the outer and inner surfaces of the insulation [3].

Figure 4. SEM photomicrograph of a 16 mil (0.41 mm) thick XLPE 22 AWG wire after 5 strokes in the needle abrasion test.

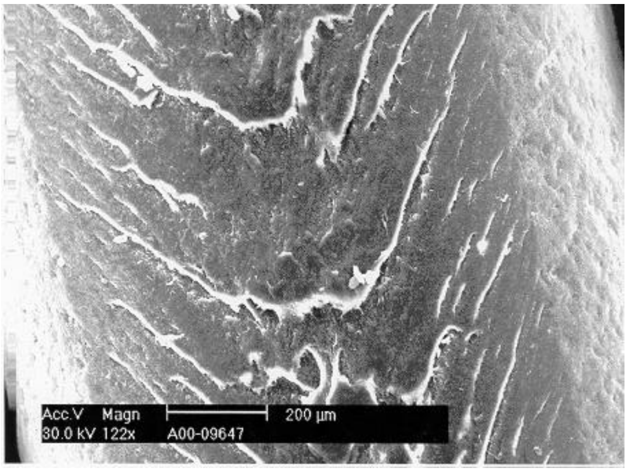


Figure 5. SEM photomicrograph of a 16 mil (0.41 mm) thick HDPE 22 AWG wire after 5 strokes in the needle abrasion test.

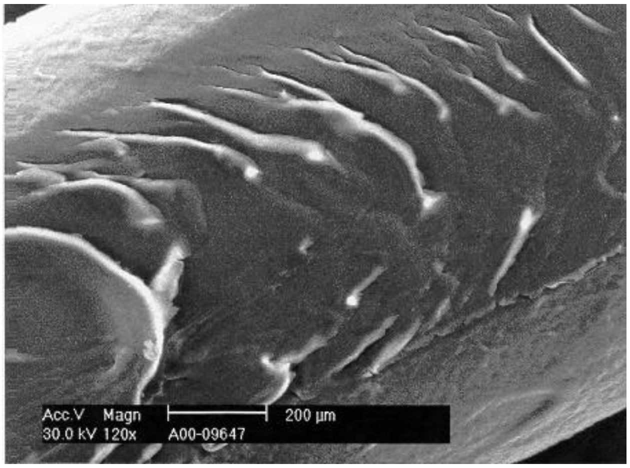
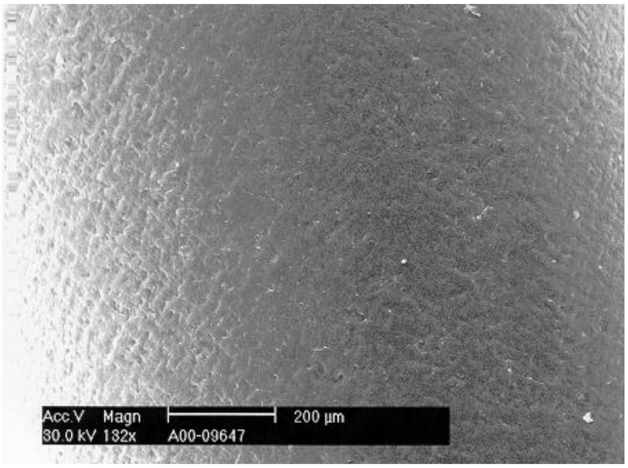


Figure 6. SEM photomicrograph of a 13 mil (0.33 mm) thick XLPE/HDPE 22 AWG co-extruded wire after 5 strokes in the needle abrasion test.



During needle abrasion tests, the normal force imposed on the insulation creates a damage zone of yielded material at the needle/insulation interface. This normal force also creates a second damage zone at the interface between the wire conductor and the inner surface of the insulation (Figure 7). As the thickness of the insulation is reduced, the inner and outer damage zones overlap. As a result the bulk of material between the conductor and test wire is past its yield point suggesting a much lower modulus and therefore a much higher compliance. This results in deeper penetration of the needle into the insulation which leads to more severe damage. Clearly, for insulation thicknesses up to a certain value, the inner and outer damage zones will overlap, resulting in severe abrasion damage and subsequently high abrasion rates. This is confirmed by the data shown in Figure 8, where the thinner samples investigated in the present work exhibit abrasion rates at least an order of magnitude higher than the thicker samples. It is interesting to note that by extruding a HDPE skin over XLPE, the abrasion rate of the co-extruded construction is similar to that of a single layer HDPE construction of comparable thickness.

Figure 7. **Damage zone on insulation of two different thicknesses.**

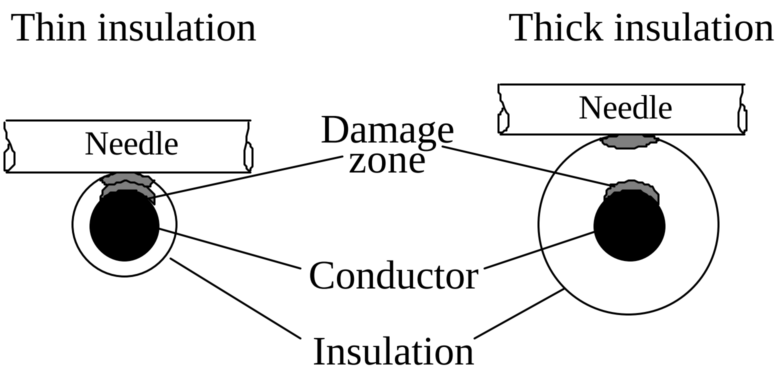
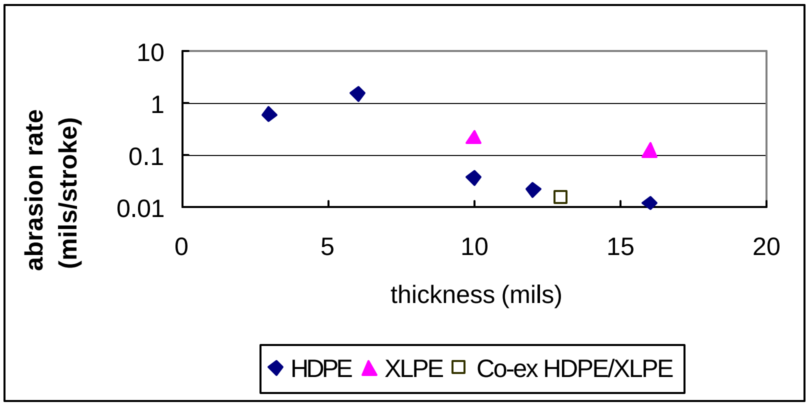


