

Development of High-sealing Foamed Rubber Gasket Material

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ABSTRACT

A high-performance durable formed rubber gasket material characterized by both superior compressive recovery and adaptability to rough surfaces was developed for automotive internal combustion engine sealing applications. Research was performed on gaskets exhibiting high sealing properties and a simplified fastening structure. As a result of the research, a gasket was produced with low surface pressure sealing properties that far exceed those of the conventional gasket materials due to the structure of the base rubber material, which is a foamed rubber material with a closed cell construction, and the optimization of the additive composition. The application of this gasket to an engine intake system facilitates the streamlining of the fastening structure.

1. Introduction

Internal-combustion engines that are lighter, more compact, and less expensive are a universal goal of the automobile industry. Recent progress toward achieving this goal includes the switch by automobile manufacturers from aluminum alloys to resin materials, and magnesium alloys as structural materials principally for air intake system parts, and the development of lightweight, compact engines through part modularization. Against this background, the field of fastening seal structures is facing the inability of rubber coated metal (RCM), joint seats, molded rubber rings and other conventionally used materials to provide the requisite sealability in some areas. This is due to lower seal surface flatness and increased roughness, lower flange stiffness, fewer joint bolts, and smaller bolt sizes. Thus, materials capable of sealing at lower joint surface pressures are needed⁽¹⁾⁻⁽³⁾.

In response, the authors have used a high-compressive-recovery foaming material to develop a gasket material that offers better low-surface-pressure sealability than existing gasket materials.

2. Determinants of Sealability

2.1. Analysis of Sealability Performance Factors

In a given fastening state, possible sealing pressure is generally determined with the experimental equation (1) below. Thus, sealability can be improved by raising the gasket coefficient, surface pressure, and surface roughness.

$$\text{Possible seal pressure} = k \times \rho \times \exp(p \times r) \quad (1)$$

k: Gasket coefficient
 ρ : Seal medium viscosity
 p: Surface pressure
 r: Surface roughness

These sealability determinants can be further divided into sealing surface conditions, tightening force, flange stiffness, and gasket material properties (Fig.1). Improving any one of these factors will improve sealability and thereby achieve advanced performance. However, improvements made with existing technology have run counter to the goal of lightweight, low-cost engine components.

Thus, reconciling reduced weight and low cost on the one hand with sealability in a system requiring seals on the other calls for a technique whereby the compressive recovery of the gasket is improved and, at the same time, surface hardness (an indicator of conformability to the sealing surface) is lowered in order to improve the sealability of the gasket itself and to compensate for the lower sealability that results from reduced flange thickness (stiffness), fewer bolts (tightening force), and the elimination of surface processing, to thereby assure a lightweight and low cost gasket.

More specifically, a decreased weight, a streamlined fastening structure, low cost, and sealability are all possible with a high-performance gasket possessing sufficiently high compressive recovery, low surface hardness, and excellent durability and reliability to offset the reduced fastening seal functionality that has resulted from the switch to materials

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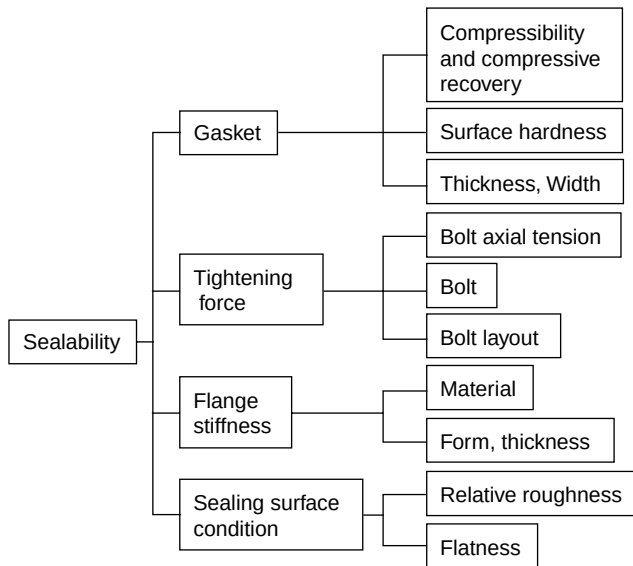


Fig.1 Sealing performance factor analysis chart

such as resins and magnesium alloys primarily in engine air intake system parts in recent years.

2.2. Improving the Compressive Recovery of Gasket Materials

NBR, FKM and other heat-resistant rubbers are currently the most widely used rubbers in automotive engine gasket applications where low hardness and high compressive recovery are required. The authors chose the approach of achieving even greater compressive recovery by intentionally creating air spaces in this type of rubber in order to combine the elasticity of rubber with that of gas. Such structures, generally referred to as foamed rubber, are widely used as fillers and damping materials for electrical appliances.

