

Development of High-heat-resistant High-nitrogen Containing Austenitic Stainless Steel for Exhaust Gasket

Takashi KATSURAI*

Tadao NISHIYAMA*

Shuji HAMANO**

ABSTRACT

SUS301-EH is widely used as a material for exhaust system gaskets, but a decline in the material's ability to seal gases due to its reduced hardness at temperatures in excess of 400 °C makes it impossible to use it in high-temperature applications. The research described in this paper determined that the following methods were effective in controlling the softening of stainless steel at high temperatures: (1) The addition of a nitrogen component; (2) Stabilization of the austenite structure; (3) The addition of a molybdenum component. The application of this material to exhaust gaskets has enabled the achievement of excellent seal performance even in tightened sections in high-temperature environments of 400 °C and above, which was problematic for conventional gasket materials.

1. Introduction

Improvements to combustion and exhaust systems are being made in recent years to balance the requirements of better exhaust emission control performance and reduction in CO₂ emissions through enhanced fuel consumption. The effect of cutting down the catalytic temperature rise time for

activating the catalyst quickly has become significant, and engines with a shortened exhaust system passageway up to the catalyst and reduced exhaust system heat capacity are currently in operation. In view of such developments, the temperature of exhaust system components is becoming higher, and the usage environment of gaskets used for sealing the exhaust is becoming more severe.

* Tochigi R&D Center

** Daido Steel Co., Ltd.

2. Development Goals

SUS301-EH stainless steel with high strength and excellent spring characteristics has been used until now as the material for metallic gaskets used for sealing exhaust at the connections of components in the exhaust system and cylinder head. This gasket is made of a thin sheet of 0.2 mm thickness as shown in Fig. 1, has a bead formed on it and has a shape that envelopes the exhaust port. This bead acts as a spring. Its function is to seal the exhaust that passes through the clearance between the cylinder head and the flanges of exhaust system components, which deform during operation due to heat from high temperature combustion gases. However, the deformation of flanges of tightened parts has tended to be excessive in recent years because of the high temperatures of the exhaust system components⁽¹⁾. Since gaskets are also subjected to high temperature usage environments, the gasket material is required to possess high spring characteristics in high temperature environments.

When the temperature exceeds 400 °C, SUS301-EH, which is conventionally used as the gasket material, suddenly becomes soft and loses its spring characteristics. Consequently, the gasket needs to be used in environments where the temperature is below 400 °C. However, for the newly developed three-cylinder engine shown in Fig. 1, a structure in which the turbocharger is directly fitted to the cylinder head is adopted in order to shorten the exhaust system passageway up to the catalyst and to reduce the heat capacity. The temperature of flanges at the connections exceeded 500 °C, and SUS301-EH could no longer be used. Thus, a high-heat-resistant gasket material that could retain its sealability characteristics adequately, without softening at temperatures of 500 to 600 °C, was required.

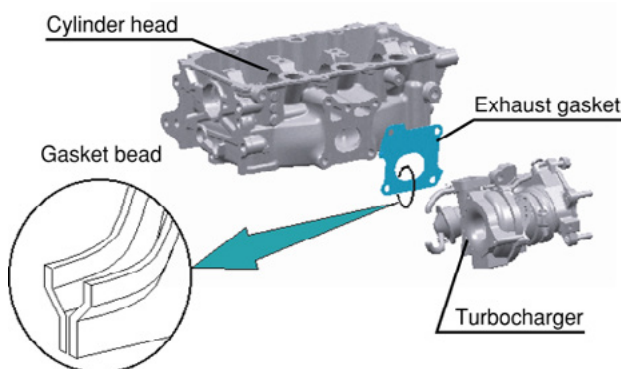


Fig. 1 Illustration of exhaust gasket

3. Study of Methods to Retain Hardness at High Temperatures

3.1. Required Properties of Gasket Material

The gasket was tightened between the flanges, held at various temperature ranges for 400 hours, and then taken out. The height of the bead remaining (residual bead height) and the hardness were measured. Figure 2 shows the relationship between the residual bead height and the hardness. According to this figure, when the hardness drops below HV400, the bead undergoes plastic deformation due to the flange tightening force and the residual bead height becomes practically zero. In this way, the hardness of the material is an important factor that governs the sealability of the gasket.

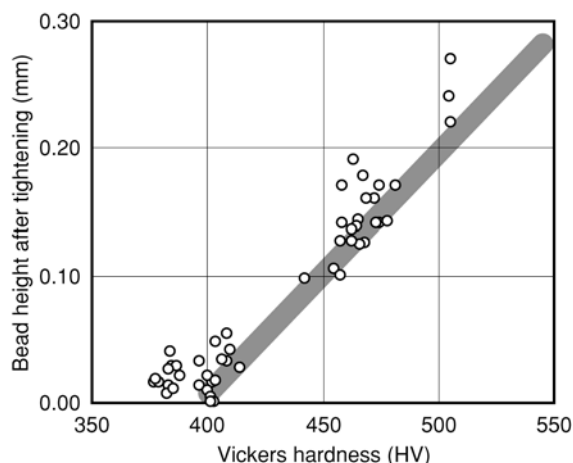


Fig. 2 Relationship between hardness and bead height after hot tightening

The higher the hardness is, the greater the spring restoring force becomes and the more superior its sealability is.

