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FATIGUE BEHAVIOURS OF A COMPRESSOR VALVE STAINLESS STEEL WITH SMALL AMOUNT OF RETAINED AUSTENITE

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ABSTRACT

Impact and bending fatigue strengths are essential properties for compressor valve steels. The increase in efficiency of compressors requires higher performance valve steels. This paper describes the influence of retained austenite on the fatigue strengths in tension, bending and impact for a modified CrMo martensitic stainless compressor valve steel.

It is shown that the impact fatigue strength was significantly improved with increasing retained austenite. The bending fatigue strength was also improved, but reached a maximum value at about 4vol% retained austenite. However, the presence of retained austenite had little influence on the fatigue strength in tension. These different fatigue behaviours were discussed in relation to the microstructures and were interpreted in terms of fracture mechanisms.

KEYWORDS

Compressor valve steels, CrMo martensitic stainless steels, retained austenite, impact fatigue, bending fatigue, residual stresses, damping capacity, fracture mechanism.

INTRODUCTION

The change in service condition and increase in compressor efficiency require valve steel with even higher impact fatigue strength. CrMo martensitic stainless steel is a standard compressor valve steel. It usually contains small amount of retained austenite. It was reported that the presence of retained austenite has a positive influence on the impact fatigue properties [1, 2].

In the present study, the influences of retained austenite in a modified CrMo martensitic stainless steel on the fatigue behaviours in tension, bending and impact were systematically investigated. The material used contained much larger amount of retained austenite than the conventional one. Different fracture mechanisms were discussed concerning the different fatigue behaviours observed.

MATERIAL AND EXPERIMENTAL

The material used was Fe-0.37C-0.4Si-0.60Mn-13.5Cr-1.0Mo (wt%) martensitic stainless steel strip with a thickness of 0,38mm. Four variants with retained austenite from 0,4vol% to 14,3vol% were investigated. Table 1 shows amounts of retained austenite and the mechanical properties. The tensile strength and hardness were indirectly increased with increasing retained austenite, but reached maximum values at about 10vol% retained austenite. The plasticity (elongation and bendability) was also improved with increasing retained austenite.

TABLE 1

AMOUNT OF RETAINED AUSTENITE AND MECHANICAL PROPERTIES

Variants	Retained austenite (γ') (%)	$R_{p0.2}$ [MPa]	R_m [MPa]	A [%]	Bendability*	HV_1
Strip-A	0,4	1420	1783	7,4	17,6	555
Strip-B	4,4	1487	1910	7,6	16,6	570
Strip-C	10,1	1490	1948	9,5	13,7	582
Strip-D	14,3	1427	1930	11,4	9,5	577

*Bendability: the ratio of the minimum radius to the specimen thickness at which a strip does not fail when it is bent. This is usually called Wertzahl value.

The microstructure and fracture were investigated using SEM. For the microstructure investigation, the samples were etched in a solution consisting of 15 grams CuCl, 300 ml ethanol, 300 ml HCl and 300 ml H_2O. The precipitation states were investigated on the thin foils using Jeol 2000FX TEM/STEM equipped with Oxford ISIS EDX system. Residual stresses were measured with an X-ray diffractometer using CrKα radiation.

The damping capacity was determined using a simple experiment [3]. One end of the specimen was clamped horizontally and another was kept free. A steel ball with diameter of 17,5 mm and mass of 22 gram was dropped from a position of 300 mm above the sample. The changes in amplitudes of the free vibrations of the specimen were recorded using an oscilloscope. The damping capacity was evaluated by the following exponential approach:

$$U=U_o \exp(-bt) \qquad (1)$$

where U is the amplitude at any vibration time, t is the time, U_o is the amplitude at t=0, and b is the damping index that is used to describe the damping capacity of material.

Three types of fatigue testing, namely pulsating tension, bending and impact, were performed in a laboratory environment at room temperature. Pulsating tensile fatigue test (R=0) was performed using a Amsler test machine with a frequency of about 150Hz. Reversed bending fatigue test (R=-1) was performed using a UMG test machine with a frequency of 25 Hz. Impact fatigue tests were performed using Sandvik Impact Fatigue Tester with a frequency of 250 Hz [3].