Fig.2 shows an evaluation model for the compressive recovery of a single cell in foamed rubber. This model, in which a rubber tube is placed between two aluminum alloy plates that simulate the flange surfaces, permits use of the desired gas in the air space and the setting of the desired pressure. Table 1 gives the conditions under which the compressive characteristics of rubber and air were evaluated with this model.

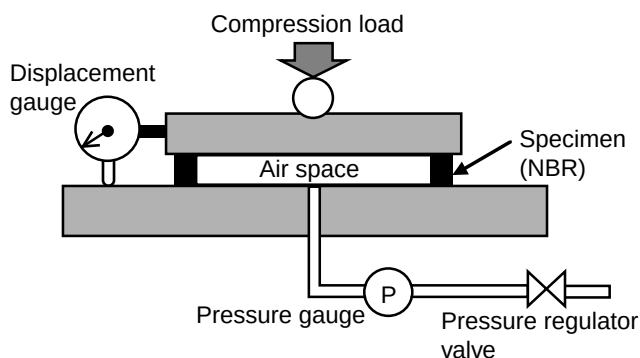


Fig.2 Compressibility evaluation model

Table 1 Compressibility test condition

Specimen specification	
Diameter	40.0 mm
Thickness	6.0 mm
Material	NBR
Rubber hardness	60 Hs
Compression speed	0.1 mm/min

Even at low compression surface pressures, the gas exhibits greater compressibility than the rubber (Fig.3). In particular, at a surface pressure of 5 MPa or less, the gas has more than twice the compressibility of rubber.

Fig.4 shows the change in compressibility at different gas volumes, determined by changing the gas volume in a simple model of rubber and gas, and demonstrates that compressibility increased with gas volume, in almost perfect agreement with the theoretical line.

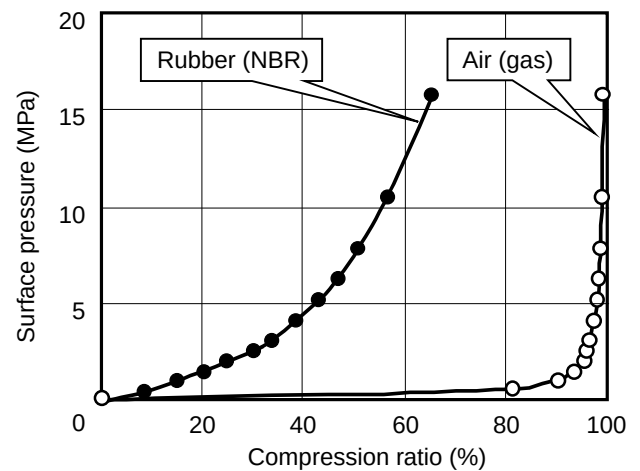


Fig.3 Comparison of compressibility between rubber and air

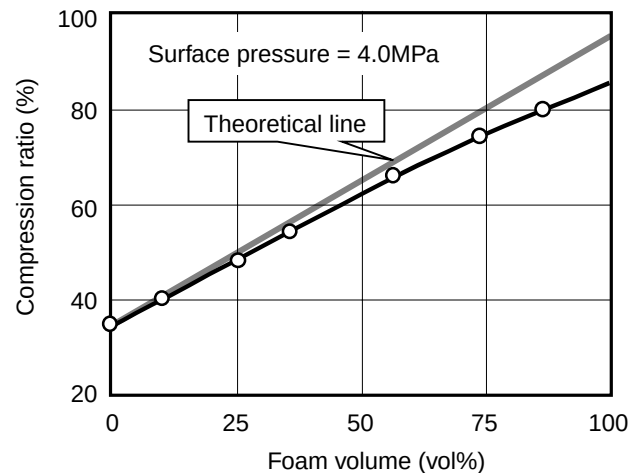


Fig.4 Relationship between volume function of air and compression ratio

The preceding demonstrates that the combining of rubber and gas is a logical method for improving the sealability determinants of low hardness and high compressibility, as the result is a compressibility that increases with gas content per unit of volume.

Next, the authors examined how compression characteristics are affected by the method of fixing gas in the rubber in two types of foam: an open-cell foam, in which cells are exposed to outside air, and a closed-cell foam. These open- and closed-cell models were created by opening or closing an air valve that connects the air spaces in the rubber sample shown in Fig.2. The results (Fig.5) indicate a marked difference in compressive recovery between these two types of foam, i.e., open and closed-cell: closed-cell foam had a compressive recovery rate 1.5 times higher than open-cell foam. This is because in closed-cell foam, the air is unable to escape to the outside and so its elasticity supplements the system's compressive recovery.

Thus, closed-cell foam, having better compressive recovery than open-cell foam, can provide greater pressure-resistant sealability and so is superior as a gasket material.

