

Development of High Fatigue Strength Ultra-Fine Grained Stainless Steel for Cylinder Head Gasket

Takashi KATSURAI*

ABSTRACT

Fatigue testing of metallic cylinder head gaskets has shown that there is a performance discrepancy between the original sheet material and the manufactured gasket. It was determined that this discrepancy was caused by the grain boundary cracking that occurs during head forming. Therefore, an improved austenitic stainless spring steel possessing high fatigue strength was developed to improve gasket performance. This new steel features a grain-refined structure achieved by controlling recrystallization with reverse transformation.

The developed steel has a composite structure consisting of a rolling induced martensite structure and a recrystallized austenitic structure by reverse transformation having an average grain size kept to within $1 \sim 2 \mu\text{m}$. When this material is applied to a cylinder head gasket, fatigue strength is increased 30% and there is no loss of combustion gas sealing performance.

1. Introduction

As engine performance improves, conventionally common graphite or similar inorganic cylinder head gaskets (hereafter referred to as “head gaskets”) are being replaced by metallic gaskets, which offer superior durability and functionality. As shown in Fig.1, the head gaskets are made from thin sheet stainless steel (approx. 0.2mm), such as SUS301, and utilize the repulsive force of the beads formed thereon to form seals against combustion gas, cooling water and lubricating oil. The bead seal for the combustion chamber (hereafter referred to as “bore bead”) is subject to the harshest environment comprised of high temperatures and high pressure gas. Furthermore, in recent years the bore bead has tended to be used in increasingly even harsh environments, particularly due to the following three factors: (1) lower

engine rigidity due to thinner cylinder heads and cylinder blocks and the change to all aluminum parts with the aim of reducing engine weight, (2) reduced center distances due to expanding bore diameters with the aim of reducing the size of high output engines, and (3) higher compression ratios in order to reduce fuel consumption.

Under these conditions, there is an increase in cylinder head lift caused by combustion pressure (hereafter referred to as “gap”). This leads to repeated crushing of the bore head by the cylinder head with each explosion and the resultant concern about reduced fatigue life. However, fatigue test results for the thin material sheets before bore bead forming and for the gasket after bore bead forming do not always show the same tendencies, making it impossible to judge applicability of the stainless steel sheet materials as a gasket material based on fatigue strength.

Therefore, the causes of the discrepancy in fatigue characteristics between material and product were clarified by analyzing the state of bore bead fatigue cracking propagation, and an austenitic stainless steel sheet with greatly improved fatigue strength was developed. This paper reports these contents.

2. Causes of Bore Bead Cracking

2.1. Bore Bead Fatigue Strength

The head gasket is formed so that the bore bead encloses the combustion chamber, so that the gasket is arranged between the cylinder head and the cylinder block. During operation, a stress amplitude acts locally under high tensile stress at the foot and the underside of the bore bead peak as shown in Fig.2. The gap reacts to this stress amplitude, with a greater stress amplitude produced on gasket bore beads

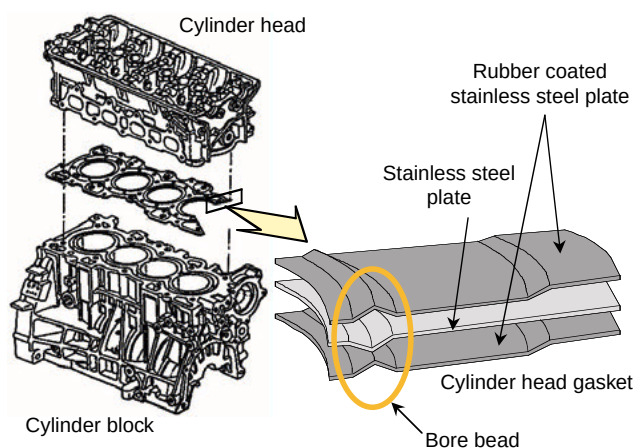


Fig.1 Illustration of cylinder head gasket

* Tochigi R&D Center

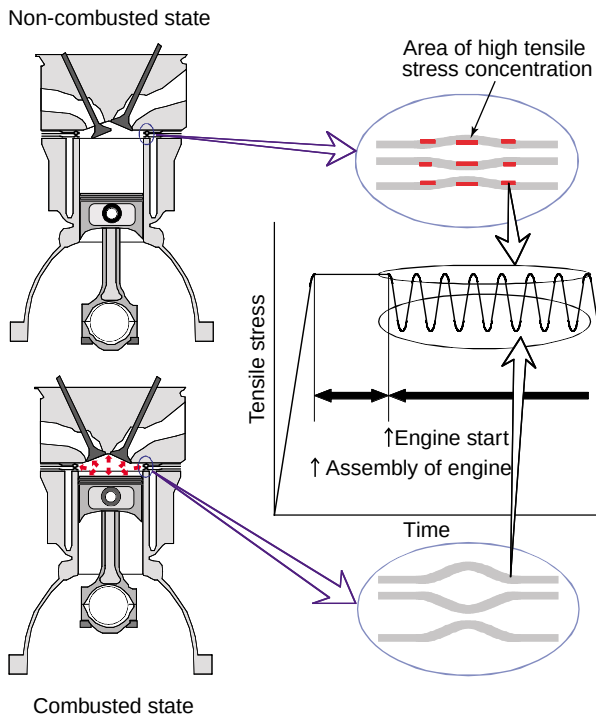


Fig.2 Tensile stress of gasket during engine running

for engines having larger gaps. For this reason, gasket fatigue strength is generally evaluated using the gap instead of a single stress event.

