

# Development of 1 600 N/mm<sup>2</sup> Class High Strength Bolts

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## ABSTRACT

Many different types of bolts are employed in automotive applications for a variety of different purposes and uses, and their strength generally ranges from 700 N/mm<sup>2</sup> to 1 200 N/mm<sup>2</sup>. The current focus on increasing fuel economy to help reduce global warming has led to the idea to increase the strength of bolts and reduce their size in order to lower weight. However, increasing the tensile strength of conventional bolts increases the incidence of delayed fractures, and is therefore not suitable for mass-market vehicles. This project studied the use of high carbon steel rods, which are less susceptible to delayed fracture than conventional bolt materials, as a solution to this issue. The difficulty of heading when employing high carbon steel rods was solved by improving the material through the addition of the optimum amount of Cr, utilizing a new forming method in which the spindle is hardened during heading, and adopting a hexalobular shape with excellent formability. The application of these techniques made it possible to form bolts from high carbon steel rods, and has enabled the development of a 1 600 N/mm<sup>2</sup> class high-strength bolt. The new material and techniques have been used in the manufacture of the conrod bolts used in 2003 models, and have enabled the size of the bolts to be reduced from conventionally used M12 to M9, and the weight of an individual bolt to be reduced by 80 g.

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## 1. Introduction

Nearly one thousand bolts are used in each automobile. In some parts such as the engine and the transmission, high strength bolts of material strength 1 200 N/mm<sup>2</sup> class are extensively used with the aim of achieving lightness/weight reduction in the automobile, and connecting rod bolts of 1 400 N/mm<sup>2</sup> class are also used. On the one hand, while automobile weight reduction has become an increasingly important issue, changing over to high strength bolts

increases the probability of delayed fracture. Thus, the use of expensive materials like maraging steel, which is only applicable to special applications such as aerospace and racing, became a necessity, and their use in mass production vehicles such as automobiles was difficult. To resolve these issues, and considering the aspects of economy and quality, research was carried out for selecting the optimum material and manufacturing process, thus the development of 1 600 N/mm<sup>2</sup> class bolts began.

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## 2. Raw-Material Settings

### 2.1 Lower-Priced Raw Material without Delayed Fracture

The authors investigated optimum materials without delayed fracture that can be deployed in mass production vehicles. Figure 1 shows the relationship between delayed fracture and strength of various kinds of iron and steel materials<sup>(1)</sup>. When the tensile strength of steel exceeds 1 200 N/mm<sup>2</sup>, there is a tendency of reduction in the characteristics of delayed fractures. This tendency is particularly noticeable as the strength increases. There are broadly two kinds of material that satisfy the delayed fracture characteristics at this high strength level. The first kind is maraging steel, but this material is expensive and difficult to use considering the cost in mass production vehicles. The second kind is non-quenched and non-tempered high tensile strength steel wire. This non-quenched and non-tempered steel wire is less expensive and compared to quenched and tempered high strength steel of similar strength, the delayed fracture characteristics are better. Delayed fracture is caused by a crack that occurs when hydrogen in steel accumulates in the stress concentration part. It is reported<sup>(2)</sup> that the main reasons why high tensile strength steel wire is superior are the ability of the microstructure of the drawn wire due to cold drawing and the high-density dislocation to inhibit hydrogen diffusion and crack propagation. The use of 1 800 N/mm<sup>2</sup> class tensile strength steel wire in the main cable of Akashi Strait Bridge is a recent example of the application of high tensile strength steel wire. The authors focused their attention on developing a totally new non-quenched and non-tempered work hardened type material for bolts.