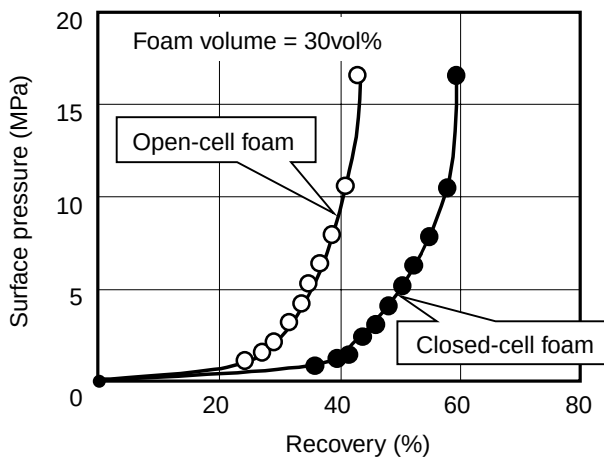


Fig.5 Relationship between foam cell type and compressive recovery

3. Rubber Foaming

The most commonly used method of rubber foaming is chemical foaming, in which a pyrolytic foaming agent such as azodicarbonamide is added to rubber, which is then heated to generate N_2 , CO_2 and other gases that are dispersed throughout the rubber. This technique makes it relatively easy to create a foam structure, and results in foamed rubber with relatively large (100 to 500 μm), cross-linked air bubbles. Fig.6-a is a cross-section photograph of chemical foaming.

As for the suitability of such foamed rubber for sealing parts, the high compressibility promised by Fig.4 is achievable, but the cross-linked air bubbles make it difficult to achieve high compressive recovery (Fig.5) and, moreover, permit the seepage of the sealing medium, eventually culminating in leakage, a fatal defect for a gasket material.

To compensate for this shortcoming, the authors turned to micro-capsule foaming, which disperses relatively small,

closed (i.e., non-cross-linked) cells throughout the rubber. This is done by filling a vinylidene chloride capsule wall with a low-boiling-point hydrocarbon, which is a liquid at room temperature but which expands upon heating, to thus yield foamed rubber. Foamed rubber produced by this method contains closed-cell, microscopic air bubbles as small as 20 μm (Fig.6-b) and has greater compressive recovery than open-cell foamed rubber (Fig.7). The disadvantage of micro-capsule foaming is the difficulty of manufacturing : For example, it is difficult to mix the rubber and the capsule because of the capsule wall's low solvent resistance, while foam properties are highly dependent on foaming conditions. To achieve the consistent production of a gasket material with both high sealability and durability, the authors chose the material specifications described in the following section for a foamed rubber gasket produced by micro-capsule foaming.

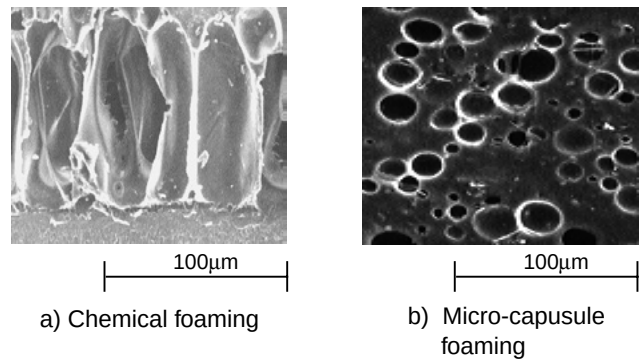


Fig.6 Cross section pictures of foamed rubber

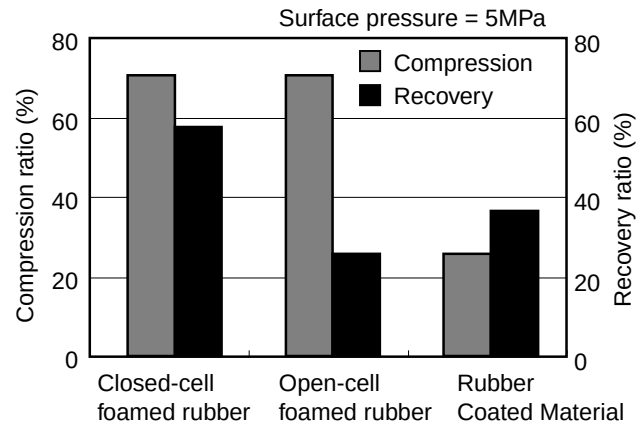


Fig.7 Compression characteristics of foamed rubbers

4. Material Specifications for a Foamed Rubber Gasket

4.1. Elements of a Foamed Rubber Gasket

A foamed rubber gasket produced by micro-capsule foaming has a structure such as that shown in Fig.8, and its primary sealability determinants are cell structure, base rubber, and primer (Fig.9)⁽⁴⁾⁽⁵⁾. The authors determined the optimum specifications for a high-performance gasket for these parameters.

