Radiation pre-vulcanization effect on properties of the truck tyre's transition layer and the truck tyre

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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.

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

1 Introduction

As early as 1950s, Firestone Co. Ltd. first carried out a research program designed to estimate possible applications of radiation to tyre manufacturing process. After more than twenty years, the company finally completed the first tyre radiation pre-vulcanization production line in the world[1]. Pre-vulcanization of body ply is irradiated by E-beam for manufacturing of radial tyres to reduce the production cost of tyres by enhancing the green strength before crosslinking of rubber sheet[1–3]. Immediately after introducing, the "radiation pre-vulcanization" concept attracted lots of foreign tyre companies to invest huge sums, and subsequently applied radiation pre-vulcanization technology in the tyre production, thus covering the following world-famous tyre manufacturers, such as Bridgestone, Michelin, Goodyear, and Continental[4].

Radiation pre-vulcanization of tyre in China started late, not until 2004 did the several scientific research units and enterprises conducted this research on passenger car tyres, including Beijing Sanqiang Heli Radiation Engineering Technology Co. Ltd., and Liaoyuan Honglin Radiation Technology Co., Ltd.[5–9]. Since their large volumes, the truck tyres consumed more raw material than car. Therefore, the radiation pre-vulcanization technology may reduce more rubber and more production cost.

In this study, we applied E-beam irradiation to transition layer of the steel radial truck tyre, and investigated the change of green strength, elongation at break, aging, and fatigue performance in different absorbed dose. Transition layers of both radiation and no-irradiation pre-vulcanization had completely been vulcanized by heating. Further, their mechanical property changes were studied. The whole tyre performance was conducted after reducing transition layer thickness to manufacture a complete tyre[1].

2 Experimental

2.1 Materials

Natural rubber (SMR10) was produced by Malaysia. Carbon black (N326) was commercially produced by Shandong Huadong Rubber Material Co. Ltd., China.

Supported by Henan Province-Chinese Academy of Sciences Cooperation project (No. 092106000021), and the Scientific and Technological Brainstorm project of Erqi District, Zhengzhou City (No. 20103315)

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Received date: 2012-09-20

Zinc oxide (ZnO) as an activator was obtained from Weifang Qinglian Zinc Oxide Co. Ltd., Shandong, China. *N*-(1,3-dimethyl-bututyl)-*N*'-phenyl-*p*-phenyl-enediamine (6PPD(4020)) as an antioxidant, and hexakis(methoxymethyl) melamine (HMMM-(RA)) as 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 accelerators was manufactured by Northeast Auxiliary Chemical Industry Co., China. The rsorcin-formaldehyde resin was purchased from SinoLegend Chemical Co. Ltd., China. Other raw materials are commercially available.

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 the 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 of radiation pre- vulcanization. Under setting irradiation parameter, the samples were irradiated by electron accelerator in atmospheric pressure at room temperature. The maximum acceleration energy was 500 keV. The samples were moved at the speed of 8.8 m/min under the 10-mA beam current. The total amount of absorbed dose was controlled by repeating the irradiation time. Some samples were selected to evaluate, and other samples were further compressed to 2.0-mm thickness by simulating actual heat cure condition at 160^{o}C for 60 min, thus obtaining the final test samples.

2.3 Mechanical properties

To measure the tensile properties, the dumbbell-shape 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. Their average values were obtained from 5 test specimens to use for the data plot.

3 Results and Discussion

3.1 Effect of absorbed dose on green strength and elongation

Belonging to the radiation crosslinking polymers, natural rubber was chosen as the main ingredient of transition layer. When the high-speed electrons enter the transition layer and collide with atom extranuclear electron on its molecular chain under E-beam irradiation, the energy transfer to the extranuclear electron and cause free radical reactions, thus increasing the green strength of transition layer due to the generation of their 3D space structure.

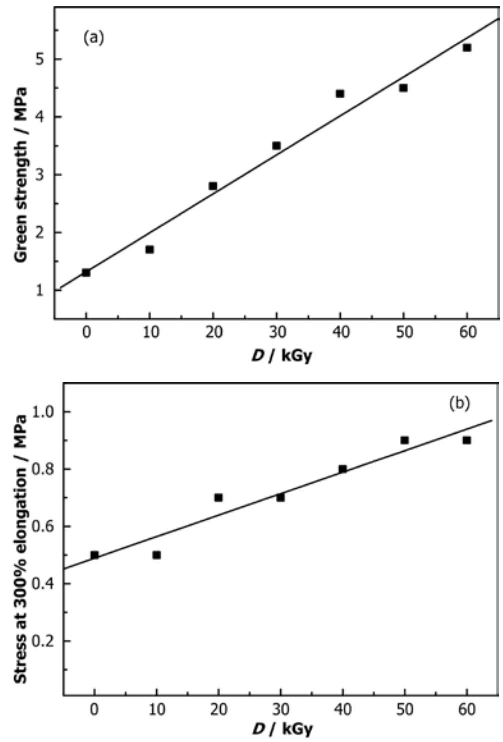

Fig.1 The effect of absorbed dose on green strength (a) and tensile strength at 300% elongation (b).

