Tire with Self-Repairing Mechanism*

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A new type of tire is presented, in which there is no air leakage when nails puncture the tire. The broken part is repaired automatically by a self-repairing mechanism. The self-repairing unit consists of two rubber sheets with internal lattices. Polymer particles, which expand their volume on adding water, are inserted into the lattices. The unit is adhered to the inside wall of the tire. Coolant fluid diluted with water is introduced to the polymers uniformly. In this system, the polymer particles expand with water-diluted coolant fluid, and become gel. Hence, they stop air leakages in the tire. Fundamental experiments are performed, and optimum conditions are found. This technique is also applied to real tires, and it is ascertained that there is no air leakage when the tire is punctured by nails.

***Key Words*:** Tire, Nonpuncture, Self-Repairing, Non-Air Leakage, Polymer, Sealant

1. Introduction

A number of nonpuncture tires, such as tires involving soft rubber or urethane materials have been reported. In the tires, however, the vibration transmissibility is large, and both the driving stability and feeling in the automobile are unsatisfactory, in addition, it is difficult to have high running speed. Therefore, tires with air inside are desirable for high-speed automobiles. Recently, some maintenance methods have been developed, such as a telecommunication technique in which tire pressures are measured and sent to a monitor(1) and a device supplies air to the tire according to the tire pressure(2). The nonpuncture technique was also developed for the motorcycles where the tires have two chambers, one filled with fluid and the other filled with air(3). Dual tube tires have also been developed for motorcycles(4). Recently, a tire called the run-flat tire was developed, in which the side walls are strengthened by thick hard rubber or metal rings. The air-loss speed is reduced, and the tire is able to run for about 200 km after being punctured. In those tires, although air-loss speeds are reduced, punctures cannot be stopped.

As mentioned above, previous research has been focused on reducing air-loss speeds. However, if the broken part can be repaired automatically by a self-repairing mechanism, changing the tire will not be necessary. In addition, if the self-repairing portion can be made of soft elastic materials, the transmissibility will be retained at almost the same value as that of normal tires. However, no research on such a situation has been reported. The object of the present study is to develop a new tire with a self-repairing mechanism, in which the broken part is automatically repaired. In this paper we present the principle of the self-repairing mechanism and the optimal conditions based on the results of fundamental experiments. To validate the principle, the nonpuncture tire is made, and its characteristics are investigated.

2. Structures and Principle of Self-Repair

Figure 1 shows the structure of the proposed tire, and Fig. 2 shows the cross section. A sealant layer (putt in Figs. 1 and 2) is bonded along the inner surface of the tire. The sealant layer comprises polymer particles, which expand upon contact with water, and has sewn lines to create lattices (the effect of the sewn portions will be reported in the next article). When water flows into the lattice, the polymer particles expand and becomes gel-like, creating a high pressure is generated in the lattice (see Fig. 3). This pressure closes the puncture hole in the lattice. Water leakage is prevented when the pressure due to the polymer particles is greater than the water pressure. When the sealant included both polymer particles and water, the same principle will be valid. Consider a tire with the sealant, which is punctured by a nail that is then removed. The pressure of the sealant due to polymer expansion repairs the

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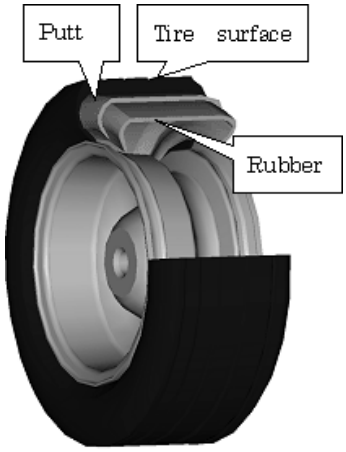