4.2. Base Rubber Properties

With the microcapsule technique, the foam properties of foamed rubber are greatly dependent on the Mooney viscosity of the base rubber. Foaming properties are excellent when the rubber's Mooney viscosity is below 50 poise, but drop sharply as Mooney viscosity exceeds this value (Fig.10).

4.3. Foaming Conditions

To obtain good foaming conditions, micro-capsule expansion must occur below the temperature at which the base rubber begins to vulcanize (Fig.11).

This entails determining the proper foaming temperature by considering the method of rubber vulcanization and the solvent injected (i.e., a low-boiling-point hydrocarbon).

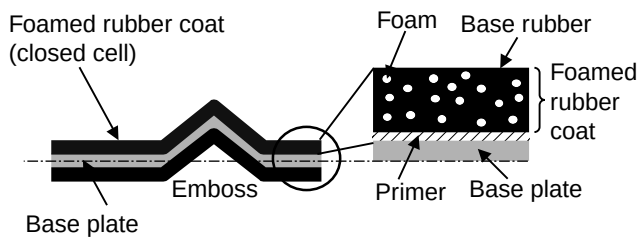


Fig.8 Schematic drawing of foamed rubber gasket

Table 2 Foaming test conditions

Foaming temperature	150°C
Foaming time	30 min
Micro capsule content	10 PHR

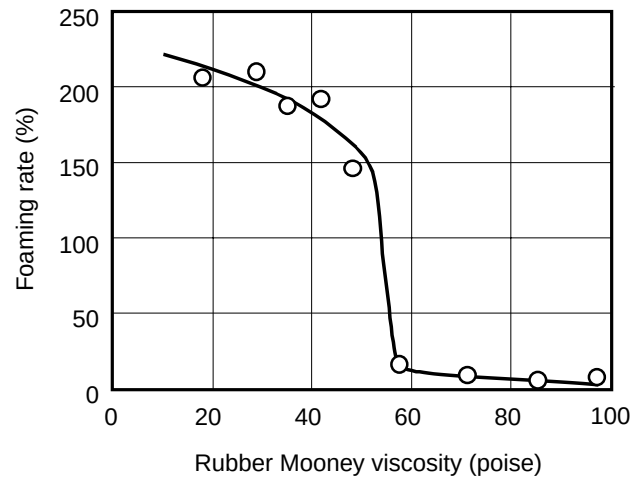


Fig.10 Relationship between rubber Mooney viscosity and volume function of foaming

