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Carbonitriding and Hard Shot Peening for High-Strength Gears

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ABSTRACT

A new process for manufacturing high-strength gears has been developed to meet the requirement of automobile transmission miniaturization. The points of the process are to increase the shot peening intensity and to perform optimal control of the initial (before shot peening) microstructure by heat treatment corresponding with the peening intensity in order to obtain higher residual compressive stress.

The new process, named Carbonitriding and Hard Shot Peening in Mazda, brings a much higher fatigue strength than the one obtained by the conventional carburizing and shot peening process.

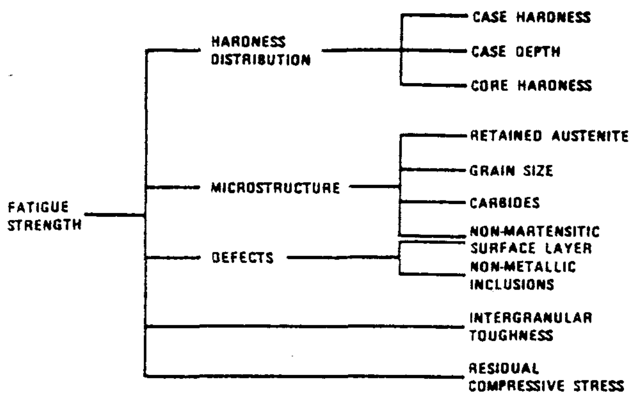

Fig. 1 METALLURGICAL FACTORS AFFECTING ON THE FATIGUE STRENGTH OF GEARS

1. Introduction

A higher drivability, stability in driving, and fuel efficiency are required for automobiles and the new systems to meet these requirements have been developed. This can be seen, for example, in multi-valve system, super charging in engines, 4 WD or 4 WS, etc. In addition, the height of engine hood has been lowered in body designing for reducing air resistance.

With such a background as those, it is desired for the transmission system to transmit higher engine output in a smaller size in order to enhance the degree of freedom in designing a power-train system or a suspension system within a restricted space.
It is one of the important subjects for the material engineers, therefore, to augment the fatigue strength of the transmission gears so as to meet these requirements.

2. Concepts of Research and Development

The fatigue strength of the gears is affected by such factors as shown in Fig. 1. In order to obtain a high fatigue strength, therefore, it is necessary to set a suitable hardness distribution by heat treatment using clean material. However, in order to augment the fatigue strength furthermore, it is necessary to make use of residual compressive stress more positively.

For enlargement of the residual compressive stress, it is most effective to increase the shot peening intensity. At the same time, it should be necessary to adjust the initial (before shot peening) retained austenite content because the formation of the residual compressive stress by shot peening is conceivably related to the phenomenon of strain-induced transformation of retained austenite into martensite.

However, there is a problem in increasing the peening intensity. That is surface roughening which occurs in case of increasing the peening intensity. The surface roughening is made conspicuous due to existence of the soft structure called non-martensitic surface layer which is inevitably formed in the conventional carburized surface of steel. In order to prevent the surface roughening, therefore, it

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is necessary to reduce the non-martensitic surface layer. The reduction of the non-martensitic surface layer simultaneously serves to mitigate stress concentration in the surface of steel, as well.

From the above matters, the following concepts of strengthening gears were introduced:

1) Reducing the non-martensitic surface layer to mitigate the stress concentration in the surface of steel and to prevent the surface roughening when the peening intensity is increased.
2) Gaining the optimal control of the initial (before shot peening) retained austenite content to maximize the residual compressive stress caused by shot peening.
3) Increasing the peening intensity to obtain greater residual compressive stress on condition that the above-mentioned two items are realized.

3. Solution of Technical Difficulty

The non-martensitic surface layer in conventional carburizing is caused by deterioration of hardenability of the surface layer due to internal oxidation of the alloyed elements.[1] In order to reduce the non-martensitic surface layer, therefore, it is conceivable to adopt such a method as to accelerate the cooling rate in quenching or to compensate the hardenability of the surface layer deteriorated due to internal oxidation of the alloyed elements by means of adding other elements.

In the above two methods, the former is not realistic because of the fault that the thermic distortion of the components becomes great. On the contrary, it has been known that nitrogen is an effective element in case of the latter.[2] In addition, nitrogen has an action to stabilize the austenite by lowering the MS point of steel.[3]

From the above consideration, it is conceivably that carbonitriding is hopeful as a technical means to realize the aforesaid development concepts 1) and 2). However, carbonitriding has been so far applied widely to carbon steel which does not contain alloyed elements such as chromium, etc., but there are not so many cases of being applied to alloyed steel which is used for gears. This is conceivably due to the reason that the renovation effect of hardenability by nitrogen permeation is not sufficient on alloyed steels. Nevertheless, the details of the reason and improving

the one in carburizing, is formed as well in the usual carbonitrided surface layer of chromium-alloyed steel. The growth of this non-martensitic structure is the technical difficulty in carbonitriding chromium-alloyed steel aiming at improving the fatigue strength.