As demonstrated above, the gasket material should possess hardness greater than HV400 and should enable the bead to be formed. SUS301, the material conventionally used in gaskets, is a metastable austenitic stainless steel. Strain energy is given to this material in the final cold rolling stage of the steel manufacturing process. As a result, a high strength strain-induced martensitic structure is obtained, which gives high hardness to the material. During final cold rolling, a large dislocation can be introduced in the strain-induced martensitic structure, giving rise to work hardening. Thanks to the transformation of martensite and the synergistic effect, a tempered rank of EH (Extra Hard) with hardness greater than HV500 can be obtained.

3.2. Causes of Hardness Reduction of SUS301-EH

If SUS301-EH is held for a long period at a high temperature, it becomes soft because the large dislocation introduced during the final cold rolling is released and recovered to its original state, and the strain-induced martensite returns to austenitic structure due to inverse transformation.

Figure 3 shows the results of hardness measured after holding SUS301-EH at a high temperature for 400 hours. It can be observed from the figure that at temperatures greater than 400 °C, the softening of the material progresses rapidly. It is well known that the inverse transformation of structure of strain-induced martensite occurs at temperatures near 800 °C⁽²⁾. The cause of the rapid reduction in hardness at temperatures near 400 °C is attributed to the recovery. Accordingly, it is important to inhibit the release of dislocation introduced by the strain so as to control softening in the temperature range of 500 to 600 °C.

SUH660 and SUS631 are well known as stainless steel materials for high temperature use. Ni-based Inconel-625 is also widely used as a heat-resistant material. Figure 3 shows the hardness characteristics at high temperatures of SUS301-EH and Inconel-625. According to this figure, Inconel-625 can retain its hardness at room temperature even up to a temperature of 800 °C. However, the initial hardness at room temperature is about HV350 to HV400, and therefore, it is unsuitable for use as gasket material. Thus, the existing heat-resistant materials could not retain high hardness in a stable condition over the range of temperatures

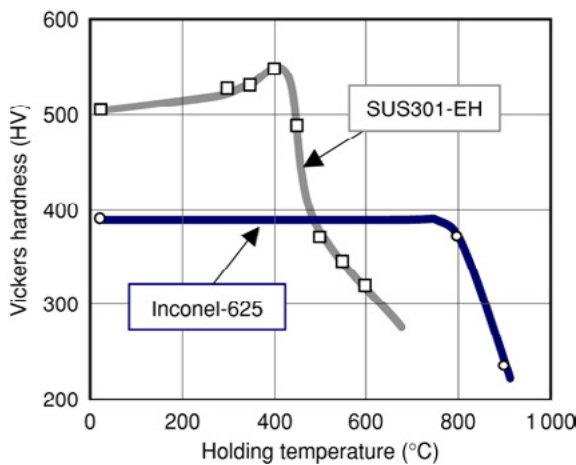


Fig. 3 Relationship between hardness and bead holding temperature after 400 Hr

from room to high temperatures, and high sealability required of a gasket material could not be attained when they were used.

3.3. Concept of Material Design

The material for gaskets used at high temperatures should satisfy the balancing requirements of: (1) high hardness to ensure spring characteristics, and (2) stable structure that inhibits softening at high temperatures. For this purpose, the dislocation introduced in the structure for high strength by work hardening should be made to adhere fast so that it is not released at high temperatures and softening does not occur. Two methods are effective for adherence of the dislocation: the method of dissolving C and N, which are interstitial solid solutions, in the crystal lattice and the method of precipitating C and N as carbides and nitrides⁽³⁾. In this development work, attempts were made to prevent as far as possible, the motion of the dislocation by the synergistic effects of both methods. Particularly, since N has a higher solubility in solid than C, it is not likely to form coarse precipitates such as Cr_{23}C_6 even if held for a long period in high temperature and is unlikely to become brittle. Thus it was decided that dissolving a large amount of N was an effective method^{(4), (5)}. Moreover, steel with high N-content has been reported^{(6) - (8)} to have high strength and excellent workability. It is also considered to be ideal for bead forming⁽²⁾ of gaskets to which strain has been applied locally.

The solubility in liquid of N in molten steel follows the Sieverts' Law $[\text{N}\%] = A [P_{\text{N}_2}]^{1/2}$. Therefore, the partial N_2 pressure (P_{N_2}) cannot be increased in the conventional Vacuum Oxygen Decarburization (VOD) process, and the general practice is to use solubility in liquid of high N containing steel at about 0.2%. Only the high Cr, high Ni, Mo-based seawater-resistant 0.5%N Super Stainless (Avesta Sheffield 654SMo)⁽¹⁰⁾ and 1.0%N steel experimentally tried out by pressurized ESR (Electro Slag Re-melting) apparatus have been reported as other high N-added steels^{(11), (12)}. It was considered that increasing the amount of additives Cr and Mn, which are elements that enhance the solubility of N in molten steel, would increase the amount of N added under similar conditions of partial N_2 pressure without changing the refining method^{(13), (14)}.