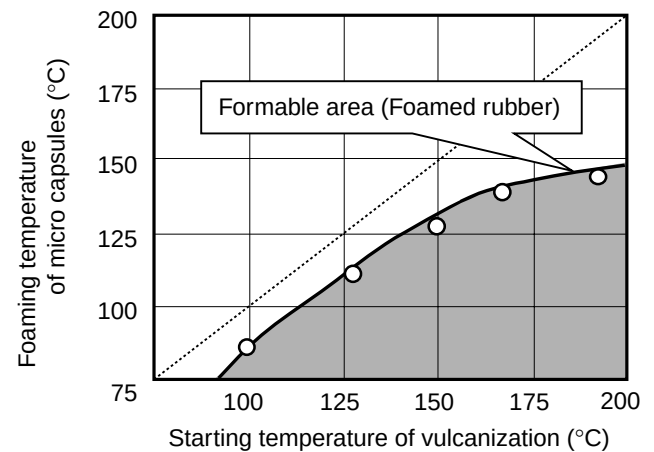


Fig.11 Formable area in foamed rubber production

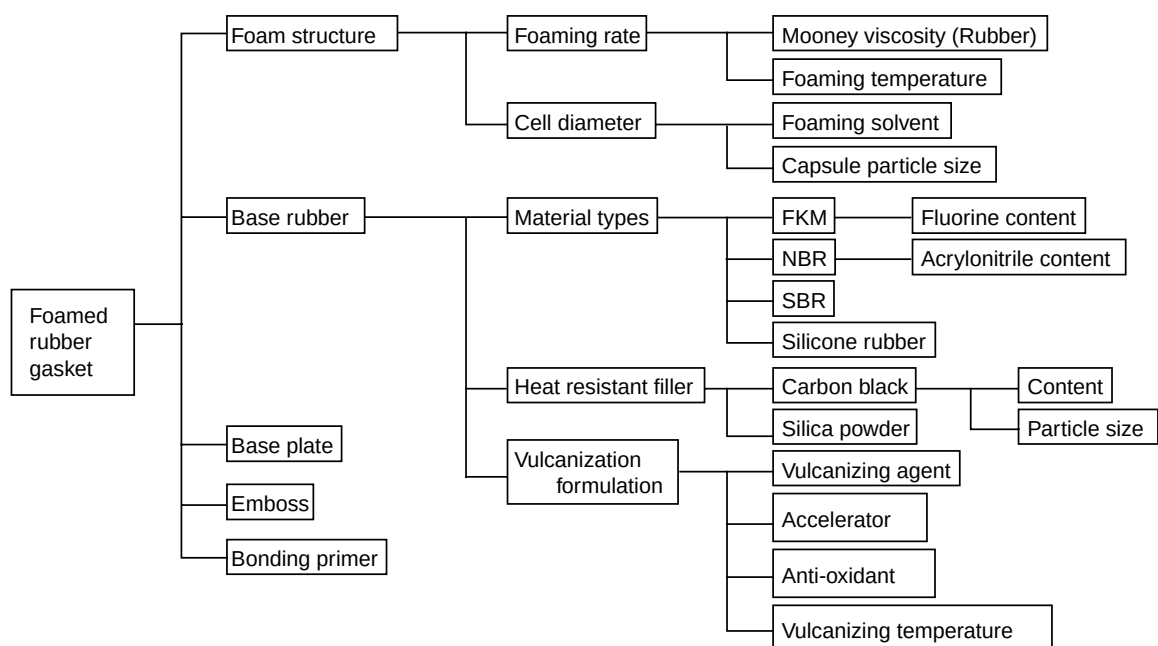


Fig.9 Component parts drawing of foamed rubber

4.4. Defining the Base Rubber Specifications

Base rubber selection must consider the environment in which gasket parts are used. As a representative example, this section considers fluorine rubber, which, among rubbers, offers exceptional thermal and fuel oil resistance. The base rubber to be used as the substrate for a foamed rubber gasket requires excellent durability and reliability in order to assure retention of cell structure, one of the necessary properties.

Fig.12 shows how compression set, which is an indicator of base rubber (fluorine rubber) durability, tends to decrease as fluorine content is increased, and that compression set can be minimized with a fluorine content of 65% or more.

Fig.13 shows the effect of carbon black content, another determinant of the base rubber's thermal resistance. Essentially, a base rubber with higher carbon black content undergoes less compression set and exhibits consistent thermal resistance at a content of 60 PHR or more.

4.5. Defining Cell Structure

In designing gasket parts using the foamed rubber material thus created, the authors focused on the foamed

rubber's cell structure in their investigation of the relationship between sealability and material specifications. Figs.14 through 16 give the results of evaluation of possible sealing pressure and compression set (indicators of sealability and durability, respectively) for different combinations of three determinants of foamed rubber properties: foaming rate, particle size, and coating thickness. The test conditions are given in Table 3.

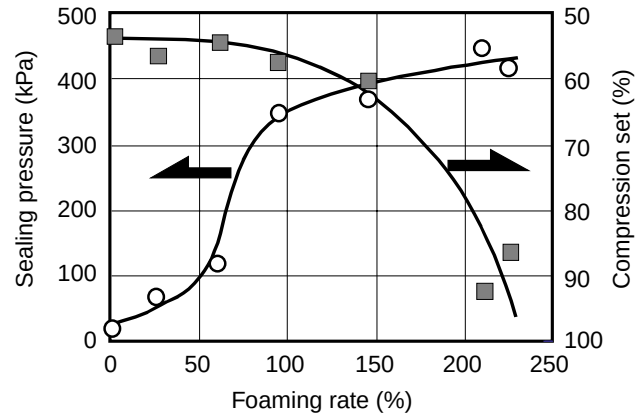


Fig.14 Optimization of foaming volume in relation to sealing performance and compression set

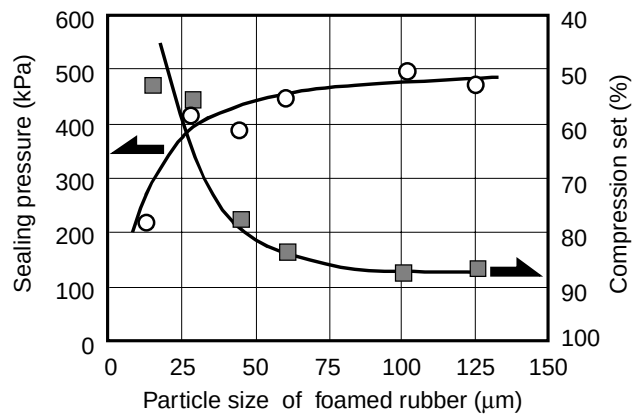


Fig.15 Optimization of particle size in relation to sealing performance and compression set

