

Downsizing Technology for Chassis Parts Fastening Structure

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ABSTRACT

Downsizing technology for fastening structures was developed to realize a low-cost, next-generation, lightweight, high-performance suspension. The key technologies developed to achieve this were strength class 12.9 and 14.9 high-strength bolts that can also be applied to the vehicle body, and technology that controls the limit friction characteristic of the fastening joint surface. When the strength is increased with conventional thermal refining steel, the delayed fracture characteristic decreases, so a high-strength hexagon flange bolt was developed that uses patenting-treated pearlite steel to realize both increased strength and an enhanced delayed fracture characteristic. Technology for controlling the limit friction characteristic of the fastening joint surface made it possible to secure stable slipping resistance by optimization of micro unevenness, evaluated using developed accurate friction coefficient measurement technology, which helped to downsize the fastening structure. These two technologies were applied separately and in combination as appropriate to each fastening position in the 2016 model year CIVIC, and helped to achieve a lightweight and low-cost suspension.

1. Introduction

Needs are increasing to reduce automobile weights from the viewpoints of enhancing fuel economy performance and vehicle dynamics. In addition, as multi-link suspensions are being increasingly adopted even in C category vehicles in order to enhance product appeal, lightweight, high-performance suspensions are demanded.

The suspension is the link mechanism that joins the vehicle body with the tires and wheels, and the link mounts are typically fastened using bolts and nuts via rubber bushings. The number of bolt fastening positions increases when using a multi-link format, so realization of a lightweight and compact link mount-fastening structure would contribute greatly to reducing vehicle weights.

The link mount rubber bushing characteristics greatly affect the isolation of vibration from the road surface while driving, driving stability performance, and ride comfort performance. Specifically, a large spring ratio is demanded, with a low dynamic spring constant to isolate vibration, a high transverse direction spring constant to enhance driving stability, and a low torsional direction spring constant to enhance ride comfort. Reducing the rubber thickness in the transverse direction typically increases the transverse direction spring constant, which makes it possible to lower

the rubber hardness, and lowering the rubber hardness reduces the torsional direction spring constant. Use of a smaller bushing diameter enables increasing the spring ratio, but also tends to reduce the rubber volume, so durability is an issue. Therefore, this study focused on increasing the spring ratio by reducing the bushing inner diameter while maintaining the rubber volume, and investigated methods of downsizing the fastening structure bolts.

In addition, the suspension bolt fastening points are the base points when designing the surrounding part layout, so reducing the bolt size also increases the freedom of the surrounding part layout design.

Conventional approaches toward bolt downsizing typically focus only on increasing the bolt strength. For example, consider the case when downsizing the strength class 10.9 high-strength M14 bolt (point A in Fig. 1) typically used for chassis fastening to M12 size. When increasing the strength of a strength class 10.9 M12 bolt (point a in Fig. 1) to obtain an equivalent allowable axial force, a strength class 12.9 M12 bolt (point b in Fig. 1) has insufficient allowable axial force, so the strength needs to be increased to strength class 14.9 (point c in Fig. 1). In addition to enhancement of the reduced delayed fracture characteristic^{(1),(2)} described hereafter, there are also such issues as securing internal thread strength and fastened

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component flange surface strength and reducing the fastening torque, limiting the positions where downsizing can be achieved simply by increasing the bolt strength.

This study therefore focused on a bolt-fastening structure with bushings, and investigated downsizing methods that do not rely solely on increasing the bolt strength. Figure 2 shows a conceptual drawing of the load state generated on a fastening structure with bushings. The bolt size is designed so that the product of the bolt axial force F and the slipping limit friction coefficient μ of the fastening joint surface exceeds the maximum input force F_v applied to the fastening structure as shown in Eq. (1). Here, the slipping limit friction coefficient is defined as the ratio between the maximum input force at which slipping does not occur and the bolt axial force.

$$F_v < \mu F \quad (1)$$

Increasing the bolt strength is being considered to secure the needed axial force without increasing the bolt size, and enhancing the slipping limit friction coefficient μ of the joint surface is being considered to increase the allowable