Fig. 1 Structure of the present tire

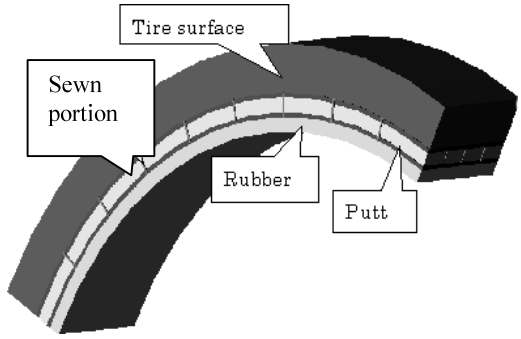


Fig. 2 Cross section of the tire with self-repairing sealant

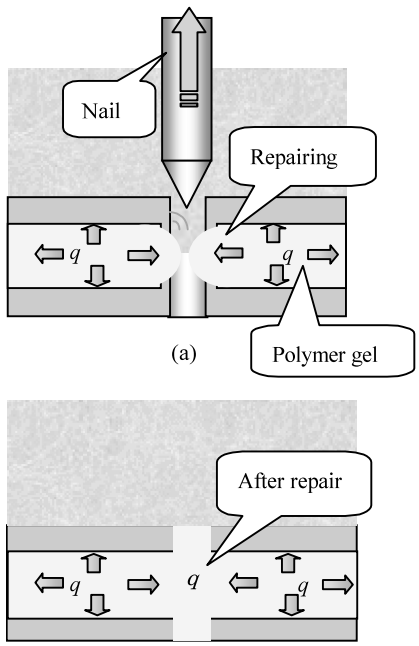


Fig. 3 Principle of self-repair

hole. In the sealant, however, there are some problems because high-pressure air moves the polymer particles and creates airflow in the sealant. Then it is difficult to stop air leakages by the principle just mentioned. However, when using, for example, paste, the movement of polymer particles is restricted and air leakages can be stopped. This also prevents the movement of polymer gels when an automobile starts or stops suddenly. Since the polymer gel bonded by adhesive materials becomes solid upon contact with air, the gel does not leak out from the puncture hole. The adhesive material should also be stable in a heated atmosphere (see later). For this reason, the adhesive material for rubber is chosen, because its adhesion speed is slow, and it does not become hard in sealant without air. In addition, it is suitable for bonding the polymer gels to the rubber cover sheet. The durability is also maintained when the polymers include both water and adhesive material. There was no variation of the polymer characteristics after three years. However, the adhesive material prevents the absorption of water by the polymer particles, because it covers the surfaces of the particles, and its volume is important.

Since automobiles are used in both hot and cold atmospheres, the sealant should be stable against temperatures. Therefore the polymer called Sun-Fresh (Sanyo Chemical Co., Ltd.) is chosen as the water-absorbing material. The particle diameters are in the range from 150 to 710 μm. It absorbs about four hundred times as much water as its own weight, is unaffected by temperature, and is stable in the range of $pH4$ through $pH10$. However, its characteristic varies under ultraviolet radiation and at temperatures greater than 150°C. Since the sealant is inside the tire, ultraviolet rays are absent, and the temperatures are in the stable zone because the maximum temperature will be less than 90°C in practical use.

The fluid in the sealant also should be stable at temperatures from +90°C through −40°C. Hence conventional water cannot be used. Therefore, in the present study, we apply water-diluted coolant fluid made of 95 wt.% ethylene glycol and a small amount of corrosion-preventing fluid. It does not evaporate or freeze when it has less than 60 wt.% water. Although the coolant fluid prevents polymer expansion, sufficient expansion is possible when using water-diluted fluid. The volume of fluid is important because high pressures cannot be obtained with small volume, and air will pass through the sealant with large fluid volume because the gel will become less viscous. Therefore there is an appropriate proportion of the weights of polymer and fluid.

A thick sealant can repair the broken part easily, but a light weight and cheaper tire is desirable. Therefore, the limit of the sealant thickness is also important in the tire. These are investigated in the following experiments.

3. Experimental Apparatus

Figure 4 shows a leak test apparatus used in this experiment. In the figure, pressure vessel 1 made of alu-