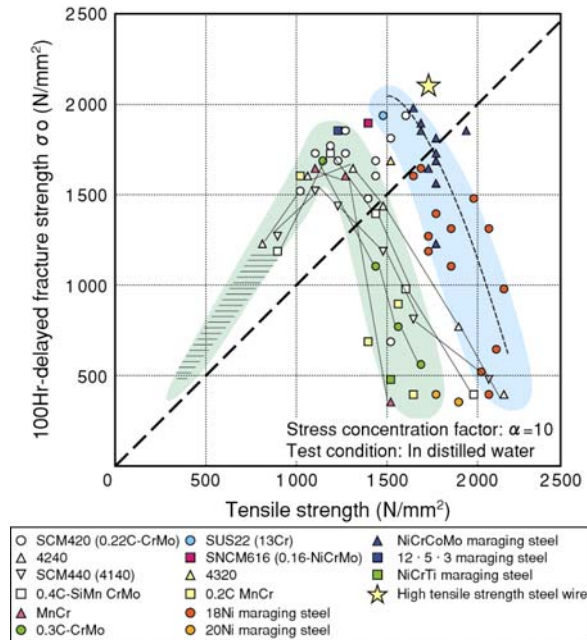


Fig. 1 Delayed fracture characteristics of various materials

### 2.2. Raw Materials – Issues

The high tensile strength steel wire is a high strength material that is less expensive and possesses excellent delayed fracture characteristics. However, since the strengthening method involves work hardening by drawing, as shown in Fig. 2, applications were limited to wires only. However, when forming the bolt using high tensile strength

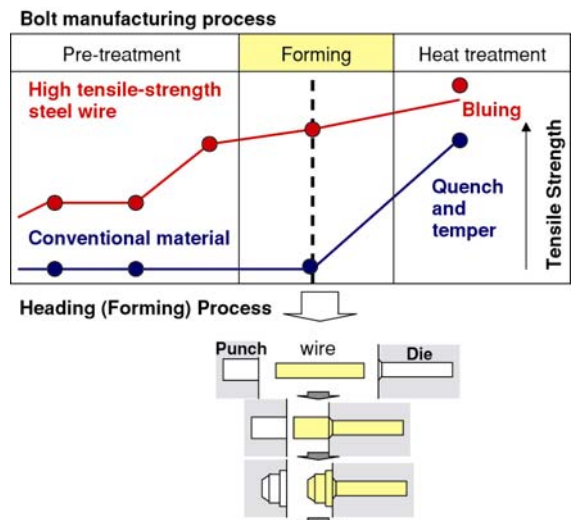


Fig. 2 Bolt manufacturing process

steel wire, a head section is required, and forming a head was considered to be extremely difficult. Head sections of bolts made of conventional materials were formed by reducing the hardness, such as by spheroidizing and annealing. Subsequently, the bolt was strengthened by quench and temper so that formability did not pose any concerns.

### 2.3. Material Improvement

Improvements were made at the raw material stage to strike a balance between high strength and formability of high tensile strength steel wires.

Normal high tensile strength steel wires consist of the C-Si-Mn composition, where Si and Mn are generally added to enhance strength. However, the value of reduction of area decreased in conventional strength improvement methods, resulting in degrading the formability of the head. Therefore, the focus was laid on Cr, which can balance strength and value of reduction in area, and a study of the components was carried out. While strength improvement by the addition of Si and Mn causes solid-solution hardening of ferrite in pearlite, the addition of Cr brings about reinforcement by grain refinement of the microstructure, thus enabling a balance to be achieved with formability improvement.

In order to determine the optimum Cr amount, Cr was added to normal high tensile strength steel wire (JIS-SWRS82B), as shown in Table 1, and the results were verified. Figures 3 and 4 show the amount of Cr added, the reduction of area, and the material structure. If Cr is added, the value of reduction of area improves up to 0.2% of the Cr amount and the strength is maintained, but when an amount exceeding this value is added, the effect is mitigated. As can be understood from the structure, Cr assists in the formation of the structure at low temperature by delaying the transformation from austenite to pearlite and also in the formation of a grain-refined structure. However, if an excessive amount is added, the transformation completion time is prolonged and the initially transformed cementite parts and spheroidizes as time elapses. Based on these results, the optimum amount of Cr to be added was fixed at 0.2%.

Table 1 Chemical composition

| C           | Si          | Mn          | P      | S      | Cr   |
|-------------|-------------|-------------|--------|--------|------|
| 0.80 ~ 0.85 | 0.12 ~ 0.32 | 0.60 ~ 0.90 | ≤0.025 | ≤0.025 | 0.20 |

