Effects of Alloying Elements on the Rotating Bending Fatigue Properties of Carburized Steels*

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Synopsis

A study was made on the effects of alloying elements such as Si, Mn, Cr, Ni and Mo on the rotating bending fatigue properties of carburized steels. At first, the effect of Si was studied using commonly used grades, JIS SCM420 and SNCM420. It was shown that the decrease in Si content remarkably reduced internal oxidation and resulted in higher fatigue strength. In order to clarify the effects of other alloying elements, fatigue tests were carried out on low Si steels where the Si contents were less than 0.15 %. Internal oxidation was reduced and fatigue resistance was improved with increasing Ni and Mo contents and with decreasing Cr and Mn contents when keeping the core hardness constant. The 0.2% C-3% Ni-0.45% Mo steel showed the highest fatigue limit of 100 kgf/mm². High Ni-high Mo-low Mn-low Cr steels are considered to exhibit superior fatigue resistance by suppressing internal oxidation and by the greater fracture toughness of carburized case.

I. Introduction

High fatigue strength and impact resistance are required for carburizing steels in accordance with the strong demands of high performance of machine structural parts especially used for automobiles. As for improving the fatigue strength, efforts have been made to optimize the metallurgical and mechanical factors, especially hardness and residual stress distributions.¹⁾ In addition, chemical compositions,²⁻⁴⁾ carburizing conditions,^{5,6)} retained austenite contents⁷⁻¹⁰⁾ and so forth have been also taken into account.

Furthermore, it has been recognized that internally oxidized layer which forms on the surface of gas carburized parts¹¹⁻¹³⁾ deteriorates the fracture resistance.^{14,15)} Internal oxidation is known as a phenomenon which strong oxide-forming elements such as Si, Mn and Cr form oxides along prior austenite grain boundaries near the surface. Generally, the longer the carburizing time, the deeper the internal oxidation. Internal oxidation results in depleting alloying elements near austenite grain boundaries,

which causes a local decrease in hardenability and promotes the formation of soft transformation products such as troostite in quenching. Moreover, the fracture resistance was reported to be improved by carburizing in vacuum,¹⁶⁾ or by removing the internally oxidized layer after gas carburizing.¹⁷⁾

Focussing this study on internal oxidation, the effects of alloying elements such as Si, Mn, Ni, Cr and Mo on the rotating bending fatigue properties were investigated.

II. Experimental Procedures

The chemical compositions of test steels are shown in Tables 1 and 2. Table 1 shows the chemical compositions of SCM420 and SNCM420 used to clarify the effect of potent oxide former, Si. Three steels with 0.05, 0.15 and 0.25 % were used in each steel group. Sulfur and phosphorus contents were reduced to less than 0.003 % respectively to prevent the influence of these impurities and to reveal the sole effect of Si. As a decrease in Si content improved fatigue strength significantly the steels with Si contents less than 0.15 % were studied to clarify the effects of other alloying elements. Chemical compositions of these steels are shown in Table 2. Steels A to D vary Ni and Mo contents from 0 to 3 % and 0.3 to 0.75 %, respectively. Hardenability was controlled by changing Cr and Mn content to keep the core hardness constant.

The 30 kg ingots of these steels were prepared by vacuum induction melting and hot forged to 25 mm diameter bars. Steels E and F, commonly used SCR420 and SNCM420 grades, were obtained as commercially produced 148 mm square billet and hot forged. Normalizing was carried out by holding at 900 °C for 2 h followed by air cooling.