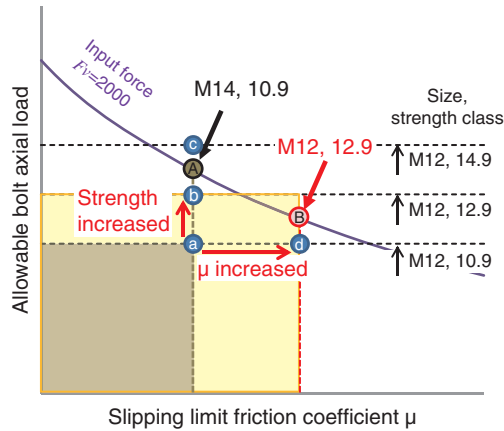


Fig. 1 Relationship between bolt axial load, slipping coefficient and bolt size

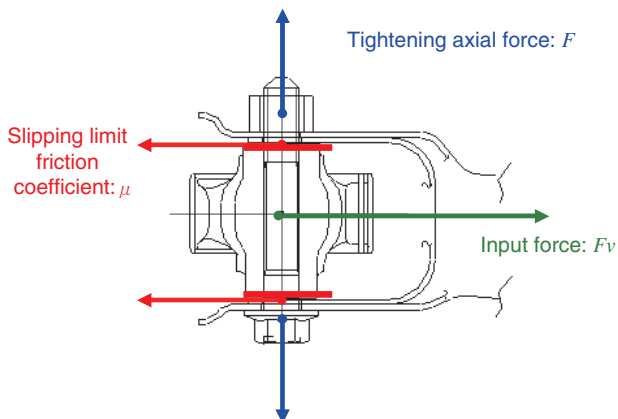


Fig. 2 Schematic illustration of bolt fastening structure

load⁽³⁾⁻⁽⁵⁾. Expressed in terms of Fig. 1, the bolt strength can be increased from point d in Fig. 1 by increasing μ , which makes it possible to withstand the maximum input force with the strength class 12.9 bolt axial force (point B in Fig. 1). This shows that these two approaches are useful for reducing the bolt size, and that the application range can be expanded and even greater weight reduction effects can be expected by applying these approaches separately or in combination as appropriate to each fastening position.

2. Development Issues and Goals

2.1. High-strength Bolts

When applying high-strength bolts, it is known that delayed fracture occurs more frequently as the material strength increases. In particular, the delayed fracture characteristic tends to decrease in the tensile strength range in excess of 1200 MPa. Delayed fracture occurs due to corrosion reaction during actual operation, and is thought to be due to occluded diffusible hydrogen. Bolts used in corrosive environments such as chassis parts have a particularly high need for an enhanced delayed fracture characteristic.

Materials that can be applied to high-strength bolts and enhance the delayed fracture characteristic are broadly classified into two types. The first is thermal refining steel wire that uses alloy addition and heat treatment. However, the material unit cost is high and securing stable heat treatment quality is an issue. The other type is steel that uses an isothermal transformation process called patenting treatment (hereafter, patenting steel), such as piano wire. Compared to thermal refining steel wire, patenting steel provides the same strength with a better delayed fracture characteristic, and Honda fastens the engine component using strength class 16.9 high-strength bolt materials⁽⁶⁾. However, patenting steel bolts have a high material strength, so as shown in Fig. 3, when the drawing processing rate before bolt forming is high, head forming is an issue for manufacturing hexagon flange bolts. Conversely, when the drawing processing rate is low, it is necessary to increase the shaft-forming processing rate during bolt forming, which increases the load applied to the heading die. Higher material strength during forming than that of thermal refining steel is needed to satisfy the strength for the drawing processing and subsequent plastic deformation, so achieving both strength and formability is an issue. Therefore, high-strength bolts that use patenting steel have so far been limited to only hexalobular internal types that have an easily formed bolt head shape. Hexalobular internal shape chassis fastening bolts have gained popularity in Europe and America, but in consideration of global deployment, there is a high need for hexagon flange bolts that can be tightened without changes to existing processes (Fig. 4). Bolt wire materials that do not use thermal refining have been developed, but the deformation resistance during heading is high, so application has been limited to

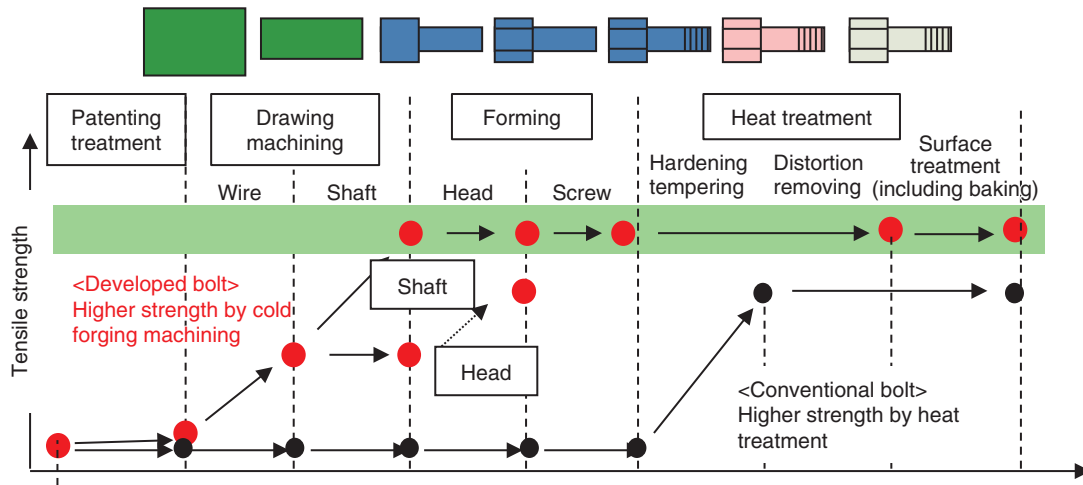


Fig. 3 Relationship between bolt manufacturing process and strength transition



(a) Hexalobular internal bolt

(b) Hexagon flange bolt

Fig. 4 Shape difference between hexalobular internal bolt and hexagon flange bolt

strength class 8.8 or lower from the viewpoints of securing formability and tool life⁽⁷⁾.