Moreover, the method of forming austenitic structure, which has a face centered cubic lattice (fcc) structure with high solubility in solid, is effective in dissolving the solid N

even at room temperature. Furthermore, the fcc structure enhances hardness at high temperature since its self-diffusion coefficient is small because of the high packing density of atoms. Therefore, the effect of forming austenitic structure is considered to be significant.

N, an interstitial element being dissolved in the austenitic structure, forms an Interstitial-Substitutional (I-S) bond with Cr, Mn, and Mo, which are substitutional solid elements, and is known to possess characteristics that enhance strength further⁽¹⁵⁾. Its combination with Cr, Mn, and Mo as an additive is considered to be very effective⁽¹⁶⁾. The addition of Mo to a newly developed material was studied in particular because of its effect in improving strength at high temperatures by solid solution hardening.

Based on the results of the study mentioned above, component design was carried out with the following as the basis: (1) addition of N; (2) stabilization of austenitic structure; and (3) addition of Mo. The development target values for the material were set as retention of initial hardness greater than HV450 and retention of residual hardness greater than HV450 even after 400 hours at 600 °C.

3.4. Results of Validity Verification of Component Design

The material of each component was held for 400 hours at 600 °C, and the effects of various parameters for residual hardness were analyzed. Figure 4 shows the effects of the addition of N. It was confirmed from this figure that the residual hardness increases almost directly in proportion to the amount of N added up to an addition of 0.3%N. Next, Fig. 5 shows the results that confirm the effects of material structure. To express the state of material structure here, the Ni equivalent (N_{ieq}) according to Delong's equation⁽¹⁷⁾ (1) is used.

$$N_{\text{ieq}}(\%) = \text{Ni}\% + 0.5 \times \text{Mn}\% + 30 \times (\text{C}\% + \text{N}\%) \quad (1)$$

The results showed that when Ni-equivalent is high and the austenitic structure is stable, the residual hardness after retention at high temperatures is high, confirming that the stable austenitic structure is effective as the parent phase. Finally, Fig. 6 shows the effects of the addition of Mo. From these results, it was confirmed that the addition of Mo is also effective in the retention of hardness at high temperatures.

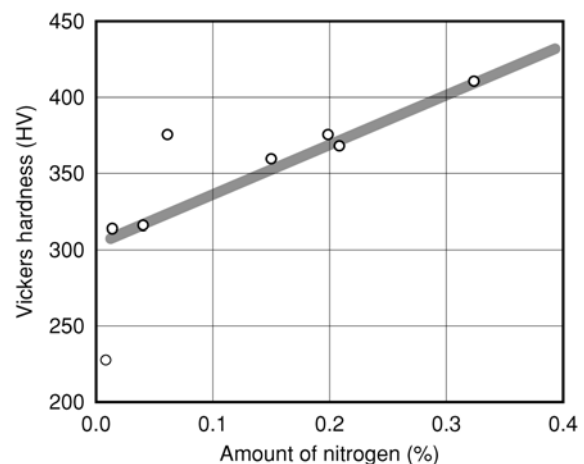


Fig. 4 Effect of amount of nitrogen on hardness after 600 °C × 400 Hr holding

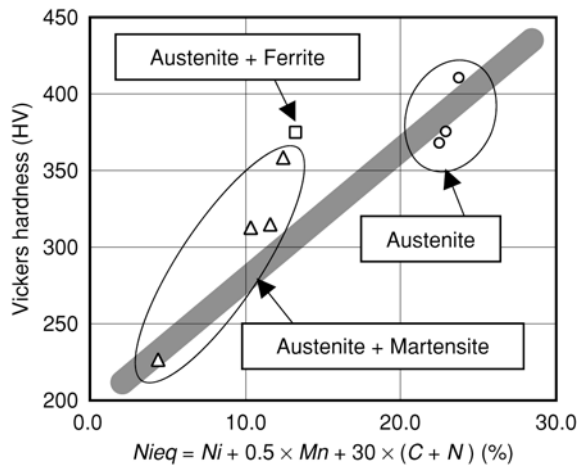


Fig. 5 Relationship between Ni equivalent and hardness after 600 °C × 400 Hr holding

The validity of component design was verified from the results above, therefore, optimum specifications that maintain an appropriate balance were studied. Since the effects of the addition of N are particularly large, it was considered that the emphasis should be placed on having N as the maximum solid solution in the component specifications⁽¹⁸⁾.

