EFFECT OF ALLOYING ELEMENTS AND SHOT PEENING ON FATIGUE STRENGTH OF CAUBURIZED STEEL

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ABSTRACT

A new carburizing steel and a manufacturing process with high fatigue strength been in demand because of the needs for higher engine output and smaller machine size. In accordance with these trends, the authors investigated the alloy design of carburized steel from the point of increasing residual compressive stress on surface layer when shot peened. As a result, it was found that raising the Mo content inhibited the formation of non-martensitic layer and increased the retained austenite content on surface layer. Furthermore, it was found that when using high Mo-low Si case hardening steel, raising shot peening intensity made it possible to greatly increase the residual compressive stress, thereby improving the bending fatigue strength by more than 100% in comparison with that of carburized conventional steel.

KEYWORDS

Fatigue Strength, Carburizing, Shot Peening, Residual Stress, Retained Austenite, Internal Oxidation, Crack Propagation

INTRODUCTION

Carburized steel is widely used in the manufacture of machine parts, such as gears and shafts, which require high fatigue strength. The fatigue strength of high hardness material, such as carburized steel, mainly controlled by the degree of residual stress [1], and increasing residual compressive stress on surface layer improves the fatigue strength. In view of this, shot peening is an efficient method for improving the fatigue strength of carburized steel [2]. In order to further improve the fatigue strength, it is necessary to increase the shot peening intensity. However, a non-martensitic structure is formed on surfce layer as a result of the reduction of hardenability caused by internal oxidation of Mn and Cr during the carburizing process when using commonly used grades in Japan, SCr420, SCM420 [3]. The presence of this non martensitic layer makes it difficult to greatly increase the residual compressive stress and lowers the surface roughness [4]. Consequently, a non-matensitic layer has to be eliminated. Furthermore, the retained austenite content on surface layer has to be controlled to increase the residual compressive stress by shot peening.
In this study, the effect of alloying elements on the degree of non-martensitic layer formation and the retained austenite content was investigated. From the results of this investigation, the new steel, which does not have a non-martensitic layer and possesses adequate amounts of retained austenite, was deisgned. Moreover, the effect of shot peening on residual stress and surface hardness using the new steel and a conventional steel was investigated. Finally, the mechanism for improving the fatigue strength by changing alloying elements of steel and shot peening was investigated.

EXPERIMENTAL PROCEDURE

Nine test steels modified on the basis of the commonly used grade, SCr420, were used in this investigation. Table 1 shows the chemical composition of these steels. These were hot-forged into 20mm diameter bars, normalized, and then machined out to 8mm bars and notched rotating bending fatigue specimens as shown in Fig.1. They were then gas carburized at 925°C for 2.5Hr., oil quenched, tempered at 180°C for 2 Hr., and shot peened according to the conditions in Table 2. Then the microstructure on surface layer was observed and surface hardness (depth from the surface ; about 5 μm) was measured. Furthermore, retained austenite content and residual stress on surface layer were measured using the X-ray diffraction method. Finally, a rotating bending fatigue test was conducted.

Table 1 Chemical composition of test steels (wt%)

Steel	C	Si	Mn	Ni	Cr	Mo
A (SCr420)	0.19	0.24	0.74	0.02	1.07	0.01
B	0.32	0.24	0.73	0.02	1.06	0.01
C	0.20	0.06	0.76	0.01	1.04	—
D	0.19	0.28	1.17	0.02	1.03	0.01
E	0.20	0.24	0.75	0.64	1.06	0.01
F	0.19	0.27	0.76	0.02	1.48	0.01
G	0.20	0.24	0.69	0.02	1.07	0.23
H	0.19	0.07	0.77	0.03	1.03	0.50
I	0.20	0.09	0.80	0.02	1.06	0.86