The fatigue strength was determined using the staircase method with 50 % fracture probability [4]. A series of 30 specimens were used. The specimen was tested at a given level of a stress until it failed, or till maximum $2 \cdot 10^6$ cycles for pulsating tension and bending and $1 \cdot 10^7$ cycles for impact. The impact fatigue strength is the impact speed (m/s) at which the specimen hits the seat [3].

RESULTS

Microstructure

Two groups of $M_{23}C_6$ particles were observed: larger ones with a mean size of 0,5μm and dense fine ones with a mean size of 0,1μm (Figure 1). With increasing retained austenite, the number and size of the larger particles were decreased, but those smaller ones were greatly increased (Figure 1a and b). However, the total fraction of $M_{23}C_6$ carbides was decreased (Figure 1c). It was found that the precipitation of these $M_{23}C_6$ carbides obeyed the Nishiyama-Wasserman (N-W) crystallographic orientation relation to martensite.

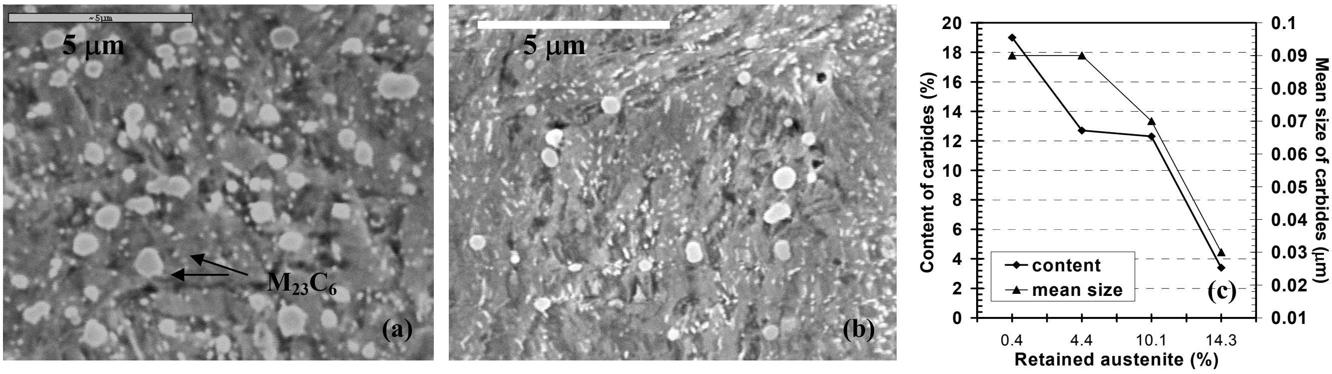

Figure 1: Precipitation of $M_{23}C_6$ in material with (a). 0,4vol% γ', (b). 14,3vol% γ'; (c). Relation between retained austenite and $M_{23}C_6$ carbides.

Another type of precipitate observed was very fine Fe_3C particles (with a typical size of 1nm) (Figure 2). It was found that its volume fraction was a function of retained austenite. In the strip with 0,4vol% retained austenite, very few Fe_3C particles could be observed (Figure 2a). With increasing retained austenite, the fraction of Fe_3C particles was increased (Figure 2b). In the strip with 14,3vol% retained austenite, very dense fine Fe_3C particles were observed (Figure2c). One of its crystallographic orientation relationships to martensitic matrix is shown in small picture in Figure 2c, which gives rise to a low energy interface through a low lattice misfit.

