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**EFFECT OF MATERIAL PROPERTIES AND SURFACE
TREATMENT ON THE PERFORMANCE OF STAINLESS FLAPPER
VALVE STEEL FOR COMPRESSORS**

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ABSTRACT

Suction and discharge valves are components critical to the function of a compressor, which must work reliably under conditions of high cyclic stresses from bending and impact. The allowable bending stress and impact velocity for the valve material are limiting factors for the compressor designer and it is thus of interest to compressor manufacturers to maximize the fatigue strength of the valves.

This paper describes fatigue testing that has been performed on a martensitic stainless valve steel (modified AISI 420) that is commonly used in compressors.

Strip steel samples with different static mechanical properties, which were given three different surface treatments (untreated, tumbled, and tumbled + shot-peened) were investigated. The samples were tested for bending- and impact fatigue properties and the results are given in the paper.

It was found that suitable surface treatments could give rise to very favorable residual stress states in the material, which led to very good fatigue testing results, particularly for some of the samples, which had a higher tensile strength. Material with increased fatigue strength in bending and impact can offer significant design advantages for future compressor designs leading to higher efficiency and reliability, as well as the possibility to design smaller compressors. This is of particular interest to CO₂-compressors using a high discharge pressure.

INTRODUCTION

Suction and discharge flapper valves, which are critical components for the function of a compressor, will suffer from both cyclic bending stresses and impact stresses during service. High bending fatigue strength and high impact fatigue strength are therefore the basic requirements for valve materials [1]. In recent years, with the change in service conditions and increase in compressor efficiency, the valve material is becoming a limiting factor and materials with even higher fatigue strengths are required in order to facilitate a further development of compressor efficiency. Efforts have therefore been made with the purpose to improve the properties of the valve steel materials [2].

It is known that the fatigue strength of a material initially increases, more or less linearly, with increasing tensile strength. However, no further increase, or even a decrease in fatigue strength is accomplished by increasing the tensile strength above a critical value. This is generally attributed to the increase in the sensitivity of the stress-raising effect at material defects by increasing the tensile strength [3]. These observations indicate that it may be possible to obtain a further improvement of the fatigue strength of a material with a high tensile strength, which retains a low sensitivity to the stress-raising effect.

Another well-documented recipe for enhancing the fatigue limit of a steel component subjected to cyclic bending loads is to introduce residual compressive stresses at its surface [5]. This is the common practice used in

flapper valve manufacturing, where compressive stresses are typically introduced by tumbling. However, residual stresses will usually be relaxed during cyclic loading depending on the material and the loading level, and little work has been done concerning this effect [5]. A material with a low stress relaxation rate is favorable.

During impact contact of a compressor valve, the crack initiation and propagation are mainly caused by induced elastic tensile stress waves and shear stress waves [1]. However, these stress waves will decay during their travelling due to internal material damping. This indicates that the damping capacity of the material is also important to the impact fatigue properties of compressor valve steels [6].

In this study, the influences of tensile properties, residual stresses, residual stress relaxation, and stress damping capacity on the fatigue properties of valve strip materials have been investigated. A new type of flapper valve material with high tensile strength, high ductility, high bending- and impact fatigue strength is discussed.

MATERIAL AND EXPERIMENTAL

Material

In this investigation, the material used was a Fe-0.38C-0.4Si-0.55Mn-13.5Cr-1.0Mo (wt%) martensitic, stainless valve steel strip material. Six variants (one reference, with standard tensile strength, and five modified variants, A to E, with increased tensile strength) with three surface conditions were investigated. Their static mechanical properties and residual stresses are shown in Table 1. The properties have been measured along the rolling direction of the strip steel.

Variants	Thickness (mm)	Tensile strength (MPa)	Elongation at fracture, A11.3 (%)	Elastic modulus (GPa)	Hardness (HV 1)	Residual stresses (MPa)		
						UNT	TB	TB+SP
Reference	0.381	1783	7.4	224	555	-363	-840	-910
A	0.381	1910	7.6	224	570	-443	-870	-910
B	0.381	1948	9.5	216	582	-469	-953	-920
C	0.381	1930	11.5	224	577	-578	-932	-1048
D	0.305	1960	8.8	224	582	-371		
E	0.305	1945	6.8	215	580	-389		

Table 1. Static mechanical properties and residual stresses in the materials.
UNT = untreated, TB = tumbled, TB+SP = tumbled and shot-peened.

Experimental

Two types of fatigue tests, namely reversed bending and impact, were performed in a laboratory environment at room temperature. 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 [7]. Fracture surfaces were investigated using scanning electron microscopy (SEM).

The fatigue strength was determined using the staircase method with 50 % fracture probability. A series of 30 specimens was used for each test. Each specimen was tested at a given level of stress until failure, or until a maximum of $2 \cdot 10^6$ cycles for reversed bending, or $1 \cdot 10^7$ cycles for impact, was reached without failure. The impact fatigue strength is the speed at which the specimen hits the seat [7].

