The Fatigue Fracture Behaviours and Metallurgical Factors of Alloyed High Strength Steels

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1. Introduction

Fatigue fracture behaviour of a very high strength steel is generally obseved to have more complexity than that of the mild steel or a little higher tensile steels particularly in enhanced sensitivity to the heterogeneity of the steel, e.g. nonmetallic inclusions.[1.) 2.) 3.)]

Concerning the heattreated condition of the high strength steel, it has recently been reported by the authors[3.)4.)] that the crack propagation behaviours by fatigue, both in terms of the microfractography and the rate analysis, are closely related to the microstructures, accordingly the fracturing modes of the specimen.

As to other metallurgical factors of alloyed high strength steels such as alloying elements and grain size of prior austenite, there have been very few published in respect with the nucleation and propagation of fatigue fracture; the effect of austenitic grain size seems yet obscure so far as the quantitative fracture behaviours of the heattreated alloy steel are concerned.

The present paper deals with experiments and observations on the influence of alloying elements, Cr, Ni and Mo as well as the prior austenitic grain size on the fatigue properties of medium carbon low alloysteels quench-and-tempered at various temperatures, viz. giving a variety of high strength level.

2. Experimentals

The materials used was JIS (Japanese standard) SCr4, SCM4 and SAE3140, the chemical composition being given in Table1. Samples were treated by various heattreatment as indicated in Table2, where a resulted austenitic grain size number of each specimen is also shown.

TABLE 1. Chemical composition of materials (%)

steel	C	Si	Mn	P	S	Ni	Cr	Mo	Cu
SCr4	0.40	0.27	0.71	0.015	0.010	0.04	1.08	0.03	0.12
SCM4	0.39	0.28	0.72	0.014	0.017	0.08	1.08	0.18	0.16
SAE3140	0.43	0.78	0.78	0.021	0.008	1.2[illegible]	0.63	0.05	0.14

TABLE 2. Heat treatment of specimens Grain size No.

A Series:	850°C	Oil Quenching.		(9)
B Series:	1150°C	30min. air cooling to 850°C	O.Q.	(8)
G Series:	1250°C	2hr. air cooling to 850°C	O.Q.	(6)
H Series:	1300°C	2hr. air cooling to 850°C	O.Q.	(4)
L Series:	1250°C	10hr. air cooling to 850°C	O.Q.	(3)

The fatigue test was conducted by Schenck type machine in unidirectional bending with a frequency of 3,000cycles/min. The applied stress amplitude was 80~120kg/mm^2 with minimum stress level being set at 10kg/mm^2. The surface of specimen was mechanically polished to a mirror finish and fatigue cracks were observed with optical and also electron microscope by replication (two-step plastic carbon technique). Crack lengths were read at ×400 magnification with a travelling microscope.

3. Results and Discussion

(A) Although the fatigue lives of specimens were scattered, the SAE3140 specimens with coarser prior austenitic grain and tempered at low temperatures showed appreciably shorter lives than the specimen of SCr4 and SCM4 steels. Initiation of fatgue crack was observed that the initiating attitude in each steel was quite similar when heat treated in the same condition, while the microcracks on the specimen with larger prior austenite grain initiated earlier than that with small grain size. All specimens tempered at 650°C and 550°C showed well defined macroscopic slip bands while the surface of the specimen tempered at lower temperatures revealed no slip band.

The endurance limit or fatigue life was reduced with increasing grain size as representatively exhibited in Fig. 1. Increasing prior austenitic grain size resulted in reduction of fatigue strength or life without significant change in the outlined form of S-N curves. The surface aspects of fatigue crack propagation showed quite a difference between A-series and L-series treatments. L-specimens with the largest prior austenite grain showed a wide plastic zone at the main crack tip, while A-specimens had a narrow and indistinct plastic zone. In the case of A-series specimens tempered at 200°C, 300°C and asquenched specimen, a characteristic alternating dimple and quasi-cleavage fracture[3.] dominated, whereas in the same specimens tempered at higher temperatures other typical fatigue fracture and ductile striations were observed.

As to the B-G-H- and L-series specimens, there were no dimple fracture on both tempered at high and low temperature but some different aspect was observed including some intergranular fracture, the latter being sometimes also seen in A-specimen tempered at lower temperature.

(B) Analysis of crack propagation rates: The fatigue crack propagation rates of the A-series specimens were exhibited as functions of stress intensity factor range, ΔK, representatively in Fig. 2, namely it can be expressed in a form:[3.]

$$d(2L)/dN = (\Delta K)^n/M \qquad (1)$$

Where L is half length of main crack, n is a variant exponent dependent on metallurgical structure and M a material constant. As summarized in Fig.3 obtained exponents n-values are plotted against tempering temperatuers together with hardness and also ΔK values corresponding to a propagation rate of 10^{-3}mm^2/cycle. When tempered at higher temperatures than 300°C, the n-value decreased with decreasing tempering temperature obeying a theoretical consideration[6.] which has been confirmed in the case of low strength steels, meanwhile at very high strength level, tempered at lower temperature, the trend became reverse.

The fatigue crack propagation rates are thought to be accelerated when the strength or hardness of the steel exceeds some threshold value and there seems to be a transition to a different mode of fracture as mentioned above.