Therefore, crack limit displacement was set as an index for expressing gasket fatigue strength. Crack limit displacement is the displacement of the “no fatigue cracking” limit of the bore bead when a compressive load is repeatedly applied to the bore bead for up to 10^7 cycles during vibration fatigue tests.

2.2. Discrepancy between Material and Bore Bead Fatigue Characteristics

Fig.3 shows the results of planar bending fatigue strength measurements taken in the direction perpendicular to 0.2

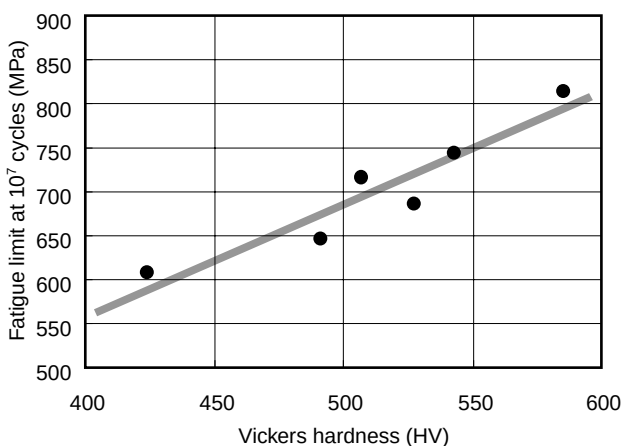


Fig.3 Relationship between fatigue limit stress and hardness for as-rolled sheet

mm thick SUS301 steel sheets with varying hardnesses. These results show that the fatigue limit increases linearly as the hardness increases. In these tests all cracking occurred from the surface, and the effects of non-ferrous inclusions⁽¹⁾⁻⁽³⁾ which cause the variations in the fatigue limit generally seen in high strength materials were not evident.

Next, Fig.4 shows the results of similar fatigue tests performed on bore beads manufactured using SUS301 materials of varying hardness. These results show a clear linear relationship between crack limit displacement and hardness. However, in contrast to the fatigue characteristics of the material, the crack limit displacement dropped as the hardness increased. In order to determine whether this was caused by the test conditions, minute strain gauges were affixed to the foot of cracked bore beads and the fatigue test results in Fig.4 were replaced with mean stress and stress amplitude. These results are shown in Fig.5, and indicate that although cracking is not affected by mean stress, it is highly dependent on stress amplitude. According to these tests, the failure limit stress amplitude did not vary with mean stress but rather was fairly constant at 90 MPa.

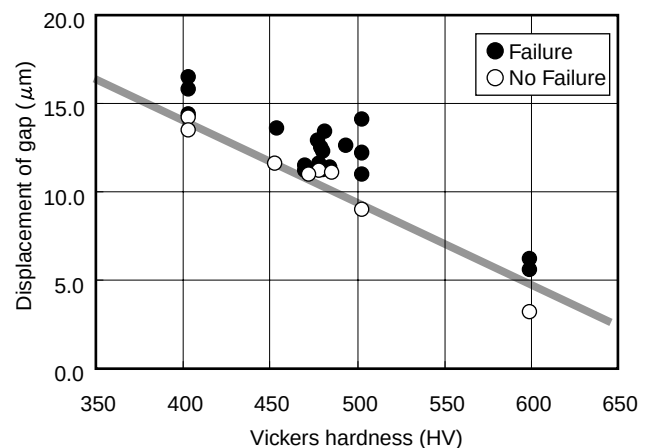


Fig.4 Relationship between displacement of gap and hardness
Solid line shows the displacement of gap against failure

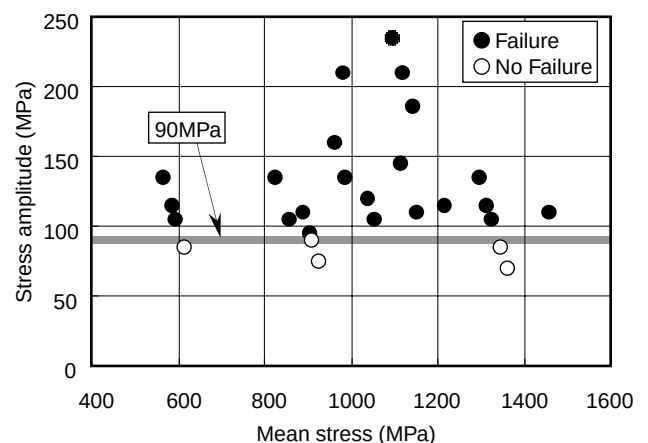


Fig.5 Effects of stress amplitude and mean stress on fatigue strength after 10^7 cycles

These results showed that the fatigue characteristics of the stainless steel sheet materials and the gasket products did not match, and that high material fatigue strength did not necessarily indicate superior fatigue characteristics when manufactured into a gasket. In other words, bore bead fatigue strength cannot be improved simply by increasing the material fatigue strength⁽⁴⁾⁽⁵⁾.