Development of high-strength bolts therefore focused on strength class 12.9 and 14.9 hexagon flange bolts that exhibit sufficient delayed fracture resistance in a corrosive environment that simulates the actual chassis part operating environment, and have thermal stability equivalent to that of conventional materials.

2.2. Control of the Limit Friction Characteristic of the Fastening Joint Surface

The limit friction characteristic of the fastening joint surface has been verified for various fastening combinations. However, there has been a lack of systematic organization, as there is no generally established method for measuring the slipping limit friction coefficient, and experimental values measured using different methods are often referenced. The reasons for this are thought to be that many environmental factors (test piece, jig, load application method, cleanliness, etc.) influence friction coefficient measurement, which leads to an increase in variance, and it is a challenge to define and determine the slipping start point. In particular, the bolt fastened structure with bushings used in the load input environment during actual vehicle driving has a complex structure and input

load configuration, so analysis of the fastening joint surface slipping behavior is a challenge.

As a result of these circumstances, consensus has not been achieved regarding the factors influencing enhancement of the slipping characteristic of the fastening joint surface or their effects. Therefore, when developing technology for controlling the friction characteristic of the fastening joint surface, the goal was to systematically evaluate the influence of the surface properties on the limit friction characteristic of the fastening joint surface, and to realize a low-cost method for achieving a high slipping limit friction coefficient.

3. Development of High-strength Bolts for Vehicle Body

3.1. Steel Type Selection

When selecting the material, highly versatile carbon steel wire for cold heading was investigated as the basic composition in consideration of cost, availability, and recyclability. As the main factor influencing the strength of carbon steel wire for cold heading is the carbon (C) content, the composition was selected in consideration of the influence on patenting treatment and subsequent drawing processing. Table 1 shows the material compositions set by this development for the strength class 12.9 and 14.9 bolts. The patenting treatment performed in this development aimed to reduce the C content in order to achieve an even and refined pearlite structure and provide a ferrite matrix with the goal of enhancing the balance between strength and ductility. Drawing processing was performed after patenting treatment to help secure strength by further refining the structure. As mentioned above, the drawing processing rate setting is the key to hexagon flange bolt forming. Figure 5 shows the results of setting a drawing processing rate that enables bolt forming. The optimal drawing processing rates were set for the strength class 12.9 and 14.9 bolts.

Table 1 Material composition

Bolt Strength class	Composition mass%				
	C	Si	Mn	P	S
12.9	0.54 -0.61	0.15 -0.35	0.60 -0.90	≤0.030	≤0.030
14.9	0.69 -0.76	0.15 -0.35	0.60 -0.90	≤0.030	≤0.030

3.2. Strain-removing Heat Treatment

Much dislocation accumulates in the ferrite layer of the bolts formed by this development due to strain introduced by drawing processing and heading processing. For this reason, when heading is simply performed the movable dislocation density is high, so the relaxation characteristic is low and a large amount of hydrogen is trapped by the accumulated dislocation, with the result that the delayed fracture characteristic decreases. Bluing treatment (strain-removing heat treatment) was then performed to enhance settling due to strain introduction during forming and to enhance the delayed fracture characteristic. Figure 6 shows the change in the material internal structure due to bluing treatment. When strain accumulates, dislocation also accumulates and electron beams are not easily transmitted, so these areas are shown by black contrast. Comparison of the metal structure before and after heat treatment at 350°C confirmed that ferrite layer dislocation is reduced and strain is released. However, when bluing treatment was performed at 450°C, spheroidization of the cementite and the start of decomposition of the pearlite structure were confirmed. This decomposition of the pearlite structure due to low-temperature heat treatment is thought to result from structural changes driven by the large amount of dislocation introduced by the strengthening process⁽⁸⁾. Figure 7 shows the results of verifying the relationship between the tensile