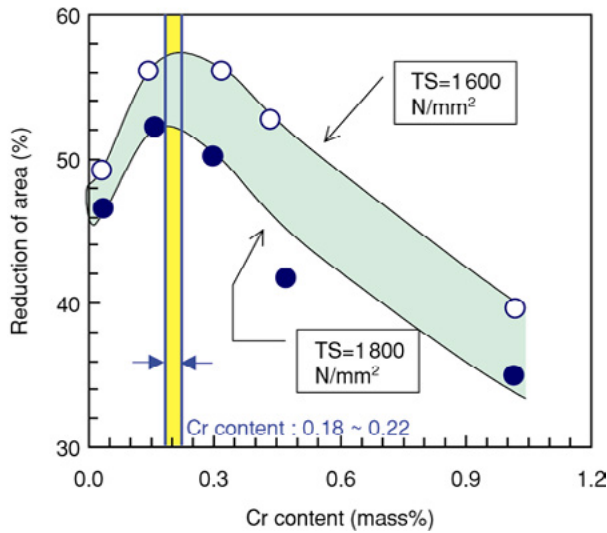


Fig. 3 Relationship between Cr content and reduction of area

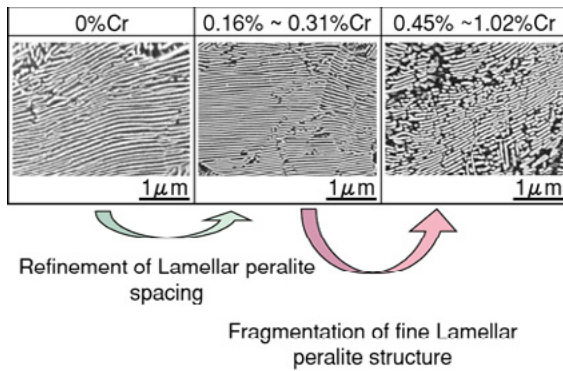


Fig. 4 Change of microstructure with changing Cr content

### 3. Applicability of New Formation Method

A study was conducted on the new formation method utilizing material characteristics.

#### 3.1. Characteristics of Wire Drawn Material

Figure 5 shows the characteristics of the material when drawn to a wire. If this material is made to undergo plastic deformation in the tensile direction, the tensile strength improves and the compression yield point is lowered. This phenomenon is called the Bauschinger effect. Utilizing this effect, a new formation method for improving the bolt formability was established.

#### 3.2. New Formation Method

An appropriately drawn wire beforehand was used for utilizing the Bauschinger effect. Figure 6 shows the newly developed formation method. The diameter of the wire loaded in the existing method and the shank diameter of the finished material are the same. When high tensile strength steel wire is used in this method, heading is difficult because the wire is very hard at the loading stage. Accordingly, the authors adopted a heading method in which a thick wire of low hardness level was used and the head was formed in the forming stage while work hardening the shank portion. Not only is the loaded wire of low hardness, but it is also close to