Figure 8. **Abrasion rate of XLPE, HDPE and co-extruded XLPE/HDPE insulated wires.**



A precise calculation of the size of the damage zone in the needle abrasion test configuration is difficult and requires numerical finite element or finite volume techniques. However, for comparing the relative performance of materials, the plastic zone size serves as an indication of the damage zone size. The plastic zone, defined as the region around the tip of a crack where the material has undergone yielding can be predicted from [3]:

$$R_p = \frac{1}{2p}\left(\frac{EG_c}{s_y^2}\right) \qquad (1)$$

In Equation (1), R_p is the plastic zone size and E, G_c and σ_y are the Young's modulus, energy release rate and yield stress of the material respectively. The energy release rate is a measure of the fracture toughness of the material. The parameter, R_p, therefore lumps into a single numerical value the compliance of the material, its toughness and its yield stress. The combined effect of these mechanical properties on needle abrasion can therefore be investigated by simply studying the effect of plastic zone size on needle abrasion performance.

Needle abrasion data has been obtained for a range of commonly available polymers for which literature values for E, G_c and σ_y are readily available [4]. Figure 9 shows the calculated plastic zone size for the polymers investigated and Figure 10 shows the corresponding needle abrasion results for 10 mil (0.25 mm) thick insulation over 22 AWG wire. It is clear that polymers such as PVC, polypropylene and nylon, with the smallest plastic zone sizes exhibit the best needle abrasion performance. It therefore appears that needle abrasion performance can be predicted by a single parameter, R_p, which takes into account the compliance of the material, its toughness and its yield stress. This is in agreement with the results obtained in the present work which suggest that material compliance and toughness do influence the needle abrasion performance of wires insulated with XLPE and HDPE.

Results such as those presented in Figures 9 and 10 have been generated for each of the mechanical properties listed above and attempts have been made to relate each of these to needle abrasion. The results indicate that a relationship between needle abrasion and each individual mechanical property does exist. However, it appears that the best correlation is obtained when all of the above mechanical properties are lumped into the plastic zone term.

Figure 9. Needle abrasion performance of some common polymers.

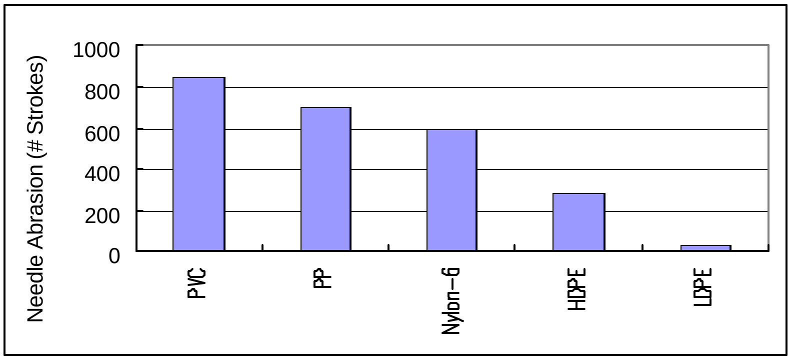
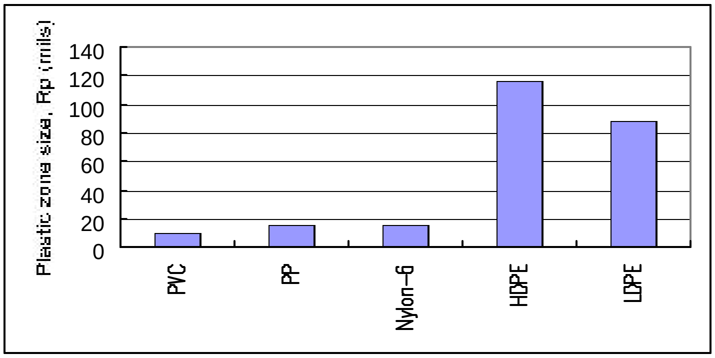


Figure 10. Corresponding plastic zone sizes for resins presented in Figure 9.



4. CONCLUSIONS

Data is presented which shows that deficiencies in the needle abrasion performance of XLPE insulated wires can be overcome by extruding a HDPE skin over a single layer XLPE wire construction. This improvement in needle abrasion is attributed to a temporary suppression of the tearing mechanism that is otherwise responsible for rapid wear. In addition, it is shown that the rate of abrasion for wires insulated with polymers is highly thickness dependent with smaller insulation thickness exhibiting much higher rates of abrasion. Finally, results are shown which suggest that a single parameter such as plastic zone size, which depends on the stiffness, toughness and yield stress of the insulation material, can be used to predict the needle abrasion performance.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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