Damage and fracture of high strength stainless steel strip during repeated impact loading

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ABSTRACT : *Edge chipping, which means that small fragments are torn off from the edge, is a typical fracture process of compressor flapper valve steel that suffer from repeated impact loading. An impact fatigue testing-a simulation of a compressor flapper valve has been performed using four variants of thin martensitic stainless steels strip. The fracture mechanisms and factors that affect the impact fatigue behaviour of thin strip have been investigated. It was found that cracks started near the impact contact area and propagated towards the edge of the specimen. These cracks propagated then in waveform in both longitudinal and transversal directions. New cracks initiated at the wave peaks of the original crack. The propagation of new cracks in radial direction lead to an edge chipping. Increases in tensile properties, damping capacity and compressive residual stresses increase impact fatigue strength of the materials. A model based on dynamic stress wave theory has been developed to understand the mechanism of the formation of edge chipping and fracture of thin strip under repeated impact loading.*

INTRODUCTION

Compressor flapper valve material will suffer from both cyclic bending stresses and cyclic impact stresses during its service. A typical fracture due to cyclic impact stress is that small fragments are torn off from the edges, which is usually termed as edge chipping [1-3]. Although much effort has been paid to find early stage of crack initiation, crack propagation and final failure, the mechanism for edge chipping is still not clear [2,3]. The earlier work considered that edge shipping occurs when two cracks propagate close to each other [2]. This was mainly based on the observation that multi-crack initiation occurred in the area between the impact area and the edge of specimens, and these cracks radially propagate towards the impact area and the edge. However, it neglected the action of the shear stress induced by the repeated impact stress. It was also considered that edge chipping occurs when the impact damage grows and gets sheared off. This model mainly discussed the crack initiation and propagation life after edge chipping [3].

In this investigation, a theoretical and experimental work on impact fatigue of thin martensitic stainless steels strip was done. The purposes were to study the mechanism of the formation of edge chipping and the factors that affect the impact fatigue behaviours of thin strips.

MATERIAL AND EXPERIMENTAL

The material used was Fe-0.38C-0.4Si-0.55Mn-13.5Cr-1.0Mo (wt%) martensitic stainless steel strip with a thickness of 0,381mm. Four variants with different tensile properties were investigated. Table 1 shows the information of these strips.

TABLE 1: Tensile properties and residual stresses in the materials.

Variants	E-modulus (GPa)	R_m (MPa)	HV_1	Residual stresses (MPa)
Strip-A	213	1783	555	-336
Strip-B	214	1910	570	-477
Strip-C	211	1948	582	-519
Strip-D	213	1930	577	-578

The impact fatigue testing-a simulation of a compressor flapper valve was performed using SIFT (Sandvik Impact Fatigue Tester). The frequency was 250Hz. The fatigue strength at 10^7 cycles, which was defined as the impact speed (m/s) at that the specimen hits the seat [2], was determined using the staircase method with 50 % fracture probability. A series of 30 specimens were used. Figure 1 shows the size of the specimen. The fractures were examined using SEM and light optical microscope.

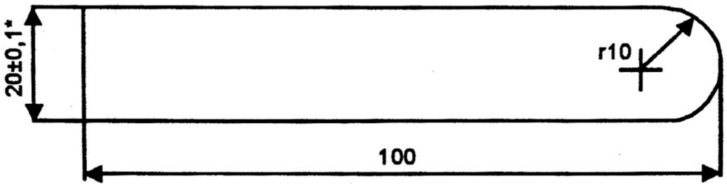

Figure 1:Schematic sketch of the specimen used in this test.

The damping capacity was determined using a simple instrument. The specimen for impact fatigue testing was used. One end of the specimen was clamped horizontally, and the other was kept free. The length of the free part was 50 mm. A steel ball with diameter of 17,5mm and mass of 22gram was dropped from a position of 300mm above the sample. The changes in amplitudes of the free vibrations of the specimen, initiating by dropping the ball, were recorded using an oscilloscope. The damping capacity can be described by an exponential expression:

$$U = U_o \exp(-bt) \tag{1}$$

where U and U_o are the amplitudes at a given vibration time t and t=0, and b is the damping index, which is used to describe the damping capacity of material.

