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FLAPPER VALVE STEELS WITH HIGH PERFORMANCE

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ABSTRACT

In recent years, environmental and economic considerations have led to changes in service conditions and demands for increased compressor efficiency. Flapper valve materials with higher fatigue strength have been a limiting factor in the development of compressor designs. Material manufacturers, therefore, have made great efforts to enhance the properties of existing materials and to develop new materials to keep pace with the needs of the industry. New flapper valve materials with high performance have been developed recently. This paper provides a review of where the technology is today. Bending fatigue strength and impact fatigue strength are the two most important properties for flapper valves. Flapper valve steel strip material with high bending fatigue strength should have a high tensile strength with high ductility. The strip surface after surface treatments should show a very good finish and high compressive residual stresses with a low stress relaxation rate. Besides all the above parameters, high damping capacity is favourable to a high impact fatigue strength.

1. INTRODUCTION

As is already known, cyclic bending stresses and impact stresses are the two main stresses that can cause a suction and discharge flapper valve to fail during service (Soedel, 1984). The impact fatigue strength and the bending fatigue strength of flapper valve strip materials are, therefore, extremely critical properties in the life of a compressor, since the flapper valves are the most critically loaded components. Considerable efforts have been made to obtain flapper valve strip materials with even higher performance (Olsson, 1992; Auren et al. 2002).

When questions of changes in service conditions and increases in compressor efficiency are raised, as a result of environmental and economic considerations, valve materials with high performance become very important. Compressor efficiency can be improved by increasing the valve lift or using thinner valves (thus lowering mechanical losses). These measures increase bending and impact stresses respectively. Consequently, flapper valve materials with higher fatigue strengths are required. To keep up with the needs of the compressor industry, a new stainless flapper valve steel, Sandvik Hiflex™, was recently introduced. This material exhibits up to 10% improvement in bending fatigue strength and as much as 25% improvement in impact fatigue strength compared with the traditional, modified AISI 420 material. It is recommended particularly for use in carbon dioxide compressors for automotive air conditioning, where higher pressures and temperatures place increasing demands on the valve material (Sandvik, 2003).

This paper provides a review of the latest investigations into the development of flapper valve strip materials with high performance.

2. DEVELOPMENT OF FLAPPER VALVE STEELS

Although several steel strip materials had been tested as flapper valve strip materials (Svenzon, 1976), the AISI 1095 type of carbon steel and the AISI 420 type of martensitic stainless steel are two most common flapper valve strip materials used today. Table 1 shows their nominal chemical compositions. Sandvik Hiflex™ is a new generation of modified AISI 420 type of martensitic stainless chromium steel.

Table 1: Nominal chemical compositions (wt%)

Material	C	Si	Mn	P	S	Cr	Mo
AISI 1095	1.0	0.3	0.4	0.020	0.010	-	-
AISI 420	0.38	0.4	0.6	0.025	0.010	13.5	1.0
Sandvik Hiflex	0.38	0.4	0.6	0.025	0.010	13.5	1.0

AISI 1095 and AISI 420 strip materials both have high tensile strength and high fatigue strength under bending and impact stress conditions (Sandvik, 2003). AISI 420 type materials, especially Sandvik Hiflex™, usually show higher fatigue strength than AISI 1095 (Figure 1), although the tensile strength of AISI 1095 is similar to that of the stainless grades. They can, therefore, be applied in environments where high pressure or high valve lift is needed, and where corrosion problems need to be considered.