As shown in Fig.1, the green strength of transition layer increasing with absorbed dose was 1.3 MPa without irradiation, and 5.2 MPa at the 60 kGy absorbed dose. The linear regression equation between the green strength of the transition layer and the absorbed dose is F=1.32 + 0.025D (R=0.98), where F is green strength (MPa); and D, absorbed dose (kGy); and R, correlation coefficient. Because the crosslinking degree in certain absorbed dose is proportional to the absorbed dose, the green strength of the transition layer increases with the dose. Thus, adjusting the absorbed dose can effectively control the crosslinking degree of predetermined vulcanization to meet the requirements of a desired product[10]. Also, a good linear relationship between a 300% elongation and the absorbed dose is F=0.49+0.0075D (R=0.97). The penetrability of E-beam is low at 500 keV, mainly resulting in radiation pre-vulcanization in the surface of the truck tyre transition layer. A large geometric deformation of more than 600%, elongation at break, is independent of absorbed dose within the tested doses, as shown in Fig.2.

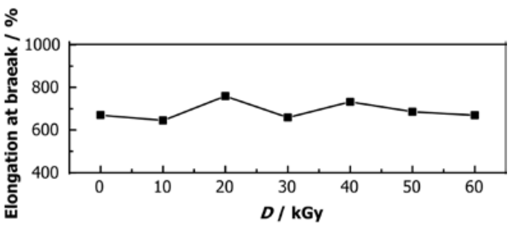

Fig.2 Effect of absorbed dose on elongation at break.

3.2 Effect of radiation prevulcanization on the final properties of transition layer

After radiation pre-vulcanization of transition layer, a whole tyre needs to be vulcanized by heating, to further improve its performance and meet the actual use. 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 in different absorbed dose. In Fig.3, the tensile strength of the transition layer after heat curing has declined with increasing absorbed dose. Although natural rubber is radiation cross-linking polymer, the crosslinking reaction and degradation always compete with each other and occur simultaneously. Because of the degradation, a small amount of macromolecules in rubber breaks into low molecules, resulting in a slight decrease of tensile strength and elongation at break. Still, the C-C bonds from radiation exist besides generating C-S_x bonds after heat vulcanization of transition layer, the 300% tensile stress increases slightly while elongation at break decreases including radiation-induced partial degradation because the length of C-C bond is shorter than C-S_x bond but its energy is greater than C-S_x bond. In the process of the actual use, the tyre deformation is very small and the transition layer locates inside the steel wire cord layer, thus bearing the most external force. So, this does not affect the tyre quality. After thermal curing, the shore hardness of transition layer is almost the same as test.

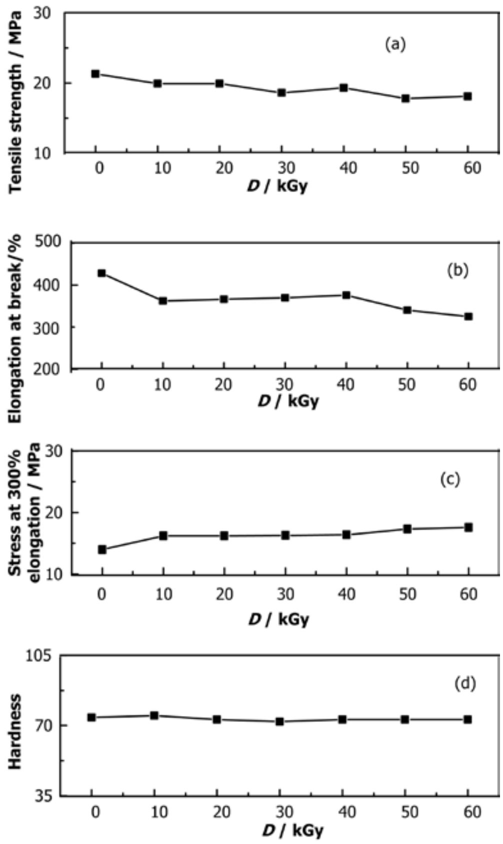

Fig.3 Effect of irradiation precuring on the final mechanical properties of transitional layer.

3.3 Effect of absorbed dose on aging and fatigue performance

To investigate the changes of tensile strength and elongation at break of transition layer, the aging and fatigue tests were conducted after radiation procuring and thermal vulcanization. The higher the absorbed dose of transitional layer was, the more the C-C crosslinking in the dose range of 0–60 kGy was. In addition, the crosslinking of polysulfudic (170 kJ/mol), disulfidic (220 kJ/mol), and monosulfidic (270 kJ/mol) are lower than that of C-C (360 kJ/mol) due to their low bond energies[11]. So the polysulfudic, disulfidic and monosulfidic crosslinking are easier to break than that of C-C during the fatigue and aging tests, this is why the tensile strength and elongation at break increased in the range of 0–60 kGy (Figs.(4) and (5)).