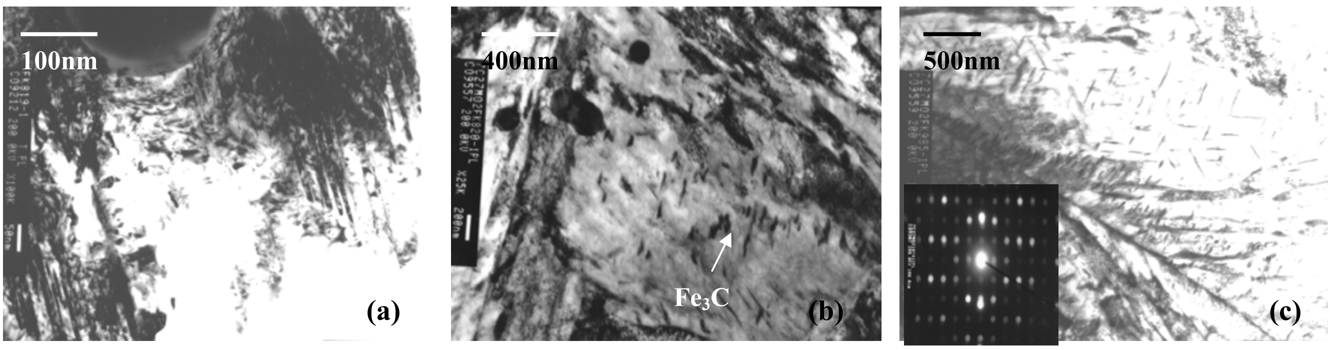

Figure 2: Precipitation of Fe_3C in material with (a). 0,4vol% γ', (b). 4,4vol% γ', (c). 14,3vol% γ', and composite electron diffraction pattern from the zone axes of $[010]_{Fe_3C}//[\bar{1}12]_{\alpha}$ (small picture).

Residual Stress and Damping Capacity

The relationship between the amount of retained austenite and the residual stress was plotted in Figure 3a and between the amount of retained austenite and damping capacity of the strips was plotted in Figure 3b. As can be seen the compressive residual stresses on the top surface of the strips were increased with the increase of the amount of retained austenite in the material. The depth of the compressive residual stresses from the surface was about 0,03 mm.

The damping capacity was also increased with increasing retained austenite (Figure 3b). This might be attributed to the increase of the total number of stacking-faults in retained austenite and the boundaries between retained austenite and martensite [5].

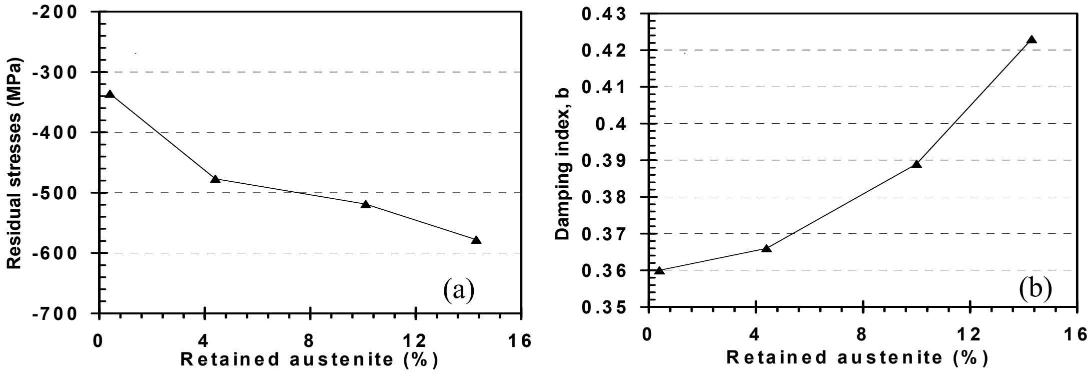

Figure 3: (a). Influence of retained austenite (vol%) on the compressive residual stresses; (b). Influence of retained austenite on the damping capacity.

Fatigue Strengths

The fatigue strengths from the different tests are summarised in Figure 4. The impact fatigue strength was significantly increased with the increase of the amount of retained austenite. However, increase of the amount of retained austenite had little effect on the pulsating tensile fatigue strength. For bending fatigue, the fatigue strength was increased with increasing retained austenite, and reached a maximum at about 4vol% retained austenite. However, the bending fatigue strength was still higher in the material with larger amount of retained austenite (or not lower in the material with 14,3vol% retained austenite) than in the material with 0,4vol% retained austenite.

