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Electron Beam Cross-linking: An Emerging Technology for Processing Electrical Wires, Cables and Accessories

V V Pattanshetti* and J Sundara Rajan*

Polymers are extensively used in various power engineering applications for its excellent dielectric and mechanical characteristics. Electron beam technology lends further support for expanding the application of polymers in power engineering. The use of electron beam cross-linking of polymers in preference to the conventional chemical cross-linking processes has several advantages. This paper discusses the advantages of this technology with particular reference to power cable and accessories for termination and joints. The improvements in dielectric, mechanical and thermal characteristics are emphasised to highlight the need for increasing the use of this technology for critical power engineering applications.

1.0 INTRODUCTION

A polymer is a versatile material for many engineering applications. It has been traditionally used for insulating applications. There is a scope for improvement of polymers further in terms of mechanical, thermal and chemical properties so that they are made adoptable for many more power engineering applications.

In a normal polymer, the chains are held together by coiling. Thus, voids and loose structure can lower the physical characteristics of these materials. These properties can be improved by cross-linking the chains to make them more compact and also reduce voids [1]. In electrical insulating materials, voids play an important role and hence cross-linking plays an equally important role in improving the electrical properties [2]. Cross-linking is achieved normally by silane or peroxide methods [3]. In these processes, active chemical species are added to the matrix which links the adjoining chains by chemically bonding with it. However, unreacted materials remain in the matrix and can affect physical as well as electrical properties.

Cross-linking by electron beam is a novel technology in which the high energy electrons are made to pass through a thin 'window' made of material like titanium, and thus can be scanned over and through objects passing directly beneath the window. By penetrating these objects, the electrons can confer upon them valuable and beneficial chemical and structural changes. In case of polymers, e-Beam cross-linking improves a number of properties including tensile and impact strength, creep resistance, durability, chemical resistance, environmental stress crack resistance, barrier properties and others.

2.0 CHEMICAL CROSS-LINKING AND ELECTRON BEAM CROSS-LINKING

Chemical cross-linking is essentially polymerisation, which has three steps namely

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*Central Power Research Institute, Bengaluru, INDIA

initiation, propagation and termination. Initiation involves decomposition of peroxides, which when heated cleave homolytically and form free radicals. These free radicals add to the monomer transferring the active site. The propagation step involves the continuation of this process of active site transfer by the addition of a large number of monomers. The termination process involves termination of the chain by a combination of two grown up chains or breaking up in disproportion, either by stripping of chain by making a double bond or by absorption of the unpaired electron by impurity. If the process is not complete, then the polymer is called a living polymer. In case of cationic and anionic polymerisation, ions or ion radicals are generated and these will initiate and propagate polymerisation.

In electron beam processing, resins generate free radicals or ionised molecules in excited states that initiate, propagate and terminate the polymerisation. For systems already polymerised, electron beam irradiation strips hydrogen from two adjacent sites and hence the two will be linked by bonding. Generally the polymers produced by normal techniques are processed to the final product size and then irradiated with electron beam. Thus, 3-dimensional cross-linking takes place resulting in a strong and very compact material [4]. Four-sided electron beaming facility is also available.

Cross-linked polymers, apart from the bonds which hold monomers together in a polymer chain, have bonds between neighbouring chains. These bonds can be formed directly between the neighbouring chains or two chains may bond to a third common molecule. Though not as strong or rigid as the bonds within the chain, these cross-links have an important effect on the polymer. Polymers with a high degree of cross-linking have ‘memory’. When the polymer is stretched, the cross-linking prevents individual chains from sliding past each other. The chains may straighten out, but once the stress is removed they return to their original position and the object returns to its original shape.

3.0 ELECTRON BEAM TECHNOLOGY

3.1 Typical electron beam processing system

A typical electron beam processing system consists of an electron beam accelerator and beam directional accessories, belt system to pass the polymeric material and make it exposed in different directions. For processing of polymers, industrial electron beam accelerators upto 10 MeV and 150 kW are generally used. Both Direct Current and Radio Frequency accelerators are used for polymer applications [5]. The accelerator in turn consists of an irradiator, a pulse transformer to provide high voltages, solid state pulse modulator, control system, power supply system and cooling system.

The system consists of a control panel, an accelerator, a beam gun and a unidirectional or multidirectional belt system. The processing of materials using high energy electron accelerators in the energy range of 200 keV—10 MeV constitutes the largest commercial radiation application in the industry. More than 800 EB accelerators are operating world wide and it is now a multibillion dollar industry offering high technology products. The specifications of an electron beam accelerator are highlighted in Table 1.

