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Tribological Properties of Carbon black added Acrylonitrile-butadiene Rubber

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Abstract The tribological properties of acrylonitrile-butadiene rubber (NBR) filled with two kinds of carbon black filler were examined. Different types of Semi-Reinforcing Furnace (SRF), and High Abrasion Furnace (HAF) blacks were used as filler material to test the influence of carbon black particle size on the friction and wear of NBR. Results from tribological tests using a ball on disk method showed that the smaller HAF particles were more effective for reducing the wear of NBR during frictional sliding. The hardness, elastic modulus at 100% elongation, and elongation at break were measured to examine the correlation between the effects of carbon black on the mechanical and tribological properties of the NBR specimens. The wear tracks of the NBR specimens were observed with scanning electron microscopy (SEM). The wear tracks for NBR with different ratios of SRF and HAF showed clearly different abrasion patterns. Mechanisms for the friction and wear behavior of NBR with different sizes of carbon black filler were proposed using evidence from wear track observation, as well as the mechanical and tribological test results.

Key words Rubber, Carbon black, Composite, Tribology.

1. Introduction

Rubber is widely used in various applications which are highly dependant on wear and friction characteristics, such as automobile tires, seals, shoe soles, conveyer belts etc[1-3]. Rubber by itself has insufficient resistance to wear for use in practical applications. Therefore, the addition of filler material is essential to improve the wear resistance of rubber products.[4] There are many types of fillers used to improve the material properties of rubber. Carbon black has proven to be both cost-effective and highly efficient for improving the wear properties of rubber.[5-7]

The addition of carbon black not only increases the wear resistance but also affects the friction characteristics of rubber products. Because most rubber applications need to meet certain frictional requirements, the effect that the addition of filler material has on the frictional characteristics of rubber must also be accounted for.[8-11]

In this study, two different kinds of carbon black were added at different ratios to observe the effect that carbon black size has on the wear and friction properties of rubber. When a certain critical ratio of carbon black was reached, there was a sudden change in the wear and friction characteristics of rubber. Observation of the mechanical properties and wear tracks of each rubber were used to explain the mechanisms which led to this sudden change in the wear and friction characteristics of rubber.

2. Experimental Procedures

2.1 Carbon Blacks

Carbon black fillers were purchased from DC Chemical Co., Ltd. Two types of carbon black were used, High Abrasion Furnace (HAF), and Semi-Reinforcing Furnace (SRF). The carbon black fillers were observed using scanning electron microscopy. The SEM images are shown in Fig. 1. The diameter of SRF was approximately 50-100 nm, while that of HAF was approximately 20-50 nm. Iodine adsorption is used to characterize the surface area of carbon black fillers. The iodine adsorption numbers of SRF and HAF are 29 mg/g and 81 mg/g respectively. X-ray diffraction patterns of the carbon black fillers are shown in Fig. 2. SRF and HAF both showed general carbon black XRD patterns with normal graphite peaks.[12,13]

2.2 Formulation

The type of rubber used was acrylonitrile-butadiene rubber (NBR). Rubber compounding was done using a 2-roll open mill using the formulation shown in Table 1. The ratio of SRF and HAF used in the experiments is

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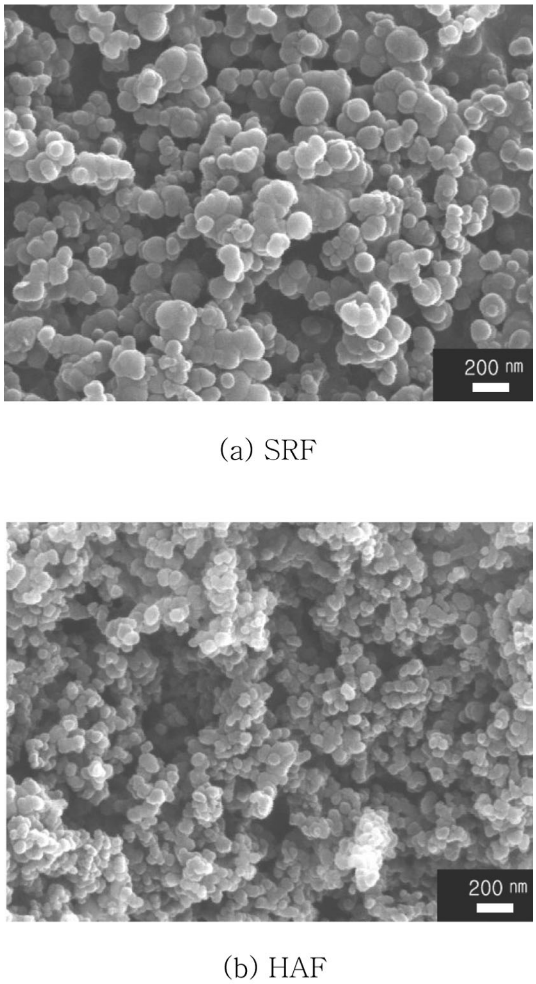