2.3. Bore Bead Cracking Condition

During bore bead forming, stress concentrates locally at the bead foot and peak as shown in Fig.6. In particular, high compressive stress is applied during bead forming at the bead foot, a starting point for fatigue failure. This is why the fatigue strength of the head gasket product exhibits reverse material fatigue strength tendencies. Further, this is thought to be the effect of local stress concentration during forming.

Fig.7 shows the results of observing the bead foot surface condition with a scanning electron microscope during bead forming and during a fatigue test. These results show the following fatigue conditions: a) although some grain boundary erosion was confirmed to have occurred in the acid-washing process after cold rolling and annealing, the surface was fairly clean before bead forming; b) bead forming caused cracking to occur at the grain boundaries, creating

undulations in the surface; c) in the early stages of the fatigue test, fatigue cracking advanced from the grain boundary cracks generated during bead forming; d) in the latter stages of the fatigue test, fatigue cracking advanced further and developed into large cracks.

Thus, the cause of the discrepancy in fatigue strength characteristics between gasket and material is thought to be due to the micro-cracks at the grain boundaries of the material surface generated during bead forming which easily lead to fatigue crack initiation⁽⁶⁾. Therefore, fatigue tests were carried out with the same load using test pieces whereon the surface of the bead foot was polished after bead forming to remove the grain boundary cracks produced by bead forming and unpolished test pieces. As shown in Fig.8, this was confirmed to extend the crack occurrence life by approximately 15 times.

Based on the above results, the discrepancy in fatigue strength characteristics between material and gasket is caused by the generation of micro-cracks in the grain boundaries at the bead foot surface due to bead forming. Conversely, it can be said that drops in fatigue strength produced when machining gaskets can be reduced by suppressing the formation of micro-cracks in the grain boundaries⁽⁷⁾.