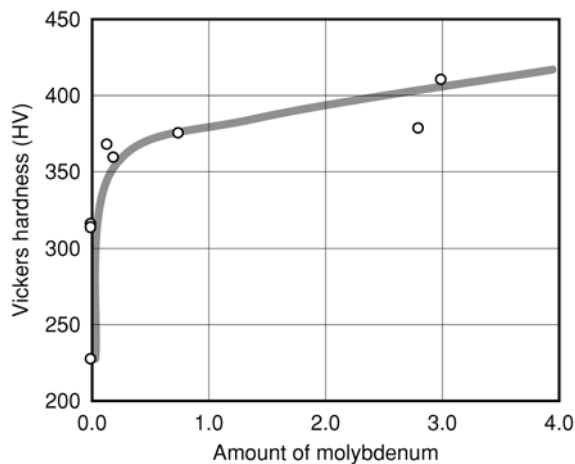


Fig. 6 Effect of amount of molybdenum on hardness after 600 °C × 400 Hr holding

3.5. Setting Material Component Specifications

Table 1 shows the approach to component design based on: (1) N as the maximum solid solution; (2) Stabilization of austenitic structure, and (3) The addition of Mo. The settings are explained in a simple manner below.

- N : Addition to molten steel until the saturated soluble amount
- C : Added as the minimum limit required for reducing other interstitial solid solutions for obtaining N as the maximum solid solution
- Ni : Element for stabilizing austenite; appropriate amount is to be added since it reduces the solubility in solid of N
- Mn : Element for stabilizing austenite; appropriate amount is to be added since it enhances the solubility in solid of N for compensating stabilization of austenite which declines due to

Table 1 Alloy design concept

N	High	Solid-solution hardening
C	Low	Increase solubility of nitrogen
Ni	Proper	Stabilize austenite
Mn	Proper	Increase solubility of nitrogen
Cr	High	Increase solubility of nitrogen
Si	Low	Stabilize austenite
Mo	Proper	Increase heat resistance
V	Proper	Prevent increase in grain size

inadequate Ni

Cr : Greatest element for N solid solution; added as 23% so that maximum solid solution is obtained at the solution temperature

Si : Added as the minimum limit since it is an element generating ferrite

Mo : Appropriate amount is to be added to enhance heat resistance

V : Added so that minute amount of C adheres as carbide and also to prevent increase in size of coarse grains

Table 2 shows the components of the newly developed material with 0.5% N solid solution, designed based on the results of the study above. It was also confirmed that a hardness level of HV470 could be attained, which is adequate for gasket material by implementing final cold rolling at a reduction of 60% for the said material.

Table 2 Chemical composition of newly developed steel

(wt%)							
C	Si	Mn	Ni	Cr	Mo	V	N
0.02	0.2	6.0	10.0	23.0	2.0	0.1	0.5

4. Verification of Effects

4.1. Hardness Characteristics during High Temperatures

Figure 7 shows the results of the measurements of change in hardness after holding the newly developed material for 400 hours at high temperatures. The figure shows that the hardness value is maximum at 400 to 450 °C. Subsequently, a softening trend that is proportional to the temperature was verified. It can also be observed that the initial hardness is retained even at 600 °C. Compared to the softening of SUS301-EH at temperatures above 400 °C, the temperature at which softening starts has been raised by more than 200 °C. Softening that occurred near 400 °C due to the release of dislocation was also completely inhibited.

Figure 8 shows the results that confirm the effects of retention time corresponding to softening at high temperatures. According to this figure, the hardness at 600 °C has increased from the initial hardness in 10 hours but subsequently there is no change. At temperatures above 700 °C, the softening has practically ended in about 100 hours. Subsequently, the onset of softening is extremely small, with dependence more on temperature than on time.

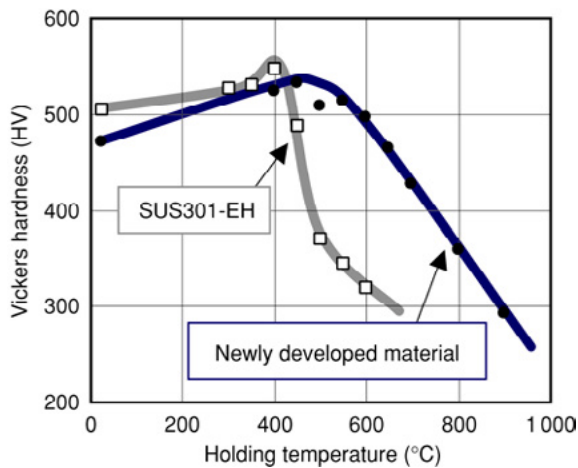


Fig. 7 Relationship between hardness and holding temperature after 400 Hr

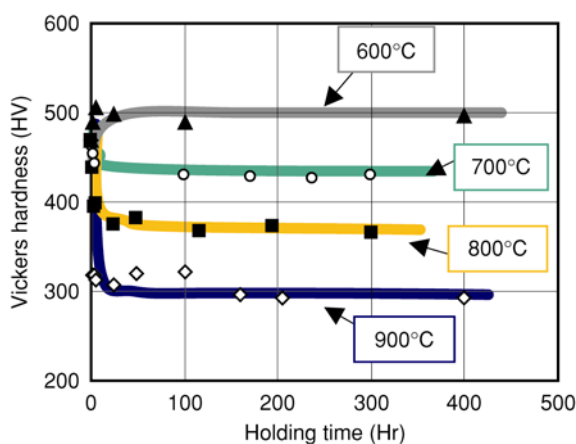


Fig. 8 Relationship between hardness and holding time

4.2. Hardening Mechanism at Temperatures below 600 °C

The hardening mechanism was analyzed since the hardness increases at temperatures of 600 °C and below compared to the initial hardness. Figure 9 shows the results of observations made on the material held at 600 to 900 °C for 400 hours using the optical microscope. These