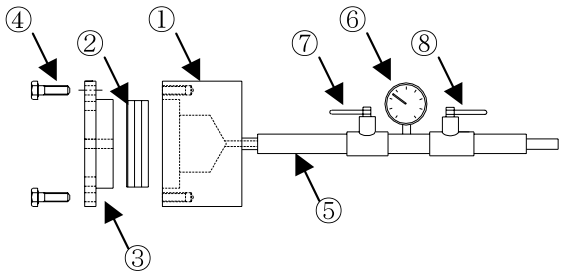


Fig. 4 Experimental equipment

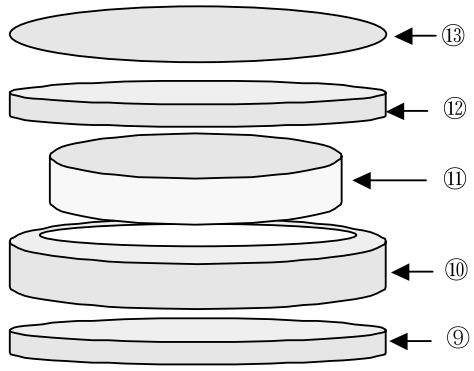


Fig. 5 Test piece used in the experiment

minum has a cavity with a step at its end for installing a test specimen. Test specimen 2, which is inserted in the step, is connected to the vessel by cover plate 3 and bolts 4. The cover plate has a hole 8 mm in diameter, where the nail passes through and pierces the test piece. Pressure gauge 6 is connected to the other end of the vessel, and valves 7 and 8 control the airflow from a compressor. When compressed air flows into the vessel and valve 8 is closed, the pressure in the vessel is measured by pressure gauge 6.

Figure 5 shows the elements of the test specimen (sealant) whose composition is essentially the same as that in Figs. 1 and 2. The elements are as follows: circular rubber plate 9 of 2 mm thickness which is assumed to be the tire surface, rubber ring 10 that prevents air leakage from the test equipment, polymer layer with the adhesive material 11 and circular rubber plate 12 of 1 mm thickness. These are bonded together into a circular sealant plate (test specimen). The fluid is supplied to the polymer layer 11 by an injector, and thin rubber plate 12 of 1 mm thickness covers injection holes. The adhesive material is a conventional rubber paste made 73.5 wt.% rubber, 20 wt.% normal hexagon and natural rubber with 6.5 wt.%.

In the experiment, a test specimen is pierced by a nail and then the nail is removed, and air leakage test is performed for the specimen with the punctured part.

4. Experimental Results

Five punches are used for puncturing the specimen, as described below: nails of 3.4 mm, 4.2 mm and 5.25 mm in diameter, and a punch of 6 mm in diameter.

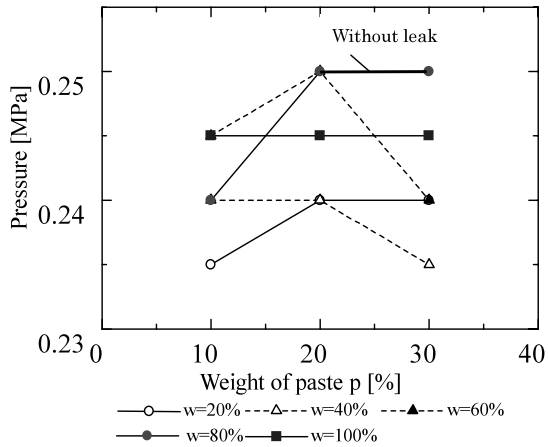


Fig. 6 Pressure versus weight percent of paste ($h = 6$ mm)

The sealing ability increases with increasing volume of fluid, but the gel becomes less viscous with a large volume of fluid. In order to restrain the movement of gel, adhesive material is supplied to the polymer. However, it inhibits the absorption of water by polymer particles. Therefore, an appropriate proportion of the weight of the fluid and that of paste should be found.

Figure 6 shows the pressure in the test vessel versus time for the sealant with 6 mm-thick polymer after 5 hours when the sealant is pierced by the nail of 3.4 mm diameter, after which the nail is removed, where p is the weight percent of paste, and w the weight percent of fluid (coolant = 50% and water = 50%). The pressure is 0.25 MPa in the vessel, and thus there is no air leakage when the pressure is maintained at 0.25 MPa. The figure shows that there is no air leakage when the paste weight is greater than 20% and water weight is greater than 60%. This shows that the sealant can stop the air leakage, but its thickness is somewhat large in practice. The effects of thickness are also investigated.

Figures 7 though 9 show the results for the sealant with 4 mm thickness, where the mass per unit area is 0.25 kg/cm^2. The initial pressure in the test vessel is 0.25 MPa, and d [mm] shows the nail diameter in the figure. Figure 7 depicts the effects of nail diameters on the pressure for the sealant of 4 mm thickness. There is no air leakage when the nail diameter is less than 4.2 mm, while the pressure decreases suddenly the instant the nail is removed, when the nail diameter is greater than 5.25 mm, but subsequently, the pressure becomes constant. The pressure-decreasing rate is only 2% in this case. When the weight of water decreases, the weight of paste can be reduced, and the tire weight will be decreased. From this standpoint, the experiment is performed with various mixing ratios of paste to water. The results are shown in Figs. 8 through 9. The most suitable condition is the combination of $p = 30\%$ and $w = 80\%$. The two sets of data lie