Fig. 1. SEM images of (a) SRF and (b) HAF carbon black particles.

shown in Table 2. Rubber mixtures were vulcanized at 160 for 15 minutes.

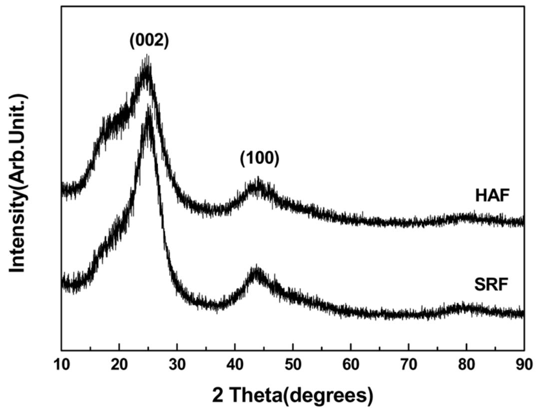

Fig. 2. XRD of carbon black fillers. Graphite peaks have been indicated.

2.3 Mechanical Properties

The hardness of the rubber specimens was measured in accordance with ASTM D2240. The elastic modulus at 100% elongation, and the elongation at break were measured in accordance with ASTM D412.

2.4 Tribological Properties

Tribological testing was done using a ball on disk method. Vulcanized rubber sheets were cut into 15 x 15 mm specimens for tribological testing. The rubber specimen was weighed using an electronic balance before being taped onto a holder with carbon tape. The holder was then fastened to the tribological tester shown schematically in Fig. 3. And the conditions used in the tribological tests are listed in Table 3.

The friction force between the counterpart and the rubber specimen was transferred along a mechanical arm from the counterpart to a load cell, where it was measured.

Table 1. Formulation and compounding ingredients of rubber specimens(wt%).

Ingredient	Content of mix(wt%)
Acrylonitrile-butadiene rubber	30.7
Carbon black	22.1
Zinc oxide	3.1
Polymerized 1,2-dihydro-2,2,4-trimethylquinoline	0.6
Tetramethyl thiuram disulfide	0.8
Tetrabutyl thiuram disulphide	0.6
Cyclohexyl-2-Benzothiazole Sulfenamide	0.9

Table 2. SRF/HAF filler ratios of rubber specimens.

Specimen	HAF0	HAF12.5	HAF25	HAF50	HAF75	HAF100
SRF/HAF Ratio (%)	SRF: 100 HAF: 0	SRF: 87.5 HAF: 12.5	SRF: 75 HAF: 25	SRF: 50 HAF: 50	SRF: 25 HAF: 75	SRF: 0 HAF: 100

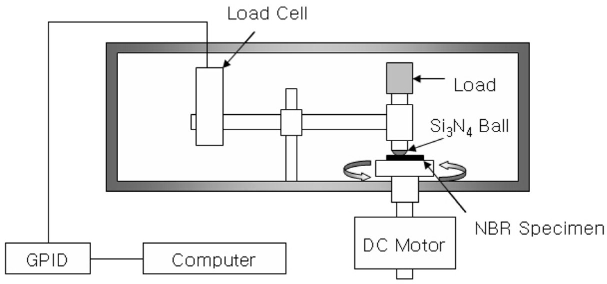

Fig. 3. Schematic diagram of the ball on disk tribological tester.