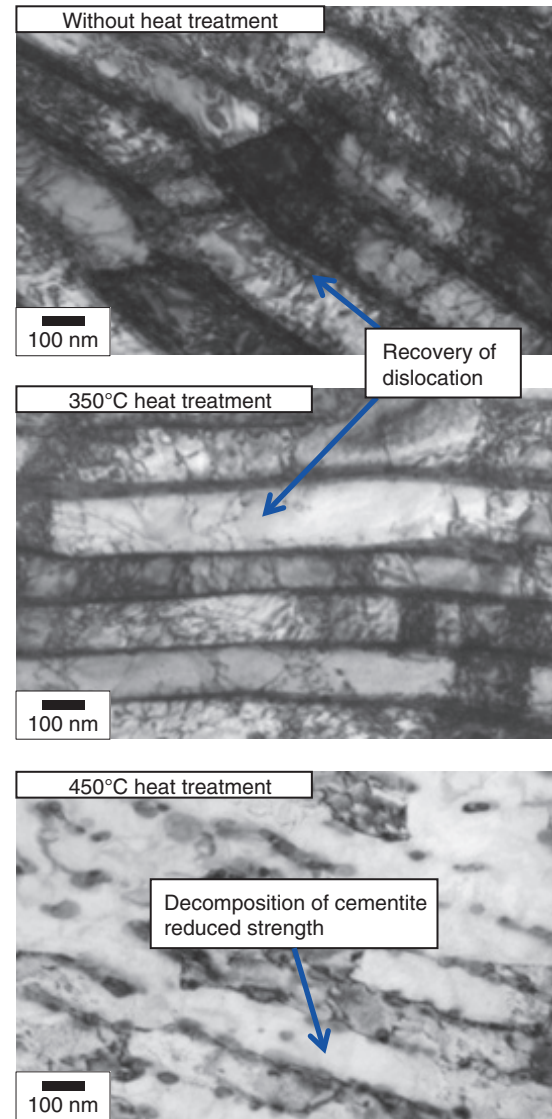


Fig. 6 Photographs of metal structure before and after heat treatment

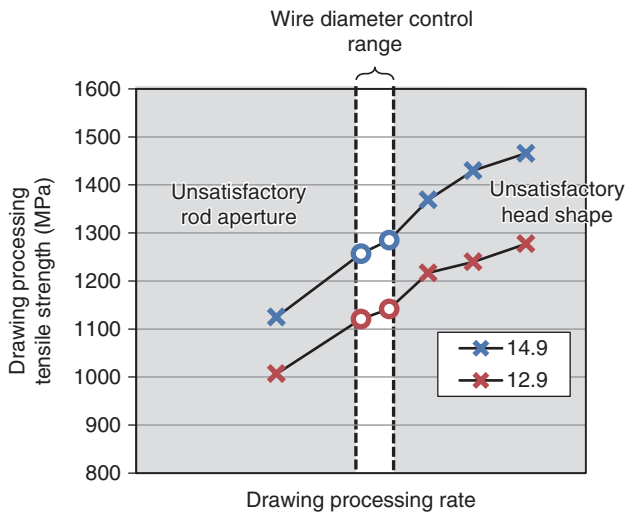


Fig. 5 Relationship between tensile strength and wire drawing rate

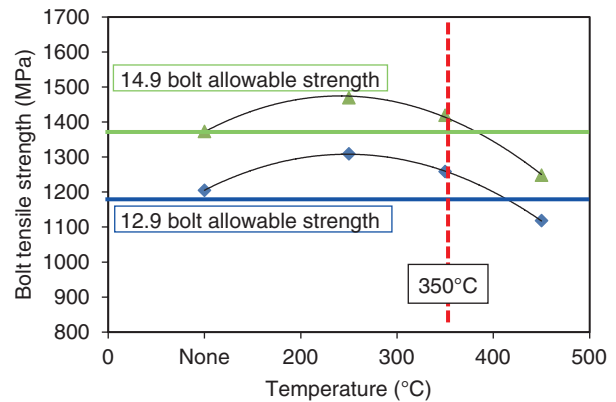


Fig. 7 Relationship between tensile strength and heat treatment temperature

strength and the bluing treatment temperature. These results show that the strength tends to drop rapidly at a temperature of 400°C or more. High thermal stability can be secured by performing bluing treatment at a temperature high enough that the strength does not fall below the target bolt strength class. Thus, this development set the bluing temperature to 350°C in consideration of quality variance during heat treatment.

The typical operating environment is assumed to be normal temperature or higher, so as it is necessary to secure thermal stability, the heat treatment stability enhancement effect of bluing treatment was verified. The developed bolts were tightened at room temperature, left for 100 h at 150°C, and the remaining fastening axial force was measured. The results confirmed that strain-removing heat-treated bolts had 20% higher remaining axial force and thermal stability equal to that of strength class 10.9 thermal refining bolts (Fig. 8).

3.3. Delayed Fracture Characteristic

Delayed fractures are produced by hydrogen that has entered the steel due to external factors such as corrosion or plating. The delayed fracture characteristic was verified by tests that apply tensile stress at a fixed load of 0.9 times the tensile strength in the condition with hydrogen forcibly input to the steel materials by the electrolytic hydrogen charging method, and then using the electrolytic hydrogen charging method to measure the critical hydrogen concentration at which fractures do not occur. Figure 9 shows the diffusible hydrogen curve when dehydrogenation treatment is performed on the developed bolt by heat treatment under various temperature conditions. Fractures do not occur for specifications with dehydrogenation treatment performed at 200°C, which indicates that the diffusible hydrogen content, which corresponds to the peak area up to 250°C, influences delayed fracture. It was therefore decided to perform subsequent evaluation of hydrogen content up to 250°C.