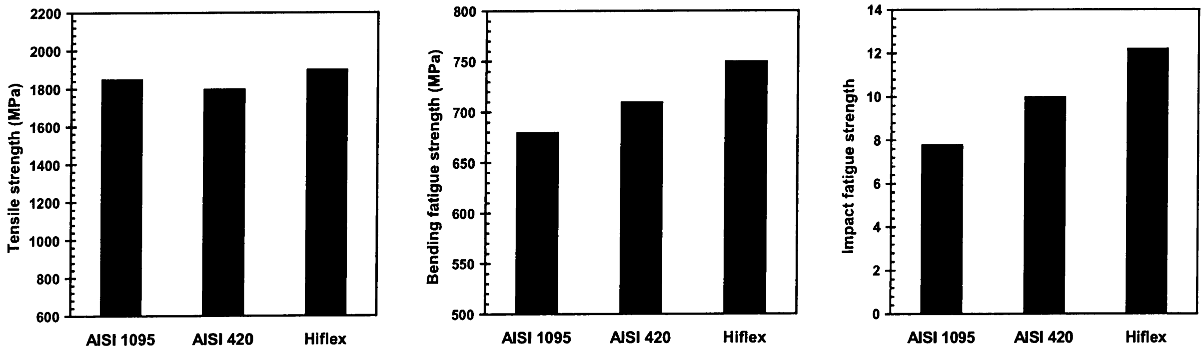

Figure 1: Tensile strength and fatigue strength of flapper valve steel strips.

3. VALVE STRIP WITH HIGH BENDING FATIGUE STRENGTH

Increases in the strength of a metal material generally increase the fatigue cracking resistance. For high strength steels such as flapper valve steels, however, a material with extremely high strength does not mean that its bending fatigue strength is high. Figure 2 shows the correlation between the bending fatigue strength and the tensile strength of AISI 1095 strip. The fatigue strength can decrease with tensile strength when it becomes higher than 1850MPa. This phenomenon was also observed in other high strength alloys. It is generally attributed to the increase in the sensitivity of the stress-raising effect at the material's surface or subsurface defects by increasing the tensile strength (Forrest, 1962). This indicates that a further improvement in bending fatigue strength of a high strength material should reduce or even eliminate the stress-raising effect or stress raisers.

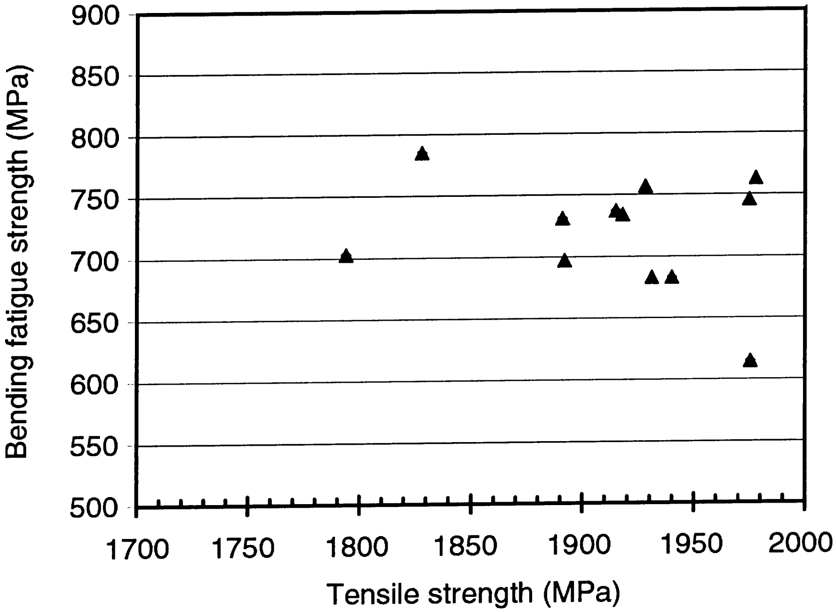

Figure 2: Influence of tensile strength on the bending fatigue strength of AISI 1095 flapper valve steel strip.