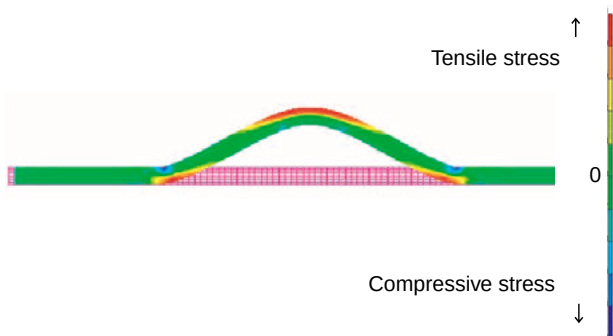


Fig.6 Distribution of stress in section of bead-formed sheet

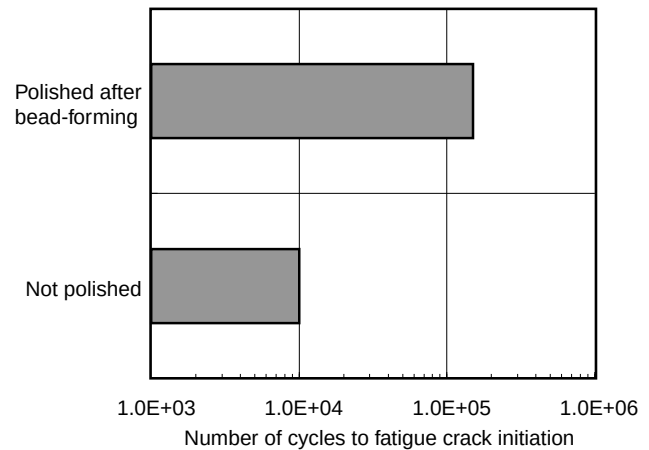


Fig.8 Effect of polish after bead-forming on fatigue crack initiation

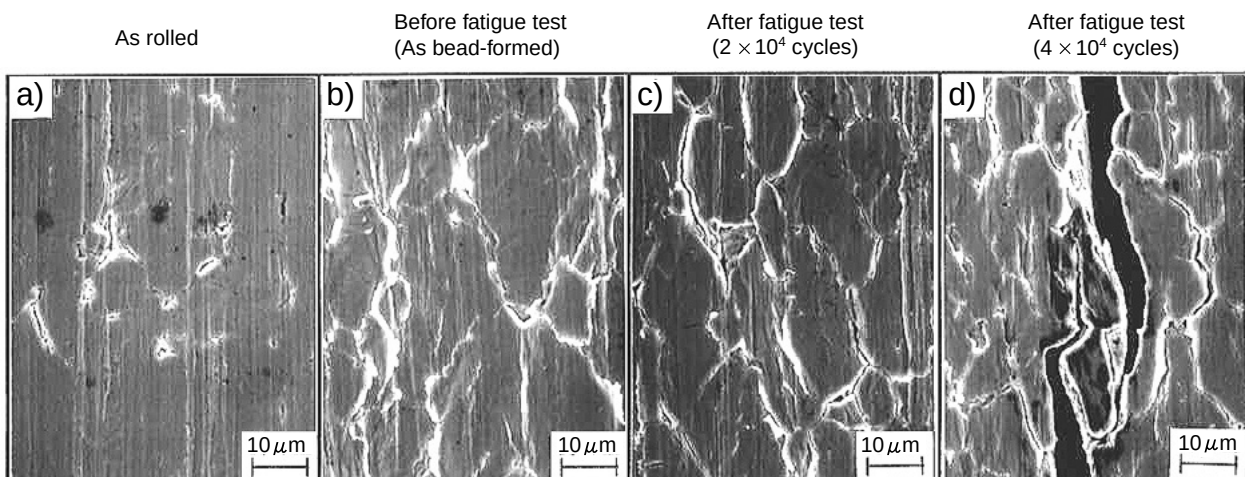


Fig.7 Surface of bead foot profile

3. Techniques for Suppressing Grain Boundary Cracking

3.1. Investigation of Grain Refinement Methods

Grain refinement which disperses deformation stress and improves grain boundary strength is thought to be the most effective means of suppressing grain boundary cracking. SUS301 is a metastable austenitic stainless steel which attains high strength by inducing a martensite structure through cold rolling. As shown in Fig.9, the sectional structure of the completed material after cold rolling has an induced martensite structure within former austenitic grains elongated in the rolling direction.

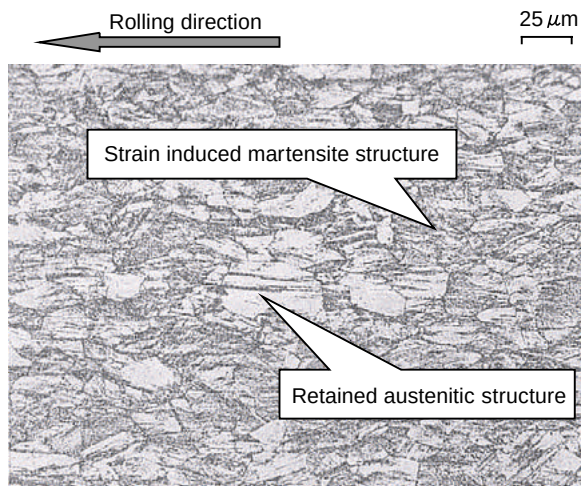


Fig.9 Microstructure of SUS301 after cold rolling

The grain refinement obtained in the completed material depends heavily on controlling the cold rolling and annealing steps in the final processing. In the final processing, the material structure undergoes a “reverse transformation sequence” in which the martensitic structure is annealed to form austenite and this is retransmitted to form the composite austenitic and martensitic structure by the final rolling. This final grain refinement is heavily dependent on the prior austenitic grain size. The control of this prior austenitic structure is accomplished by controlling the driving forces that govern recrystallization. Therefore, it is particularly important to control the strain energy of the cold rolling before annealing as well as the thermal energy of the annealing process.⁽⁸⁾⁻⁽¹¹⁾

3.2. Investigation of the Optimum Component System

The critical manufacturing processes for grain refinement are the cold rolling and annealing processes. However, the material components also have a great effect on grain growth behavior in the annealing process.

Fig.10 shows the change in austenitic recrystallized grain size with reverse transformation with respect to the annealing temperature for two types of steel, SUS301 with a carbon content of approximately 0.10% and SUS301L wherein the

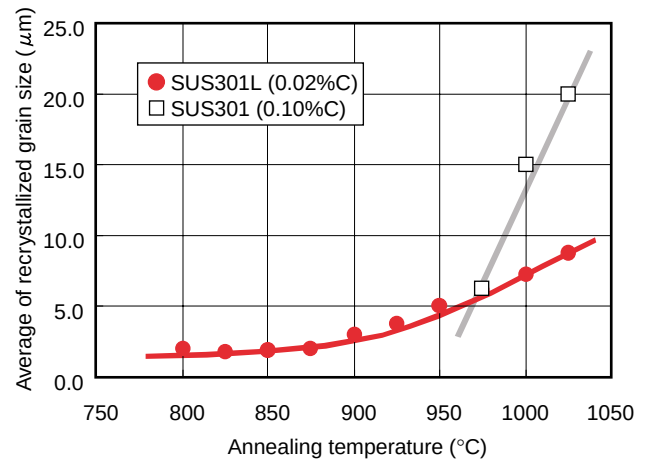


Fig.10 Effect of carbon on recrystallized grain size

carbon content was reduced to approximately 0.02%. When carbon-content is high, the recrystallization start temperature increases and, further grain growth also progresses rapidly, which facilitates roughness. In contrast, when there is little carbon, recrystallization starts from a relatively low temperature and the grain growth behavior is also slower, making this an effective means for refinement.