The delayed fracture resistance was quantitatively evaluated by measuring the critical hydrogen content (Hc) and the entered hydrogen content (He). Hc was measured

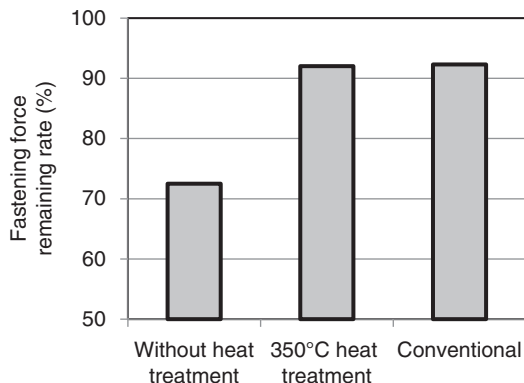


Fig. 8 Effect of strain-removing heat treatment

using the electrolytic hydrogen charging method. Here, an anode potential was generated on the steel material surface under various charging conditions to force hydrogen into the steel materials. He was calculated by having hydrogen enter the bolts in a rust endurance test simulating the actual vehicle environment, and then measuring the hydrogen content immediately after the test.

The delayed fracture resistance increases together with the Hc/He value. Figure 10 compares the Hc/He measurement results for the developed bolts with the values for conventional thermal refining bolts of the same strength. This shows that the developed strength class 12.9 and 14.9 bolts have better delayed fracture characteristics than the thermal refining bolts. In addition, the developed bolts have a sufficiently large critical hydrogen content relative to the hydrogen content that entered in the test simulating the actual vehicle rust environment, which confirmed that the developed bolts are high-strength bolts that can be applied to chassis parts.

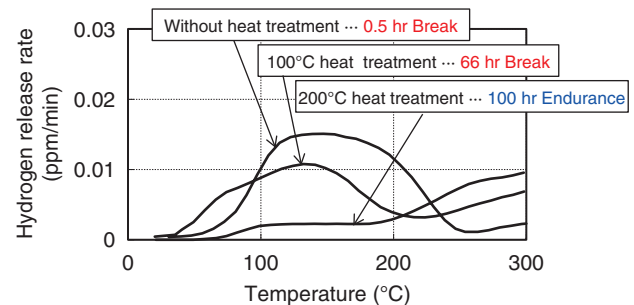


Fig. 9 Relationship between hydrogen release rate and temperature

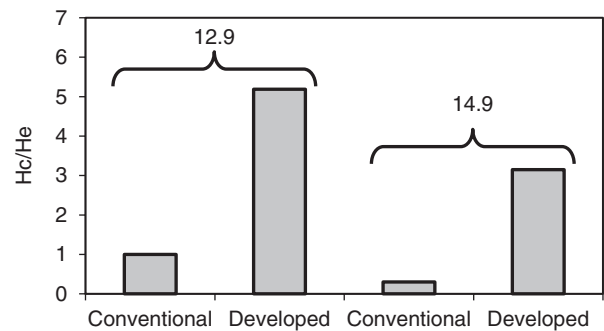


Fig. 10 Comparison of Hc/He between conventional and developed bolts

4. Realization of a Bolt Fastening Joint Surface with a High Slipping Limit Friction Coefficient

4.1. Establishment of Technology for Evaluating the Limit Friction Characteristic of the Joint Surface

This study attempted to establish a method that enables

stable evaluation of the slipping characteristic of the joint surface by developing and modifying a test apparatus with a simple structure that models the target fastening structure.

Figure 11 shows a schematic illustration of the measuring apparatus used by this development to evaluate the limit friction characteristic. This jig simulates the bush clamping structure, and has a structure that clamps a test piece B pipe part with two test pieces A. The test specimens were the typical fastening combination used in mass production, with cathodic electrodeposition-coated strength class 440 MPa steel plate selected for A, and SWCH10R⁽⁹⁾ selected for B. The prescribed axial force was applied beforehand to B by bolt fastening, and then external force simulating the actual vehicle input was statically applied at a rate of 1 mm/min in the direction perpendicular to the initial axial force. The limit friction characteristic of the joint surface was evaluated from the relationship between the external force and the relative displacement between A and B obtained at this time. Figure 12 shows the results obtained by this test. In addition to the relationship between