Table 3. Tribological test conditions.

Condition	Value
Counterpart	Si_3N_4 ball (diameter : 6.35 mm)
Applied load	1.96 N
Test time	1 hour
Sliding speed	2.62 m/s
Sliding distance	9425 m
Temperature	Room temperature

The friction force data was stored onto a computer through a General Purpose Interface Bus-board (GPIB). The wear loss was obtained by measuring the weight of the specimens before and after testing. Scanning electron microscopy was performed on each specimen to examine the wear surface.

3. Results and Discussion

SRF and HAF were mixed in different ratios with NBR to determine the effects of carbon black size on the tribological properties of carbon black.

The hardness and elastic modulus with respect to HAF ratio is shown in Fig. 4. Increasing the ratio of HAF particles increased the hardness and elastic modulus values of the rubber specimen. The smaller HAF particles were shown to be more effective at reducing the amount of deformation occurring due to external forces applied to the rubber.

The wear loss results from the tribological test are displayed in Fig. 5. The rubber specimen using only SRF as filler showed the highest amount of wear loss. As expected, the smaller HAF particles showed better reinforcement than the larger SRF particles. For small amounts of HAF there was only a slight decrease in wear loss. However, there was a sharp decrease in wear loss when the ratio of HAF was over 12.5%.

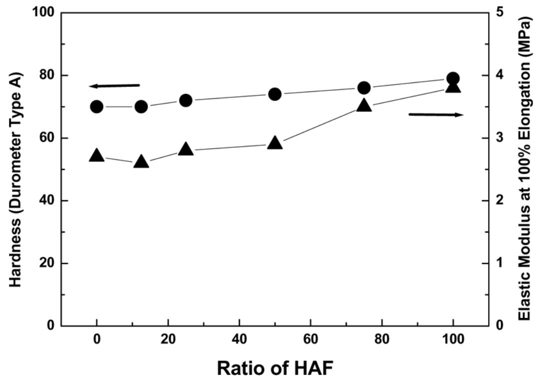

Fig. 4. Plot of hardness and elastic modulus at 100% elongation with ratio of HAF.

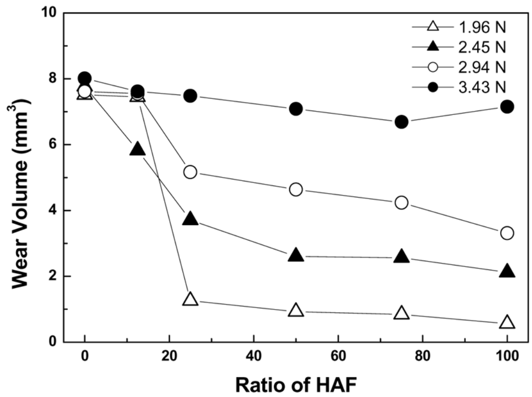

Fig. 5. Plot of wear volume with ratio of HAF at different applied loads.

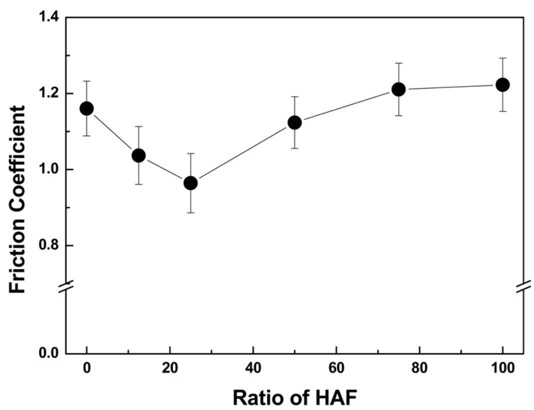

Fig. 6. Plot of friction coefficient with ratio of HAF.

The friction coefficient results of the tribological tests are displayed in Fig. 6. The friction coefficient gradually decreased with increased ratio of HAF until reaching a minimum value at 25%. Thereafter, the friction coefficient gradually increased as the ratio of HAF was increased. The specimen using only HAF filler showed the highest friction coefficient value.