As shown in Fig. 2, this non-martensitic structure is characterized by that the range of the structure existing along the grain boundary is deeper than the case of carburizing. It is inferable from this fact that the growth mechanism of the non-martensitic structure in the carbonitrided chromium-alloyed steel should be different from internal oxidation of the alloyed elements in the case of carburizing.

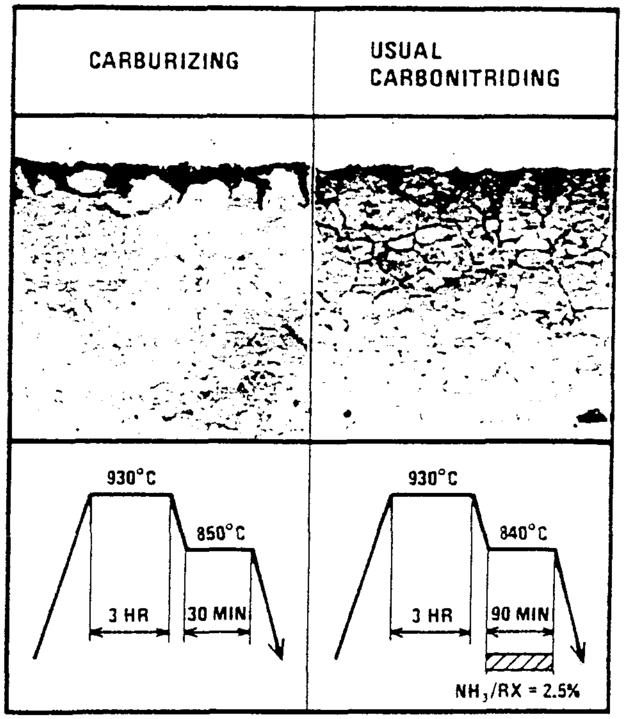

Fig. 2 NON-MARTENSITIC STRUCTURE OF CARBURIZED, USUAL CARBONITRIDED SURFACE OF CHROMIUM-ALLOYED STEEL

3.2 Growth mechanism of non-martensitic structure of carbonitrided surface layer of chromium-alloyed steel

By various experiments and analyses, an information on the growth mechanism of the above-mentioned grain-boundary non-martensitic caused by the growth of chromium nitride is shown in Fig. 4. It is indicated from Fig. 4 that the distribution of soluble chromium and that of permeated nitrogen correspond with each other.

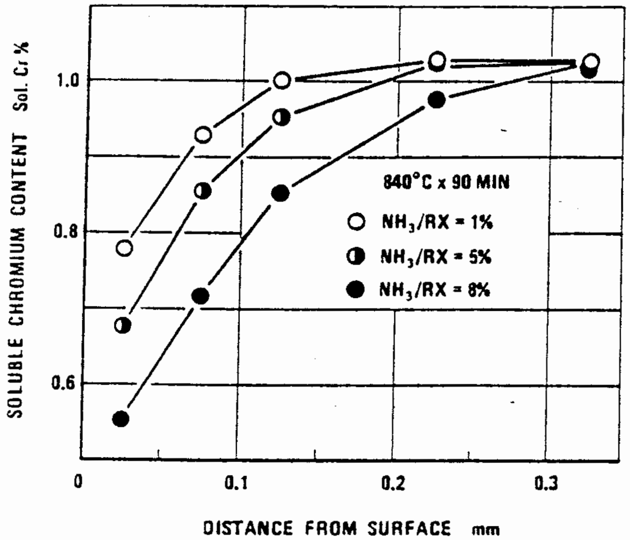

Fig. 3 STATE OF SOLUBLE CHROMIUM REDUCTION IN THE CARBONITRIDED SURFACE OF CHROMIUM-ALLOYED STEEL (SCR420)