Fig.11 shows the half-value width of X-ray diffraction of austenitic grains in the annealed SUS301L. The half-value width caused by recrystallization drops sharply at around 800°C, indicating that the start temperature for recrystallization with reverse transformation exists in this temperature area. In addition, there is almost no change in the half-value width at temperatures above 800°C, suggesting that recrystallization is complete and grain growth is occurring.

In this manner, lowering the carbon content is an effective means of controlling grain refinement. However, since bore bead spring performance must also be ensured when applied as a head gasket material, an appropriate amount of nitrogen was added to the developed material to compensate for the drop in matrix hardness resulting from the lower carbon content.

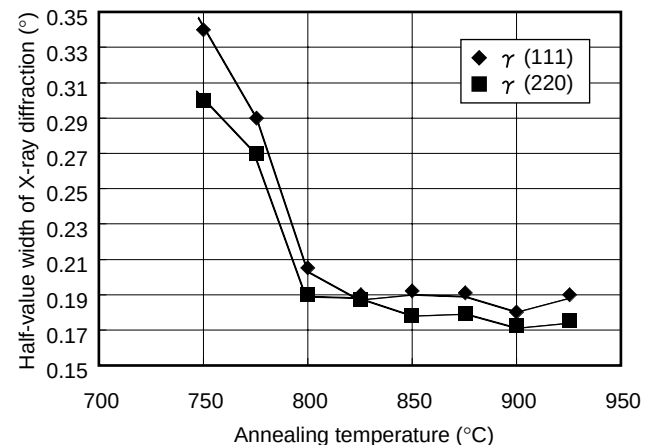


Fig.11 Relationship between half-value width of X-ray diffraction and annealing temperature

3.3. Grain Refinement Limit

Fig.12 shows the relationship between the average crystallized grain size and the hardness of the developed material after annealing. When the average crystallized grain size was 2.0 μm or less, the reverse transformation recrystallized austenitic structure was a composite structure consisting of rolling induced martensite structure enclosed by a reverse transformation recrystallized austenitic structure as shown in Fig.13. Like the full recrystallized single-phase austenitic structure, the relationship between the average crystallized grain size and hardness for this type of composite structure exhibits a clear linear relationship following the Hall-Petch formula⁽¹²⁾⁽¹³⁾. If grain refinement is further pursued to achieve an ultra-fine grained structure with a grain size of 1.0 μm or less, the ratio of rolling induced martensite structures increases and this structure is no longer enclosed

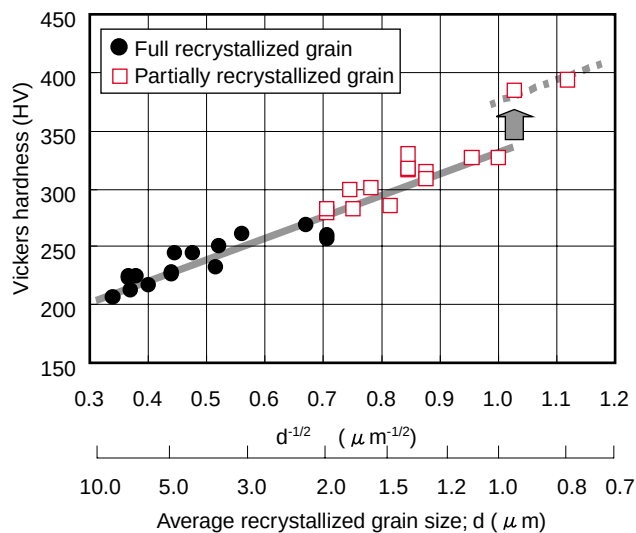


Fig.12 Relationship between hardness and average recrystallized grain size

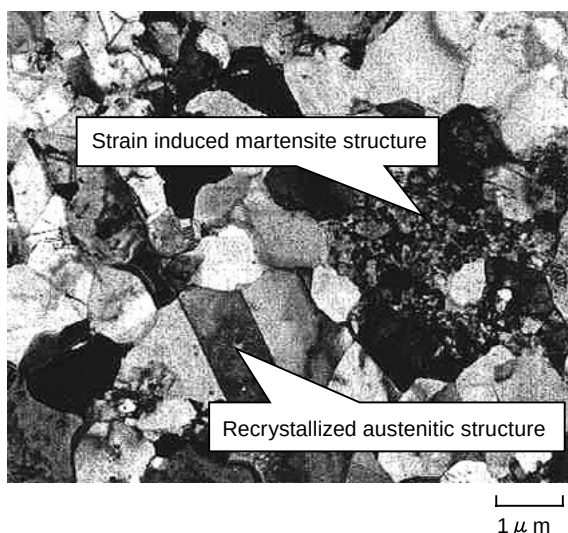


Fig.13 Transmission electron micrograph of post-bright annealing (Average of grain size: 1.0~2.0 μm)

by the reverse transformation recrystallized austenitic structure as shown in Fig.14. As a result, the relationship between grain size and hardness does not follow the Hall-Petch formula, so the limit of grain refinement effects for this material is thought to be up to approximately 1.0 μm .