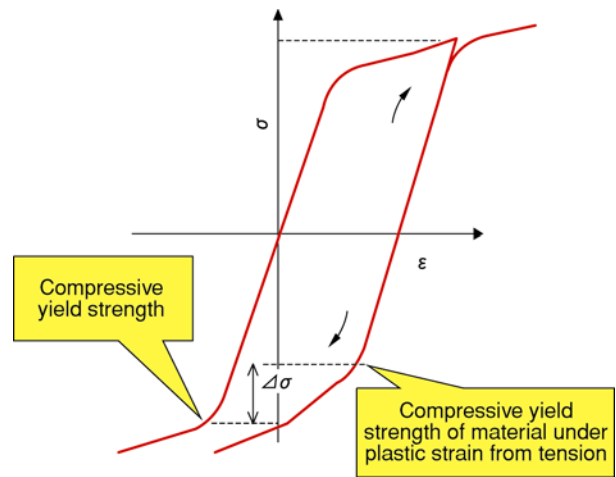


Fig. 5 Bauschinger effect

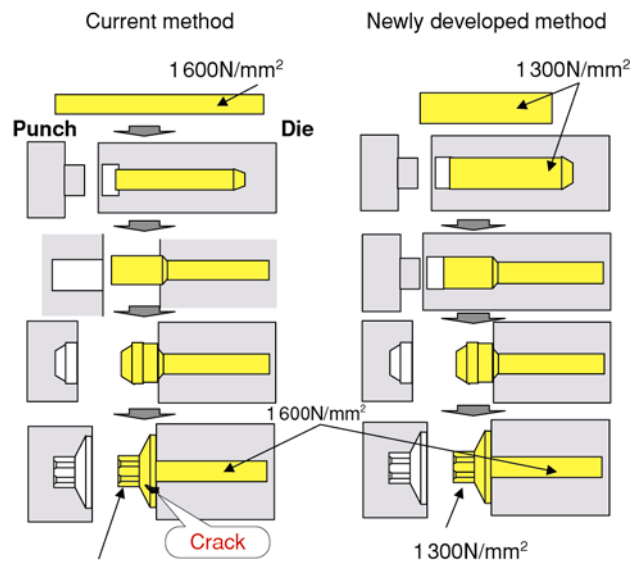


Fig. 6 Current method and newly developed method

the diameter of the completed head, therefore, the formation of the head by this method is easy. However, the strength guarantee of the head section needs to be considered when using this method. This is because the head section and the shank section have the same hardness in the conventional quenched and tempered materials, and in this case, a low hardness portion exists in a part of the head section.

#### 3.3. Strength Guarantee for Head Section

Figure 7 shows the FEM analysis results for a tightened bolt for analyzing the strength of the head section. They are bolt stress distribution and bolt hardness distribution after heading, and its ratio. Hardness is directly proportional to strength; therefore, the value obtained by dividing the hardness distribution by stress distribution represents the strength margin of every section. Values of each section are shown assuming the value of the shank section as 1. As observed above, the value of the head section is greater than 1 over the entire range, and the minimum value occurs in the shank section. This indicates that the weakest part is the shank section and not the head section. It was confirmed from actual tensile tests that the fractured location is in the shank section (threaded part), similar to that of conventional bolts.

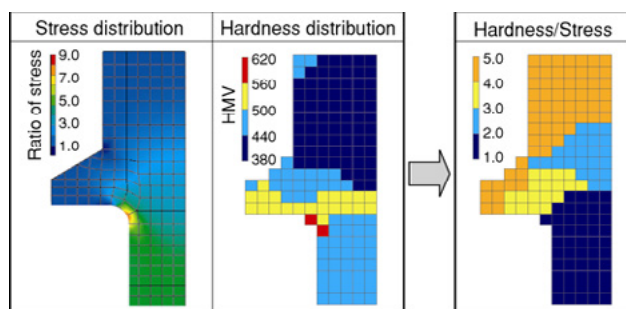


Fig. 7 Stress and hardness distribution in bolt

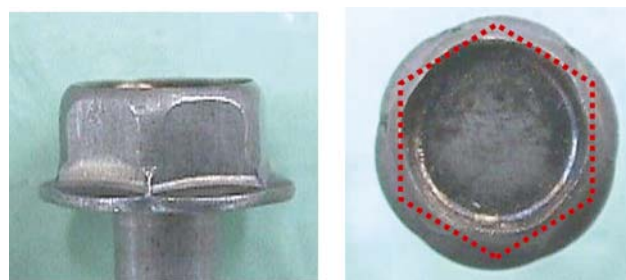


Fig. 9 Hexagon

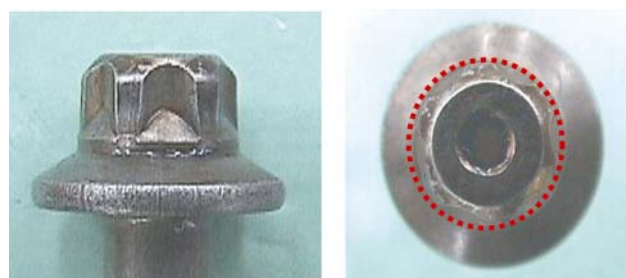


Fig. 10 Hexalobe

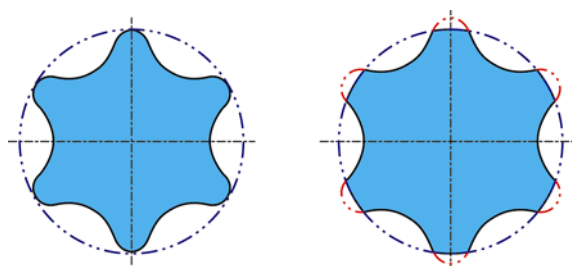


Fig. 11 Improved hexalobe

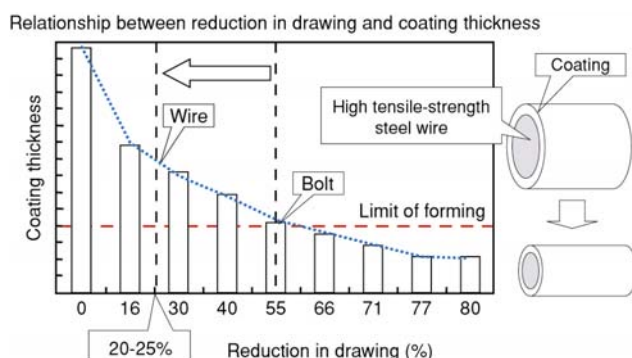


Fig. 8 Relationship and reduction of area in drawing and amount of lubricant adhering