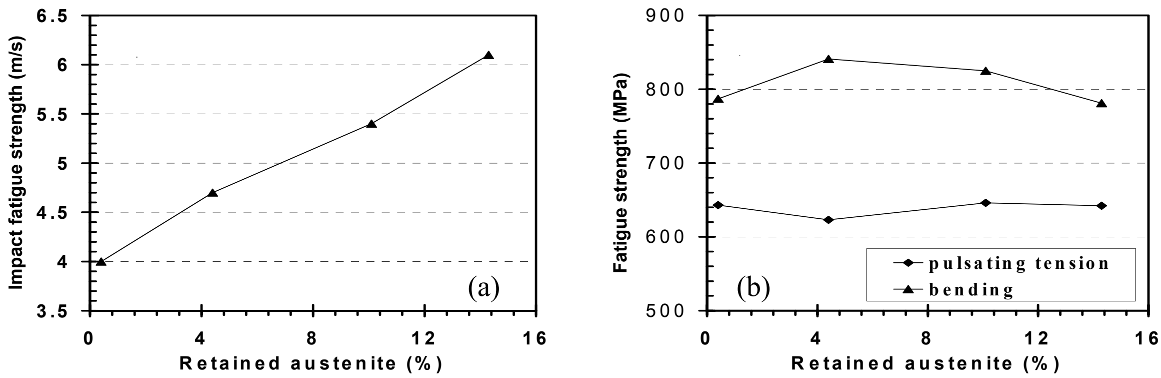

Figure 4: (a). Influence of retained austenite (vol%) on the impact fatigue strength; (b). Influence of retained austenite on the fatigue strengths in tension and in bending.

DISCUSSION

Precipitation Strengthening

In Table 1, it shows that the tensile strengths increased with increasing retained austenite in the strips. Austenite is a soft phase comparing with the matrix (martensite phase). It is unlikely that the presence of retained austenite could result in the increase of the tensile strength or hardness. The strengthening or hardening, therefore, could be attributed to the precipitation of densely dispersed fine $M_{23}C_6$ and Fe_3C particles as shown in Figure 1 and 2. Hence, the changes in the strengths or hardness were the resultant of the precipitation strengthening and softening due to the increase of retained austenite. It reached a maximum value at about 10vol% retained austenite. Slight decrease in the strength or hardness was owing to the large amount of retained austenite.

Influence of Retained Austenite on Fatigue Behaviours

As shown in Figure 4a, increase in retained austenite significantly improved the impact fatigue strength. This is quite promising since this property is very critical to compressor valve steels.

Different from other fatigue behaviours, the loading time of impact fatigue is very short. The specimen at each impact has suffered from very high strain rate. Fatigue-crack initiation results from plastic-deformation accumulation [6] and occurs at sub-surface [3]. The impact fatigue resistance mainly depends on both the strength and plasticity of the material [6]. In this investigation, the influence of the strength on the impact fatigue strength was relatively small. This was consistent with the earlier observations. The impact fatigue strength has shown little dependence on the tensile strength in the range of 1600-2500MPa [3]. One explanation is that the specimen at each impact has withstood very high strain rate, hence the impact fatigue strength should be compared with the tensile properties at high strain rate. On the other hand, the ductility (bendability or elongation) shows a great influence on the impact fatigue strength (Figure 5a).

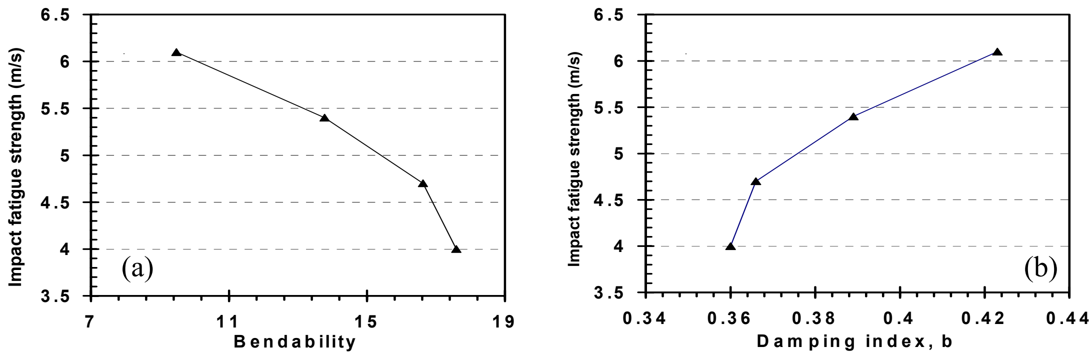

Figure 5: (a). Correlation between bendability and impact fatigue strength; (b). Effect of damping capacity on impact fatigue strength.