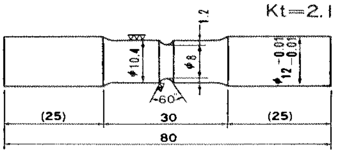


Fig.1 Dimensions of rotating bending fatigue specimen

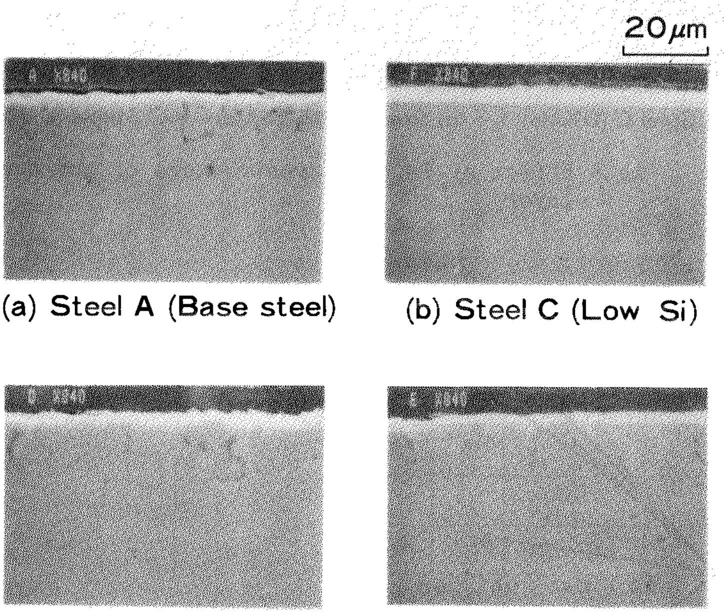
Table 2 Shot peening condition

Shot size	ϕ0.6mm
Shot hardness	HRC 48~62
Shot velocity	60, 100m/sec.
Coverage	100~700 %

RESULTS

Effect of Alloying Elements on Surface Layer Properties

Examples of grain bundary oxidation on surface layer are shown in Fig.2. From the microscopic observations, it was found that lowering the Si content decreases the depth of grain boundary oxidation. Raising the Mn and Cr contents increases the depth of grain boundary oxidation, whereas Ni and Mo have no effect on grain boundary oxidation. The reason for this is considered to be that affinities of Si, Mn, and Cr for oxygen are higher than that of Fe, and affinities of Ni and Mo for oxygen are lower than that of Fe [3].
The effect of alloying elements on surface hardness are shown in Fig.3. Raising the Mo content greatly increases the surface hardness, but other elements have little effect on surface hardness. The effect of Mo on the surface layer microstructure is shown in Fig.4. It is clear that raising the Mo content inhibits the formation of non-martensitic layer which disappears when Mo content is 0.8%. This is because Mo is a low affinity element for oxygen and greatly increases hardenability in the high C region [5].
The effect of alloying elements on retained austenite content is shown in Fig.5. Raising the Mn, Cr, and Mo contents increases the amount of retained austenite, whereas Si decreases it. The reason why retained austenite content increases by raising the Mn, Cr, and Mo contents is that these elements lower the Ms temperature and increase surfacae C content on carburizing [6]. From these experimental results, High Mo-low Si-Mn-Cr steel, such as steel I, is thought to be suitable for increasing the residual compressive stress by shot peening.



(a) Steel A (Base steel)   (b) Steel C (Low Si)

(c) Steel D (High Mn)   (d) Steel F (High Cr)

Fig.2 Examples of grain boundary oxidation

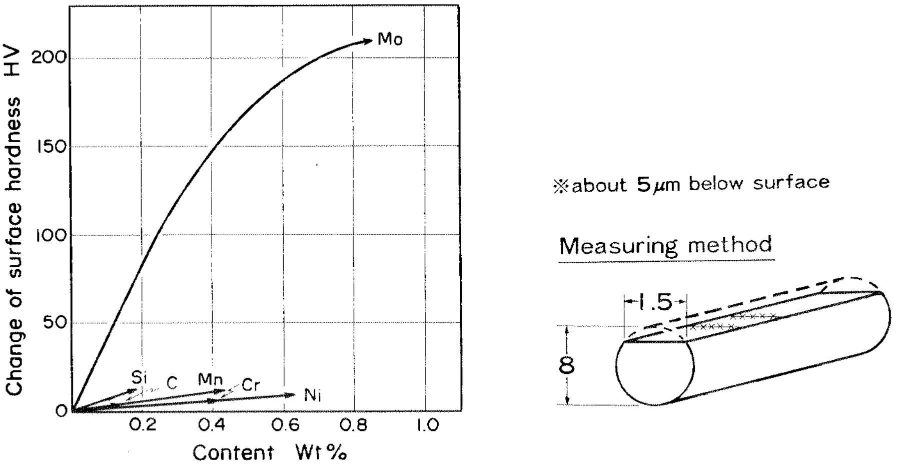
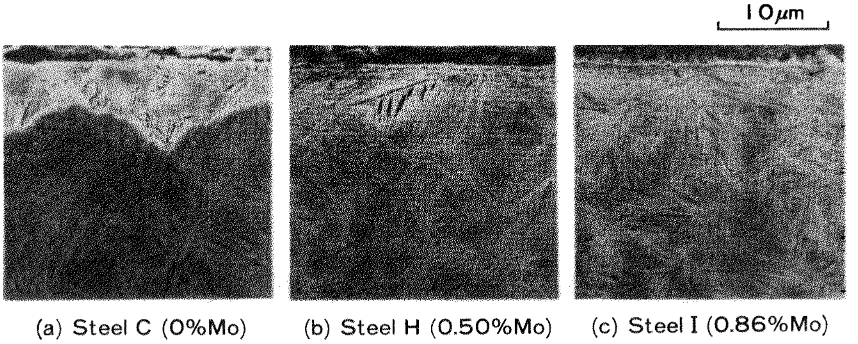