Rotating bending fatigue specimens were prepared

Table 1. Chemical compositions of test steels. (wt%)

Grade	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	sol. Al
SCM420	0.20	0.04	0.72	0.003	0.001	<0.01	<0.01	1.00	0.20	0.027
	0.21	0.14	0.72	0.002	0.002	<0.01	<0.01	1.01	0.20	0.028
	0.21	0.26	0.71	0.003	0.001	0.01	0.01	0.99	0.20	0.025
SNCM420	0.21	0.05	0.55	0.002	0.001	<0.01	1.81	0.55	0.20	0.028
	0.21	0.15	0.56	0.002	0.001	<0.01	1.81	0.55	0.20	0.029
	0.21	0.24	0.55	0.002	0.001	<0.01	1.82	0.55	0.20	0.028

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Table 2. Chemical compositions of test steels. (wt%)

	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	sol. Al
A	0.25	0.13	0.80	0.006	0.018	0.03	0.02	0.99	0.39	0.038
B	0.22	0.06	0.71	0.005	0.014	<0.01	1.00	0.73	0.30	0.024
C	0.21	0.06	0.29	0.003	0.017	<0.01	2.00	0.30	0.75	0.033
D	0.21	0.06	0.29	0.003	0.016	<0.01	2.99	0.31	0.45	0.033
E	0.22	0.24	0.86	0.021	0.019	0.11	0.05	1.19	0.02	0.0027
F	0.19	0.26	0.59	0.017	0.026	0.14	1.64	0.47	0.20	0.022

Fig. 1. Carburizing, quenching and tempering conditions.

in accordance with JIS, Z2274. After the parallel portion, 8 mm diameter, was finish machined and ground with emery paper, specimens were carburized, quenched and tempered by the conditions shown in Fig. 1. Fatigue tests were conducted by rotating bending fatigue test machine of 60 kgf load capability and 3 500 rpm in cyclic speed.

Hardness profiles across the case were obtained using 300 gf load Vickers hardness tester. Retained austenite contents and residual stresses were measured by X-ray method using the parallel portion of the specimens. Scanning electron microscopy was carried out to make clear the fracture modes of fatigue specimens.

III. Results

1. Effect of Si Contents

Photograph 1 shows the internal oxidation layers of carburized SCM420 and SNCM420 grades with various Si contents observed on the cross section without chemical etching. White layers on the surface are Ni plating for simplifying the observation. In conventional SCM420 and SNCM420 containing 0.25 % Si, internal oxidized layers of 10~20 μm depth were observed. With decreasing Si contents internal oxidation was reduced; in 0.05.% Si steels, for example, the depth was less than 5 μm. Moreover, the electron microscopy of surface layer by replica method revealed that no high temperature transformation products like troostite existed. Even though the internal oxidation might have deteriorated the hardenability, the parallel portion of the fatigue specimen was considered to be small enough to obtain the perfect martensitic structure in the surface layer.

Table 3 shows the carburized case properties of test specimens. The hardnesses at 0.05 mm from the

Photo. 1. Internal oxidations observed in the rotating bending fatigue specimens.

surface and the core of these steels were HV 650 to 700 and HV 400 to 450, respectively. The effective case depths of SCM420 were deeper than those of SNCM420 grades. No differences were observed in retained austenite content, austenite grain size and residual stress between the steels. Furthermore, there was no significant influence of Si contents on the carburized case properties in both steels.

S-N curves obtained from rotating bending fatigue tests, and the relation between fatigue limits at 10⁷ cycles and Si contents are shown in Figs. 2 and 3, respectively. In this study tests were ended at 10⁷ cycles, and the stress with which a specimen did not fracture was defined as 10⁷ fatigue limit. Fatigue limits of these steels increased with decreasing of Si contents, which is considered due to the reduction of internal oxidation. Compared at a given Si content SNCM420 showed higher fatigue limits than SCM420. Scanning electron microscopy revealed that all the fatigue fractures initiated from surfaces. The examples of SEM fractographs are shown in Photo. 2. There was a little difference in fracture

Table 3. Carburized case properties of SCM420 and SNCM420.

Grade	Si content (%)	Hardness at 0.05 mm depth (HV)	Effective case depth (mm)	Core hardness (HV)	Retained austenite (%)	Depth of internal oxidation (μm)	Austenite grain size (JIS)
SCM420	0.04	663	0.75	423	14.9	4	8.2
	0.14	678	0.61	408	16.3	10	8.2
	0.26	704	0.75	449	19.0	12	8.2
SNCM420	0.05	649	0.50	416	16.6	5	9.0
	0.15	650	0.50	422	16.3	10	8.8
	0.24	639	0.55	422	16.5	10	8.5

Fig. 2. S-N curves of SCM420 and SNCM420.