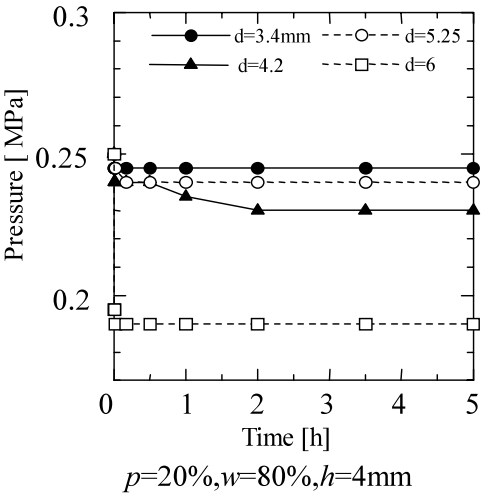


Fig. 7 Pressure versus time for various nail sizes

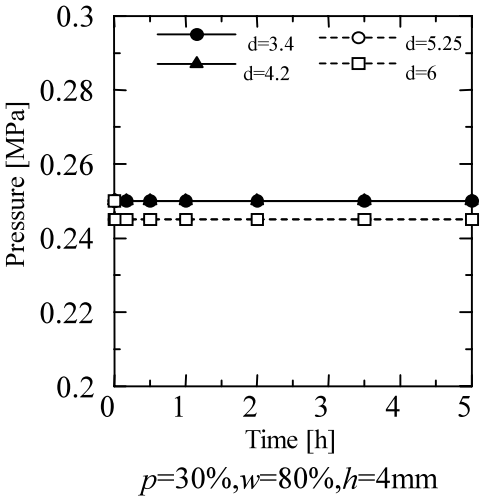


Fig. 8 Pressure versus time for various nail sizes

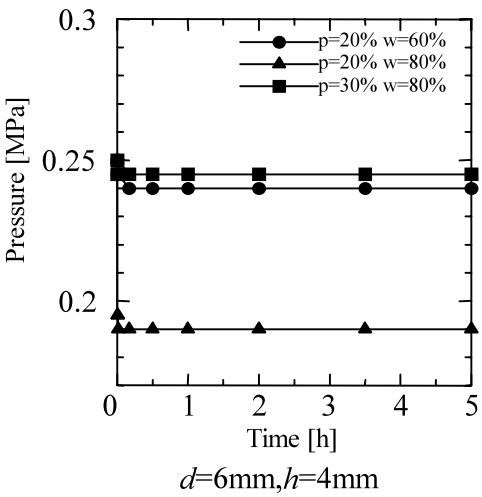


Fig. 9 Pressure versus time for various volumes of water

on the same axis because air leakage time is small. The time for self repairing is less than one minute in every case.

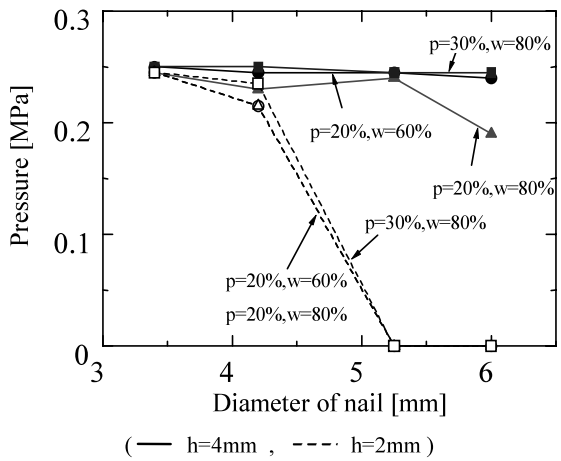


Fig. 10 Pressures versus nail diameters after five hours

Results for the sealant of 2 mm thickness (mass density per unit area is 0.125 g/cm^2) are also obtained. Figure 10 shows the effects of polymer thickness for five hours after the sealant was pierced by the nails.

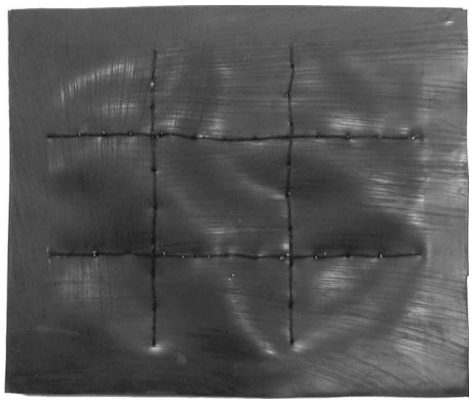
The appropriate values for the weight percents of paste and water are the same as described above in this case, and the limitation of the nail diameter is 4.2 mm. Therefore, the 2 mm thickness is dangerous in practical use. On the basis of these discussions, the appropriate thickness of the polymer layer is concluded to be 4 mm.