Fig.3 Effect of alloying elements on *surface hardness



(a) Steel C (0%Mo) (b) Steel H (0.50%Mo) (c) Steel I (0.86%Mo)

Fig.4 Effect of Mo on microstructure of surface layer

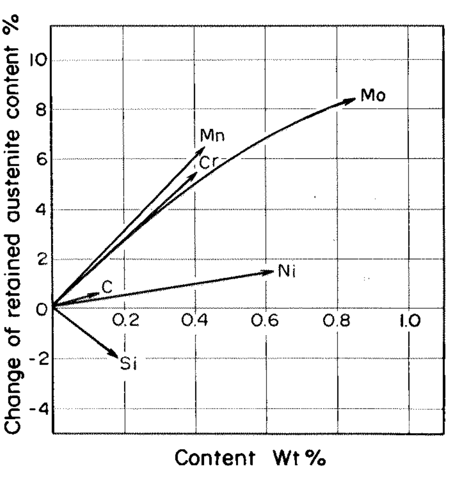


Fig.5 Effect of alloying elements on retained austenite content on surface layer

Effect of Shot Peening Condition on Surface Layer Properties

It is necessary to increase shot peening intensity in order to greatly increase residual compressive stress. The main factors which influence the peening intensity are shot hardness, shot velocity, and coverage. Their effects on residual stress and surface hardness of conventional steel A and Steel I are shown in Fig.6 ~ Fig.8.

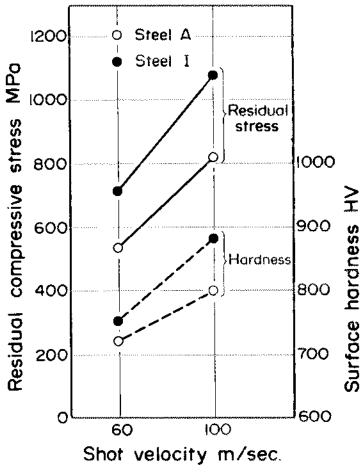


Fig.6 Effect of shot velocity on residual stress and surface hardness (Shot hardness: HRC62, Coverage: 500%)

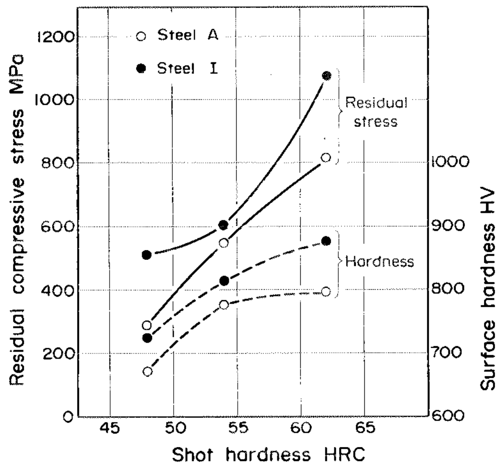


Fig.7 Effect of shot hardness on residual stress and surface hardness (Shot velocity: 100m/sec., Coverage: 500%)

The higher the shot hardness and shot velocity, the greater the residual compressive stress and surface hardness are on each steel. They become greater with increasing coverage up to 500%, then they drop as coverage increases over 500%. The residual compressive stress and surface hardness of steel I, in which the surface layer is strengthened and which contains adequate amounts of retained austenite (about 30%), are greater than those of conventional steel A.
Moreover, surface roughness of steel I is less than half in comparison with that of conventional steel A when being shot peened on the condition of shot hardness : HRC62, shot velocity : 100m/sec., and coverage : 500%.