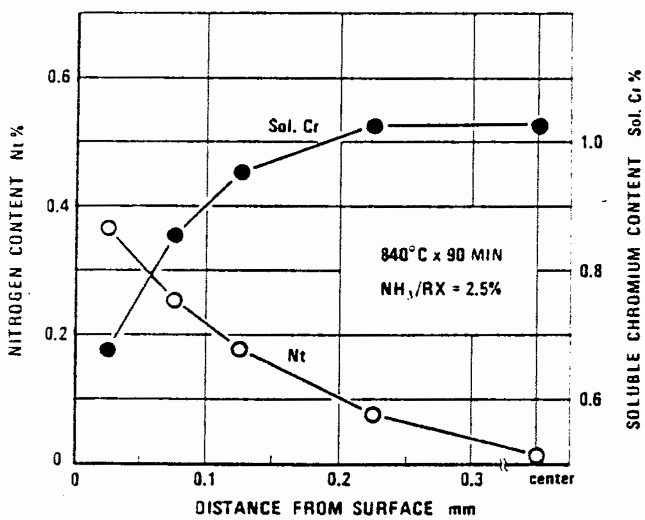

Fig. 4 DISTRIBUTION OF SOLUBLE CHROMIUM CONTENT AND PERMEATED NITROGEN IN THE CARBONITRIDED SURFACE OF CHROMIUM-ALLOYED STEEL (SCR420)

3.3 New carbonitriding process for chromium alloyed steel

As aforesaid, the amount of solved chromium is very small in carburized surface layer due to internal oxidation. By means of permeating nitrogen into this extremely shallow surface layer only, the growth of chromium nitride can be minimized.

This conception is shown in Fig. 5. A new carbonitriding process, shown in Fig. 6, has been developed based on this conception. The process is characterized by that a small amount of NH_3 is added within an extremely short time to permeate nitrogen into the extremely shallow surface layer only.

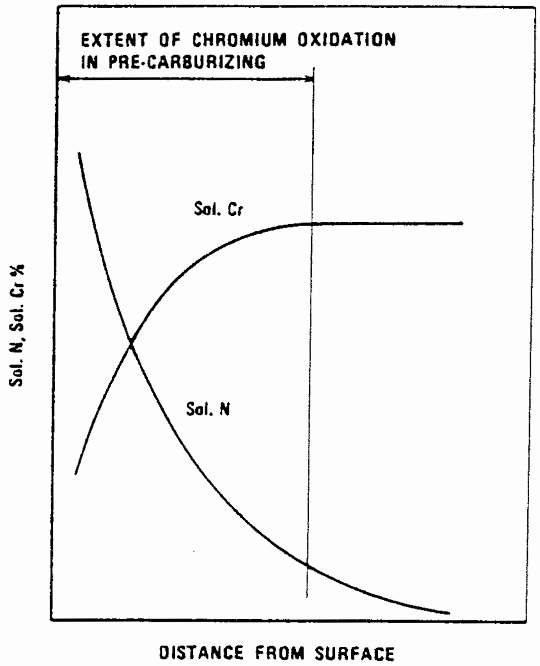

Fig. 5 CONCEPTION OF NEW CARBONITRIDING TO MINIMIZE THE GROWTH OF CHROMIUM NITRIDE

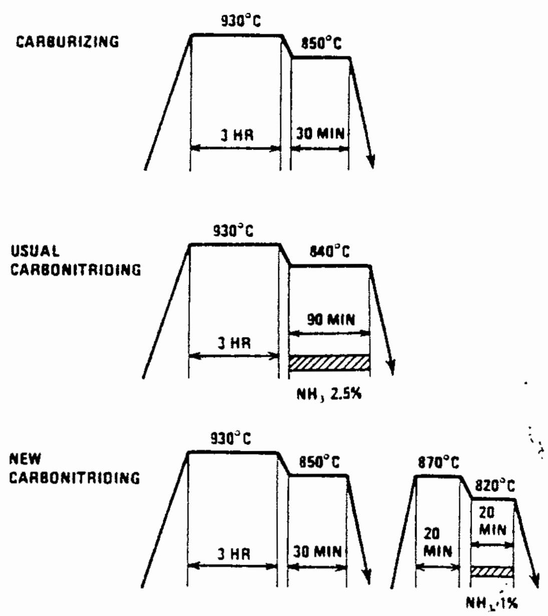

Fig. 6 NEW CARBONITRIDING PROCESS

4. Microstructure Control by New Carbonitriding Process

4.1 Reduction of non-martensitic layer of carburized surface

Fig. 7 shows the microstructure of the surface layer obtained by the new carbonitriding process. The depth of non-martensitic surface layer is extremely small compared with the case of conventional carburizing or carbonitriding by usual process, and is several μm or under.