observations show the processed structure in grains caused by strain and grains elongated due to rolling at 600 °C. Elongated grains remained at 700 °C similar to the condition at 600 °C, but it was also observed that microstructures of recrystallized fine-grains or precipitates near the grain boundary were formed. Furthermore, at temperatures of 800 °C and 900 °C, these microstructures grew and became coarse.

To verify whether the hardening mechanism at 400 to 600 °C was due to precipitates or not, an attempt was made to identify the precipitates in samples held for 400 hours at 600 °C by the melting extraction method, but precipitates could not be detected. Moreover, no change in hardness was observed and precipitates could not be detected even when solution treated materials without strain were held for a long period at the same temperatures. From these results, the hardening mechanism at 400 to 600 °C is considered to be strain aging with enhanced adhering capacity of dislocation, as a result of accumulation of solid N around the dislocation introduced at final cold rolling at a reduction of 60%, which forms a Cottrell atmosphere. The mutual interaction due to the I-S bond is also predicted to have a considerably large effect^{(15), (16), (18)}.

4.3. Hardening Mechanism at Temperatures above 600 °C

It was confirmed from the results of observation with an optical microscope that the microstructure generated in the vicinity of the grain boundary has a large effect on the change in hardness of the newly developed material at high temperatures. Figure 10 shows the results of analysis by the scanning electron microscope for material held at 400 hours at 900 °C. It was verified from the results that two kinds of precipitate — black-colored high Cr, N-based precipitate less than 2 μm and white-colored high Cr, Mo-based precipitate of about 3 μm — existed in these microstructures. Figure 11 shows the results of the analysis of these precipitates by an electron beam diffraction pattern. It was confirmed from these results that the black-colored high Cr, N-based precipitate was Cr₂N but similar identification of the white-colored high Cr, Mo-based precipitate could not be made.

It is well known that in the case of high nitrogen containing steel, Cr₂N precipitates at temperatures above 600 °C^{(19), (20)}. In the case of the newly developed material too, precipitation hardening is considered to occur due to precipitation of Cr₂N

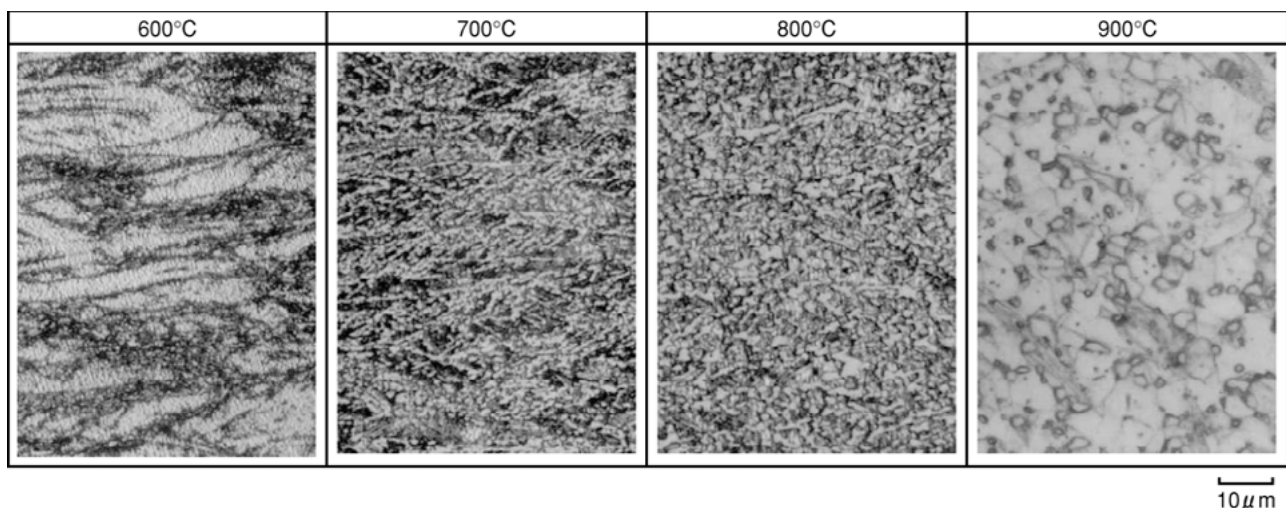


Fig. 9 Microstructure of newly developed material (600 – 900 °C : After 400 Hr holding)