There are some problems in practical applications, one of which is the sewn portion. On the sewn portion, the thickness is small due to the sewing pressure, and the volume of polymer becomes small. To maintain a constant thickness, a net is applicable, because the net keeps the polymer particles in its lattices. In addition, the surface of the sealant has an uneven shape due to the expansion of polymer particles, but the shape becomes flat after pressing.

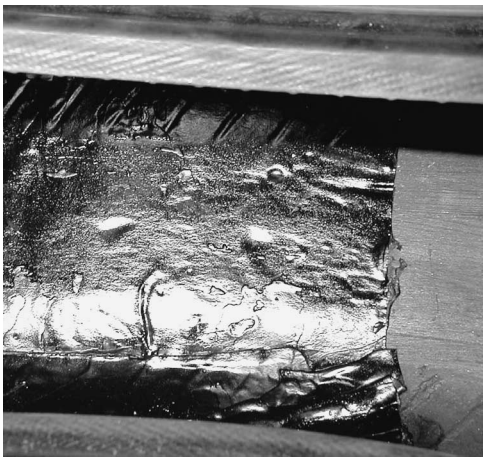
5. Nonpuncture Tire and Its Characteristics

5.1 Static characteristics

Using the results of the abovementioned experiments, a nonpuncture tire is made. Figure 11 depicts the process of making the nonpuncture tire. For the nonpuncture portion, a rubber plate (thickness = 4 mm) with a rectangular hole is pasted on a thin rubber plate (thickness = 1 mm). Rubber paste is mixed in polymer particles, where the proportion of the paste is 30 wt.%. These polymer particles are stacked in the rectangular hole, and the hole is covered by a thin rubber sheet (thickness = 1 mm). The plate with the polymer layer is sewn, as shown in Fig. 11 (a). To perfect the bonding, a butyl rubber sheet is bonded to the inner surface of the tire before bonding the sealant, because the inner surface of a tire is uneven (see Fig. 11 (b)). The sealant plate is bonded to the butyl rubber sheet, and the fluid is injected inside the lattices (see Fig. 11 (c)). After that, a thin rubber sheet is pasted over the sealant. In order



(a)



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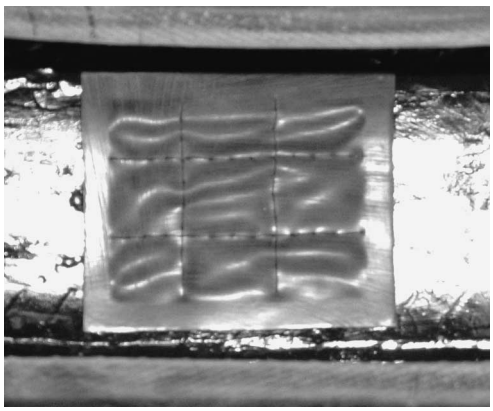

(c)

Fig. 11 Process of making nonpuncture tire

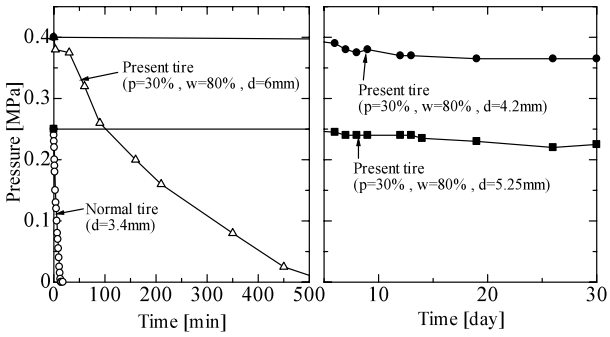

Fig. 12 Pressure versus time for the nonpuncture tire

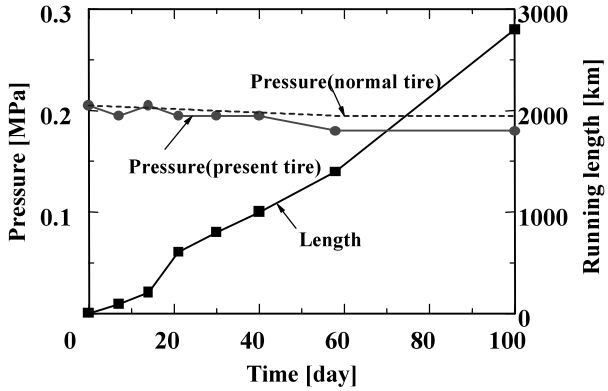

Fig. 13 Results of a mounting examination

to maintain balance, the same sealant is pasted at exactly the opposite side of the tire. After attaching the wheel to the tire and injecting air, the nonpuncture tire is complete.