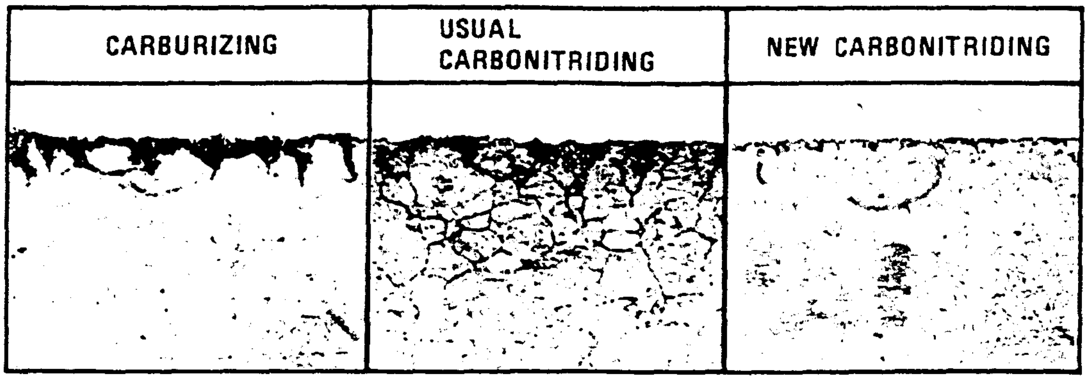

Fig. 7 MICROSTRUCTURE OF THE SURFACE LAYER OBTAINED BY NEW CARBONITRIDING PROCESS

4.2 Control of retained austenite content

By means of regulating carbon potential (C.P.) and nitrogen potential (N.P.) based on the new carbonitriding process shown in Fig. 6, the retained austenite content in the surface layer can be controlled. The range of the control is 20 - 50%, which covers more amount of retained austenite content than the case of the carburizing process only as shown in Fig. 8.

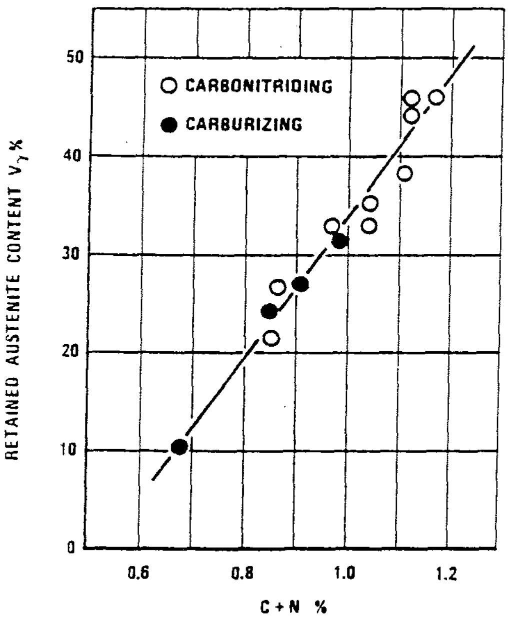

Fig. 8 RELATIONSHIP BETWEEN THE RETAINED AUSTENITE CONTENT OF CARBURIZED, CARBONITRIDED STEEL AND THE CARBON AND NITROGEN POTENTIAL IN HEAT TREATMENT ATMOSPHERE

5. Enlargement of Residual Compressive Stress

The tests were conducted to optimize the shot peening condition and the initial microstructure (retained austenite content) aiming at obtaining greater residual compressive stress. The test results are shown hereunder.

5.1 Increasing the peening intensity

The main factors to effect the peening intensity are shot hardness and shot velocity. The effects of them on the residual compressive stress are shown in Figs. 9 and 10 respectively. The harder the shot hardness is, the greater the residual compressive stress is made. However, when shot hardness is H_RC55 or over, its working effect seems to be saturated. In addition, the higher the shot velocity is, the greater the residual compressive stress is made. However, judging from the present installed capacity of shot peening, it is difficult to obtain a shot velocity of over 100 m/sec.

The new shot peening method shown in Table 1 has been developed based on the test results as above-mentioned. The characteristics of the method are that the shot hardness is greater and the shot velocity is higher than those of the conventional method. In order to obtain a high shot velocity of 90 - 100 m/sec, the injection system is applied instead of the conventional projection system. From the great peening intensity, the method is called Hard Shot Peening.