3.4. Effectiveness of a Composite Structure

The developed material lowers the carbon content and adds nitrogen to SUS301 in order to control refinement of the reverse transformation recrystallized structure. Therefore the machining hardness behavior after cold rolling differs. Fig.15 shows a comparison of hardness after 48% cold rolling. First is the complete austenitic structure with an average full recrystallized grain size of approximately 2.0 μm . In this case, grain refinement strengthens the grain boundary, resulting in an increase in hardness of approximately 10 HV compared to SUS301L which is a low carbon material like the developed material. However, this is still approximately 30 HV below the target SUS301 material hardness (470 HV).

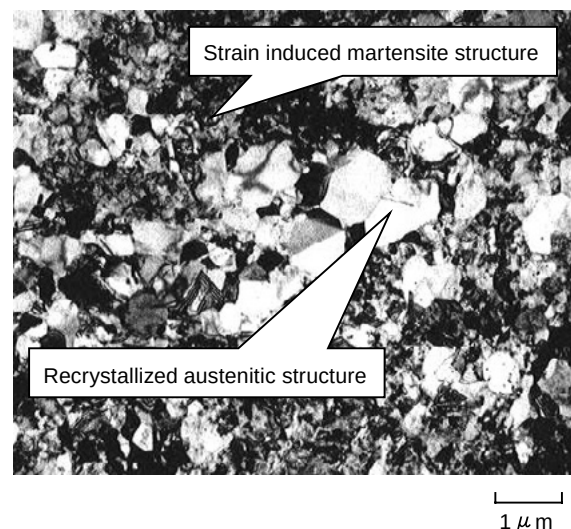


Fig.14 Transmission electron micrograph of post-bright annealing (Average of grain size: less than 1.0 μm)

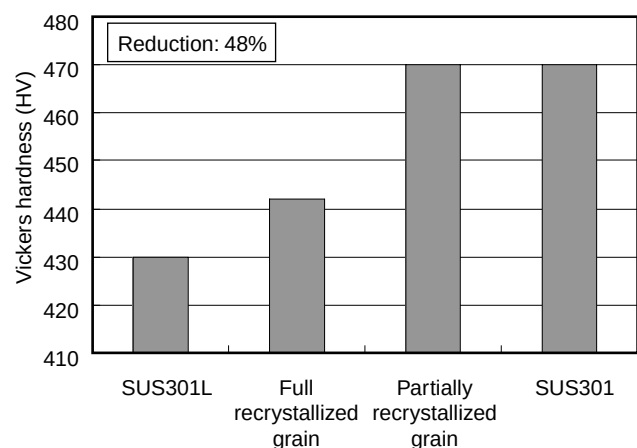


Fig.15 Comparison with hardness after 48% cold rolling

In order to raise the hardness, the first thing that comes to mind are methods of increasing the cold rolling reduction rate. However, increasing the reduction rate more than is necessary increases the amount of rolling induced martensite structure produced and greatly deteriorates the workability, and therefore is inappropriate.

Next, the amount of added nitrogen can be increased to raise the solid solution strengthening performance. However, the nitrogen partial pressure (pN_2) cannot be raised with the normal Argon Oxygen Decarburization (AOD) refining method, making it difficult to increase the nitrogen to the same level as carbon. Increasing the chromium also raises the nitrogen solid solidifying process, but this increases costs. Furthermore, if large amounts of nitrogen are added, the nitride solid solution treatment temperature rises sharply, making it difficult to establish grain refinement as a mass production process. In addition, methods of increasing hardness through aging also increase costs, and are therefore inappropriate.

Therefore, when an ultra-fine grained composite structure consisting of rolling induced martensite structure and reverse transformation recrystallized austenitic structure having an average grain size of 2.0 μm or less is adopted, the synergistic effects of a stronger matrix and further grain refinement make it possible to obtain hardness equivalent to SUS301 with the same rolling reduction rate.

3.5. Bore Bead Fatigue Strength Improvement Effects

Fig.16 shows the relationship between the average grain size of the reverse transformation recrystallized structure after bright annealing and the fatigue strength of this same material cold rolled to a hardness of HV470 and having a formed bore bead. These results show that the fatigue strength increases as the grain size becomes smaller not only for the full recrystallized structure material, but also for the partially recrystallized composite structure material containing martensite structure. In these tests, the bead crack limit displacement was increased by approximately 35% by refining the crystallized grains to achieve a composite

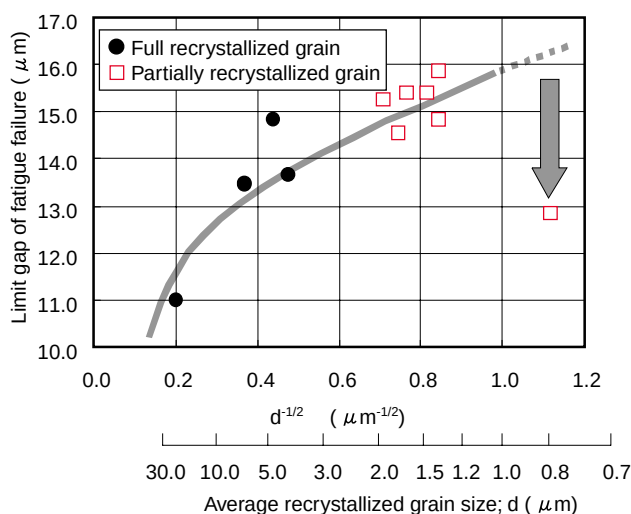


Fig.16 Relationship between limit gap of fatigue failure and average recrystallized grain size

structure state of approximately 2.0 μm , or about 1/15 the average SUS301 materials grain size of approximately 20 to 25 μm .