RESULTS

Damping Capacity and Impact Fatigue Strength of thin strip material

Figure 2 shows a summary of the test results from this investigation. The fatigue strengths and damping capacity of this martensitic stainless steel strip material show the same tendency. Strip D shows both the highest impact fatigue strength and the largest damping capacity.

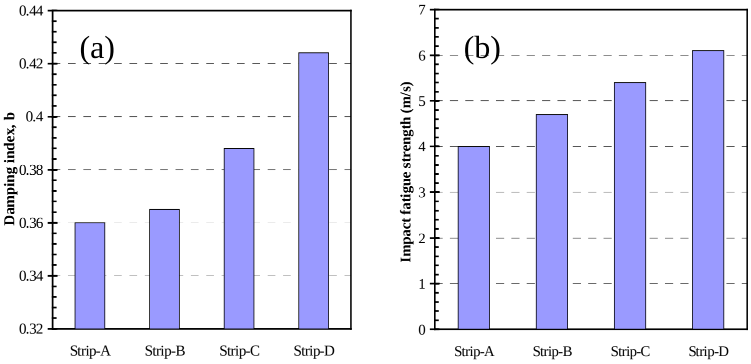

Figure 2: Damping capacity (a) and impact fatigue strength (b) of a martensitic stainless steel strip material.

Impact fatigue damage and fracture

Figure 3a shows the fractures of the impact specimens at the early stage. As expected, they are small edge chipping. The cracks propagated then into the impact area, and finally propagated into the middle of the specimen and also in the transversal direction until a catastrophic failure occurred (Figure 3b).

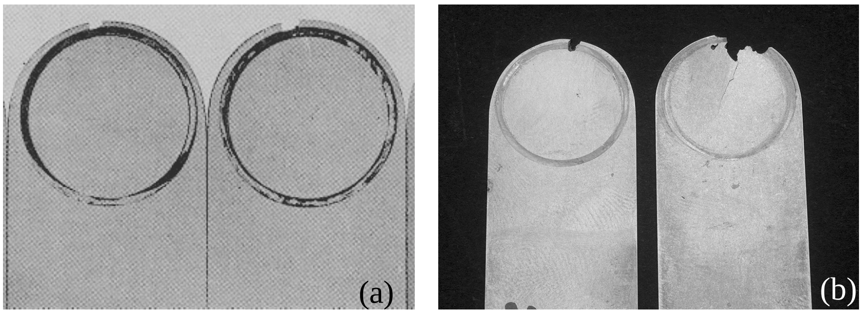

Figure 3: Failures of strip specimens due to repeated impact stress, (a). At the early stage, (b), At the late stage.

Microscopically, micro-cracks were observed near the impact areas (Figure 4a and b). It seems that these cracks propagated towards to the edge. Figure 4c shows that the cracks then propagated in waveforms in the transversal direction. Two new cracks have been initiated at the peaks of the original crack. The propagation of these two new cracks in radial direction lead to an edge chipping (Figure 4d).