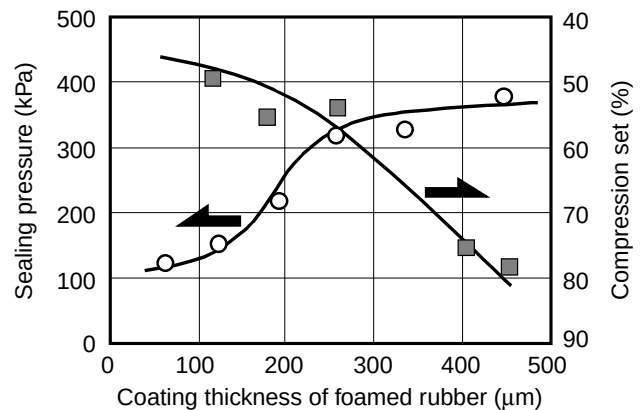


Fig.16 Optimization of coating layer thickness in relation to sealing performance and compression set

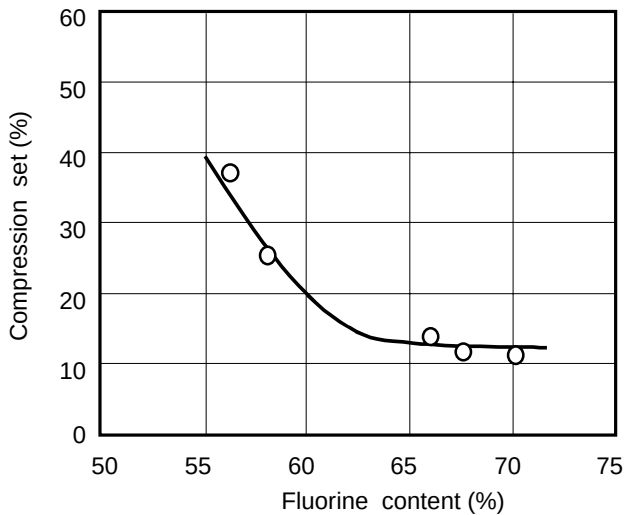


Fig.12 Relationship between fluorine contents and compression set

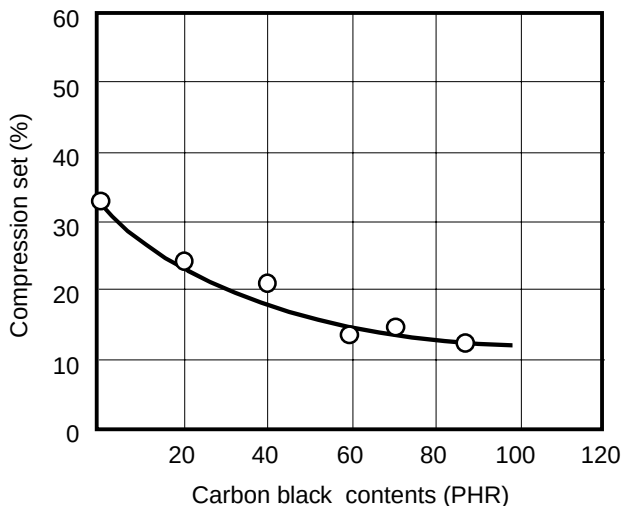


Fig.13 Relationship between carbon black content and compression set

Table 3 Components of foamed rubber and sealing test conditions

Base rubber	FKM (F content=65%)
Carbon black content	60PHR
Foam type	Closed-cell
Foaming temperature	150°C
Vulcanizing temperature	250°C
Foaming rate	120% (basic)
Particle size of foam	25 μ m (basic)
Thickness	80 μ m (basic)
Seal test conditions	Surface pressure=0.5MPa Sealing temp=-30°C
Compression set test conditions	Heating temp=120°C Holding time=24hr

The relationship of foaming rate (Fig.14) to sealability and compression set is such that a higher foaming rate results in better sealability but worse compression set. Larger particle sizes (Fig.15) improve sealability but worsen compression set. A thicker coating layer (Fig.16) also improves sealability while worsening compressive set.

Thus it was verified that a trade-off relationship exists between possible sealing pressure (i.e., sealability) and compressive set (durability and reliability) for each of the determinants of foamed rubber layer properties, and that an optimum value also exists for each.

