Microelectronics Reliability 49 (2009) 972–976

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel

Ensuring the reliability of electron beam crosslinked electric cables by the optimization of the dose depth distribution with Monte Carlo simulation

Mauro Ciappa [a,*], Luigi Mangiacapra [a], Maria Stangoni [b], Stephan Ott [b], Wolfgang Fichtner [a]

[a] Swiss Federal Institute of Technology (ETH), Integrated Systems Laboratory, ETH-Zentrum, CH-8092 Zurich, Switzerland
[b] HUBER+SUHNER AG, Wire+Cable Division, R&D, Tumbelenstrasse 20, CH-8330 Pfaeffikon, Switzerland

ARTICLE INFO

Article history:
Received 1 July 2009
Available online 11 August 2009

ABSTRACT

The reliability of electric cables and wires using electron beam crosslinked polymers as isolator materials strongly depends on the accuracy in predicting the dose deposited during irradiation. This paper presents the main reliability issues that can be encountered in field operation, experimental data showing the criticality of the dose parameter, and proposes the use of a built-in reliability approach based on Monte Carlo simulation to design optimum processing conditions. The main requirements and advantages of the Monte Carlo based methodology are discussed in conjunction with the limitations of the traditional heuristic calculation procedure. Finally, Monte Carlo simulation is used for the first time to point out some relevant effects that occur during processing and that can lead to severe dose estimation errors.

1. Introduction

Besides in the fundamental research, electron beams (EB) with varying power and energy are getting crucial also in radiation processing of electronic materials. This is the case of EB processing of polymer materials used as isolators in electric cables, which represents a market share that is steadily growing at double digits every year. EB processing is becoming so popular that at least one third of the 2000 industrial EB accelerators operated worldwide are used to manufacture electric cables wires. The most common polymeric materials used for the insulation of cables and wires are thermoplastics, to a lesser degree, elastomeric compounds, and foams. EB crosslinking of these materials improves their toughness, flexibility, impact resistance, resistance to solvents and chemicals, as well as their service temperature. This obviously results into an improvement of cable life, performance, and reliability, especially when they are operated in extreme environments.

The EB crosslinking of polymers bases on the fact that ionizing radiation changes the material behavior from thermoplastic into elastomeric. In particular, high-energy electrons can produce significant improvements in the mechanical, thermal, and chemical properties of the irradiated polymers even at a temperature below the crystal melting temperature. The reaction kinetics during electron beam crosslinking is quite complicated. For sake of simplicity, the discussion is confined here to the case of polyethylene, where the impinging electrons split hydrogen atoms from polyethylene chains. At this point, different competitive reactions can occur at the free radical, which lead to stronger carbon–carbon bonds. This includes among other crosslinking between two adjacent chains, formation of allyl radicals, and combination of two radicals along the same backbone to form a trans-vinylene group. In polyethylene, the usual degree of crosslinking is between 65% and 90% [1]. A higher degree would result into brittleness and stress-cracking of the material. If properly crosslinked, the tendency to flow of polyethylene is reduced and it keeps an adequate mechanical strength up to at least 150 °C. Crosslinking is also beneficial at low temperature, where impact and tensile strength, scratch resistance, and resistance to brittle fracture are substantially enhanced.

The doses required for electron beam crosslinking of a polymer range from 100 to 500 kGy depending on the material and on the addition of promoters. Fig. 1 shows the typical configuration of an electrostatic accelerator for polymer crosslinking applications. Commercially available accelerators operate in the energy range from 0.5 to 5 MeV and at a beam current from 10 to 100 mA. Pulsed or continuous electron beams of few centimeters diameter are generated in accelerators and delivered through a scan horn with a titanium thin window separating the vacuum column from the irradiation chamber. Cables and wires are transported through the scanning beam by complex conveyor systems, which usually enable multiple irradiations of the cable from different directions.

2. Ensuring the reliability of cables

Polyethylene has excellent dielectric properties, such that it is used for cables in the voltage range from the 600 V up to 500 kV. The typical maximum rated temperature is around 90 °C, while the emergency rating and the conductor short circuit rating may reach 250 °C. The function of electrical cable is to provide a medium for transmitting electrical energy (power control or signals)

* Corresponding author. Tel.: +41 44 632 2436; fax: +41 44 632 1194.
E-mail address: ciappa@iis.ee.ethz.ch (M. Ciappa).

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doi:10.1016/j.microrel.2009.07.035

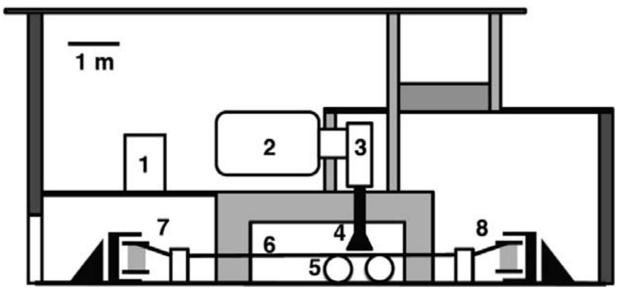

Fig. 1. Typical layout (cross-section) of an electron beam accelerator for crosslinking applications working in the energy range up to 5 MeV: (1) oscillator, (2) pressure tank, (3) accelerator. (4) scan horn, (5) conveyor, (6) cable, (7) pay-off, and (8) take-up.

between two points in a common electrical circuit, while simultaneously maintaining the electrical isolation of the transmission path from other elements of the same circuit and from other co-located circuits. Cable failure, therefore, implies loss of continuity in the energy transmission path or diversion of a sufficient fraction of the available electrical energy to an unintended circuit destination such that proper function of the circuit is no longer assured [2].

