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Effect of electro-cleaning roughness on steel wire-rubber adhesion strength

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ABSTRACT

In this article, a correlation was established between the electro-cleaning current density and the electro-cleaning surface roughnesses (R_z, distance between the surface peak and valley; R_a, average roughness) of steel wire and finally with the steel wire-rubber adhesion strength. A numerical simulation model with moving mesh technique using COMSOL Multi-Physics® was adopted to evaluate the electro-cleaning behavior of steel wire surface. The model is capable of tracking the moving boundary of steel–electrolyte electro-cleaning interface. Simulation result shows that the roughness (R_z) of electro-cleaned surface of steel wire decreases with increasing electro-cleaning current density which varies closely with the experimental results. Pull-out test results confirmed that an optimum electro-cleaning current density of 600 A/m^2 is required to obtain the maximum steel-rubber adhesion strength of 141 N compared to the base sample (120 N with no electro-cleaning). Furthermore, it can be concluded that the electro-cleaning roughness of R_z ~ 17.5 μm and average roughness of R_a ~ 2.52 μm of steel wire surface would provide the maximum steel-rubber adhesion strength.

1. Introduction

In today's tire technology, motor tire bead (MTB) wires are vulcanized with rubber to form a composite structure which provides tire's structural support and mechanical stability. The interface between steel wire and rubber plays the most crucial role like all other composite structures. Therefore, proper adhesion of the steel wire with rubber is the prime importance for strength and durability of the tire and a widely researched topic. Adhesion between steel and rubber takes place during the vulcanization/curing process of the green rubber formulation which provides the interfacial strength. It has been reported that the adherence between steel and rubber takes place due to the physical bonding through mechanical interlocking and chemical/electrochemical bond formation at the interface, as reported earlier [1,2]. Van Ooij et al. [3,4] reported the steel-rubber bonding mechanism and theories of adhesion of brass-plated steel cords with rubber. The chemical reaction between pristine/engineered steel surface and sulfur, which is used as cross linking agent in rubber, reacts during the vulcanization process and forms the interface [3]. It is established that pristine steel wire surface does not adhere to rubber due to lack of chemical bond formation during the vulcanization [4]. Therefore, different surface treatments on bare steel wire such as metallic alloy coating, thin polymer coating, bonding agents, selective surface oxidation, micro-roughening was studied by researchers to improve the adhesion strength between rubber and steel wire [5–13]. Recently, Banerjee et al. [14–19] has extensively studied Cu–Sn alloy coating system to improve the adhesion strength. Steel surface with copper (Cu) coating is the most preferred technique to improve the interface bonding with rubber because the Cu present in the coating and sulfur, which is used as cross linking agent in rubber, reacts during the vulcanization process and forms copper sulfide at the interface [4,20–22].

Although different surface treatments affect the adhesion properties, steel wire surface properties such as roughness, cleanliness, coating uniformity, etc. also play an important role in controlling the strength. Surface characteristics of the wire greatly influence the quality of the interface. The manufacturing of motor tire bead wires involves many steps and processes, starting from wire drawing, stress relieving in lead bath, electro-cleaning, metallic coating and post treatment before winding into coils. The surface properties of the bare wire are influenced mainly by the speed of drawing, surface finish of the drawing dies and type of lubricants used [23]. The initial surface roughness of the wire is an important factor which affects the uniform coverage of subsequent metallic coating as well as the optimum thickness of coating. Achieving uniform coverage of such a rough wire surface with thin layer of Cu or Cu-alloy coating through displacement or substitution plating route could be a problem [23]. Low residence time (~2 s) of the steel wire in plating bath for high speed lines leads to inhomogeneous coating coverage on the peaks present on the wire surface profile which are more anodic in nature leaving deep uncoated valleys due to lack of coating penetration inside the roughness grooves [14]. Cho et al. [20,21] studied the presence of such uncoated regions on the wire surface with 90 nm thick Cu coating. Further study using Auger Spectroscopy revealed the uncoated regions which contains 80–90 atom % Fe at the surface. They