Fig. 3. Effect of Si content on the fatigue limit of SCM420 and SNCM420.

appearances among these steels. Intergranular fractures near surfaces were observed more markedly in SCM420 and higher Si steels than in SNCM420 and

(a) SCM420: 0.04%Si (b) SCM420: 0.26%Si
(c) SNCM420: 0.05%Si (d) SNCM420: 0.24%Si
Photo. 2. Scanning electron micrographs of the fatigue fractured surfaces of SCM420 and SNCM420.

low Si steels. When considered the internal oxidations were more prominent in higher Si steels as shown in Photo. 1, internal oxidations are believed to act as the origin of intergranular fracture.

2. Effects of Ni, Mn, Cr and Mo

Table 4 shows the carburized case properties of test steels A to D. Indications of the hardness gradients can be obtained from the surface hardness, core hardness and effective case depth which is defined as the depth for HV 550 value. The effective case depths of steels A to D were from 0.65 to 0.85 mm and core hardnesses were HV 420 to 450. Internal oxidation depths were less than 6 μm. Steels C and D with 2 and 3 % Ni contain higher amount of retained austenite than other steels.

The effect of alloying elements on the fatigue limits at 10⁷ cycles was given in Fig. 4. Fatigue limits increased with increasing Ni and Mo contents, but with decreasing Mn and Cr contents. As Cr and Mn contents were reduced in high Ni and high Mo steels to keep the hardenability unchanged, the

Fig. 4. Effects of Mn, Cr, Ni and Mo contents on the fatigue limits of test steels.

Table 4. Carburized case properties of test steels.

	Hardness at 0.05 mm depth (HV)	Effective case depth (mm)	Core hardness (HV)	Retained austenite (%)	Depth of internal oxidation (μm)	Austenite grain size (JIS)
A	656	0.75	450	16.6	5	9.2
B	641	0.65	426	16.9	6	8.8
C	666	0.84	446	25.1	4	8.9
D	690	0.85	449	30.1	3	9.0
E	692	0.78	421	14.3	10	9.2
F	632	0.60	428	19.3	8	9.4

effect of each alloying element appeared markedly in Fig. 4.

To clarify the role of alloy elements, the relation between intergranular oxidation depths and alloy contents was studied. The regressional analysis for relating internal oxidation depths with oxide-former contents revealed that the contribution of Si was almost ten times as large as that of Mn and Cr. On the basis of this result, the internal oxidation parameter, 10Si+Mn+Cr(in wt%), was defined in this study. As shown in Fig. 5, a linear relation was obtained between this parameter and internal oxidation depths.

Figure 6 shows the effect of internal oxidation depth on the fatigue limits. It was clearly shown that the fatigue limits decreased with increasing internal oxidation depth. Moreover, these data were divided into two groups, Ni containing steels and Ni free steels.

Fig. 5. Relation between internal oxidation depth and composition parameter 10Si+Mn+Cr.

Fig. 6. Effect of internal oxidation depth on fatigue limit.

Fig. 7. Relation between fatigue limit and composition parameter $(\text{Ni} + \text{Mo}) / (10\text{Si} + \text{Mn} + \text{Cr})$.

The former exhibited higher fatigue limits than the latter. The results indicate that the alloying element has an intrinsic influence on fatigue properties besides internal oxidation.

Figure 7 shows the relation between fatigue limits and the composition parameter $(\text{Ni} + \text{Mo}) / (10\text{Si} + \text{Mn} + \text{Cr})$. This parameter was defined on the concept that oxide former, especially Si, deteriorates the fatigue strength by promoting internal oxidation, whereas Ni and Mo raise fatigue resistance without forming oxides. The data could be plotted by a single curve according to this parameter.