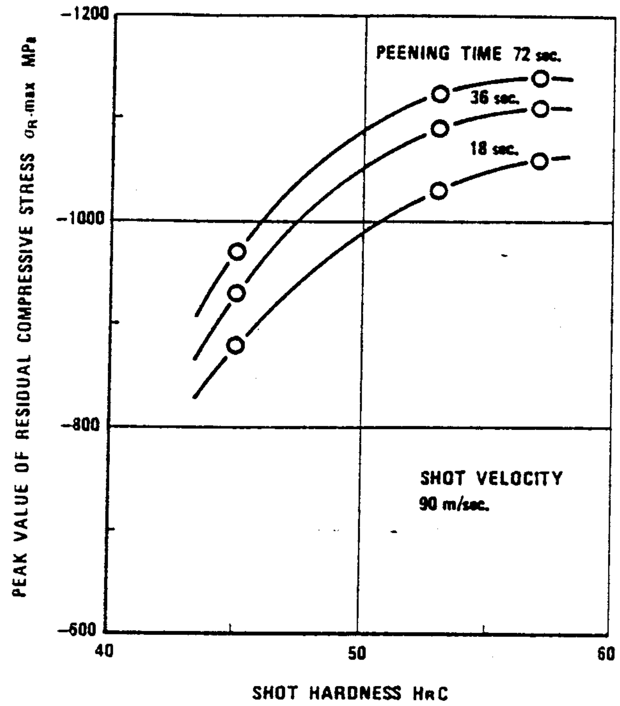

Fig. 9 EFFECT OF SHOT HARDNESS ON THE RESIDUAL COMPRESSIVE STRESS

Table 1 HARD SHOT PEENING METHOD

	CONVENTIONAL SHOT PEENING	HARD SHOT PEENING
TYPE OF SYSTEM	PROJECTION	INJECTION
SHOT HARDNESS	HRC 46 ~ 48	HRC 53 ~ 55
SHOT DIAMETER	ϕ0.6	ϕ0.6
SHOT VELOCITY	50 ~ 60 m/sec	90 ~ 100 m/sec
PEENING TIME	50 sec	80 sec

5.2 Gaining the optimal control of initial retained austenite content

The ffect of the initial retained austenite content on the value of the residual compressive stress after shot peening is shown in Fig. 11. The initial retained austenite contents of the test pieces were controlled by regulating C.P. and N.P.

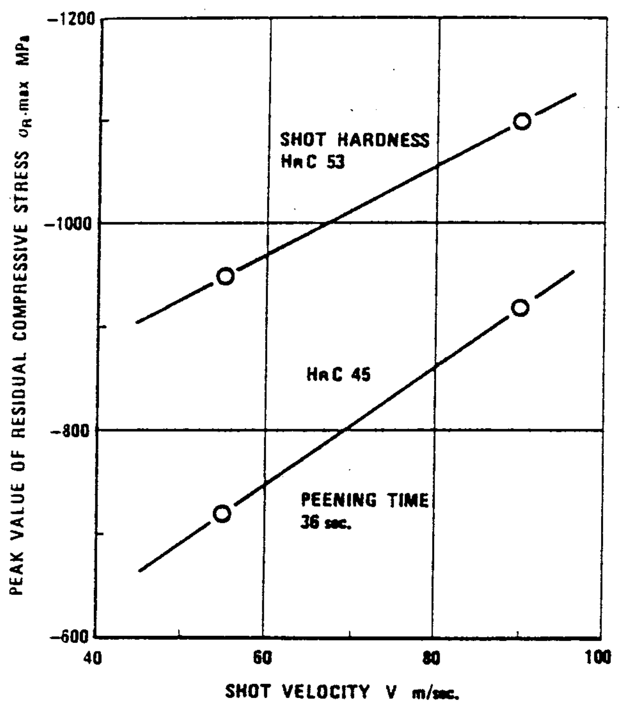

Fig. 10 EFFECT OF SHOT VELOCITY ON THE RESIDUAL COMPRESSIVE STRESS

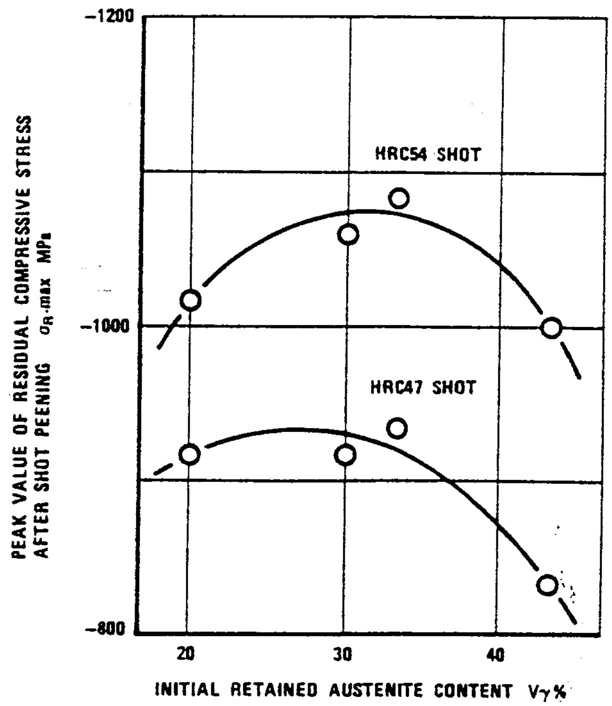

Fig. 11 EFFECT OF INITIAL RETAINED AUSTENITE CONTENT ON RESIDUAL COMPRESSIVE STRESS AFTER SHOT PEENING

Fig. 11 indicates that there is an optimum value in the initial retained austenite content against residual compressive stress caused by shot peening. The optimum value varies more or less depending on the shot peening condition and, the greater the shot hardness is, the greater the optimum value becomes. In the Hard Shot Peening with shot hardness of H_RC54, the optimum value of the initial retained austenite content is 30 - 35%.

