Effect of Radiation Pre-vulcanization on the Properties of the Truck Tyre' s Transition Layer and the Truck Tyre (Postprint)

Authors: YANG Mingcheng, ZHANG Benshang, ZHU Jun, LI Zhaopeng, LI Kunhao, GUO Dongquan, ZHANG Hongna

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Abstract

In this paper, the natural rubber is chosen as the main constituents for the transition layer of all-steel load radial tyre, which is pre-vulcanized by 500-keV E-beam irradiation of up to 60 kGy. The results show that the green strength of transitional layer increases with the dose, reaching four times as much as the control (without irradiation) at 60 kGy. The final mechanical properties do not differ significantly from those of the control except that the aging and fatigue performance increased. However, thickness of the natural rubber transitional layer for an average single tyre can be reduced by 1 mm (or 1.5 kg) without obvious adverse effect on tyre performance.

Full Text

Preamble

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YANG Mingcheng[1],*, ZHANG Benshang[1],[2],[3], ZHU Jun[1], LI Zhaopeng[1],[2], LI Kunhao[1], GUO Dongquan[1], ZHANG Hongna[1]

[1]Isotope Institute Co. Ltd., Henan Academy of Science, Zhengzhou 450015, China
[2]School of Materials Science and Engineering, Zhengzhou University, Zhengzhou 450052, China
[3]Aeolus Tyre Co. Ltd., Jiaozuo 454003, China

Abstract

In this study, natural rubber was chosen as the main constituent for the transition layer of all-steel load radial tyres, which was pre-vulcanized by 500-keV E-beam irradiation of up to 60 kGy. The results show that the green strength of the transitional layer increases with dose, reaching four times that of the control (without irradiation) at 60 kGy. The final mechanical properties do not differ significantly from those of the control, except that the aging and fatigue performance improved. However, the thickness of the natural rubber transitional layer for an average single tyre can be reduced by 1 mm (or 1.5 kg) without obvious adverse effects on tyre performance.

Key words: All-steel load radial tyre, Transitional layer, Radiation pre-vulcanization, Absorbed dose

Introduction

As early as the 1950s, Firestone Co. Ltd. first carried out a research program designed to estimate possible applications of radiation to the tyre manufacturing process. After more than twenty years, the company finally completed the first tyre radiation pre-vulcanization production line in the world. Pre-vulcanization of the body ply by E-beam irradiation for manufacturing radial tyres reduces production costs by enhancing the green strength of the rubber sheet before crosslinking. Immediately after its introduction, the "radiation pre-vulcanization" concept attracted many foreign tyre companies to invest huge sums, and radiation pre-vulcanization technology was subsequently adopted in tyre production by world-famous manufacturers such as Bridgestone, Michelin, Goodyear, and Continental.

Radiation pre-vulcanization of tyres in China started late; it was not until 2004 that several scientific research units and enterprises began conducting research on passenger car tyres, including Beijing Sanqiang Heli Radiation Engineering Technology Co. Ltd. and Liaoyuan Honglin Radiation Technology Co., Ltd. Since truck tyres have large volumes, they consume more raw materials than car tyres. Therefore, radiation pre-vulcanization technology may achieve greater reductions in rubber usage and production costs.

In this study, we applied E-beam irradiation to the transition layer of steel radial truck tyres and investigated changes in green strength, elongation at break, aging, and fatigue performance at different absorbed doses. Transition layers with and without radiation pre-vulcanization were completely vulcanized by heating, and their mechanical property changes were studied. After reducing the transition layer thickness, whole tyre performance was evaluated by manufacturing complete tyres.

2.1 Materials

Natural rubber (SMR10) was produced in Malaysia. Carbon black (N326) was commercially produced by Shandong Huadong Rubber Material Co. Ltd., China. Zinc oxide (ZnO) as an activator was obtained from Weifang Qinglian Zinc Oxide Co. Ltd., Shandong, China. N-(1,3-dimethyl-butyl)-N' -phenyl-p-phenylenediamine (6PPD(4020)) as an antioxidant and hexakis(methoxymethyl) melamine (HMMM-(RA)) as an adhesive were manufactured by Shengao Chemical Co. Ltd., China. Sulfur (IS7020) as a vulcanization agent was from Hengye Henan Kailun Chemical Co. Ltd., China. N-cyclohexyl-2-benzothiazole sulfenamide (DCBS(DZ)) as an accelerator was manufactured by Northeast Auxiliary Chemical Industry Co., China. The resorcinol-formaldehyde resin was purchased from SinoLegend Chemical Co. Ltd., China. Other raw materials were commercially available.

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Corresponding author. E-mail address: ymch-7305@126.com

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2.2 Preparation of Test Specimens

Natural rubber (SMR10, 100 kg), carbon black (N326, 60 kg), ZnO (8 kg), antioxidant (6PPD (4020), 2 kg), and other raw materials were mixed in an internal mixer. The vulcanizing agent (IS7020, 4.4 kg), adhesive (HMMM (RA), 3 kg), and accelerator (DCBS (DZ), 1.25 kg) were added into the open mill to obtain the mixing rubber. The mixed rubber was compressed into 2.5 mm thickness at 100°C for 2 min, thus obtaining the samples for radiation pre-vulcanization.

Under set irradiation parameters, the samples were irradiated by an electron accelerator at atmospheric temperature. The maximum pressure at acceleration energy was 500 keV. The samples were moved at a speed of 8.8 m/min under the 10-mA beam current. The total absorbed dose was controlled by repeating the irradiation time. Some samples were selected for evaluation, and other samples were further compressed to 2.0-mm thickness by simulating actual heat cure conditions at 160°C for 60 min, thus obtaining the final test samples.