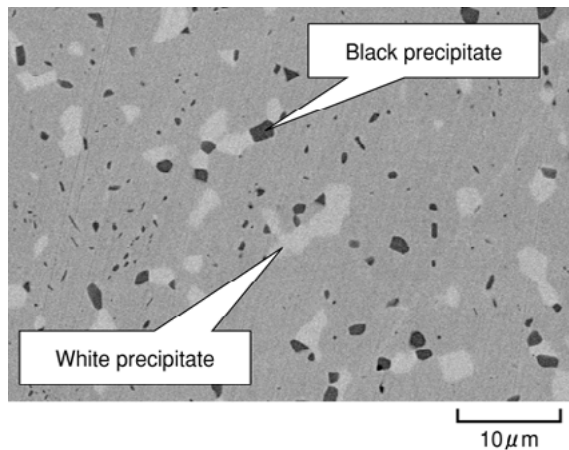


Fig. 10 Scanning electron micrograph after annealing (900 °C × 400 Hr)

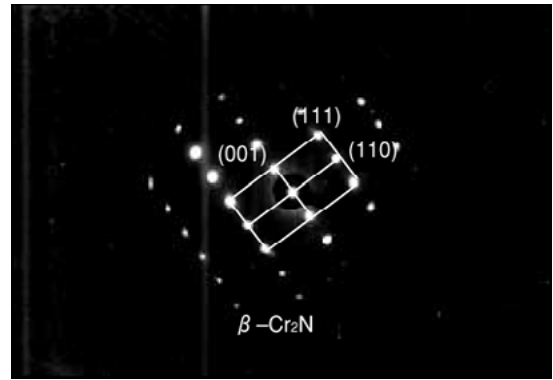


Fig. 11 Result of analysis by electron beam diffraction pattern

at temperatures above 600 °C. Cr_2N is said to precipitate preferentially over grain boundary and dislocation⁽²¹⁾. It has been confirmed also from Fig. 9 that it precipitates near the recrystallized grain boundary in the structure at 900 °C.

Figure 12 shows the change in structure corresponding to holding time at temperatures of 700 °C and 800 °C at which hardness reduction occurs. It is observed from the figure that precipitates are formed in the structure after a holding time of 100 hours at both temperatures, but practically no change in the structure occurs even if held up to 400 hours. Comparing the condition of such a structure with the softening characteristics shown in Fig. 8, it is seen that practically no change in hardness occurs in the range where no change in the structure occurs.

Based on these results, it can be concluded that Cr_2N precipitates preferentially on the grain boundary or on the dislocation at temperatures above 600 °C and inhibits softening due to the release of the dislocation. Furthermore, softening progresses because recrystallized structure is formed in addition to the release of dislocation at high temperatures of 800 to 900 °C. However, the precipitated Cr_2N generates

pinning effects, therefore, growth of the recrystallized grains is probably inhibited. That is probably why the change in structure and hardness at high temperatures above 700 °C became extremely slow. However, as the temperature increases, Cr_2N , which possesses pinning effects, flocculates and becomes coarser. These pinning effects reduce and the grain growth inhibiting effect at the grain boundary decreases, therefore, the softening is considered to have increased.

It is presumed that the same factors have participated in the growth inhibiting effect of precipitates and secondary recrystallized grains in case of white-colored high Cr, Mo phase, but it could not be confirmed.

4.4. Conclusion Related to Hardening Mechanism

It was confirmed that the newly developed material possesses two levels of hardening mechanisms when N is added. The first is the strain aging due to solid N in the temperature range below 600 °C, while the second is the precipitation hardening of Cr_2N in the temperature range above 600 °C. The dislocation introduced during final cold rolling is considered to act effectively in both levels.