## 4. Improvement of Formability in Shape

### 4.1. Shape of the Head

Normally the bolt head shape is hexagonal, as shown in Fig. 9. However, packing the raw material in the six corners for forming a hexagonal shape from a round bar requires a large reduction ratio, and in the case of high tensile strength steel wire, the header properties degrade excessively. Therefore, as shown in Fig. 10, the hexalobular shape was used that can be formed from a round bar with little processing. Since the completed hexalobular shape is comparatively closer to the round shape, the reduction ratio of the raw material is small, and forming is simpler. We have made improvements to further enhance the formability of the hexalobular shape. As shown in Fig. 11, a part of the convex portion of the hexalobular shape was ground off and the

difference in height between the concave and convex portions was reduced. This resulted in the completed shape coming closer to the rounded shape, which resulted in a smaller reduction ratio, and contributed to improving the formability. However, grinding off a part of the convex portion is likely to reduce the limiting value of the tightening torque. To avoid this, a part of the convex portion was ground off from a hexalobular shape that was one size larger. Even though the contact area is less, the radius is large and therefore, it is likely that a large torque equivalent to that of the conventional shape can be applied. Moreover, by using a tool that is one size larger, off-the-shelf products can be used.

Figure 12 shows the torque values that can be transmitted by the improved hexalobular shape and hexagonal shape with the same outer shape. Compared to the hexagonal shape, the hexalobular shape can transmit larger torques with smaller dimensions. Based on these observations, it can be said that the hexalobular shape does not only improve the header properties but also has superior properties from the point of view of torque transmission and weight savings in the head section. This is a very satisfactory situation that contributes to weight savings and size reduction, and fulfils the aim of this study. The shank section of the bolt could be reduced in size by providing higher strength material, and furthermore, the head shape could also be set to have the minimum weight for the required tightening torque.

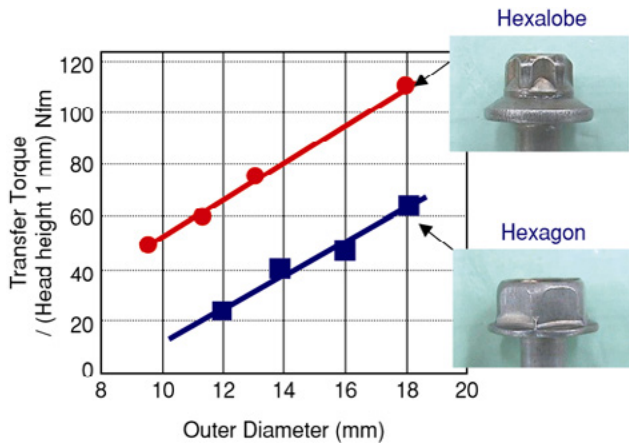


Fig. 12 Impact of hexalobular heads on weight reduction

#### 4.2. Improvement in Rollability

After the heading threading may also be performed by roll forming, in which cold forging is used, but an improvement in formability was necessary for this process also. As shown in Figure 13, formability was improved by increasing R, the radius at the thread root, and reducing the thread height. Increasing R, the radius of the root, helps to improve the fatigue strength of the thread, and this specification is therefore used for threads of bolts used in the fields of aeronautics and space aviation. The improvement in fatigue strength of the 1 600 N/mm<sup>2</sup> bolt was verified, as shown in Fig. 14. There was a 9% improvement in the fatigue strength under the condition of 80% of average stress (tension in case of bolts) at 0.2% yield.