However, this tendency holds true only for an average grain size of 1.0 μm or more where the relationship between the crystallized grain size and hardness follows the Hall-Petch formula. Based on these results, even if a martensite structure remains after annealing, most of it is enclosed by a reverse transformation recrystallized austenitic structure. Therefore fatigue strength improvement effects can be obtained from grain refinement within if the material falls within a range that follows the Hall-Petch formula.

As described above, the authors developed a metastable austenitic stainless steel for application as a head gasket material having a composite structure consisting of a reverse transformation recrystallized austenitic structure mixed with a martensite structure, and an average grain size which is controlled to 1 to 2 μm . This developed material was named NAR301L-HS1, and ensures the same level of hardness needed to seal high pressure combustion gas as SUS301, while at the same time dramatically improving gasket fatigue strength.

4. Effects of Application to an Actual Vehicle

Fig.17 shows the results of bore bead fatigue tests performed up to 10^7 cycles using test pieces. These results show that even taking into account the variance in fatigue strength due to hardness and crystallized grain size, the composite structure grain-refined material has a crack limit displacement approximately 30% higher than SUS301.

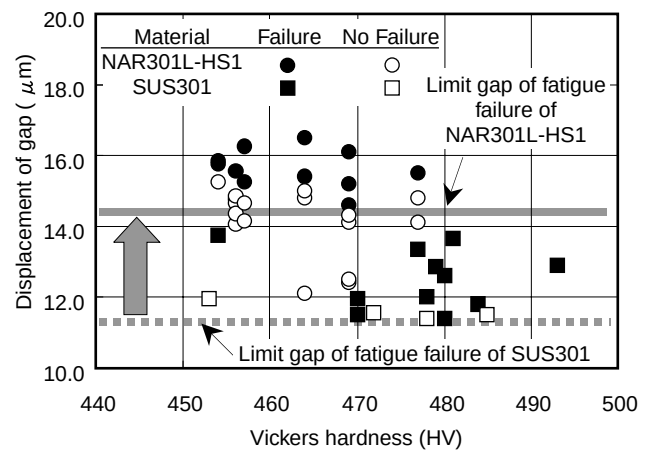


Fig.17 Relationship between displacement of gap and hardness after cold rolling

Fig.18 shows the results of applying the composite structure grain-refined material to the head gasket of a newly developed engine. This engine uses the basic structure of same-bore pitch engines (A to D) currently on the market, while aiming for even higher output. The maximum combustion gas pressure (P_{max}) is higher than conventional engines, and the maximum gap is also increased by approximately 50%.

For this reason the crack limit displacement of the

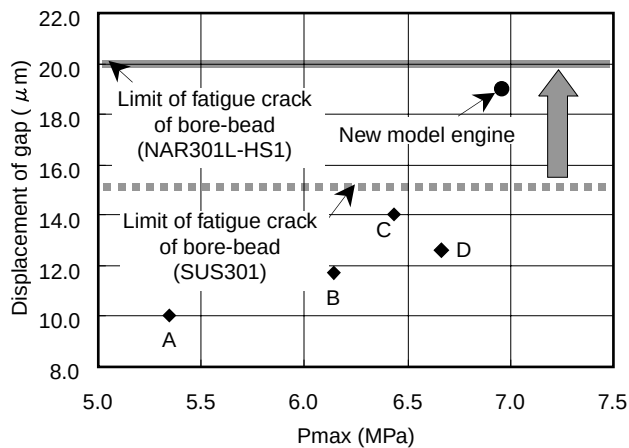


Fig.18 Effect of application of cylinder head gasket for new model engine

SUS301 material 3-layer structure head gasket used in conventional engines is exceeded by a wide margin. Therefore, a head gasket with superior fatigue characteristics was considered necessary. Generally, the crack limit displacement is increased by increasing the number of bore bead layers to reduce the gap load on each layer, or a stepped type gasket which concentrates the load on the bore is adopted to reduce the gap itself. However, all of these countermeasures involve exclusive parts and increased costs. On the other hand, the newly developed composite structure grain-refined material makes it possible to develop a low cost head gasket with superior durability.