A residual stress relaxation test was performed using the same test facility and type of specimen as the reversed bending fatigue test. The test was performed at a stress level corresponding to the fatigue strength at $2 \cdot 10^6$ cycles, and stopped at a given number of cycles. The residual stress at the surface was then measured with an X-ray diffractometer using $\text{CrK}\alpha$ radiation. The relaxation was calculated using the following equation:

$$r(\%) = \frac{\sigma_{res,o} - \sigma_{res,n}}{\sigma_{res,o}} \cdot 100 \quad (1)$$

where r = relaxation rate at a given cycle
 $\sigma_{res,o}$ = initial residual compressive stress
 $\sigma_{res,n}$ = residual compressive stress at a given cycle

The damping capacity was determined using a simple experiment [7]. One end of the specimen was clamped horizontally while the other was kept free. A steel ball with a diameter of 17.5 mm and a mass of 0.022 kg was dropped from a position 300 mm above the sample. The change in amplitude of the free vibrations of the specimen was recorded using an oscilloscope. The damping capacity was evaluated by the following exponential approach:

$$U = U_0 \exp(-bt) \quad (2)$$

where U is the amplitude at any vibration time, t is the time, U_0 is the amplitude at $t=0$, and b is the damping index that is used to describe the damping capacity of material.

RESULTS AND DISCUSSION

Table 2 shows a summary of the test results from this investigation. Of the samples that were tested in both bending and impact fatigue, sample A has the highest bending fatigue strength while sample C has the highest impact fatigue strength. The surface treatments by tumbling and shot peening have increased the bending fatigue strengths by 2 to 14% and the impact fatigue strength by 17 to 47%, depending on the material and the surface treatment. In this investigation, the fatigue strengths after shot peening were generally lower than that after tumbling alone.

Strip	Damping Index, b	Bending fatigue (MPa)			Impact fatigue strength		
		UNT	TB	TB+SP	UNT	TB	TB+SP
Reference	0.36	±787	±803	±883	4.0	5.0	4.7
A	0.37	±841	±910	±866	4.7		
B	0.39	±825	±897	±852	5.4	7.1	6.8
C	0.42	±781	±895	±883	6.1	7.5	9.0
D		±873					
E		±834					

Table 2. Bending and impact fatigue properties of the materials.

Influence of Tensile Properties on the Fatigue Strength

According to early results by Forrest [3], no further improvement of fatigue strength can be obtained by increasing the tensile strength above 1520 MPa for steels. Figure 1 shows the influence of the tensile strength on the reversed bending fatigue strength of the reference standard stainless flapper valve steel and the modified samples A-E with increased tensile strength. Although the tensile strength of these materials is significantly higher than 1520 MPa, the fatigue strength continuously increases with increased tensile strength. There is no indication that the rate of the increase of the fatigue strength begins to decrease with the tensile strength investigated. This result shows the possibility enhance the fatigue strength for high strength steels by increasing tensile strength.

It is generally believed that increase in tensile strength increases the defect sensitivity of the material. For high strength steels, the ductility is usually low and decreases further with increasing tensile strength. Consequently, this increases the localized stress concentration around the defects, which may counteract or exceed the contribution of tensile strength. In this investigation, as shown in table 1, the elongation or ductility of the material does not decrease with increasing tensile strength. A relatively high elongation (8.8%) is retained for the material with rather high tensile strength (1960 MPa). This makes it possible for localized yielding to occur around defects, which

decreases the stress concentration. Therefore, an increase in tensile strength, which is equal to an increase in overall fatigue load resistance, will increase the fatigue strength.

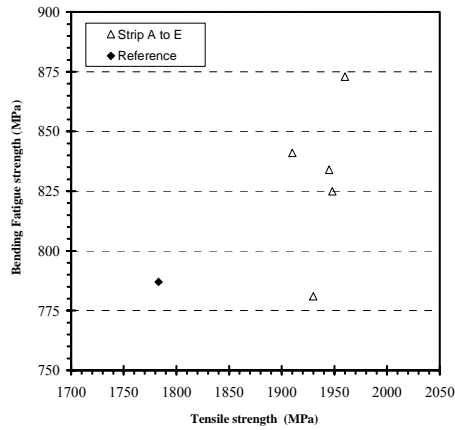


Figure 1. Influence of tensile strength on the reversed bending fatigue strength of the investigated valve steels.

Since impact fatigue fracture is mainly caused by transformed stress waves [1, 6], the increase in tensile strength will certainly increase the impact fatigue strength. However, as shown in table 2, no direct relation between the tensile strength and the impact fatigue strength can be obtained. This indicates that other factors are also important to the impact fatigue strength, which will be discussed later.