5. Sealability of Foamed Rubber Gaskets

5.1. Low-Temperature Sealability

The low-temperature sealability of foamed rubber gaskets was evaluated first in view of automotive engine applications. Ordinarily, a rubber gasket exhibits reduced sealability in low-temperature environments due to hardening of the rubber⁽⁶⁾. However, in contrast to the precipitous decline in sealability that gaskets made of molded rubber (typically

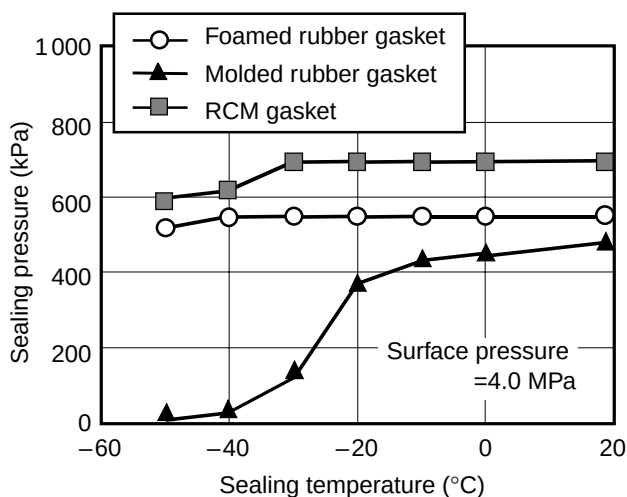


Fig.17 Sealing performance at low temperature

used for resin part sealing) undergo at -20 °C and below (Fig.17), a gasket made of foamed rubber developed by the authors displays consistent sealability, proving that this combination of low hardness and high compressive recovery assures superior sealability even when the same rubber material is used.

5.2. Sealability at Low Surface Pressures

In a light weight, low cost system, the gasket must seal at the lower fastening surface pressures that accompany reduced tightening forced flange stiffness. Commonly used RCM loses its sealability at low surface pressures. However, the authors' foamed rubber gasket, provides four times the sealability of RCM even at surface pressures below 3.0 Mpa (Fig.18), and it maintains its sealability even at a surface pressure as low as 0.5 Mpa. This means that a gasket between an intake manifold and the cylinder heads (Fig.19) would require only 1.5 bolts (Fig.19-b) to assure sealability if made of foamed rubber, instead of the approximately 2.5 fastening bolts per intake port (Fig.19-a) required with current gaskets.

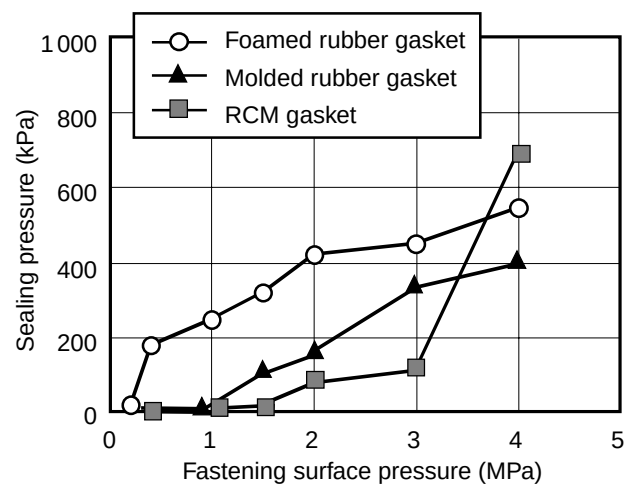


Fig.18 Relationship between fastening pressure and sealing performance

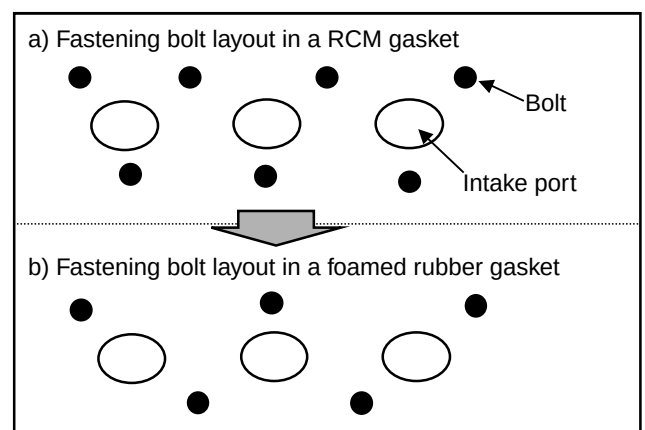


Fig.19 Fastening bolt layout depends on gasket type

5.3. Surface Roughness and Flatness Adaptability

The surface roughness adaptability and flatness adaptability of the seal flange of a foamed rubber gasket are shown in Figs.20 and 21, respectively. As for surface roughness adaptability, sealability is maintained to a surface roughness of R_t -80 μm , suggesting applicability in the unprocessed state for the casting surface of light-metal alloys.

As for flatness adaptability, sealability is maintained to a fastening surface clearance of 0.6 mm, again suggesting applicability, in the unprocessed state, to the deformation and waviness that are generated during, for example, the molding of resin parts. Thus, foamed rubber gaskets possess excellent properties as automotive sealing parts, and can be applied to streamline help fastening seal structures and lower their cost.