TABLE 1

TYPICAL SPECIFICATIONS OF AN ACCELERATOR

Sl No.	Characteristics	Range
1.	Energy range	8–15 MeV
2.	Average beam power	10 kW
3.	Pulse repetition rate	50/100/200/sec
4.	Beam current	300 mA
5.	Radiation dose	100–120 kGy

3.2 Applications of e-Beam for cross-linking of polymers

Electron beam (e-Beam) is used to improve the properties of plastics and elastomers through cross-linking. This process is also used to extend the operating temperatures over which the polymers can be used and to increase their stability under abnormal working conditions. Cross-linking also improves the barrier properties of polymers and resistance to liquids and gases.

Electron beam (e-Beam) cross-linking for plastics/polymers provides all advantages of cross-linking namely very high tensile and impact strength, creep resistance, durability, solvent and chemical resistance, abrasion resistance, environmental stress crack resistance and barrier properties. Interestingly, none of the disadvantages of chemical cross-linking are relevant to e-Beam cross-linking. E-Beam cross-linking does not require any additive nor does it generate hazardous chemical by-products. It is energy efficient and the minimal amount of exposure time ensures high throughputs.

Electron beam cross-linking is most frequently used for polyethylene and polyvinyl chloride products, but there is a growing interest in e-Beam cross-linking of fluoro polymers including ETFE in moulded parts, specialty wires and cables.

Polyethylene is the most commonly used commodity polymer. Polyethylene, in its various forms, is a long chain carbon-based macromolecule. The chains are not linked directly to each other, but the bundle structure is held by entanglement of long chains. Only in crystalline areas, weak intermolecular bonding holds them together. Molecules start moving with ease on thermal treatment and hence allow easy processing. Polyethylene at high temperature becomes soft and more elastic and hence deforms. Under these conditions, the material fails to perform due to weak tensile and creep resistances. At room temperature, the material because of its high degree of porosity is vulnerable to treeing failure when used in high voltage cables. Hence, cross-linking is very essential. The cross-linked systems will have improved temperature resistance, pressure resistance, oxidation resistance, chemical resistance and environmental stress cracking resistance.

Several methods have been used to cross-link polyethylene. Chemical methods involve use of peroxides and azo type initiators. These will release free radicals, which will initiate ionisation and radical formation in chain back-bone. Two such formed radicals combine to form chemical bonding. Such bonding will provide a networking of the material. Azo type of initiators will also function in the same way to cross-link the chains. Cross-linking can also be achieved by graft co-polymerisation with the help of organosilanes.

High Density Polyethylene (HDPE) with a good degree of cross-linking, has shown properties suitable for high voltage insulation applications. Cross-linked Polyethylene (XLPE) does not suffer from toxic fumes and smoke formation on burning, which is typical of halogenated polymers like PVC. These problems of PVC have resulted in major fire accidents and losses to human life and property. Thus, PVC is being phased out with alternatives like XLPE and others.

Chemical methods of cross-linking are costly and are poor in quality for processing of polymers as density of cross-linking is low. Various irradiation techniques are being evaluated for radiation initiated cross-linking like gamma, UV and electron beam. Among the different radiation techniques, electron beam radiation cross-linking of polyethylene has been found to be more significant. Ease of cross-linking and availability of instrumentation which provides control of process parameters with precision; have made e-Beam the most favoured method. Irradiation of polymeric materials can also lead to undesirable characteristics like oxidation and chain scission coupled with other forms of degradation. These are to be controlled by using the suitable intensity of radiation.

3.3.1 HDPE and its cross-linking

Cross-linking of HDPE is being practiced by different methods. Chemical methods involve use of chemicals such as peroxides, azo compounds or organosilane compounds. In the first two cases, active chemicals like peroxides and azo compounds, undergo rearrangement to generate free radicals and get attached to carbon in the backbone and creating free radicals. These will link together to form chemical bonding across the length of polymeric chains.

Different methods of irradiations can be used for polymer processing. Polymers can be continuously irradiated, films can be blown or surface can be scanned such that the required curing/cross-linking can be achieved. The process is very significant in that it consumes low energy and does not need any chemicals for further processing, hence cost is low.