6. Analysis and Test Results

6.1 Distribution of residual compressive stress formed by Hard Shot Peening

Fig. 12 shows the distribution of residual compressive stress of carbonitrided steel after Hard Shot Peening, in which the initial retained austenite content was controlled so as to be 32%. The peak value of the stress amounts to -1100 MPa at the depth of 50 µm below surface and is conspicuously greater than that by conventional shot peening.

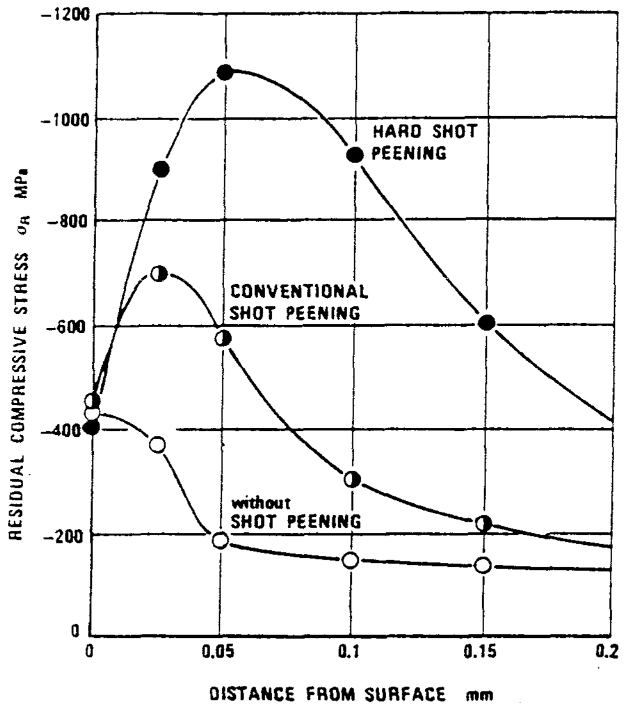

Fig. 12 RESIDUAL COMPRESSIVE STRESS DISTRIBUTION OF CARBONITRIDED STEEL AFTER HARD SHOT PEENING

6.2 Microstructure change by Hard Shot Peening

Shot peening, which is a sort of microscopic plastic working, changes the microstructure of the peened surface layer. In case of carbonitrided steel, retained austenite, which has relatively greater deformability, is preferentially worked, and results in showing the following changes:

(1) Change of retained austenite content
Fig. 13 shows the change of the retained austenite content distribution of carbonitrided steel by conventional shot peening and the one by Hard Shot Peening. The latter is much great compared with the former, and the retained austenite content after Hard Shot Peening changes to less than 10%. The depth of the change is so great as to reach up to 200 µm below surface, and conforms to the depth of forming residual compressive stress.

(2) Change of hardness
Fig. 14 shows the change of section hardness distribution of carbonitrided steel by conventional shot peening and the one by Hard Shot Peening. The latter is much great compared with the former, and the maximum hardness after Hard Shot Peening amounts to over Hv900. The depth of the change is so great as to reach up to 200 µm below surface same as in the case of change of the retained austenite content.

(3) Relationship between the changed amount of retained austenite content and the one of hardness
Fig. 15 shows the relationship between the changed amount of retained austenite content and the one of hardness. From Fig. 15, it can be seen that the change of hardness by shot peening is caused by the change of retained austenite content (that is, transformation into martensite).

(4) Relationship between the residual compressive stress and the changed amount of retained austenite content
Fig. 16 shows the relationship between the residual compressive stress and the changed amount of retained austenite content. From Fig. 16, it can be seen that the formation of the residual compressive stress is related to the cubical expansion caused by the decrease in the retained austenite content, that is, strain-induced transformation from austenite into martensite.