The wear tracks were observed using scanning electron microscopy. Fig. 7(a) shows the wear track of the HAF0 rubber specimen. Sets of parallel ridges are seen on the wear track at right angles to the direction of sliding. These ridges are called abrasion patterns and are evidence of abrasive wear in rubber during frictional sliding.

Abrasive wear in rubber occurs when tearing of rubber occurs during sliding due to stress concentrations caused by deformation. During sliding of rubber with a hard material, rubber adheres locally to a point on the counterpart material and is stretched in the direction of sliding. This causes a stress concentration at the rear of the contact area, illustrated in Fig. 7. The rubber is in tension at this point, and repeated sliding causes the opening of tears in a direction at right angles to the direction of travel. This tearing causes the parallel ridges which combine to form the abrasion pattern. Therefore, the presence of abrasion patterns on rubber specimens with low ratios of HAF proves that heavy abrasive wear has occurred.

The wear track of the HAF100 specimen is displayed in Fig. 7(b). Although some scarring of the surface is observed, the distinct abrasion pattern and directionality observed in the HAF0 wear track is not evident. Thus, we can see that the wear that occurred for rubber specimens with high ratio of HAF was not caused by the same abrasive wear mechanism apparent in high SRF ratio rubbers. This absence of abrasive wear helps explain the significant reduction in the wear amount of high HAF ratio rubber specimens compared with that of high SRF ratio rubber specimens.

The absence of abrasive wear in high HAF ratio rubbers means that in contrast to the case of high SRF

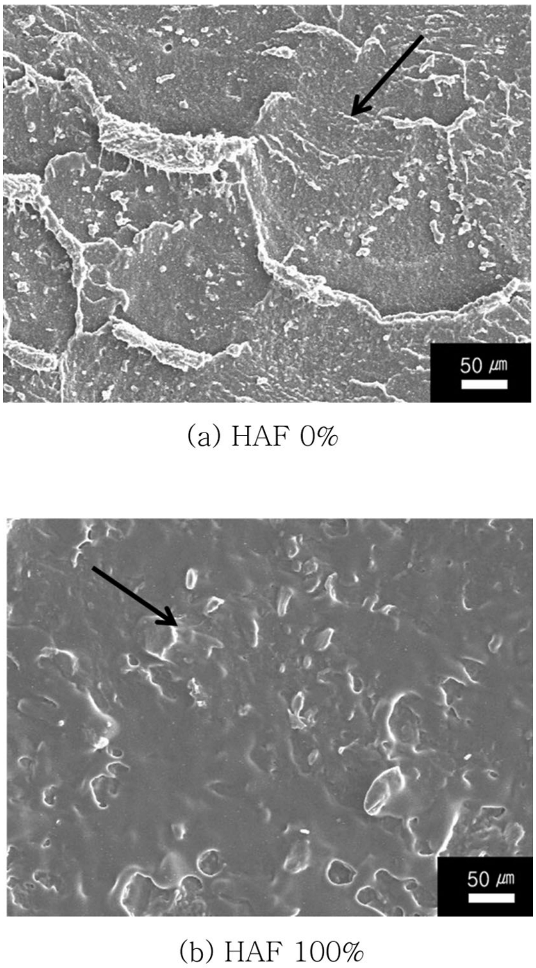

Fig. 7. SEM micrographs of the wear track of (a) 0% HAF and (b) 100% HAF ratio rubber at applied load of 1.96N (arrow denotes direction of sliding).