3.3.2 Electron beam irradiated cross-linking of HDPE

HDPE on cross-linking becomes heat shrinkable and possess memory to regain its shape characteristics. XLPE expands on heating above the crystalline melting point due to the disappearance of the crystalline structure. On cooling, the crystalline forms re-appear and have elastic memory characteristics to come back to the original dimensions. Blends of HDPE with other systems can be used to produce heat shrinkable products. During manufacturing, a pre-form of the product can be produced to the geometric shape to which the final product will ultimately return. An electron beam can then be used to irradiate the whole surface of the product uniformly. The product will cross-link, after which it will regain its original form. It is also possible to provide a protective coating to get the desired hydrophobic and anticorrosion characteristics which are useful for outdoor polymers.

Typical compound formulations containing polymers, antioxidants, processing aids, fillers, coupling agents, curing agent sensitisers and plasticisers can be used to formulate the compound and the product is then exposed to electron beam radiation. During the process, gelation occurs indicating the extent of cross-linking of the material. Normally, the radiation dose will be in the range of 100-120 kGy (10M rads) and the cross-linking density achieved will be in the range of 75-85%. This technique is promising as it is fast, efficient and does not use chemicals. The products developed have a high degree of cross-linking and hence show good mechanical and electrical properties. The state of art technology for developing many products for electrical applications is being contemplated, particularly for power cables, HDPE and its blends with other polymeric matrices are also being evaluated for cables, cable terminations, bushings and other applications.

4.0 POWER CABLE AND WIRE SHEATHING APPLICATION

4.1 Mechanical and electrical property requirements

Electron beam cross-linking of wires and cables are well established and it is the most important commercial application of radiation technology. The process results in a product that offers many advantages over chemically cross-linked cables viz. higher operating temperature of 120°C, much lesser thickness of the insulating material, high throughput and energy savings by very low consumption of power, since cross-linking is carried out at room temperature. Materials with e-Beam cross-linking are finding application in development of heat shrinkable products with memory. These can be used in fabrication of components for cable end joints, terminations, films for bunching, wrapping and other applications [6- 8].

In wires of AWM (Appliance wiring material) category and power cables, HDPE can be used by curing through a continuous process. Sufficient exposure to the accelerated electron beam is required to cover the entire surface of the insulation. Improvement in properties of the electron beam cross-linked material, with respect to electrical properties and mechanical properties in comparison to the chemical cross-linking technique are promising. Table 2 shows the range of properties and comparison between the two. It is observed that the cross-linked systems are far superior in their mechanical, thermal and electrical characteristics. At higher temperatures, there are further improvements in mechanical characteristics. It also results in improved resistance to stress cracking and better fluid resistance. There is generally little or no change in flame resistance, improvement in electrical characteristics and thermal stability. Without cross-linking, polyethylene is usually rated at 75°C, due to the fact that the material becomes soft and will flow at higher temperatures. Properly compounded and cross-linked polyethylene can have a temperature rating as high as 125°C. The material no longer flows at elevated temperatures and therefore can be effectively used at relatively higher temperatures.

A comparison of size, diameter and current carrying capacity of elastomeric conventional cable and thin-walled e-Beam irradiated cable is furnished in Table 3. The advantages of e-Beamed cable are obvious. In case of thin walled cables, it is also necessary to specify the operating temperature of the cable based on the type of insulation used. For example, in a thin-walled cable of 90°C continuous rating may not be suitable for a particular application because of its limited temperature withstanding capability. Similarly to prevent overheating of a cable, it may be necessary to use a cable having a larger conductor diameter in some applications. Thus, by judicious choice of conductor diameter and continuous temperature rating of the cable insulation, it is possible to overcome the problems of cable overheating and also improve the short time temperature rating of cable. In some applications, it is preferable to have single material for cable insulation and sheath. This is because dual layer cable insulation, i.e., different material for insulation (EPDM) and sheathing (ex. EVA) is to be avoided if possible, to prevent de-lamination under adverse environmental conditions like high temperature, extreme heat and steam.

The biggest advantage of the use of e-Beam technology is the ability to precisely control the insulation/sheath thickness, irrespective of the thickness. Thus, adjustments and alignments in conductor diameter and insulation/sheath thickness can be easily achieved to meet the demands of any given situation. Since the wall tolerance on thickness is very close to zero, the insulation failures due to electric stress concentration at a point are very much reduced. This technology is very useful for such applications where replacement of a cable with improved temperature performance and current rating are required. This can be achieved by increasing the conductor diameter and by replacing the insulation with one having better temperature index and by reducing the insulation wall thickness. Thus, for critical applications, this technology will be very handy.

5.0 ENVIRONMENTAL CONSIDERATIONS OF e-BEAM TECHNOLOGY

Electron beam (e-Beam) technology neither produces nor stores any radiation in the target materials, once those materials are away from the beam. When the ionising radiation is present and the accelerator is on, the personnel involved in the work are far away and are protected from this potential hazard by thick concrete walls. When the accelerator is switched off, the ionising radiation stops and hence threat potential would no longer exist. Moreover, nonusage of peroxide or silane type of chemicals would be eco-friendly in industrial applications.