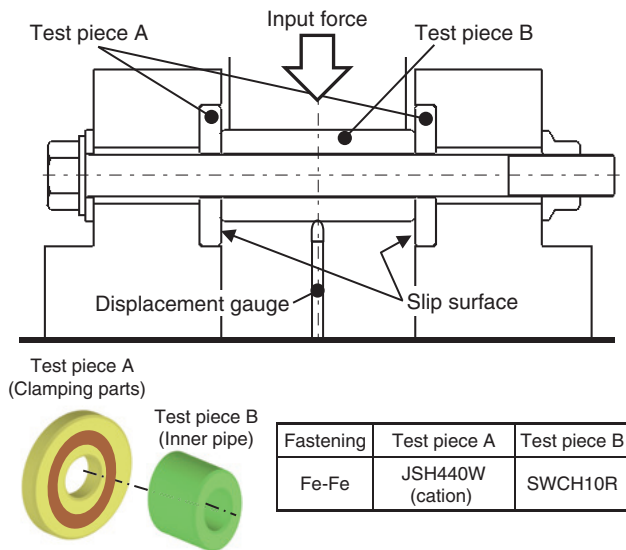


Fig. 11 Developed slipping test method and specimens

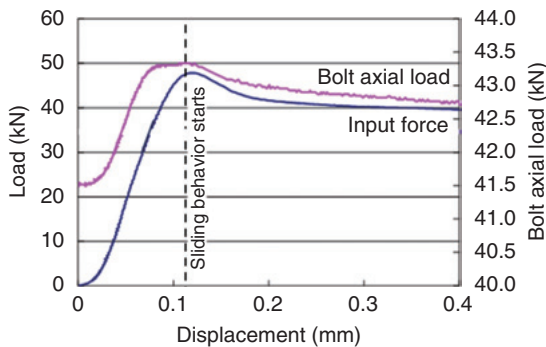


Fig. 12 Relationship between bolt load and displacement

the external force and the displacement, the bolt axial force also fluctuated during the test. The axial force fluctuation also exhibits an inflection point at the external force inflection point, and then gradually decreases thereafter. Therefore, the maximum axial force position was defined as the slipping start point, and the slipping limit friction coefficient was calculated. Note that the test method used in this development was modified in various ways to suppress test result variance. These modifications include stabilization of the shaft when applying external force, stabilization of the fastened component fixing position and fixing method, and stabilization of the displacement measurement position. The results of multiple tests confirmed a stable relationship between the external force and displacement as shown in Fig. 13.

4.2. Influence of Joint Surface Properties on Limit Friction Characteristic

Static verification of the limit friction characteristic with respect to different surface properties obtained by various control methods was performed to verify the influence of the surface properties on the limit friction characteristic of the joint surface. Table 2 shows the surface property control methods used by this development. Samples with various surface properties were created by varying the setting parameters for these methods. Figure 14 shows the relationship between the surface roughness (R_k) and the slipping limit friction coefficient of the joint surface. R_k is a parameter that indicates the level difference of the core part of the roughness curve excluding the peaks and valleys⁽¹⁰⁾. A slipping test was performed with $n = 3$, and the average values were plotted. The slipping limit friction coefficient was confirmed to increase together with R_k , and the friction coefficient tended to decrease in the range where R_k is 30 μm or more. While this suggests that increasing the surface roughness increases the friction coefficient, excessive surface roughening treatment reduces the friction coefficient.

When slipping occurs between contacting solids, shearing typically occurs at the junction of the real contact region. Labeling the junction shearing strength as S ,

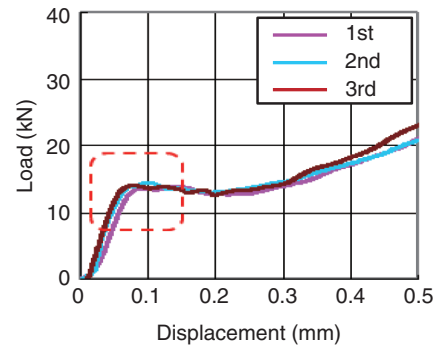


Fig. 13 Relationship between load and displacement for developed method

Table 2 Methods for controlling surface roughness

Sample	a	b1, b2	c1, c2	d1, d2, d3
Process	As forged	Forming	Wet blast	Air blast
Method	-	Form-rolling	Sprayed pressure (up to 5 MPa)	Sprayed air pressure

the friction force F_s due to shearing is expressed by the following equation.

$$F_s = ArS \quad (2)$$

Here, Ar is the real contact area. When Ar increases, the friction force due to shearing also increases, indicating a high friction coefficient. This is thought to suggest that appropriate surface roughening treatment increases the real contact area, while excessive surface roughening treatment reduces it.