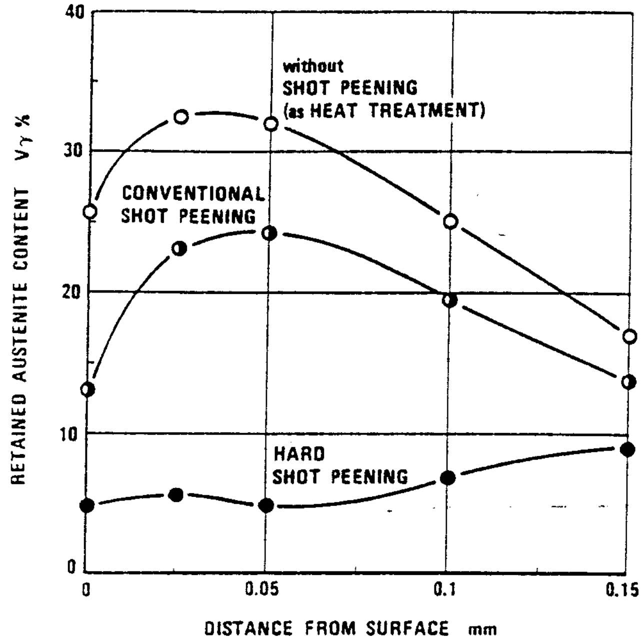

Fig. 13 CHANGE OF RETAINED AUSTENITE CONTENT DISTRIBUTION OF CARBONITRIDED STEEL BY HARD SHOT PEENING

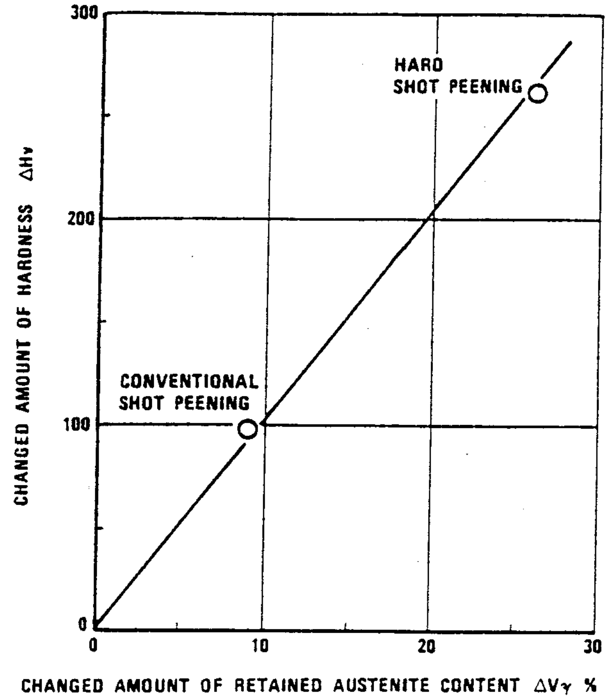

Fig. 15 RELATIONSHIP BETWEEN THE CHANGED AMOUNT OF RETAINED AUSTENITE CONTENT AND THE ONE OF HARDNESS

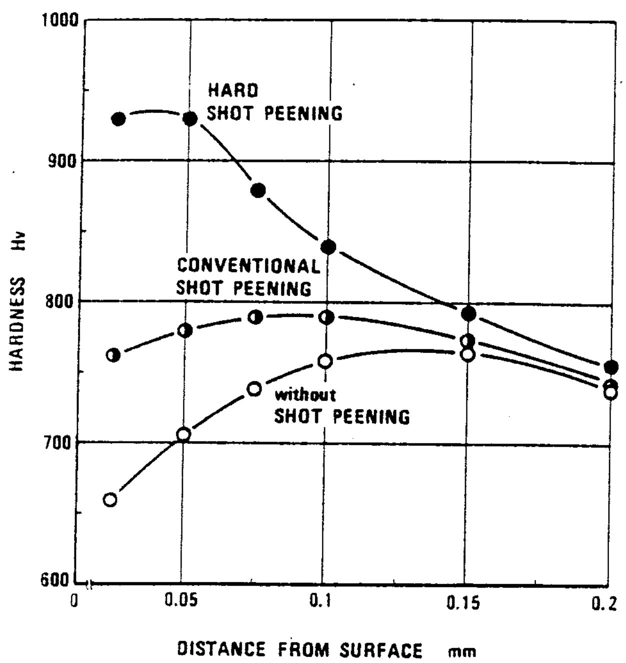

Fig. 14 CHANGE OF HARDNESS DISTRIBUTION OF CARBONITRIDED STEEL BY HARD SHOT PEENING

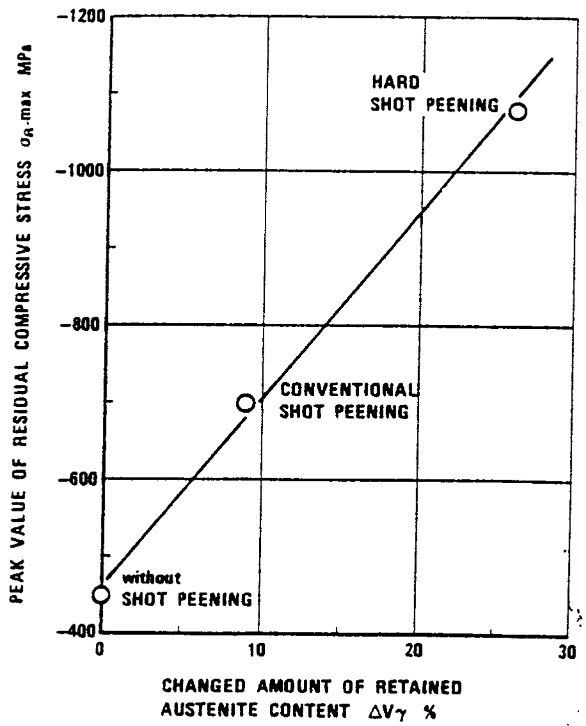

Fig. 16 RELATIONSHIP BETWEEN THE CHANGED AMOUNT OF RETAINED AUSTENITE CONTENT AND THE PEAK VALUE OF RESIDUAL COMPRESSIVE STRESS

6.3 Fatigue strength improvement by new process

The rotating bending fatigue test results of the test pieces obtained by the new process are shown in Fig. 17. The new process allows, compared with the conventional process, to make the fatigue strength at 10^6 cycles improved to be about 1.3 times and the fatigue life at the nominal bending stress of σn = 750 MPa improved to be about 10 times.

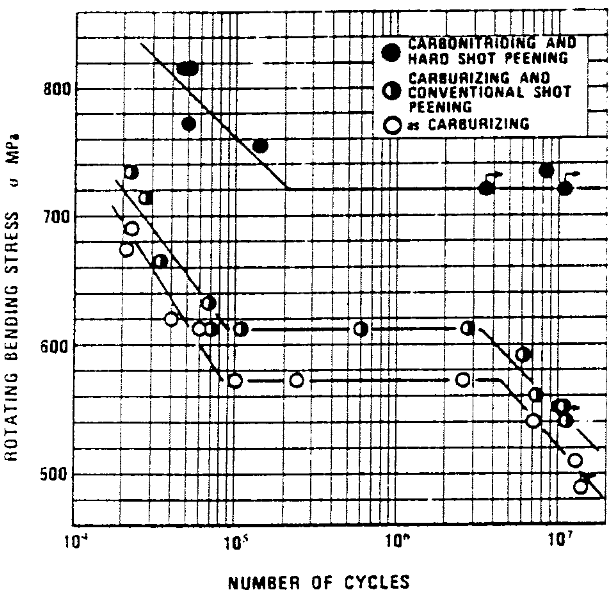

Fig. 17 ROTATING BENDING FATIGUE STRENGTH OBTAINED BY CARBONITRIDING AND HARD SHOT PEENING

7. Concluding Remarks

(1) The new carbonitriding process has made it possible to reduce the non-martensitic surface layer whereas such abnormal layer has been inevitable to be formed in the conventional carburizing process or the usual carbonitriding process. As the results, it has been made possible to increase the shot peening intensity without surface roughening together with to mitigate stress concentration in the surface. In addition, by means of regulating C.P. and N.P., the retained austenite content can be controlled arbitrarily within the range of 20 - 50%.