5. Conclusion

The bore bead fatigue failure mechanism of the cylinder head gasket was analyzed, crystallized grain refinement with a composite structure was proposed as a means of improving fatigue strength, and a new material was developed. As a result, the following conclusions were obtained:

- (1) The discrepancy between the fatigue strength characteristics of the material and the head gasket was caused by cracking at grain boundaries due to bore bead forming, and fatigue failure initiated and advanced from these grain boundary cracks.
- (2) Refinement of the crystallized grains is an effective means for suppressing grain boundary cracking.
- (3) Refinement to an average grain size of approximately 1.0 μm is possible by controlling the reverse transformation recrystallization behavior. The material forms a composite structure with an average grain size of 2.0 μm or less consisting of rolling induced martensite structure enclosed by a reverse transformation recrystallized austenitic structure. In addition, the relationship between grain size and hardness follows the Hall-Petch formula.
- (4) Metastable austenitic stainless steel was developed for application as a head gasket material. This material has a composite structure consisting of martensite structure and a reverse transformation recrystallized structure.

Further, the average grain size is controlled to 1 to 2 μm . This ensures the level of hardness needed to seal high pressure combustion gas as possessed SUS301, while at the same time improving gasket fatigue strength by 30% or more.

Acknowledgment

In closing the authors wishes to express his deep thanks to all concerned parties at Sumitomo Metal Industries who participated in this joint development and at Nihon Leakless Kogyo for manufacturing the cylinder head gaskets.

References

- (1) Yukitaka Murakami, Shotaro Kodama, and Shizuyo Konuma: Quantitative Evaluation of Effects of Nonmetallic Inclusions on Fatigue Strength of High Strength Steel, Transactions of JSME Vol.A-54, No.500, p.688-p.693(1988) (Written in Japanese)
- (2) Yoshihiro Ohkomori, Ikujiro Kitagawa, Keigo Shinozuka, Toshiyuki Toriyama, Kenji Matsuda, Yukitaka Murakami: Effects of Nonmetallic Inclusions and Small Surface Pits on the Fatigue Strength of a High Strength Steel at Two Hardness Levels, *Tetsu-to-Hagane*, No.77, p.438-445(1991) (Written in Japanese)
- (3) Yukitaka Murakami, Motokazu Kobayashi, Taizo Makino, Toshiyuki Toriyama, Yoshiaki Kurihara, Souichi Takasaki, Ryuichiro Ebara: Quantitative Evaluation of the Factors Influencing Fatigue Strength of Spring Steels (Effects of Nonmetallic Inclusions, Shot Peening, Decarburized Layer and Small Surface Pits), Transactions of JSME Vol.A-57-542, p.2305-p.2313(1991)(Written in Japanese)
- (4) Takashi Katsurai, Tatsumi Tozawa, Hajime Kato, Yoshimasa Takayama: Fatigue Fracture for Bead-formed Sheet of Austenitic Stainless Steel, CAMP-ISIJ, Vol.6, p.1763-1753(1993) (Written in Japanese)
- (5) Takashi Katsurai, Tatsumi Tozawa, Hajime Kato, Yoshimasa Takayama: Fatigue Fracture for Bead-formed Sheet of Austenitic Stainless Steel, *Tetsu-to-Hagane*, No.80, p.54-59(1994)
- (6) Keisuke Tanaka, Yoshikazu Nakai, Yoshiaki Akiniwa: Mechanisms and Mechanics of Fatigue Fracture of Steels, *Tetsu-to-Hagane*, No.79, p.12-23(1993) (Written in Japanese)
- (7) Takashi Katsurai, Tatsumi Tozawa, Hajime Kato, Yoshimasa Takayama: Effect of Surface Feature on Fatigue Fracture for Bead-formed Sheet of SUS301 Steel, CAMP-ISIJ, Vol.8, p.1682-1682(1994) (Written in Japanese)
- (8) Kouki Tomimura, Yuuji Kawauchi, Setsuo Takaki, Youichi Tokunaga: Effect of Prior Deformation on Grain Refining Process of Martensitic Shear Reversion in Metastable Austenitic Stainless Steel, *Tetsu-to-Hagane*, No.77, p.139-146(1991) (Written in Japanese)
- (9) Ken Moriya, Ryo Matsuki, Haruo Aoyama: Development of High Strength SUS304 Stainless Steel by Grain Refining, CAMP-ISIJ, Vol.12, p.514-514(1999) (Written in Japanese)

- (10) Setsuo Takaki: Reversion of Deformation Induced Martensite to Austenite and Mechanism of Ultra Grain Refining, *Tetsu-to-Hagane*, No.80, p.529-535(1994) (Written in Japanese)
- (11) Setsuo Takaki: Ultra Grain Refining of Steels –Driving Force for Grain Refining and Limitation of Refinement–, *Netsushori*, No.34-5, p.260-264(1994) (Written in Japanese)
- (12) Kurzydowski K.J., Bucki J.J.: “Flow Stress Dependence on the Distribution of Grain Size in Polycrystals”, *Acta Metall. Mater.*, Vol.41, p.3141-3146 (1993)
- (13) Setsuo Takaki: Suggestion for the Evaluation of Grain Size in Ultra Fine Grained Steels, *CAMP-ISIJ*, Vol.12, p.1150-1152(1999) (Written in Japanese)

■ author ■



Takashi KATSURAI