In addition, two specifications (b1 and c1) with an R_k around 10 μm can be confirmed in Fig. 14 that have greatly differing slipping limit friction coefficients despite having nearly the same R_k . Figure 15 shows the results of

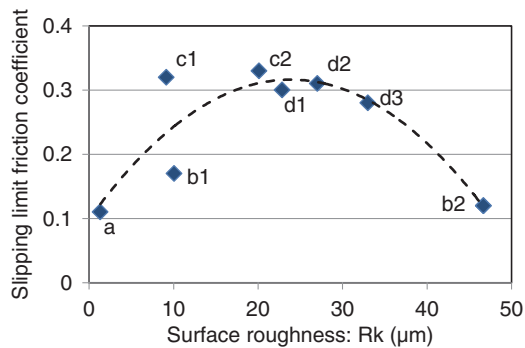
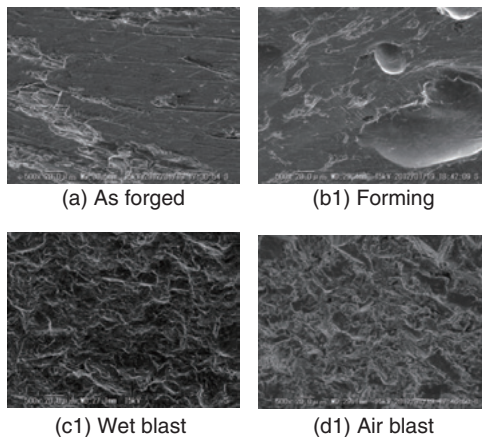
Fig. 14 Relationship between R_k and slipping limit friction coefficient

Fig. 15 SEM images of inner pipe surface after phosphate treatment

Table 3 Laser processing conditions

Frequency	Rated output	Peak output
30 Hz	30 W	20 kW

comparing the surface properties using SEM images of the micro-structure in order to verify the difference between these specifications. Figure 15 (b1) is the image after surface roughening treatment by heading, and shows coarse unevenness. In contrast, Fig. 15 (c1) confirms that micro unevenness is densely distributed by wet blast treatment. This comparison suggested that micro unevenness has a large influence on enhancement of the limit friction characteristic of the joint surface, so this influence was verified as described in the following section.

4.3. Clarification of Mechanism Contributing to Enhancement of Slipping Limit Friction Coefficient

The limit friction characteristic of different specifications created by applying surface unevenness by fiber laser treatment was evaluated to analyze in detail the influence of micro unevenness on the limit friction characteristic of the joint surface. The reason why fiber laser treatment was used here was that micro unevenness can be applied in a regular and stable manner by making arbitrary input parameter settings. Surface roughening treatment such as blast treatment applies coarse unevenness as well as micro unevenness, so it was thought that this would hinder verification focused only on the influence of micro unevenness. Table 3 shows the fiber laser processing conditions. The convex height was set to 1.25 μm . Figure 16 shows the slipping coefficient measurement results under the same conditions. The results in this figure confirmed that the limit friction characteristic at the chassis fastening axial force level tends to be higher than the setting at a pitch of 0.12 mm or less. This indicates that densely distributing the micro unevenness enhances the limit friction characteristic, even at a micro unevenness height of 1.25 μm .

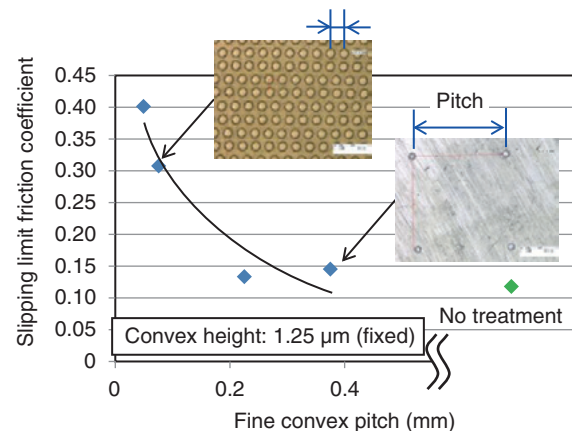


Fig. 16 Relationship between convex pitch and slipping limit friction coefficient

These results clarified that applying μm -order micro unevenness has a large influence on enhancement of the limit friction characteristic joint surface, and that dense distribution of this type of micro unevenness is an effective means of enhancing the limit friction characteristic, even for specifications controlled using simple methods such as shot blast or wet blast treatment.

4.4. Evaluation of Repeated Input Resistance

The repeat limit friction characteristic when 30 Hz repeated alternating input is applied was verified using a test apparatus similar to that used in the abovementioned static test in order to verify the limit friction characteristic under conditions approximating the actual vehicle input state. Slipping judgment consisted of confirming that apparent macro slipping did not occur and that the drop in fastening axial force was 10% or less after applying the repeated input 100,000 times. The critical load at which slipping does not occur at the set alternating input load was verified, and that critical load was converted into the repeat slipping limit friction coefficient.

Figure 17 shows the repeat slipping limit friction coefficients when repeated input conditions are applied. The developed specification with micro unevenness exhibits a high repeat slipping limit friction coefficient, albeit slightly lower than the static slipping limit friction coefficient evaluated in the previous sections. These results showed that the micro unevenness specification set by this development is useful for achieving a high limit friction characteristic even in an actual vehicle input environment.