6.0 ECONOMIC CONSIDERATIONS

The contribution from e-Beam technology in terms of value addition is significant. It is the prohibitive cost of establishing the e-Beam

TABLE 2

CHARACTERISTICS OF POLYETHYLENE AND CROSS-LINKED POLYETHYLENE SYSTEMS

Characteristics	**Polyethylene**	**PE-X chemically cross-linked**	**PE-X e-Beam processed**
Dielectric strength (kV/mm)	40	40	40
Dielectric constant	2.3	2.3	2.3
Dielectric loss	$<4x10^{-4}$	$<4x10^{-4}$	$<4x10^{-4}$
Volume resistivity; Ω cm	~ 10^{18}	~ 10^{18}	~ 10^{18}
Short time temperature withstand under short circuit conditions (°C)	150	180	200
Tensile strength (MPa)	>14	>14	18
Elongation at break (%)	>400	>400	>400
Melting temperature range (°C)	122-124	150-170	150-170
Maximum operating temp (°C)	70	90	90
Maximum short-circuit temp (°C)	150	250	250
Thermal resistivity (Km/W)	3.5	3.5	3.5
Specific gravity (kg/m^3)	920	920	920
Heat deformation	good	Very good	Excellent
Ozone resistivity	Fine	Fine	Very good
Oil resistivity	Excellent	Excellent	Excellent
Weather resistance	Good	Good	Very good

TABLE 3

COMPARISON OF CONVENTIONAL AND THIN WALLED CABLE

Conventional Cable			**Thin walled cable**		
Size (mm^2) Nominal conductor cross-sectional area	**Diameter (mm)**	**Current (A)**	**Size (mm^2) Nominal conductor cross-sectional area**	**Diameter (mm)**	**Current (A)**
300	37.9	578	300	30.20	917
225	32.17	498	185	24.30	659
185	30.3	432	150	22.40	579
150	27.20	378	120	20.10	500
120	25.20	329	95	17.80	423
95	23.30	282	70	16.10	348
70	20.60	234	50	14.0	278
50	18.50	192	35	12.1	221
35	16.3	152	35	12.1	221
25	14.70	123	25	10.6	174
16	12.8	93	16	8.7	133
10	11.3	69	10	6.7	96
6	10.0	50	6.0	5.5	68
4	9.3	38	4.0	4.9	53
2.5	8.7	28	2.5	4.1	39

technology that has prevented the use of this technology. The cost of installing and operating a dedicated e-Beam plant is very high and would depend on the accelerator voltage. The facility would include the beam, shielding, physical plant, conveyor system, safety system, utilities and support equipment. Hence, manufacturers of products turn towards contract service companies to provide reliable, high-quality, cost-effective processing on toll basis.

7.0 CONCLUSIONS

Electron beam irradiated elastomeric cables and heat shrinkable accessories for cable joint and termination offer many advantages and choice for demanding power engineering applications. The advantages of e-Beam cables, wires, components and accessories are:

- higher tensile strength, improvement in abrasion/cut through, better crush resistance, decrease in flexibility, high temperature mechanical characteristics
- better solder iron resistance, current over-load characteristics and related temperature rise
- good resistance to stress cracking, improved fluid resistance, better flame resistance
- improvement in electrical properties
- improvement in thermal stability
- better performance of insulation under short time temperature rise due to short circuit conditions
- possibility of replacing conventional elastomeric cables with thin-walled cables of higher temperature rating
- possibility of using single material for insulation/sheath to prevent delamination
- greater flexibility in balancing the overall size of conductor by adjusting the conductor and insulation/sheath diameter

In addition, e-Beam cross-linking offers many advantages over the conventional chemical cross-linking process. These are:

- Curing can be carried out near room temperature, allowing the use of low cost, low temperature tooling such as wood, plaster or foam.
- Curing at low temperature can reduce residual thermal stresses.
- Co-bonding and co-curing operations with EB-curable adhesive allow fabrication of large integrated structure.
- Cost comparisons of e-Beam with thermal fabrication have shown that e-Beam processing can reduce costs by 10-40% for production of a variety of e-Beam processing applications.

The cable and wire industry should come forward to make the best use of this technology to improve quality and consistency of the products manufactured by them. It will be a significant advantage to establish this system for carrying out effective and specific product and application oriented R&D for power sector in India.

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