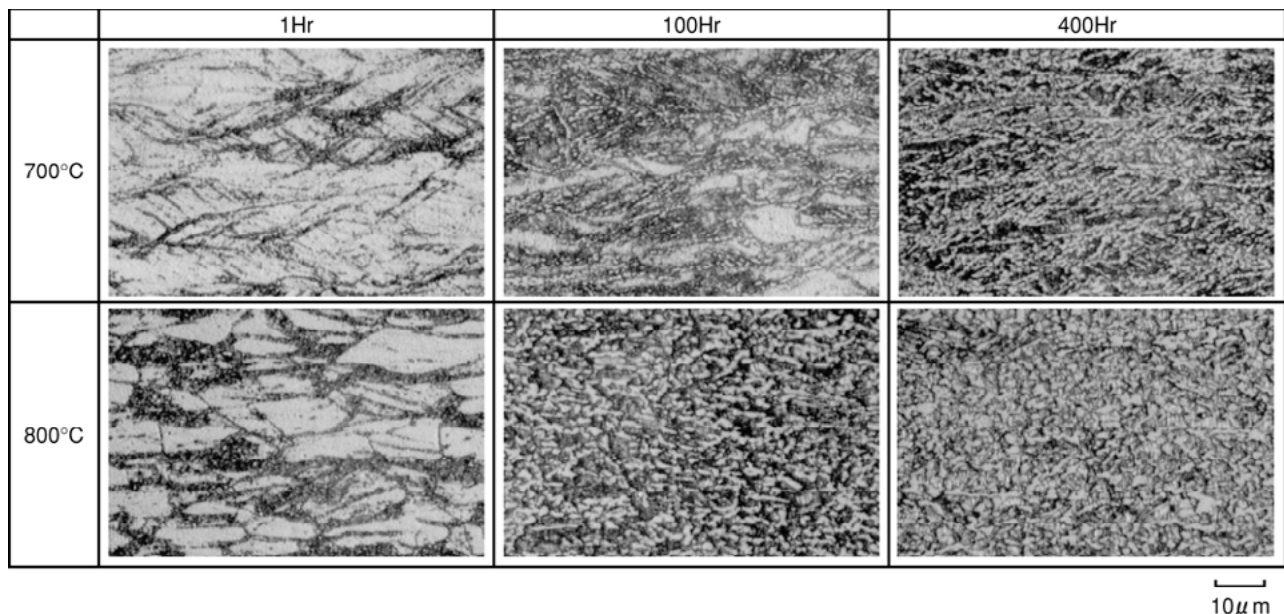


Fig. 12 Microstructure of newly developed material (700, 800 °C : After 1 – 400 Hr holding)

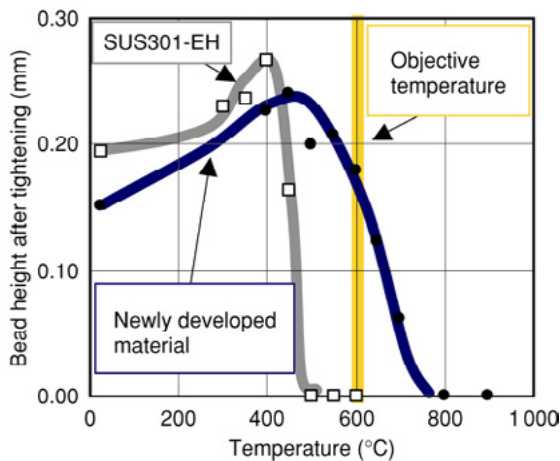


Fig. 13 Relationship between temperature and bead height after tightening test

In conclusion, when material with alloy components in which (1) solid N has been increased, (2) stable austenitic structure has been formed, and (3) Mo has been added, is subjected to final cold rolling at a reduction of 60%, inhibition of growth of recrystallized grains due to micro-precipitates of Cr_2N and strain aging due to solid N could be achieved. Thus, softening at high temperatures that had occurred in SUS301-EH conventionally was inhibited, and the temperature at which softening starts could be improved by more than 200 °C.

5. Results of evaluation of engine compatibility

A gasket was manufactured using the newly developed material. It was fitted to an actual engine, the engine was operated and the height of the residual bead was measured. From the results and the hardness reduction characteristics at high temperatures shown in Fig. 7, the relationship between the change in height of the residual bead and temperature was determined. This relationship is shown in Fig. 13. From the figure, it was observed that while the residual bead height reduced rapidly and sealability degraded at temperatures above 400 °C when SUS301-EH was used, the residual bead height above initial values was retained at temperatures up to 600 °C and no degradation in sealability occurred in the case of the newly developed material.

The temperature of the gasket of the newly developed engine using the newly developed gasket material was about 500 °C, indicating that the residual bead height had adequate sealability against heat deformation of the flange. Furthermore, it was also confirmed that the gasket had excellent sealability in the engine endurance tests.

6. Conclusion

To inhibit softening at high temperatures, efforts were made to develop a new material focusing on strain aging by using N and inhibition of growth of recrystallized grains by using nitrides. The result was the development of a spring material for use at high temperatures up to 600 °C wherein no hardness degradation occurred. This temperature was more than 200 °C higher than the temperature of conventional materials at which hardness degradation occurred. This newly developed material was used as the material in exhaust

gaskets, and it was confirmed that it possessed excellent sealability when used in tightened parts at temperatures higher than 400 °C at which sealing was difficult in conventional gasket materials such as SUS301-EH. The results of the development are summarized below.

- (1) The sealability of the gasket was evaluated by the hardness of the material. For attaining stable sealability, hardness greater than HV400 is necessary.
- (2) At temperatures below 600 °C, the dislocation introduced in final cold rolling adheres due to strain aging of solid N, and the initial hardness can be retained.
- (3) At temperatures above 600 °C, softening occurs because of the release of the dislocation. However, micro-precipitates of Cr_2N occur in the grain boundary, which causes precipitation hardening and inhibits the growth of recrystallized grains. Therefore, softening almost stops even if held for a long period.
- (4) By using the gasket with the newly developed material, the initial sealability can be retained up to about 600 °C.

Acknowledgments

The authors acknowledge with gratitude all the staff of Nippon Leakless Corporation who manufactured the gasket.