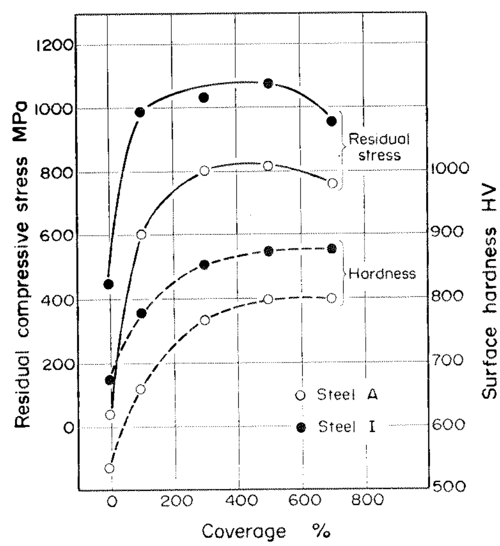


Fig.8 Effect of coverage on residual stress and surface hardness (Shot hardness: HRC62, Coverage: 100m/sec.)

Fatigue Strength

The rotating bending fatigue test results of as-carburized speciments and carburized and shot peened (shot diameter : 0.6mm, shot hardness : HRC62, shot velocity : 100m/sec., coverage : 500%) specimens for conventional steel A and steel I are shown in Fig.9. Shot peening greatly improves the fatigue strength in both steels. Moreover, the fatigue strengths of steel I are superior to those of conventional steel A in the as-carburized and as-shot peened condition. Specifically, the fatigue strength at 10^7 cycles of steel I, which was shot-peened at the above mentioned hard condition, increases by more than 100% in comparison with that of conventional steel A.

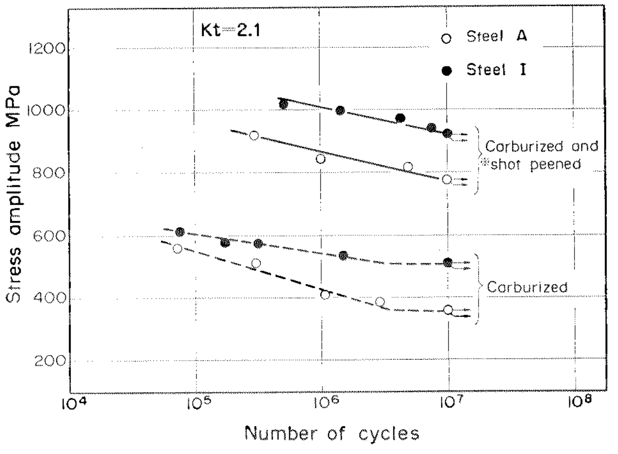


Fig.9 Results of rotating bending fatigue test (Kt=2.1)

DISCUSSION

The mechanism of improving fatigue strength by changing alloying elements of steel and shot peening at the hard condition was investigated. The relationship between residual stress and fatigue strength at 10^7 cycles for test results in Fig.9 is shown in Fig.10. The solid mark indicates the fatigue strength in terms of maximum stress at the notch-root of the specimen, and its slope is relatively high at 0.94 which value is close to 1.0. From this experimental result, it is considered that the fatigue strength is improved by mainly increasing the residual compressive stress on surface layer by shot peening.

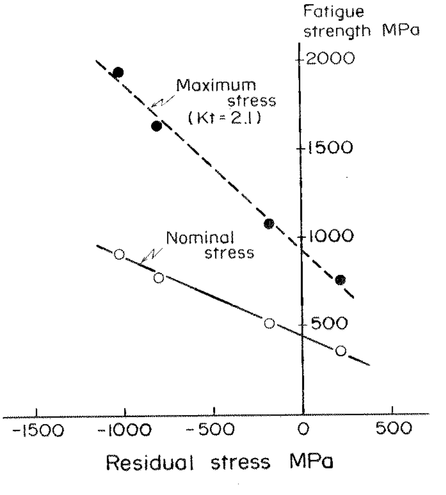
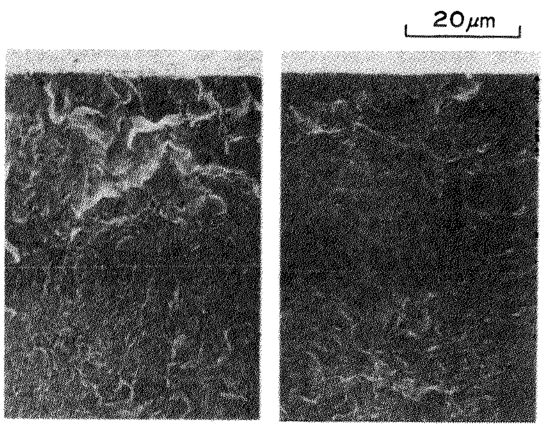


Fig.10 Relationship between residual stress and fatigue strength at 10^7 cycles

On the other hand, the process of fatigue fracture is thought to consist of three stages, which are : 1) microscopic damage and crack initiation, 2) crack propagation, and 3) final breakage. Masuda and others have shown that mode I crack propagtion originating from inclusions of carburized steel plays an important role when cracking starts from an inclusion inside the specimen [7].