Influence of Residual Stress on the Fatigue Strength

Figure 2 shows the influence on the residual stresses introduced at the surface of the strip specimens on the reversed bending fatigue strength and impact fatigue strength. Generally, both reversed bending strength and impact fatigue strength increase with increasing residual compressive stresses. However, they show large scatter in the bending fatigue strength, or different rates of the increase in the impact fatigue strength for different variants. This is probably due to stress relaxation, which occurred during cyclic loading.

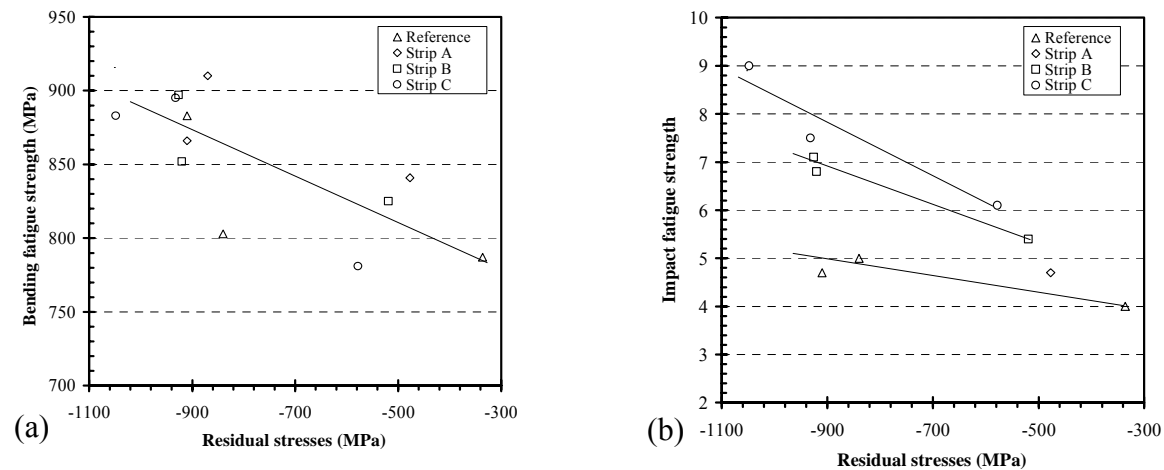


Figure 2. Influence of residual stress on the reversed bending fatigue strength (a) and impact fatigue strength (b).

Figure 3a shows some examples of stress relaxation in the specimen surface during cyclic bending loading. Stress relaxation occurred rather quickly during the early stages of cyclic loading, and then changed relatively little with further loading. Table 3 shows a summary of relaxation rates in the thin strip specimens investigated. The relaxation rates were higher in the untreated materials. Surface treatments significantly reduce the stress relaxation rate. For

the surface treated strips, the stress relaxation rates are lower in the specimens with increased tensile strength than in the reference material.

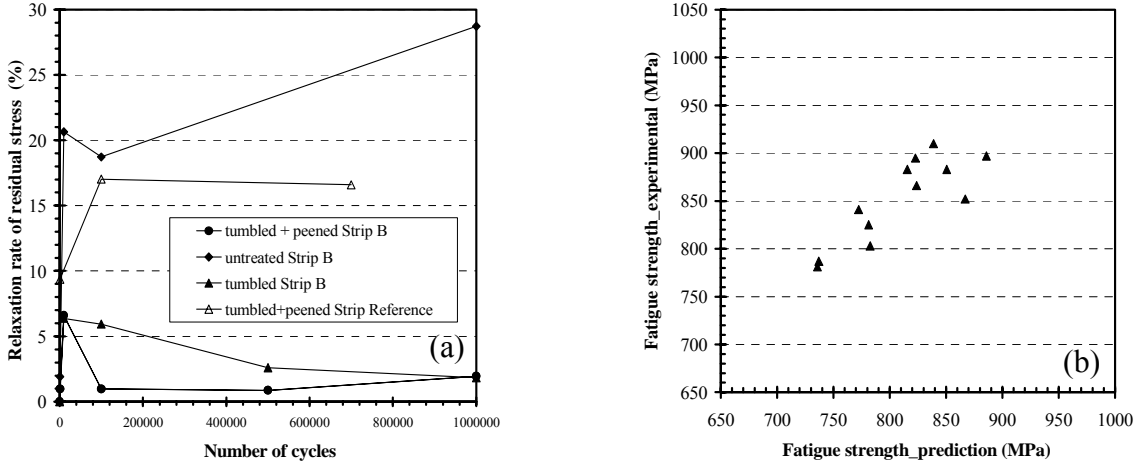


Figure 3. (a). Stress relaxation in strip materials during cyclic bending loading, (b). Comparison of the theoretical prediction and the experimental results.