3.1 Influence of strength and ductility on the bending fatigue resistance of flapper valve steels

As know, the ductility of high strength steels usually decreases with increasing tensile strength. Consequently, the localised stress concentration around the defects increases due to its reduced capability to promote the localised yielding that can cause blunting of the defect tip and decrease the stress concentration. A high ductility is, therefore, important for high strength steels to obtain high fatigue strength. Figure 3 shows the correlation between the bending fatigue limit and the tensile strength and the ductility (elongation or bendibility) for three flapper valve steels. The following empirical formulas can be obtained:

$$S_b = 0{,}32\sigma_{TS} + kA \tag{1}$$

or

$$S_b = 1{,}56 H_v + 6{,}96L \tag{2}$$

where S_b is the bending fatigue strength, σ_{TS} is the tensile strength, A is the elongation, Hv is the hardness, L is the bendability, and k is the constant between 18,8 to 25,1 depending on the material. k is higher for the material with higher elongation.

Sandvik Hiflex™ shows the highest fatigue limits. This result is expected since Sandvik Hiflex™ shows not only higher tensile strength, but also higher ductility than both AISI 1095 and traditional AISI 420 flapper valve steels (Sandvik, 2003; Auren et al. 2002). It was reported that there is no decrease in the fatigue limit for Sandvik Hiflex™ flapper valve strip, even when its tensile strength is up to about 2000MPa (Auren et al. 2002). The decreases in the stress concentration by local yielding, due to the high ductility of the material, is equal to an increase in overall fatigue crack initiation resistance.

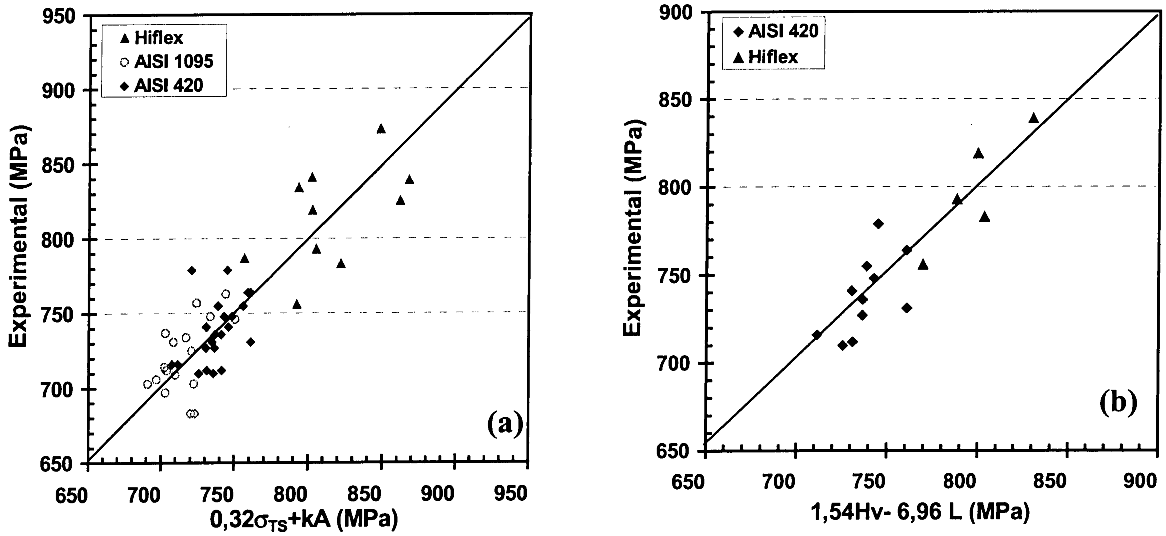

Figure 3: Influence of tensile strength and ductility on the bending fatigue strength of the flapper valve steel strips.

3.2 Influence of surface condition on bending fatigue behaviour

Bending fatigue cracks originate mainly at surface defects where the stresses are highest. Inclusions and mechanical surface defects are the two main sources. Since the purity of modern flapper valve steels is very high, it is very rare that an observed bending fatigue crack originates at a surface or subsurface inclusion. Mechanical surface defects are, therefore, critical to bending fatigue crack initiation. Figure 4 shows examples of surface fatigue crack origins, where the depth of the defects is less than 5μm. This indicates that very small defects, introduced by improper handling, can lead to flapper valve failure.