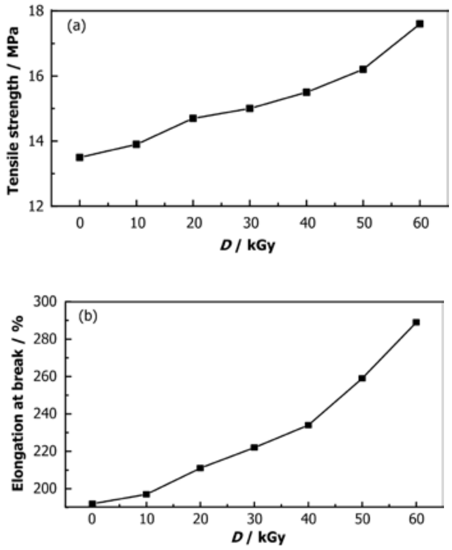

Fig.4 The effect of absorbed dose on tensile strength and elongation at break after aging test.

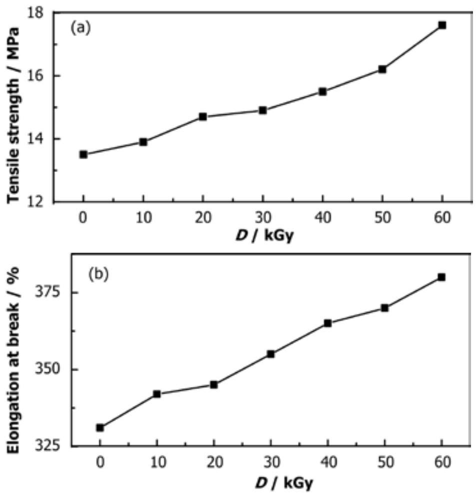

Fig.5 The effect of absorbed dose on the tensile strength and elongation at break after fatigue test.

3.4 Performance after thinning of transition layer

The radiation pre-vulcanization technology was applied to trial-produce a batch of all-steel load radial truck tyres with the model of 12.00R20 154/149K. Compared with normal truck tyre, the single tyre mass can reduce an average of 1.5 kg (Fig.6), and passenger cars tyre can reduce the 0.3–0.7 kg on average[12]. If truck tyres manufacturers adopt our technology, the manufacturing cost can be greatly reduced. After hot vulcanizing and tyre cross-section analysis, the transition layer thickness reduces from 2 mm to 1 mm by comparison of their cross-sections of the tyre tread and tyre shoulder with normal tyre (Fig.7). The trial-produced tyre passes the quality supervision and assessment of 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.

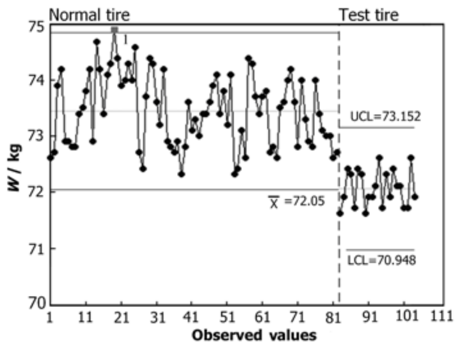

Fig.6 Weight-single-value control chart of the finished product of normal and test tyres.

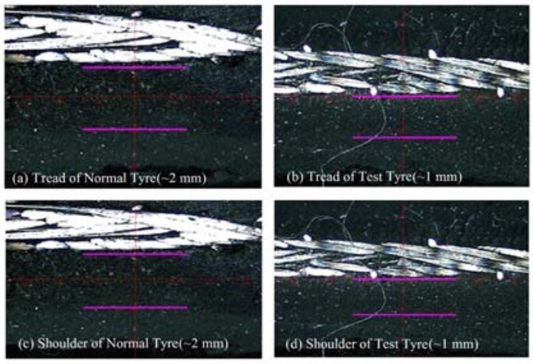

Fig.7 The section contrast from the tread and the shoulder of normal and test tyres.

Table 1 Test results of the type of 12.00R20 154/149K all-steel load meridian tyre

Test items and methods		Standard values	Test data	Results
Sizes (GB/521-2003)	*OD* / mm	1106−1144	1122.3	Pass
	Section width / mm	302−328	310.3	Pass
Abrasion mark height (GB/521-2003) / mm		≥ 2.0	2.5	Pass
Strength (GB/T4501-2008) / J		≥ 2825	2825−3391	Pass
Durability (GB/T4501-2008) / h		≥ 47	≥ 47	Pass

4 Conclusions

In this study, natural rubber was selected as the base material for the transition layer of the 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 transition layer thickness reduced 1 mm, a batch of all-steel load radial truck tyre with the model of 12.00R20 154/149K were trial-produced, finding that each tyre mass reduced 1.5 kg on average and did not affect its main performance. The radiation pre-vulcanization technology was applied in all-steel load radial truck tyre, thus providing tyre enterprises with some levels of theoretical guidance and technical support.

Acknowledgements

We thank the Henan Province-Chinese Academy of Sciences Cooperation project (No. 092106000021) and the scientific and technological brainstorm project of Erqi District, Zhengzhou City (No. 20103315). We also thank YING Shizhou and Aeolus Tyre Co. Ltd. for supporting this work.

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