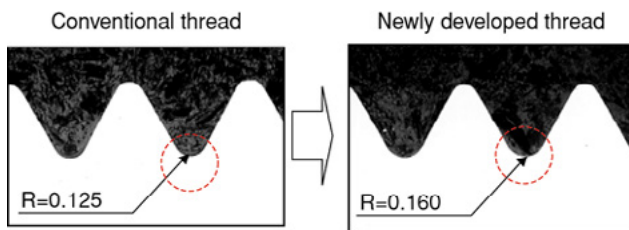


Fig. 13 Increasing the radius at the thread

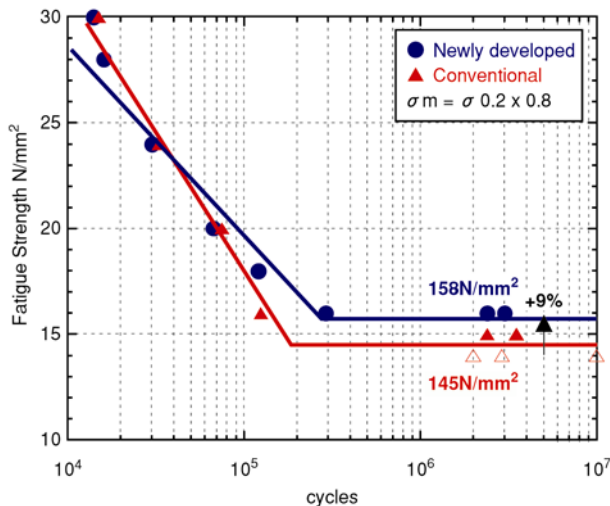


Fig. 14 Fatigue strength of newly developed bolt

Moreover, when this technology is used, the contact areas of the male and female threads become a little bit smaller. As in the connecting rod, there is no buckling in the contact area of the female thread of the steel bolt. However, when aluminum is used, it does affect the buckling of the surface but it is possible to cope with this by extending the engaging length.

#### 5. Coping with Stress Relaxation

It is well known that stress relaxation occurs when non-quenched and non-tempered material like high tensile strength steel wire is used in a high temperature environment, and in the case of automobiles, it is applicable to the engine or the transmission. Figure 15 shows the relationship between initial bolt tension and residual bolt tension when the temperature is maintained at 140 °C, equivalent to that of the engine environment. From this, we can understand that high tensile strength steel wire if used near the material strength limit has large stress relaxation due to heat compared to quenched and tempered material. If used as is, then the concern of reduction in tension occurs. Moreover, as mentioned earlier, the quenched and tempered material being compared, may be subjected to delayed fracture in the high stress region. Therefore, the results of these tests only reflect stress relaxation and ignore the delayed fracture of quenched and tempered material.

The dislocation introduced during the wire drawing process is activated by the rise in temperature, shifts under the influence of the stress field, and as a result, deforms. This is the cause of the stress relaxation in the high tensile strength steel wire. Accordingly, we studied how to introduce the Cottrell atmosphere, which is formed by giving thermal energy to the mobile dislocations and thus activating light elements like C, N, to penetrate the unstable parts of the dislocation and make it a sessile dislocation. By maintaining the temperature at 200-300 °C so that C, N are sufficiently diffused in order to introduce the Cottrell atmosphere, characteristics equivalent to quenched and tempered material were obtained, as shown in Fig. 15.

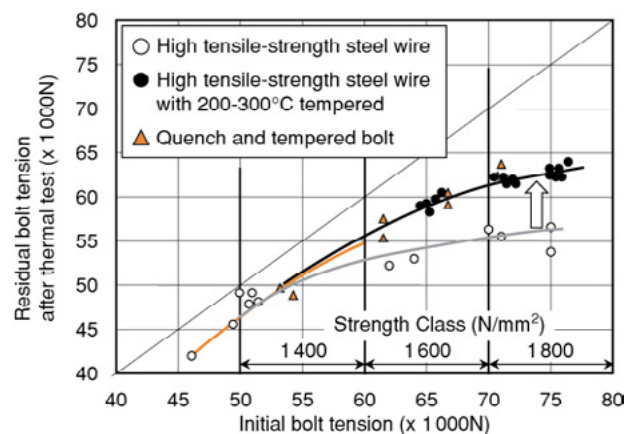


Fig. 15 Relationship between initial bolt tension and residual bolt tension

#### 6. Application Results

Figure 16 shows the comparison of bolts manufactured using this technology and actual examples of bolts manufactured using the existing materials. The thread size of

the connecting rod bolts was reduced from M12, when using the existing materials, to M9. As a result, the weight of an individual bolt in each connecting rod was reduced by 80 g, and when the connecting rod was included, the weight was reduced by 240 g per unit. The outer dimensions of the big end could also be reduced from 88 mm to 81 mm.