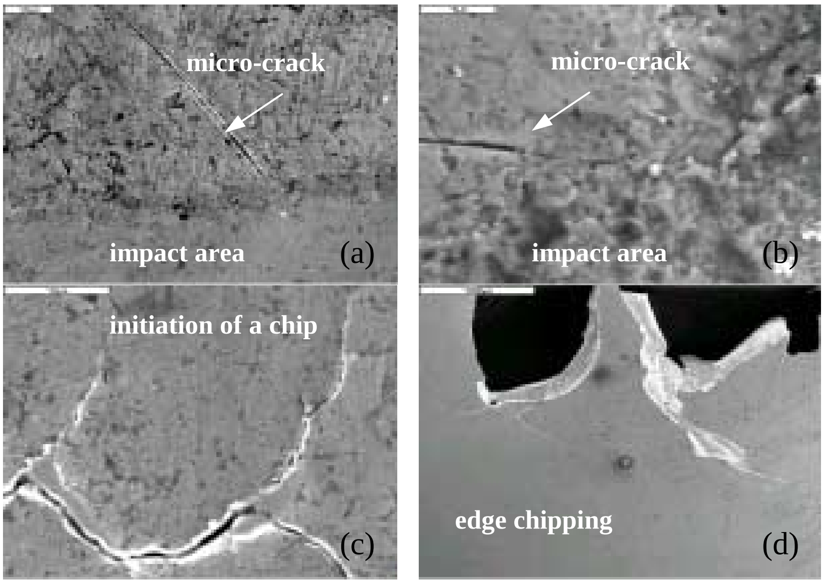

Figure 4: Damage and failures of strip specimens, (a) and (b). Initiation of micro-crack, (c), Crack propagation, (d). Final failure.

DISCUSSION

Impact induced stresses

When an impact specimen hits the seat, compressive stresses are induced at the impact area. These surface impact stresses are then transformed into tensile and shear stresses and propagate away as elastic waves at high speed through the specimen. The initial transformed stress can be [3]:

$$\sigma_o = v_o \sqrt{E\rho} \tag{2}$$

When stress waves propagate through a solid material, the stress amplitude will gradually decrease due to damping:

$$\sigma = \sigma_o e^{-tA\sqrt{E\rho}\,/\,M} \tag{3}$$

where σ_o and σ are the initial and damped stresses, v_o is the impact velocity, t is the time, ρ and M are the density and mass of the strip, A is the impact area, E is the modulus of elasticity.

Actually, these elastic waves travel through the specimen as a combination of longitudinal (tension) waves and shear waves. On the surface, they form a surface wave called Rayleigh wave, which is considered to be the most damaging [1]. The velocities of to longitudinal (tension) waves and shear waves in a solid are [4,5]:

$$C_1 = \sqrt{E/\rho}\,;\ \ C_2 = \sqrt{G/\rho}\,;\ \text{and}\ \ t = \frac{L}{Ci} \tag{4}$$

where C_1 and C_2 are the velocities of longitudinal waves and shear waves, which are represented by C_i, L is the wave travel distance at time t, and G is the shear modulus. By putting eq. 4 into eq. 3, we get:

$$\sigma = \sigma_o e^{-LA\sqrt{E\rho}\,/\,MCi} \tag{5}$$

Eq. 4 and eq. 5 show that both longitudinal stress and shear stress decay with increasing wave travel distance, and the shear stress decays faster than the tension stress.

Fracture mechanism

The fracture observations from this investigation show that the fracture by edge chipping can be a result of a combined effect of the tension stress wave and the shear stress wave. A model based on dynamic stress wave theory was proposed. It is illustrated in Figure 5 and described as follows:

1). In the early stage of impact fatigue, crack initiation starts near the impact area (in this test) or in a zone between the impact area and the specimen edge [2] due to localised damage by oblique impact [2, 3]. These cracks will propagate in the longitudinal wave direction (Figure 4 and Figure 5a).

2). The propagating cracks become unstable (Figure 5a) (or new cracks have initiated) due to the effect of Rayleigh waves. Now the cracks propagate neither in the radial direction nor in the transversal direction, but in a direction depending on a combined effect of the tension stress wave and the shear stress wave. Near the impact area, or short wave travel distance, the cracks will propagate more transversally due to the higher shear stress. Since the shear stress wave decays more quickly, the cracks will propagate more radially with increasing wave travel distance until they reach the edge of the specimen where an edge chipping occurs (Figure 5a).