In this investigation, all cracks originated from the surface. Fig.11 shows examples of scanning electron micrographs of fatigue fracture surface.

A semicircular propagation region largely characterized by the transgranular fracture, which has a radius of about 200 μm, was observed. The fractographic feature near the crack origin of carburized and that of shot peened specimens were different. Intergranular fracture to the depth of 20 μm was observed in the former and transgranular fracture was observed in the latter.



(a) Carburized (b) Carburized and shot peened

σa=535MPa, Nf=1.1×10^6 σa=945MPa, Nf=7.3×10^6

Fig.11 Scanning electron micrographs of fatigue fracture surface (Steel I)

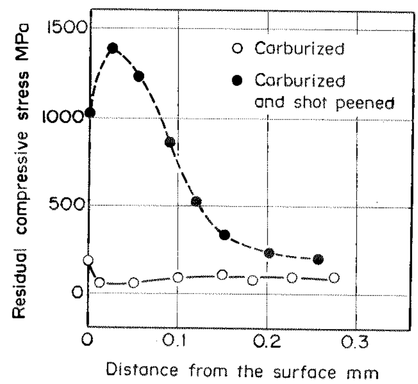


Fig.12 Residual stress distribution (Steel I)

The distribution of residual stress σ_R in the cross section of steel I were measured to predict the crack propagation period Np, as shown in Fig.12. The equation of ΔK is expressed as follows [8]:

$$\Delta K = H \cdot F \cdot (\sigma a + \sigma_R)\, \pi \cdot a / E \qquad (1)$$

where a is the depth of crack and σ_a is the stress in notched cross section considered with the stress concentration factor and its distribution. Np is expressed as follows:

$$Np = \int_{a0}^{af} \frac{da}{C(\Delta K)^m} \qquad (2)$$

where C is 1.73×10^{-15}, m is 6.62(9), initial crack size is 20 μm and crack propagation size at, af is 200 μm.

Examples of numerical calculation results for steel I are shown in Fig.13. As a result, the ratio of the crack propagation period for total life is predicted to be relatively high, that is to be about 10 ~ 30%, when cracking is starting from the furface. In this calculation, redistribution of residual stress by crack propagation was not considered, so further study considering this point is necessary.

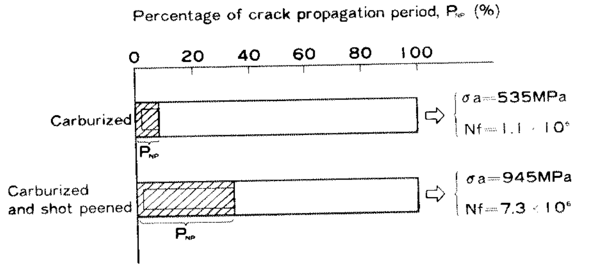


Fig.13 Percentage of predicting crack propagation period for total life (Steel I)

On the basis of the above mentioned investigation, the fatigue strength of shot peened steels after carburizing is mainly controlled by residual stress on surface layer. However, it is considered that crack propagation plays an important role in the case of fracture originating on the surface.

CONCLUSION

(1) Lowering the Si content makes the depth of grain boundary oxidation shallow, whereas raising the Mo content inhibits the formation of a non-martensitic layer which disappears when the Mo content is 0.8% during carburizing.

(2) Raising the Mn, Cr, and Mo contents increases the retained austenite content.

(3) The higher the shot hardness and shot velocity, the greater the residual compressive stress caused by shot peening will be on surface layer. There is an optimum value concerning coverage to increase the residual compressive stress.

(4) The residual compressive stress on surface layer of the new steel characterized by high Mo-low Si content is higher than that of a conventional steel when being shot peened. Especially, the fatigue strength of the new steel improves by more than 100% when it was shot peened under the condition of high hardness shot, high velocity, and high coverage. This improvement is mainly caused by increasing the residual compressive stress on surface layer.

At present, the new steel, such as high Mo -low Si -Mn-Cr steel, is in practical use and the scope of application to components is expected to be widened in the future.

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