IV. Discussion

Scanning electron microscopy was conducted to examine the effects of alloy contents and microstructures on the fracture mechanism of carburized steels. Photograph 3 shows the SEM fractographs of conventionally used steel E (SCr420) tested at the stress of 87 kgf/mm² and fractured at the 1.87×10^6 cycles. Photograph 3(a) reveals that the fracture initiated from the surface and the final fracture occurred after the crack propagated to some depth. Photograph 3(b) is the magnified fractograph near the fracture origin arrowed by "b" in Photo. 3(a), which shows the crack initiated along prior austenite grain boundaries. Photographs 3(c) and (d) are taken from the fatigue crack propagated area and the fast fractured portion indicated by an arrow "c" and "d", respectively, in Photo. 3(a). Although both fractographs showed the combination of transgranular fracture and intergranular fracture mode, the fast fractured portion "d" was distinguished from the fatigue crack propagated area "c" by the increased intergranular fracture ratio. Moreover, the inner parts of the specimens exhibited ductile fractures owing to low carbon content and low hardness. Dimple patterns observed in the finally fractured portion are shown in Photo. 3(e).

Photograph 4 shows the SEM fractographs of steel D which gave the highest fatigue limit 100 kgf/mm² in this study. The observed specimen was stressed at 103 kgf/mm² and fractured at 8.19×10^6 cycles. Although the crack initiated from the surface like steel E, no intergranular fractures were observed near

- (a) Low magnified fractograph
- (b) Origin of fatigue crack
- (c) Fatigue crack propagated area
- (d) Fast fractured portion
- (e) Final fractured portion

Photo. 3. Scanning electron micrographs of the fatigue fractured surface of steel E tested at 87 kgf/mm² and fractured at 1.87×10^6 cycles.

the origin. It must be recognized, furthermore, that the intergranular fracture ratio of the fast fractured region in steel D was smaller than in steel E. In addition, in these steels, most of the specimens fractured from surface and fish eyes were observed only in about 10 % of specimens. It was concluded from these microfractographs that internally oxidized layer played as stress riser and assisted the crack initiation, since the intergranular fracture was prominent in the steel, like E, in which very deep internal oxidation was observed.

It is reasonable, furthermore, to assume that the strength and the toughness of the case of these two steels differ from each other. In 0.8 % C steels, which simulate the case of carburized steels, Ni and Mo were confirmed to improve Charpy impact value and fracture toughness accompanied by smaller intergranular fracture ratio.¹⁸⁾ Accordingly, the toughness of the case is considered to affect the fatigue resistance, especially the crack initiation resistance, when latent defects like internally oxidized layer exist on the surface.

(a) Low magnified fractograph
(b) Origin of fatigue crack
(c) Fatigue crack propagated area
(d) Fast fractured portion
(e) Final fractured portion

Photo. 4. Scanning electron micrographs of the fatigue fractured surface of steel D tested at 103 kgf/mm² and fractured at 8.19 × 10⁶ cycles.

Next, to evaluate the resistance to final fast fracture, the fracture toughness of the fatigue specimen was calculated.¹⁵⁾ Using the low magnified fractographs like Photos. 3(a) and 4(a), the depths of fatigue crack propagated regions, which were dark areas indicated by the arrow “c”, were measured. When the depth of this area is defined as *a*, and the stress amplitude of the rotating bending fatigue test as σ_{max} , Eq. (1) is obtained according to the concept of fracture mechanics,

$$K_{IC} = C \sigma_{max} \sqrt{\pi a} \dots\dots\dots(1)$$

where, *C*: the crack shape concentration factor, 1.04.¹⁹⁾

It is appropriate to assume the depth of fatigue crack region as the initial crack length in fracture mechanics when considered that this length is the critical one to start an brittle fast fracture. Figure 8 shows the relation between *a* values for steels D and E fractured at less than 10⁷ cycles and 1/ σ_{max} . From the gradient of lines shown in Fig. 8, *K_{IC}* are calculated to be 96

Fig. 8. Relation between $\sqrt{\pi a}$ and $1/\sigma_{max}$.

and 75 kgf/mm^{3/2} for steels D and E, respectively. These values are in good agreement with the *K_{IC}* values obtained in 0.8 % C steels which simulated carburized case.¹⁸⁾ The result indicates that high Ni and high Mo steels exhibit higher fast fracture resistance besides higher crack initiation resistance. It is concluded from the discussion that alloy elements affect the fatigue strength through the internal oxidation tendency and the fracture toughness of carburized case when the hardness profile is similar.