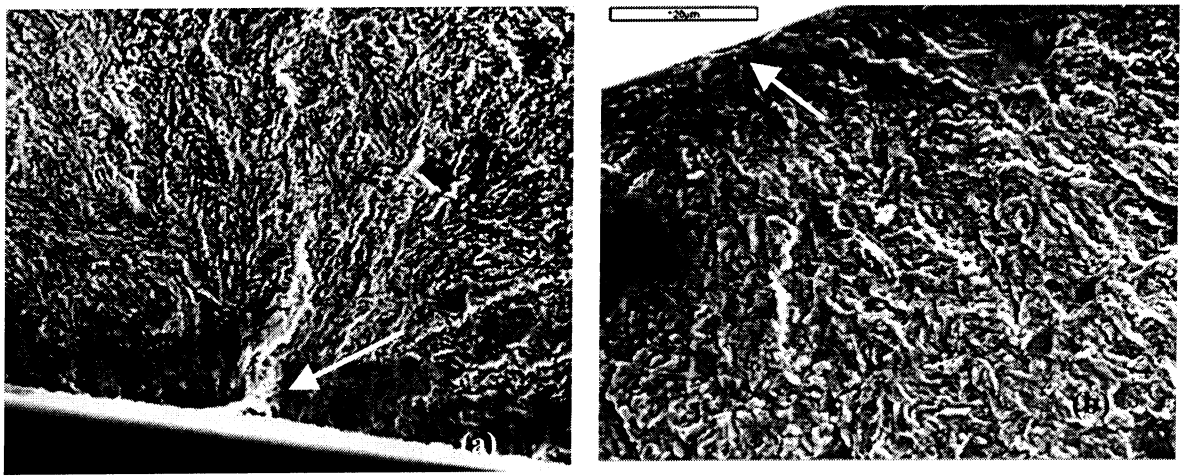

Figure 4: Examples of fatigue crack origins at the surfaces of flapper valve strip material.

3.2.1 Influence of surface treatments on the fatigue properties of flapper valve steels: Surface treatments such as tumbling and shot peening are common methods used for reducing or eliminating surface defects and introducing compressive residual stresses at the surface of flapper valve strips, which can significantly improve the bending fatigue strength (Soedel, 1984; Svenzon, 1976). In fact, tumbling or tumbling and shot peening can also increase the hardness near the surface (about 0,1mm), due to plastic deformation occurring during the surface treatments (Figure 5a). Obviously, this, together with the compressive residual stresses, will make the bending fatigue crack initiation more difficult.

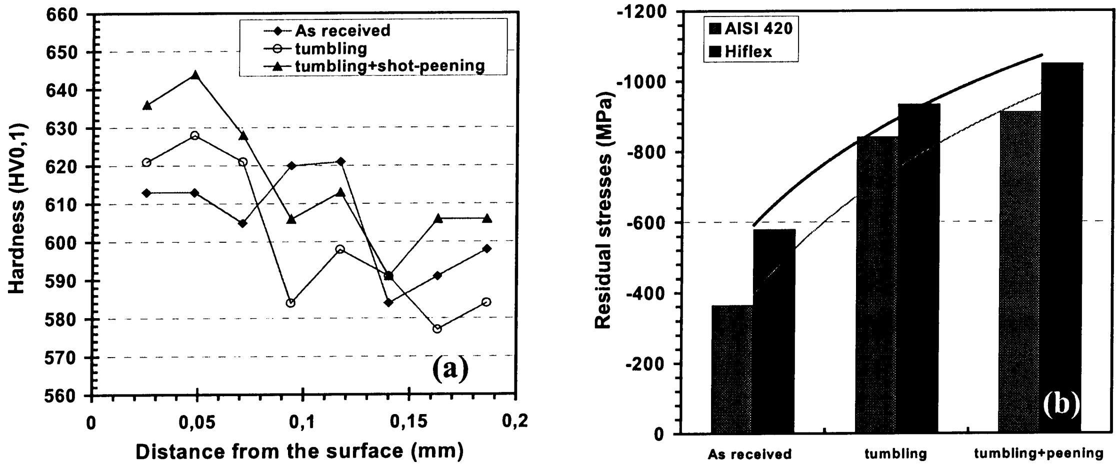

Figure 5: Influence of surface treatments on the hardness (a) and residual stresses (b) in flapper valve steel strip.