The impact of the specimen from this test was caused by high frequency flexural and torsional vibration [3]. This vibration can be more effectively damped in the steel with high damping capacity. Consequently, the impact stresses will become smaller, and the measured impact fatigue strength will be higher. This is shown in Figure 5b.

The above discussion indicates that the improvement of the impact fatigue strength of the valve steel strip can be attributed to the combination of its high strength and high absorption capacity of impact energy (plasticity and damping capacity).

As shown in Figure 3a, compressive residual stresses were increased with increasing retained austenite. This may also contribute to the improvement of the impact strength.

TABLE 2

DISTRIBUTION OF CRACK INITIATION OF FAILED SPECIMENS FROM EACH VARIANT [%].

Sample	Retained austenite (γ') (vol %)	Inclusion	Surface and edge	Corner
Strip A	0,4	73,3 (37%)*	6,7	20
Strip B	4,4	71,4(10%)	14,5	14,3
Strip C	10,1	71,4(10%)	28,6	0
Strip D	14,3	73,4(9%)	20,0	6,7

*: Probability of crack initiation at subsurface inclusion.

As known, the fatigue properties are correlated to the tensile strength and the compressive residual stresses in the materials. The results from the pulsating tension fatigue testing were therefore unexpected. Fracture investigation (Table 2) shows that most crack initiations started at inclusions. Increase in retained austenite could not change this distribution (see inclusion in Table 2). On the other hand, it seems that the increase of retained austenite could have facilitated the crack initiations at surface inclusion (comparing with subsurface inclusion) or other surface defects. This is contrary to the conventional phenomena where increase in compressive residual stress on the top surface will lead to crack initiation at subsurface inclusions. One explanation might be that the presence of relatively high amount of retained austenite near the surface causes the crack initiation more easily [7]. The increase in compressive residual stresses and tensile strength might compensate for the reduced fatigue resistance due to softening by retained austenite.

Since the maximum stress in a bent strip is on its top surface, the bending fatigue strength is mainly dependent on the surface conditions and its strength. In spite of the fact that the compressive residual stresses and the tensile strength were increased with the increase of retained austenite, no continuous increase in the bending fatigue strength was obtained. This might also be attributed to the presence of retained austenite. The earlier experiences [7, 8] show that due to its weakness and easily slipping the presence of retained austenite near the top surface will facilitate the crack initiation during bending cyclic loading. In this investigation, however, very fine elongated retained austenite (about 0,1μm) was observed to have been embedded between two acicular martensite phases [2]. This might reduce the risk of retained austenite for crack initiation, and may also give an explanation why high bending fatigue strength can still be maintained in the material with large amount of retained austenite (14,3vol%).

CONCLUDING REMARKS

Increase in the strength or hardness of the material was the additive of the precipitation strengthening of fine dispersed $M_{23}C_6$ and Fe_3C particles and the softening due to the increase of retained austenite. It reached a maximum value at about 10vol% retained austenite.

The impact fatigue strength was significantly improved with increasing retained austenite. The presence of retained austenite however had little influence on the fatigue strength in tension. For the bending fatigue strength, it increased with increasing retained austenite and reached a maximum value at about 4 % retained austenite.

Increase in impact fatigue strength was likely attributed to the increase in its ability for impact energy absorption (damping capacity and plasticity) by increasing retained austenite and its tensile strength by precipitation strengthening. For fatigue in tensile, crack initiation at inclusion was the main fracture mechanism. For fatigue in bending, the presence of retained austenite near the top surface may facilitate crack initiation. High bending fatigue strength maintained in the material with large amount of retained austenite was owing to its high tensile strength and fine dispersed retained austenite.

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