Strip	Untreated	Tumbled	Tumbled + Shot-peened
Reference	4.8	13.1	16.4
A	18.2	8.0	15.4
B	26.8	7.1	7.6
C	33.4	6.6	6.0

Table 3. Relaxation rate (%) in the strips without and with surface treatments during cyclic bending loading.

The influence of residual stresses on the fatigue properties can be calculated using the modified Goodman's equation:

$$\sigma_a = \sigma_{a0} \left\{ 1 - \frac{\sigma_m}{\sigma_{TS}} \right\} \quad (3)$$

where σ_a is the fatigue stress amplitude (or strength) at a mean stress of σ_m at the surface, which includes applied mean stress and residual stress, and σ_{a0} is the fatigue stress amplitude when the mean stress is zero, σ_{TS} is the tensile strength. In this test, the applied mean stress used is zero, which means that σ_m in the equation is equal to the residual stress σ_{res} .

If stress relaxation, r , is considered, the influence of tensile strength and residual stresses on the fatigue strength can be calculated as follows:

$$\sigma_a = \sigma_{a0} \left(1 - \frac{\sigma_{res}(1-r)}{\sigma_{TS}} \right) \quad (4)$$

Figure 3b shows a comparison between the experimental results of the reversed bending fatigue strengths and the theoretical prediction by equation 4. The predicted values are somewhat smaller than the experimental results. This can be explained by the fact that no localized deformation hardening is considered in this equation [8].

Influence of Damping Capacity on the Impact Fatigue Strength

When an impact fatigue test specimen hits the seat, compressive stresses are induced at the impact area. These stresses are transformed into tensile and shear stresses that propagate away as elastic waves at high speed through the specimen. The initial transformed stress is:

$$\sigma_0 = v_0 \sqrt{E\rho} \quad (5)$$

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

$$\sigma = \sigma_0 e^{-tA\sqrt{E\rho}/M} \quad (6)$$

where σ_0 and σ are the initial and damped stresses, v_0 is the impact velocity, t is the time, ρ is the density of the material, M is the impacting mass, A is the impact area, and E is the modulus of elasticity.

These two equations are used to describe the formation of the transformed stress waves and their decay during the valve seat impact of a compressor valve [7, 9]. However, equation 6 mainly describes the influence of the time and wave travelling distance on the decay. The influence of material parameters is not very well understood. In this investigation, the materials used have similar elastic modulus and density. However, they show different internal damping capacities as shown in Table 2. Therefore, they exhibit very different impact fatigue strengths. This is because the stress waves decay more quickly in the material with higher damping capacity. This indicates that the induced stress peaks will be lower, which consequently reduce the risk for both fatigue crack initiation and propagation, which explains the substantial increase in impact fatigue strength. Figure 4 shows the influence of damping capacity on the impact fatigue strength of the valve strip material from this test.

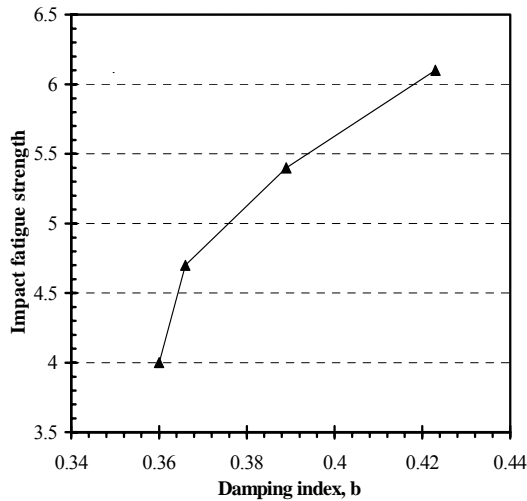


Figure 4. Influence of damping capacity on the impact fatigue properties of thin stainless steel strip.

CONCLUSIONS

A modification of standard stainless flapper valve steel, with high tensile strength, ductility and damping capacity, has been shown to have high fatigue strength under bending and impact loading conditions.

Surface treatment by tumbling and shot peening increase the compressive residual stresses and reduce stress relaxation, which also lead to an increase in fatigue strength.

The higher reversed bending fatigue strength of the valve steel specimens with increased tensile strength is due to the high ductility, high residual compressive surface stress, and low compressive stress relaxation rate.

Impact fatigue strength of valve strip material not only depends on the tensile strength and the compressive residual stresses, but also on the damping capacity. High damping capacity reduces the induced stress waves and consequently the risk for both crack initiation and propagation and increases the impact fatigue strength.

The high fatigue properties of the material with increased tensile strength could be utilized to improve efficiency in future compressor designs, as well as solve existing reliability problems. Development of CO₂ compressors may require stronger flapper valve materials due to the higher pressures involved.

The results presented here has enabled an optimization of stainless flapper valve material; a new generation of valve steels that can meet the requirements of the most demanding flapper valve applications in the compressor industry.

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