V. Conclusions

- A study was made on the effects of alloying elements such as Si, Mn, Cr, Ni and Mo on the rotating bending fatigue properties of carburized steels. The conclusions obtained in this study are the following.
- (1) With decreasing the potent oxide forming element Si, internal oxidation was reduced and fatigue strength increased remarkably.
 - (2) Internal oxidation was reduced and fatigue strength increased with increasing Ni and Mo contents and with decreasing Cr and Mn, when the carburizing properties such as core hardness and effective case depth were the same. The 0.2%C–3%Ni–0.45%Mo steel showed the highest fatigue limit of 100 kgf/mm².
 - (3) Scanning electron microscopy revealed that most of all the fatigue fracture initiated from the surface. The fracture mode near the surface was intergranular in the commonly used steel like SCr420 where internal oxidation was prominent. In high Ni–high Mo steels, on the other hand, intergranular fracture ratio was reduced considerably.
 - (4) High Ni–high Mo–low Mn–low Cr steels are considered to exhibit superior fatigue strength by suppressing internal oxidation and by their greater crack initiation and propagation resistance of the case.

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REFERENCES

- 1) B. E. Boardman: Metals Handbook, 9th ed. I, ASM, Ohio, (1978), 665.
- 2) D. E. Diesburg: SAE Technical Paper Series, 780771, (1978).
- 3) D. E. Diesburg and G. T. Eldis: *Met. Trans.*, **9A** (1978), 1561.
- 4) T. Furukawa, S. Konuma and H. Sakaniwa: *Tetsu-to-Hagané*, **65** (1979), 1024.
- 5) T. Furukawa, S. Konuma and S. Nishiwaki: *Tetsu-to-Hagané*, **67** (1981), 596.
- 6) H. Wiegand and G. Tolasch: *Harterei-Tech. Mitt.*, **22** (1967), 330.
- 7) R. H. Richman and R. W. Landgraf: *Met. Trans.*, **6A** (1975), 955.
- 8) H. Brandis and W. Schmidt: TMS Paper Selection, A83-8, (1983).
- 9) Y. Yamazaki, K. Hasegawa, H. Nakanishi, S. Okazaki, M. Suzuki and H. Nakamura: *J. Soc. Mat. Sci., Japan*, **31** (1982), 915.
- 10) S. Okazaki and K. Hasegawa: *J. Kansai Soc. Naval Architects*, (1980), No. 178, 113.
- 11) R. H. Fischer: *Met. Trans.*, **9A** (1978), 1553.
- 12) M. Ichihara and S. Kakuwa: *J. Japan Inst. Metals*, **30** (1966), 307.
- 13) M. Ichihara and S. Kakuwa: *J. Japan Inst. Metals*, **32** (1968), 745.
- 14) T. Naito, H. Ueda and M. Kikuchi: *Met. Trans.*, **15A** (1984), 1431.
- 15) E. Nakanishi, H. Ueda and T. Kajiura: *J. Soc. Mat. Sci., Japan*, **26** (1977), 68.
- 16) K. Isokawa, K. Takada and T. Kato: *J. Japan Soc. Heat Treatment*, **22** (1982), 163.
- 17) C. Masuda, A. Ishii, Y. Tanaka, K. Kanazawa, T. Nishijima and E. Sumiyoshi: *Tetsu-to-Hagané*, **70** (1984), S1226.
- 18) K. Isokawa and K. Namiki: *Denki Seiko (Electric Furnace Steel)*, **57** (1986), 4.
- 19) H. Tada, P. C. Paris and G. R. Irwin: *The Stress Analysis of Cracks Handbook*, Del Research Corp., (1973),