References

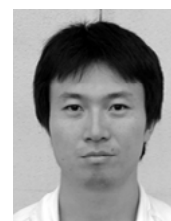
- (1) Ishii, K., Katsurai, T., Nakata, M., Wakamatsu, H., Nakasone, H.: Analysis of Sealing Behavior of Exhaust Manifold Gasket during Running the Actual Engine, HONDA R&D Technical Review, Vol. 8, p. 152-159 (1996)
- (2) Katsurai, T.: Development of High Fatigue Strength Ultra-Fine Grained Stainless Steel for Cylinder Head Gasket, Honda R&D Technical Review, Vol. 12, No. 1, p. 151-158 (2000)
- (3) Kubota, S., Tomoda, Y.: Characteristic Features of Work Hardening in Nitrogen Bearing Austenitic Steels, CAMP-ISIJ, Vol. 10, p. 538 (1997)
- (4) Koga, T., Shimizu, T., Okabe, M.: The mechanical Properties at Elevated Temperatures of High Nitrogen Stainless Steel, CAMP-ISIJ, Vol. 13, p. 638 (2000)
- (5) Wada, S., Ohta, Y.: Effect of Alloying Elements on Properties for Ultra High Nitrogen Containing Stainless Steel, Nippon Stainless Technical Report, No. 24, p. 13-30 (1989)
- (6) Katada, Y., Sagara, M., Kobayashi, Y., Kodama, T.: Creation of High Nitrogen-bearing Stainless Steel and Its Mechanical Properties, CAMP-ISIJ, Vol. 15, p. 438-441 (2002)
- (7) Speidel, Markus O.: Corrosion Science of Stainless Steels, Proceedings of International Conference on Stainless Steels, ISIJ, p. 25-35 (1991)
- (8) Koga, T., Shimizu, T., Okabe, M.: Warm Workability and Tensile Property of High Nitrogen Austenitic Stainless Steel, Electric Furnace Steel, 67-2, p. 81-86 (1996)
- (9) Takahashi, I., Yoshida, T., Mineura, K., Ohta, Y.: Study of Ultra High Nitrogen Containing Stainless Steel,

- Nippon Stainless Technical Report, No. 22, p. 1-27 (1987)
- (10) Azuma, S.: Characteristics of Constitution of High Nitrogen Containing Stainless Steel, Fushoku-Boshoku Symposium, No. 119, p. 7-12 (1998)
- (11) Uno, H., Katada, Y.: The State and the Point at Issue of the Development of Corrosion Resistant High Nitrogen-bearing Stainless Steels in NRIM, Function of Alloy and Development of New Material by Nitrogen on Stainless Steel, ISIJ-Forum, p. 38-45 (1999)
- (12) Katada, Y., Uno, H., Kodama, T.: Creation of High Nitrogen-bearing Stainless Steel by Pressurized ESR Method, CAMP-ISIJ, Vol. 13, p. 356 (2000)
- (13) Kikuchi, M., Kajihara, M., Frisk, K.: Solubility of nitrogen in austenitic stainless steels, Proc. Intl. Conf. High Nitrogen Steels, p. 63-74 (1989)
- (14) Kowanda, C., Speidel, Markus O.: Solubility of nitrogen in liquid iron base and nickel base alloys with Co, Fe, Mn, Mo and Cr under elevated nitrogen partial pressure, CAMP-ISIJ, Vol. 13, p. 355 (2000)
- (15) Murayama, M., Hono, K., Hirukawa, H., Ohmura, T., Matsuoka, S.: The Microstructural Evolution of Nitrogen Doped Austenitic Stainless Steel after Fatigue Testing, CAMP-ISIJ, Vol. 12, p. 458 (1999)
- (16) Ito, H., Nakamura, N., Takagi, S.: Effect of Chromium and Manganese Content on Equilibrium Soluble Nitrogen Content in High Nitrogen Austenitic Stainless Steels, CAMP-ISIJ, Vol. 11, p. 1151 (1998)
- (17) Long, C. J. et al: The ferrite content of austenitic stainless steel weld metal, The Welding Journal, Vol. 7, p. 281-297 (1973)
- (18) Isobe, S., Okabe, M.: Aging Behavior of Cold Worked Austenitic Stainless Steels with Nitrogen, Electric Furnace Steel, 56-2, p. 122-132 (1985)
- (19) Ogawa, M., Hiraoka, K., Shiga, C., Katada, Y., Uno, H.: Nitride Precipitation Behavior at HAZ of High Nitrogen Bearing Stainless Steel, CAMP-ISIJ, Vol. 13, p. 636 (2000)
- (20) Ogawa, M., Hiraoka, K., Katada, Y., Sagara, M.: Study on Nitride Precipitation Behavior at HAZ of High Nitrogen Stainless Steels and of it, CAMP-ISIJ, Vol. 15, p. 446-449 (2002)
- (21) Woo, I., Horinouchi, T., Kikuchi, Y.: Influence of Nitride Precipitation on the HAZ Toughness of High Nitrogen Containing Ni-Free Austenitic Stainless Steel, Tetsu-to-Hagane, Vol. 88, p. 29-35 (2002)

■ Authors ■



Takashi KATSURAI



Tadao NISHIYAMA



Shuji HAMANO