This reduction in weight also extended to the complete engine, and the results are shown in Fig. 17. The layout shown in red lines is the design using conventional technology, while the layout in blue lines show the design using the newly developed technology. The specifications of the dimensions shown by the blue lines are the same as those of the mass production engine. The results obtained using the new technology show a significant improvement in the output even though the basic framework of a conventional engine has remained unchanged.

The weight reduction effect when all the vehicle's bolts were substituted by bolts using the new technology was investigated. When the bolt size was reduced to achieve tension equivalent to the strength and size of the conventional bolt, a reduction in weight in the bolts alone of about 7-8 kg/vehicle was achieved. Furthermore, if the reduction in weight of peripheral parts such as connecting rods is also considered, then further savings in weight can be anticipated.

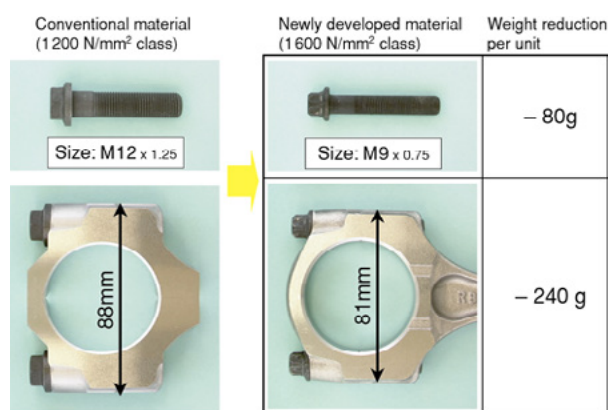


Fig. 16 Application for connecting rod bolt

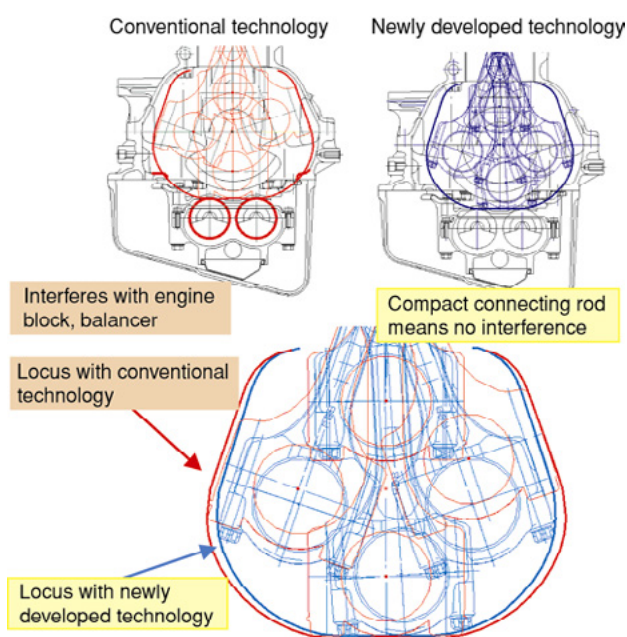


Fig. 17 New engine with newly developed connecting rod bolt

## 7. Conclusion

High tensile strength steel wire, considered to be unsuitable for formation of bolts by conventional methods was studied, and formability of the bolts was improved as given below, with the aim of developing bolts of the 1 600 N/mm<sup>2</sup> class.

- (1) The optimum Cr addition amount for the high tensile strength steel wire was set at 0.2% to improve the value of reduction in area.
- (2) A method to form the head section from low hardness, large-diameter wire while work hardening it, was used.
- (3) The optimum reduction rate was taken as 20-25% for balancing the Bauschinger effect and residual solid lubricant amount.
- (4) The hexalobular shape was used in the head section considering the ease in formability and weight savings this shape offers.

Finally, the optimum bluing conditions were set as measures against relaxation specific to non-quenched and non-hardened materials.

In view of the above-mentioned points, it was possible to mass-produce 1 600 N/mm<sup>2</sup> class bolts with superior delayed fracture characteristics for the first time in the world.

## Acknowledgements

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