Comparing the results on carbon steels of the previous paper[3.] with alloy steels of this work, it is to say that the tempering temperature to obtain the minimum n-value is about 100°C lower in the latter case, and by tempering at 200°C the n-values of carbon steel are much higher than that of alloy steels. The fatigue fracture behaviours of high strength steels are very sensitive to the metallurgical factors.

(C) Factors of chemical composition: The three kinds of Aluminum killed steels studied had similar cleanliness level(around 0.12~0.15 JIS-cleanliness value/area percentage) and no particular relation was observed between the nonmetallic inclusion and fatigue properties, but some higher value of phosphorus in the SAE steel may be a cause for the trend of short fatigue lives by coarse austenite grain size.

Concerning the metallic alloying elements, molybdenum seems to have a favourable effect on the resistance to fatigue crack propagation when the microstructure is as quenched or tempered to higher strength level, though it is not thought to be simply associated with a known embrittlement phenomenon. 1 % chromium, and also molybdenum bearing, steel showed an improvement in the resistance to fatigue crack propagation when soaked at high temperatures, presumably because of homogenization of austenite containing some undissolved carbo-nitride particles.

Dimple pattern observed in the fracture surface of A-series steel may be ascribed to the heterogeneity of austenite, and in fact nickel steel, SAE3140, with less chromium appears not to be favoured by such factor of high temperature soaking.

(D) Effect of prior austenite grain size: Observed effects of prior austenite grain size on fatigue were mainly in close relation with the nucleation process at an early stage of fatigue crack and also number of micro-cracks increased with coarsening the prior austenite grain.[4.)] In the case of relatively clean steel the fatigue crack nucleation is considered to be essentially effected by prior austenite grain size in a manner as could be interpreted by highly piled-up dislocations between a wide spacing of barriers for slipping.

On the other hand, prior austenite grain size had no substantial effect on the rates of the fatigue crack propagation, the fact being in agreement with Weiss[4.)] and Sinclair, Dolan.[5.)] Meanwhile crack propagation, represented by the n-value, was conditioned by the microstructure mainly reflecting the strength of matrix as stated above on Fig. 3, thus the n-value may be called as a structure constant.

(E) Consideration of initiation and propagation of crack: The initiationof fatigue crack was accelerated by growing prior austenite grain by soaking at high temperature, whereas the resulted homogeneous prior austenite grain can show an improvement of the resistance to crack propagation, typically observed in the SCr steel. Those effects should be differently interpreted in relation with initiation and propagation mechanism of fatigue crack. The n-value was proved to be dependent on the strength of the steel, therefore, it would be possible to obtain a lower fatigue crack propagation for desirable strength level by homogenizing the steel for a short time as well as by selecting appropriate chemical design.

References

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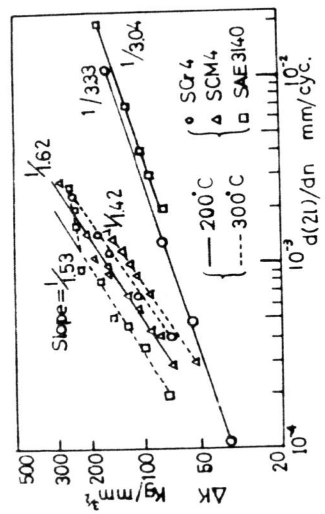

Fig. 2. Relation between crack propagation rate and stress intensity factor range for tempering at 200°C and 300°C

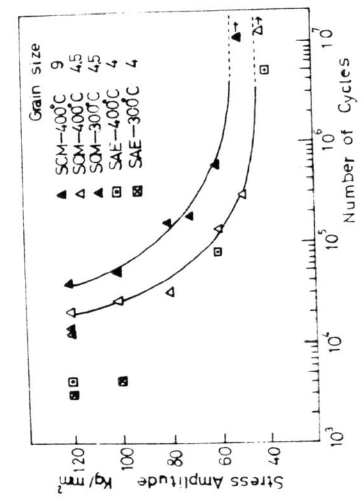

Fig. 1. S-N curves of SCM4 and SAE3140 steel specimens with different prior austenite grain sizes tempered at 300°C or 400°C

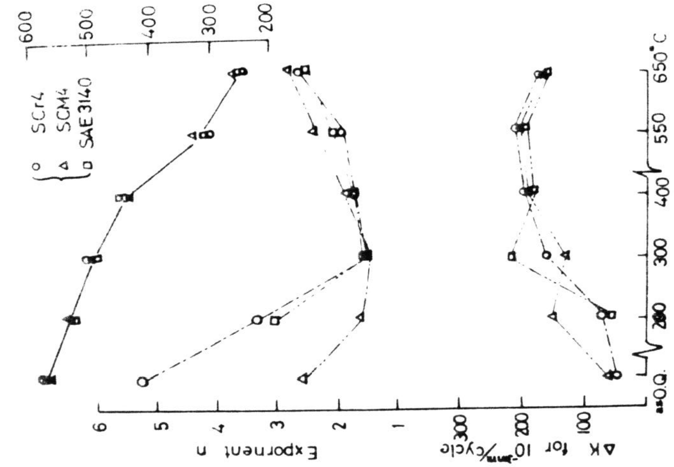

Fig.3. Structure depending exponent n, vickers hardness and Δk value for 10^{-4}mm/cycle as functions of tempering temperatures