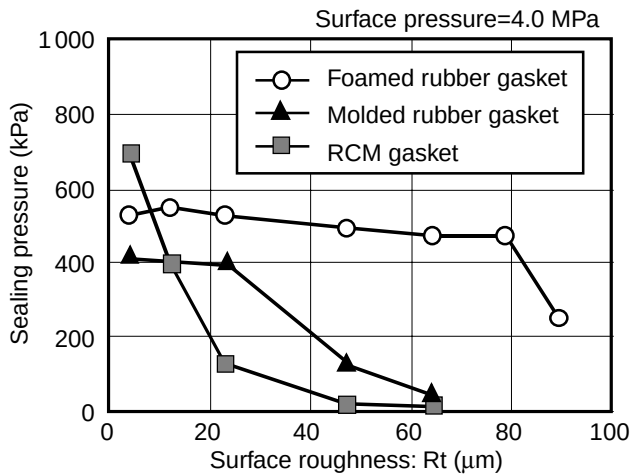


Fig.20 Relationship between surface roughness and sealing performance

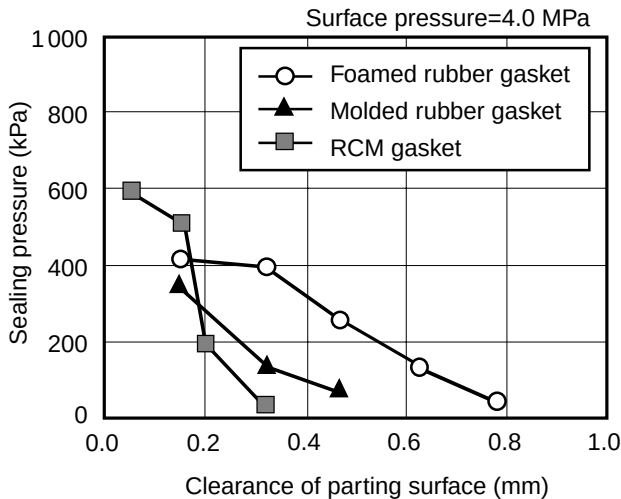


Fig.21 Clearance adaptability of foamed rubber

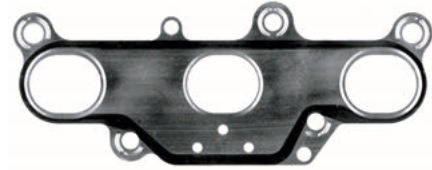
6. Example Applications to Engine Gasket Parts

This section describes applications in the air intake system gaskets of an automobile engine. The gaskets were those in the engine of the Insight (a mass production hybrid car): a gasket between the cylinder head and EGR plate, and

a gasket between the resin intake manifold's throttle body spacer and the throttle body. The gaskets comprise a foamed rubber coating over a thin metal substrate; their shapes are shown in Fig.22.

FKM was used as the base rubber for the EGR plate gasket, a part which is subjected to a thermal load of up to 130°C by the EGR gas. NBR is used as the base rubber for the throttle body gasket as it is subjected to a relatively low thermal load of 100°C or less. Detailed specifications for each gasket are given in Table 4.

A) EGR plate gasket



B) Throttle body gasket



Fig.22 Foamed rubber gasket for a engine air intake systems

Table 4 Foamed rubber gasket specification

Gasket	EGR plate gasket	Throttle body gasket
Base rubber	FKM (F content=65%)	NBR (AN content=40%)
C.B content	60PHR	40PHR
Foaming type	Closed-cell	Closed-cell
Foaming rate	120%	120%
Foaming size	25 μm	25 μm
Thickness	50 μm	100 μm

This engine's fastening seal specifications called for a minimum of two gaskets when designing with RCM, the currently used gasket material. Replacing RCM with foamed rubber made possible a single-layer EGR plate gasket, a thinner EGR plate, and fewer fastening bolts. Similarly, the foamed rubber also permitted a single-gasket design for the throttle body gasket, as well as a thinner plate.

In durability testing with an actual engine, no loss of sealability was exhibited by the foamed rubber gasket. Further, the gasket also possessed sufficient durability and reliability with a sealing pressure of 150 kPa or higher after testing.

7. Conclusion

The authors developed a closed-cell foamed rubber gasket whose high compressive recovery and low surface hardness make it applicable to seal parts for automotive internal-combustion engines. In comparison with conventional RCM or molded rubber gaskets, this foamed rubber gasket offers superior sealability at low surface pressures, and also at low-temperature and on rough-surfaces. The authors demonstrated that the high sealability of this foamed rubber gasket can help streamline fastening seal structure by permitting fewer fastening bolts, thinner seal flanges, and unprocessed seal surfaces.

Foamed rubber gaskets are a potentially effective approach to seals for new components made of the resin materials, magnesium alloys and other new materials that automakers are expected to use to achieve lighter, less-expensive internal combustion engines for their automobiles.

8. Acknowledgments

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