First, a normal tire of 0.25 MPa pressure was pierced by a nail of 3.4 mm diameter which was then removed. The air pressure in the tire became zero after only eighteen minutes (see the white dots in Fig. 12). Our nonpuncture tire of 0.25 MPa pressure was also pierced by a nail of 5.25 mm diameter. The air pressure in the tire did not vary after five hundred minutes. The pressure decreased about ten percent after thirty days.

The pressure of truck tires is about 0.4 MPa, so the experiment was also performed at this pressure. The results are shown by the black dots in Fig. 12. There was air leakage when the nail diameter was large ($d = 6$ mm), but not when the nail diameter was less than 4.2 mm, after five hundred minutes. The pressure decreased about nine percent in thirty days. As just mentioned, there was only a slight pressure drop after many days. The leaks occurred at the time of pressure measurement, because air leakage was not found when the tire was checked in water.

5.2 Characteristics in running

The tire was mounted on an automobile after improving the balance, and the sealant of the tire was pierced by the nail of 3.2 mm diameter. Figure 13 depicts the results of running tests, in which the left axis is the tire pressure, and the right axis the running length. The solid line shows the results for the nonpuncture tire with the above-mentioned punctured part, and the dashed line shows the results for a normal tire without a punctured part. The air pressure decreased about 0.01 MPa in the normal tire without any punctured part. This shows that there are natural air leakages in the tire. The pressure decrease of our tire was about 0.025 MPa after sixty days of running. The difference is due to the air leakage when measuring pressure. It can be seen that there was significantly small air leakages in the range from 60 days to 100 days, where the pressure was measured only twice. The small varia-

tions of pressure will be due to variations of temperature. Therefore, the punctured part was perfectly repaired, and the self repairing mechanism was maintained for a long term.

In the previous run-flat tire, the running length was less than 200 km after puncture, while our tire had no air leak until 3 000 km (100 days) after puncture. Therefore our tire has advantages in comparison with run-flat tires. In our experiment, a sealant patch was bonded at the inner surface of the tire. In the nonpuncture tire, the entire inner surface of the tire would be covered by sealant.

The performance of the sealant is better when a nail remains in the tire, because the punctured part is small in such a case.

6. Conclusion

A nonpuncture tire based on a new self-repairing principle was presented. The self-repairing ability was realized by using sealant bonded to the inner surface of the tire. The punctured part was repaired by the pressure generated by the expansion of polymer particles in the lattices made in the sealant.

The polymer expansion was achieved by injecting polymer-expansion fluid into polymer particles. The appropriate proportion of the weight of the adhesive material to that of polymer was about 30 percent, and the appropriate proportion of the polymer to fluid was 80 percent. The sealing effect was large when the thickness of polymer sealant was large. The appropriate thickness was about 4 mm from an economical point of view. There was no air leakage at 0.4 MPa (the truck tire) when our tire was pierced by a nail of 5.25 mm diameter. There was also no air leakage after one hundred days of running (running length = 3 000 km) when the tire was pierced by a nail of 3.4 mm diameter.

References

(1) Grossmann, R., Quartz Crystals as Remote Sensors for Tire Pressure, Conf. IEEE Instrument Technol. Conf, Vol.16, No.3 (1999), pp.1745–1749.

(2) Bradley, J., Eckhardt, L. and Soznala, F., Design of Emergency Tire Inflation System for Long Haul Trucks, SAE Tech. Pap. (Soc. Automot Eng.), SAE-95.2592, (1995), p.4.

(3) Yamagiwa, T., Nakayama, K., Kiyota, S., Tanaka, A. and Makisaka, N., Development of Puncture Resistance of Tire Tube, Preprint of Society of Automotive Engineers of Japan, No.976 (1997), pp.279–282.

(4) HONDA NO NIRIN GIJYUTU, ATARASHII BOUSIEKI NO KOUKA, Car and Maintenance, Vol.51, No.1 (1997), pp.40–41.