Due to the manifold of applications, it is almost impossible to define just a single mission profile for all electric cables. As an example in the communication field mission profiles are developed to establish the thermal and mechanical stress limits that cables must endure in service, as well to define the related test sequence designed to measure relevant parameters as the tensile strength, flexural abrasion endurance, crush resistance, creep under static tension, performance in a tube, etc. (e.g. [3]). In some critical applications, like in the nuclear field, the ability of cables to survive to fire exposure is of paramount relevance, since exposure to fire can cause among other a loss of insulation resistance, loss of insulation physical integrity (i.e., melting of the insulation), and electrical breakdown or short-circuiting.

The most frequent failure mechanisms observed in cables mainly depends on the environmental stress factors. As an example, extreme conditions like the close contact with motors or hot piping can obviously turn into catastrophic failures. Mechanical stress is known to accelerate the aging phenomena in polymers. In particular, it shows synergistic effects with other driving forces like temperature, humidity, or radiations. Vibrations, bending around sharp edges, pressing, and squeezing often result into microcracks both at the surface and inside the isolation, which can coalesce by leading to the formation of voids that can impair the functional properties of the cable. Polymers can be also be degraded by humidity and steam, especially under contaminated conditions (ions, hydrocarbons, etc.). Moisture may enter polymers through voids and cracks produced by hardening and can degrade their dielectric and isolation characteristics. Long-term exposure of energized cables to environmental water may also turn into water treeing in the insulator [4]. Finally, besides random scission and depolymerization, ionizing radiation and high temperatures in presence of oxygen have observed to lead to the formation of free radicals into the polymer materials, causing the loss of the mechanical properties, hardening, and cracking.

3. The process optimization problem to be solved

The speed of the conveyor (Fig. 1) is regulated as a function of the EB current and energy to ensure that the required dose distribution is delivered to the target. In this circumstance, the dose rate has also to be controlled to avoid overheating of the cable by the injected power (several kilowatts), and the energy of the impinging EB has to be calibrated in such a way that the minimum required dose is reached even in critical locations.

At present, EB equipment manufacturers provide heuristic procedures and formulas (range equations) for the calculation of the required energies and processing rates. These recipes base on irradiation of simplified slab geometries and make use of the effective range concept, which is defined empirically as the thickness, in which the exit plane dose equals the incident surface dose, while the ratio of the peak dose to the entrance dose is defined as dose uniformity. Such a simple procedure usually overestimates the EB energy to be used. This can on lead one side to the need of more expensive, oversized equipment, and on the other side to product over-irradiation with consequent pre-damaging. In fact, as shown in Section 4, an excessive dose deposition can result into the formation of voids in the polymer leading to the degradation of its dielectric and mechanical properties. On the contrary, decreasing the acceleration voltage in an uncontrolled way is not valid solution. In fact, an insufficient EB energy could result both into a poor crosslinking of the polymer, and at the same time into a local accumulation of excess space charge in the isolation. The inaccuracy of the heuristic approach has been confirmed by recent publications, where range equations have been compared with one-dimensional Monte Carlo simulations of uniform slabs of simple materials [5]. This investigation pointed out that even under these idealized conditions, analytical approaches may produce noticeable errors in the low and medium EB energy range (from 0.5 to 3 MeV), where the most popular electron beam crosslinking facilities are operated. Furthermore, it has been shown that the accelerator features cannot be neglected.

Finally, it has to be considered that the process optimization problem has to be solved under production conditions, i.e. by keeping into account arbitrary geometries, uneven penetration and the geometry-dependent scattering of the electrons, the presence of different materials, the need of multiple irradiations, the generation of Bremsstrahlung, as well as the electrons escaping from the region of interest.

4. Experimental

As usual, this built-in reliability program for electrical cables starts with the experimental characterization of the physical parameters of interest and with the definition of the best irradiation conditions to realize the specified mechanical properties. The experimental data reported here show that the obtained mechanical properties of the irradiated polymer strongly depend on the deposited dose. In some cases, an increasing dose improves the strength of the material and thus the reliability. In some other cases, an excessive dose turns into an unwanted degradation of relevant mechanical parameters.

Due to the complexity of the geometry, to the variety of the materials in a typical cable, and because of the difficulty to extract quantitatively the specified parameters from a real product, the optimization process is carried out by dedicated test structures. In this case, the considered test structures are polyethylene ($CH_2{=}CH_2$, PE) strips with 25 mm width, 1 mm thickness, and a density of 0.93 g/cm^3. The strips are irradiated at 1 MeV and the process conditions are selected based on empirical techniques to reach the specified dose. The test conditions are validated by measuring the surface dose by thin film dosimetry. Here, radiachromic dosimeters FWT-60-00 [6] have been used, whose optical density before and after irradiation has been characterized at 510 nm with a spectrophotometer. In order to obtain a more uniform dose depth distribution in the sample, the strips are irradiated from both sides.

Once irradiated to the specified dose, the test specimens are cut with a shape according to the insert of Fig. 2 to perform thermome-