2.3 Mechanical Properties

To measure tensile properties, dumbbell-shaped specimens were prepared according to ASTM D412-87. The tensile strength was determined with a testing machine (RGM-3010, Shenzhen Reger Instrument Co. Ltd., China) at a crosshead speed of 500 mm/min. Tension set at 300% elongation was carried out according to ASTM 1566. The Shore A hardness was tested according to ASTM D2240 on a hand-held Shore A Durometer. All tests were measured at 23°C. Average values were obtained from 5 test specimens for data plotting.

3.1 Effect of Absorbed Dose on Green Strength and Elongation

Natural rubber, being a radiation-crosslinkable polymer, was chosen as the main ingredient of the transition layer. When high-speed electrons enter the transition layer and collide with extranuclear electrons on its molecular chain under E-beam irradiation, energy is transferred to the extranuclear electrons, causing increasing green strength of the transition layer due to the generation of a three-dimensional network structure through radical reactions.

As shown in Fig.1, the green strength of the transition layer increased with absorbed dose, from 1.3 MPa without irradiation to 5.2 MPa at 60 kGy absorbed dose. The linear regression equation between the green strength of the transition layer and absorbed dose is $F = 1.32 + 0.025D$ ($R = 0.98$), where F is green strength (MPa), D is absorbed dose (kGy), and R is correlation coefficient. Because the crosslinking degree at a certain absorbed dose is proportional to the absorbed dose, the green strength of the transition layer increases with dose. Thus, adjusting the absorbed dose can effectively control the crosslinking degree of predetermined vulcanization to meet product requirements. A good linear relationship also exists for 300% elongation stress: $F = 0.49 + 0.0075D$ ($R = 0.97$).

The penetrability of E-beam is low at 500 keV, mainly resulting in radiation pre-vulcanization at the surface of the truck tyre transition layer. Elongation at break, with a large geometric deformation of more than 600%, is independent of absorbed dose within the tested range, as shown in Fig.2.

[Figure 1: see original paper]

[Figure 2: see original paper]

3.2 Effect of Radiation Pre-vulcanization on Final Properties of Transition Layer

After radiation pre-vulcanization of the transition layer, the whole tyre needs to be vulcanized by heating to further improve its performance and meet actual use requirements. Therefore, the effect of radiation pre-vulcanization on the final heat curing process must be taken into account. Simulating the actual pressure, temperature, and time in the production process, the transition layer properties changed at different absorbed doses. As shown in Fig.3, the tensile strength of the transition layer after heat curing declined with increasing absorbed dose. Although natural rubber is a radiation cross-linking polymer, crosslinking reactions and degradation always compete and occur simultaneously. Because of degradation, a small amount of macromolecules in rubber break into smaller molecules, resulting in a slight decrease in tensile strength and elongation at break. Still, besides generating C-Sx bonds after heat vulcanization of the transition layer, the C-C bonds from radiation remain, causing the 300% tensile stress to increase slightly while elongation at break decreases due to radiation-induced partial degradation.

[Figure 3: see original paper]

3.3 Effect of Absorbed Dose on Aging and Fatigue Performance

To investigate changes in tensile strength and elongation at break of the transition layer, aging and fatigue tests were conducted after radiation pre-vulcanization and thermal vulcanization. The higher the absorbed dose of the transitional layer, the more C-C crosslinking occurred in the dose range of 0–60 kGy. In addition, the crosslinking energies of polysulfidic (170 kJ/mol), disulfidic (220 kJ/mol), and monosulfidic (270 kJ/mol) bonds are lower than that of C-C (360 kJ/mol) due to their lower bond energies. Therefore, polysulfidic, disulfidic, and monosulfidic crosslinks are easier to break than C-C bonds during fatigue and aging tests, which is why tensile strength and elongation at break increased in the range of 0–60 kGy (Figs. 4 and 5).

[Figure 4: see original paper]

[Figure 5: see original paper]

3.4 Performance After Thinning of Transition Layer

Radiation pre-vulcanization technology was applied to trial-produce a batch of all-steel load radial truck tyres with the model 12.00R20 154/149K. Compared with normal truck tyres, the single tyre mass can be reduced by an average of 1.5 kg (Fig.6), while passenger car tyres can be reduced by 0.3–0.7 kg on average. If truck tyre manufacturers adopt this technology, manufacturing costs can be greatly reduced. After hot vulcanizing, the transition layer thickness was reduced from 2 mm to 1 mm by comparison of cross-sections of the tyre tread and tyre shoulder with normal tyres (Fig.7). The trial-produced tyre passed quality supervision and assessment by the National Rubber Tyre Supervision Center, China, indicating that peripheral dimension, tread wear indicators, strength test, and durability tests accord with the national standard GB/9744-2007, as shown in Table 1.

[Figure 6: see original paper]

[Figure 7: see original paper]

4 Conclusions

In this study, natural rubber was selected as the base material for the transition layer of all-steel truck tyres and pre-vulcanized by E-beam irradiation technology. The effect of absorbed dose on transition layer green strength, elongation at break, and properties after heat curing were investigated. After reducing the transition layer thickness by 1 mm, a batch of all-steel load radial truck tyres with the model 12.00R20 154/149K were trial-produced, finding that each tyre mass was reduced by 1.5 kg on average without affecting its main performance. The radiation pre-vulcanization technology was successfully applied in all-steel load radial truck tyres, thus providing tyre enterprises with theoretical guidance and technical support.

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Note: Figure translations are in progress. See original paper for figures.