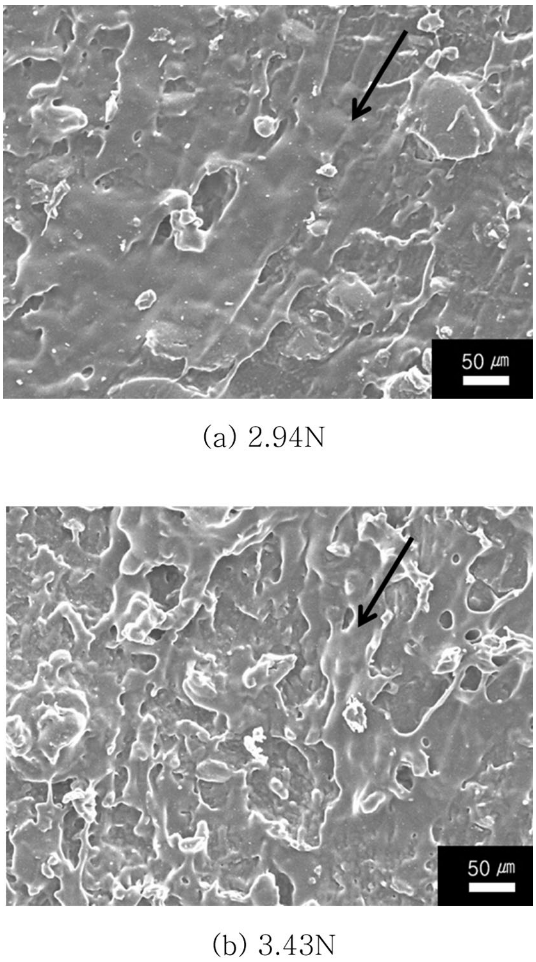

Fig. 8. SEM micrographs of the wear track of 100% HAF ratio rubber at applied loads of (a) 2.94 N and (b) 3.43 N(arrow denotes direction of sliding).

ratio rubbers tearing did not occur after repeated sliding. As was mentioned earlier, tearing is ultimately caused by stress concentrations produced when the rubber is severely stretched during sliding. Reducing the distance that rubber is stretched when stuck to the counterpart material during sliding reduces the stress concentration. Therefore, reducing the distance that rubber is stretched below a critical point resulted in the elimination of tearing and thus abrasive wear. This is supported by wear and mechanical test results (Fig. 4 and 5) which showed that increasing the HAF ratio made the rubber more difficult to stretch. After the HAF ratio reached 25%, stress concentration from stretching was insufficient to cause tearing during sliding.

Further tribological tests were performed on rubber specimens at applied loads of 2.45 N, 2.94 N and 3.43 N. The wear results were plotted in Fig. 5, with regard to HAF ratio. The abrupt transition from heavy to mild wear observed at 1.96 N becomes gradually less defined until it is nonexistent at 3.43 N. High SRF ratio rubbers showed very small differences in wear loss, whereas high HAF ratio rubbers were more affected by applied load changes. The wear loss of high HAF ratio rubber at 3.34N was similar to that of high SRF rubber. However, SEM images of the worn track of high HAF ratio rubbers at 3.43N do not show a similar abrasion pattern (Fig. 7 and 8). Instead, it is similar (albeit more developed) to the wear track of high HAF ratio rubbers at low applied load. From this we can conclude that abrasive wear, caused by tearing at areas of stress concentration caused by stretching of the rubber during sliding, did not occur for rubbers with high HAF concentration, even when a higher applied load caused much larger wear loss during sliding. Therefore, the wear of high HAF ratio rubbers at high applied loads must have been produced by the fatigue wear mechanism caused by the repeated compression and expansion of rubber during sliding. Minimum friction volume at 25% of HAF as shown in Fig. 6 must be related to the transition of the wear mode.

4. Conclusion

The effect of two different kinds of carbon black filler on the tribological properties of NBR was studied. Different ratios of SRF and HAF were mixed with NBR to produce the rubber specimens. Mechanical testing, tribological testing, and observation of the worn tracks produced the following conclusions.

The smaller HAF carbon black filler was more efficient in wear reduction than the comparatively larger SRF.

The friction coefficient decreased with higher ratio of HAF for rubber with high ratio of SRF until it reached a minimum value. Afterwards, the friction coefficient increased with higher ratio of HAF.

Observation of rubber specimens with high ratio of SRF revealed a distinct abrasion pattern on the worn surface. The abrasion pattern was formed by abrasive wear caused by tearing of the rubber surface under stress concentration due to stretching of the rubber during sliding.

Observation of rubber specimens with high ratio of HAF revealed the absence of a distinct abrasion pattern. The higher surface area of the smaller HAF particles helped reduce the stretching of the rubber surface which occurs during sliding, reducing stress concentration, and thus eliminating abrasive wear.

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