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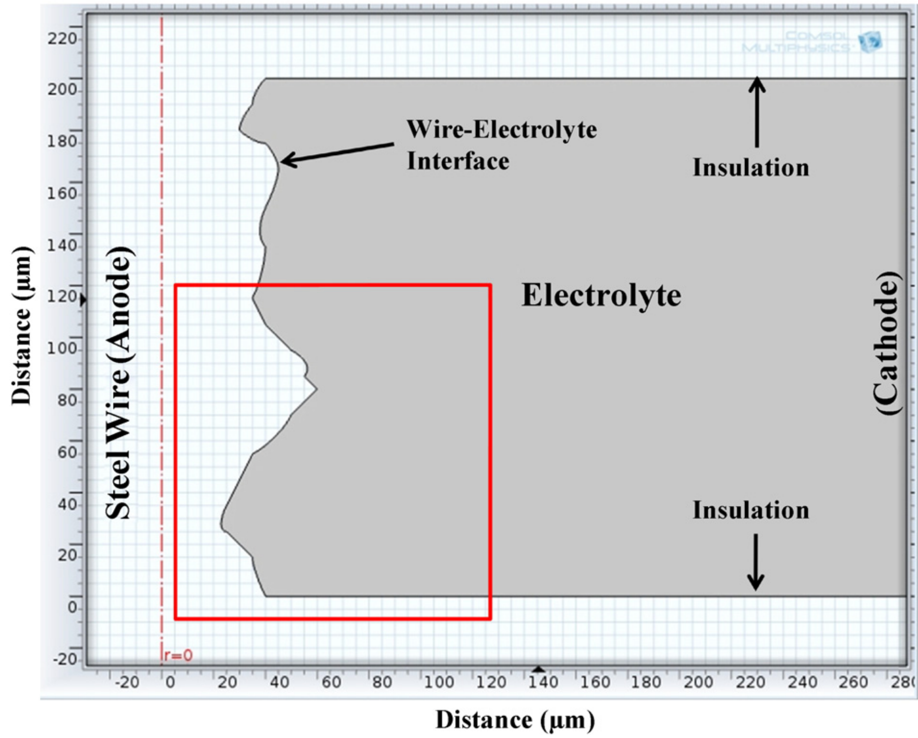

Fig. 1. The schematic geometry for eletro-cleaning simulation of steel wire surface.

observed complete adhesive failure with no rubber coverage after adhesion test which confirmed inadequate surface coverage with coating due to the high wire surface roughness originated from cold drawing. To overcome the problem, they applied zinc coating prior to Cu coating on the cold drawn wire samples with limited success due to the dissolution of the zinc coating in the acidic bath used for subsequent Cu coating [20,21].

As an alternative, electro-cleaning could be an important step toward controlling the roughness of cold drawn wire by selectively dissolving peaks and valleys present on the wire surface profile. In electro-cleaning, the peaks could be dissolved faster due to higher current density compared to the valleys which could reduce the overall roughness (R_z) and thereby improving subsequent coating coverage and adhesion strength. Unfortunately, very limited information exists on optimization of electro-cleaning current density for controlling roughness that can improve the adhesion strength between steel wire and rubber.

In the current work, the effect of electro-cleaning current density on surface roughness of steel wire was studied using both electrochemical modeling through COMSOL Multi-Physics® and electro-cleaning experiments. Furthermore, the correlation between the different surface roughness (R_z and R_a) and steel-rubber adhesion strength was established.

2. Eletro-cleaning simulation

2.1. Governing equations

The electro-dissolution or electro-cleaning behavior of the steel wire surface was studied using the model geometry shown in Fig. 1. The simulation results for the selected area (red rectangle) was presented in the following section for better illustration.

The geometry containing a single electrolyte (H_2SO_4) domain where the anode (steel wire) and cathode (inert) are modeled as electrode surfaces. The other two boundaries were considered as insulating surface where electro-neutrality was applied for charge balance equations. Concentration gradients in the electrolyte are neglected. The model is set up using the secondary current distribution. The electro-cleaning reactions are shown in Eqs. (1)–(2).

At the anode, oxidation or dissolution reaction takes place according to Eq. (1).

$$\mathrm{Fe} \rightarrow Fe^{++} + 2e \quad E^0_{\mathrm{Fe}/Fe^{++}} = +0.44 \ V \ \text{vs. SHE} \tag{1}$$

Hydrogen evolution may also takes place at the cathode surface shown in Eq. (2).

$$H^+ + e \rightarrow \tfrac{1}{2} H_2 \quad E^0_{H_2/H^+} = 0 \ V \ \text{vs. SHE} \tag{2}$$

Table 1
Fixed input parameters used for COMSOL electro-cleaning simulation.

Name	Value	Description
$E^0{}_{Fe/Fe^{++}}$	−0.44 V vs. SHE	Iron oxidation equilibrium potential
i_0	0.00423 A/m^2	Iron oxidation exchange current density
β_a	0.41 V vs. SHE	Tafel slope for Iron oxidation
n	2	Number of participating electron for iron oxidation
α	0.5	Anodic charge transfer coefficient
W_a	0.0558 kg/mol	Molar mass of iron
ρ_a	7874 kg/m^3	Density of iron
D_a	7.19×10^{-10} m^2/s	Diffusion coefficient of Fe^{++} ion
$C_{electrolyte}$	50 g/l	H_2SO_4 concentration
T	25 °C	Electrolyte temperature

Table 2
Variable parameters (user defined) used for COMSOL electro-cleaning simulation.

Name	Value	Description
$i_{app,\ a}$	300–700 A/m^2	Applied current density on steel wire surface
t	1–500 s	Electro-cleaning time