(2) Residual compressive stress caused by shot peening in the surface layer of case-hardened steel is affected by shot hardness, shot velocity and, together with them, the initial (before shot peening) retained austenite content.
Accordingly, there is an optimum value in the initial retained austenite content corresponding with the shot peening intensity. In case of the new process, the optimum is 30 - 35%.

(3) By means of optimizing the initial retained austenite content and carrying out shot peening with harder shot at higher velocity, it has been made possible to obtain much greater residual compressive stress distribution than the one by the conventional process.
It is conceivable that the formation of the residual compressive stress should be caused by cubical expansion due to the transformation of retained austenite into martensite.

(4) The above-mentioned new process, namely Carbonitriding and Hard Shot Peening, has extended the fatigue life 10 times as long as that by the conventional process.

References

1) M. Ichihara, S. Kakuwa: Journal of the Japan Institue of Metals, Vol. 32, No. 8 (1968)

2) G. Beck, B. Mignot, A. Lallemount: TRAITMENT THERMIQUE, No. 84 (1974)

3) M. Nishi, K. Miura: Netsushori, Vol. 6, No. 1 (1966)

4) Y. Miwa, Y. Arimi, M. Suzawa, Y. Kojima: Journal of the Iron and Steel Institute of Japan, No. 29 (1985)