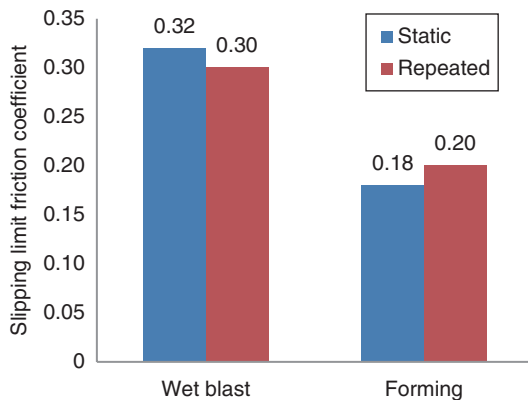


Fig. 17 Results of repeated force input test on Fe-Fe part with micro unevenness

5. Effects of Application

The high-strength bolts and technology for controlling the limit friction characteristic of the joint surface developed by this study were applied to multiple fastening positions of the 2016 model year CIVIC suspension parts. Figure 18 shows an example of positions where this technology

was applied. The developed technology was confirmed to achieve a weight reduction effect of approximately 0.05 kg per location, including the bolt, bushing, and surrounding parts. Figure 19 shows the weight reduction effects achieved by combining the two key technologies developed by this study. The weight reduction effect of technology to enhance the limit friction characteristic of the fastening joint surface is approximately 0.6 kg per vehicle. The combination of high-strength bolts and this key technology was confirmed to provide an additional weight reduction effect of 0.2 kg per vehicle, for a total weight reduction effect of 0.8 kg per vehicle. This indicates that even greater weight reduction effects can be obtained by using the technologies established by this development in combination. The weight reduction effects presented here are for the model used in this study, and similar compound effects can also be expected by applying the technologies separately or in combination as appropriate to other models. In addition, the downsizing effects achieved by this development not only enhanced vehicle fuel economy, but downsizing the bushing outer diameter by approximately 9% also helped to increase the parts layout freedom.

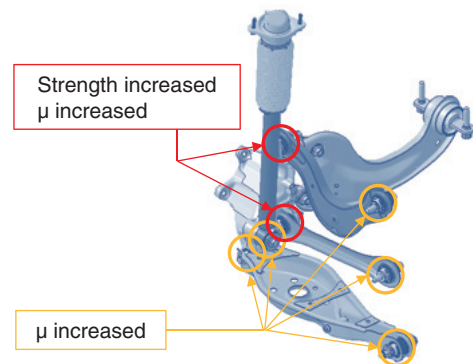


Fig. 18 Illustration of 2016 model year CIVIC rear suspension with weight reduction technology

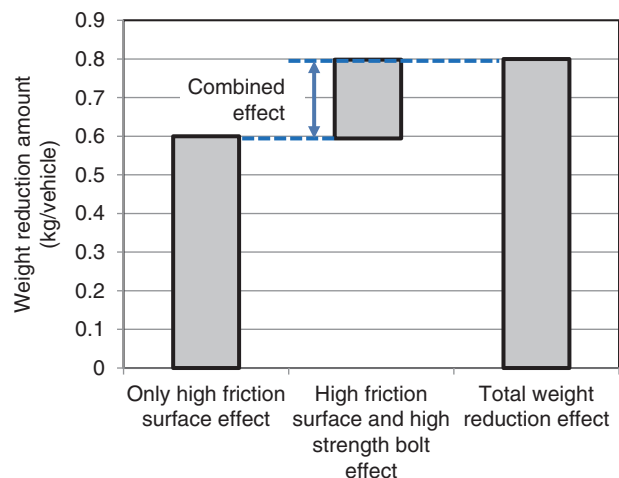


Fig. 19 Illustration of weight reduction effects for 2016 model year CIVIC rear suspension

6. Conclusion

High-strength bolts with a good delayed fracture characteristic and technology for enhancing the limit friction characteristic of the fastening joint surface were developed to downsize the fastening structure used to fasten chassis parts via bushings. In addition, it was shown that even greater downsizing effects can be obtained by using these two development technologies separately or in combination as appropriate. The obtained results are summarized below.

- (1) To achieve both strength and formability, the optimal drawing processing rate for the bolt wire material was set, and the C content corresponding to strength classes 12.9 and 14.9 was respectively set to 0.54 wt.%C-0.61 wt.%C and 0.69 wt.%C-0.76 wt.%C.
- (2) Bluing treatment was performed at 350°C to relieve the strain introduced in the drawing and bolt heading processes. This enhanced the relaxation characteristic and helped ensure the thermal stability needed for chassis parts. In addition, the delayed fracture characteristic was verified in consideration of the corrosive environment during actual operation, and the developed bolt was confirmed to have sufficient delayed fracture resistance.
- (3) Regarding the limit friction characteristic of the joint surface, μm -order micro unevenness was shown to be an effective means of enhancing the slipping limit friction coefficient. In addition, wet blast and shot blast treatments were confirmed to be effective methods for achieving this at low cost.

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