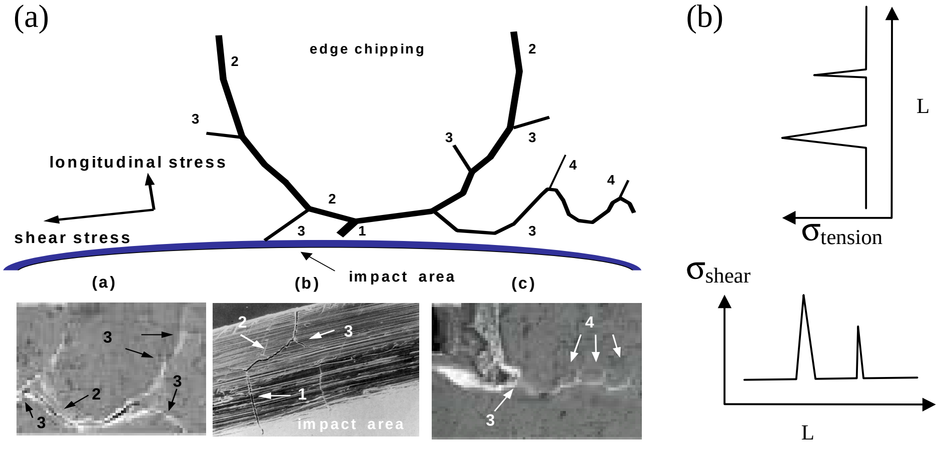

Figure 5: Crack initiation and formation of edge chipping. (a). Model and observations, (b). Dynamic stress concentrations.

3). Since both tension stress wave and shear stress wave are generated at the front of the impact area and each type of wave moves at the same velocity, the instantaneous energy input from each impact is always in phase. This indicates that dynamic stress concentrations can be formed in certain wave travel distance as shown in Figure 5b, and initiate even higher order cracks (3rd or 4th cracks in Figure 5a). This successive crack initiation and propagation process causes a waveform of impact fracture (Figure 4d).

Factors affecting impact fatigue behaviour of thin strip

According to eq. 2, the initial stresses introduced in the specimen due to repeated impact loading increase with increasing impact velocity. This indicates that increase in tensile strength of the material can improve its impact fatigue properties. In this investigation, however, the tensile strength of Strip C is higher than that of Strip D, but the impact fatigue strength of the later is higher than the former. This shows that other factors also have an important influence on the impact fatigue properties.

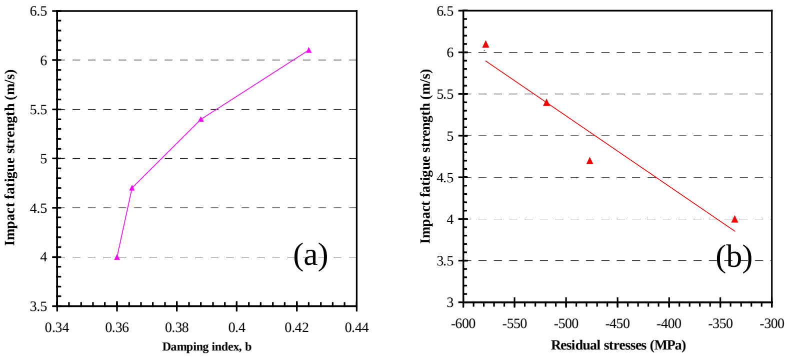

Figure 6: Influence of damping capacity. (a) and compressive residual stress (b) on the impact fatigue properties of thin stainless steel strip.

As mentioned previously, both tension stress waves and shear stress waves will decay during its travelling due to damping. However, the rate of the stress decay depends on the damping capacity of the material. The wave stresses will decay more quickly in the material with higher damping capacity. This indicates that the induced stresses will be lower. Consequently, this reduces the risk for both crack initiation and propagation and increases the impact fatigue properties. Figure 6a shows the influence of damping capacity on the impact fatigue strength of the strips from this test.

It is well known that the presence of residual compressive stresses at the surface of a component subjected to cyclic loading is beneficial to its fatigue properties. The compressive layer delays fatigue crack initiation and retards small crack propagation, which can enhance the fatigue limit. Figure 6b shows the influence of residual stress on the impact fatigue strength of the strips from this test.

CONCLUSIONS

The stresses that cause the fatigue damage or fracture are the tensile stress wave and shear stress wave induced by repeated impact loading. Increase in tensile strength and compressive residual stresses increase the resistance of fatigue crack initiation and propagation. The material with high damping capacity reduces the induced stresses and consequently the risk for both crack initiation and propagation and increases the impact fatigue properties.

Due to a combined effect of longitudinal stress waves and shear stress waves, initiated micro-cracks propagate in waveforms in the transversal direction, and new cracks will initiate at the peaks of the original crack. The propagation of new cracks in radial directions leads to edge chipping.

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