It was found that the amount of residual stresses near the surface, introduced by tumbling and shot peening, strongly depends on the type of material and the material conditions. Figure 5b shows a comparison of residual stresses introduced by surface treatments in AISI 420 and Sandvik Hiflex™ flapper valve strip. Although these two materials have similar compositions and Sandvik Hiflex™ also has a higher tensile strength, the compressive residual stresses are higher in the Sandvik Hiflex™ strip than in the AISI 420 strip. Similar results were also observed earlier. The residual stresses in the valve surface after tumbling are higher in the AISI 420 strip than in the AISI 1095 strip (Svenzon, 1976). The ductility of the material is therefore an important factor for high compressive residual stresses.

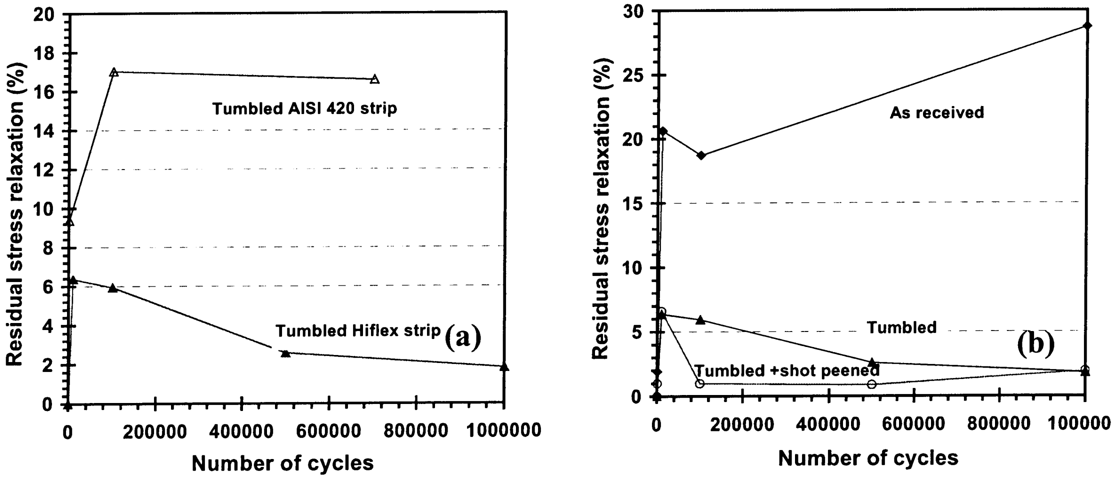

Figure 6: Relaxation of residual stresses in different flapper valve strips (a) and different surface conditions (b).

3.2.3 Relaxation of residual stresses in flapper valve strip during repeated bending: In service, a flapper valve is subjected to alternating bending stresses that cause alternating tensile stresses in the material. This can lead to a reduction of compressive residual stresses by relaxation, and consequently, the bending fatigue strength. However, the relaxation rate of residual stresses also varies with the material and its conditions. Figure 6 shows the influence of number of cycles on the stress relaxation of AISI 420 and Sandvik Hiflex™ flapper valve steels. The stress relaxation rate is lower in the Sandvik Hiflex™ strip than in the AISI 420. For the same material, the stress relaxation rate is lower in the surface treated materials than in the as received material. Obviously, the presence of plastic deformation in the strip can reduce the stress relaxation rate. High compressive residual stresses are equal to enhance the resistance to fatigue crack initiation and propagation.

4. VALVE STRIP WITH HIGH IMPACT FATIGUE STRENGTH

4.1 Impact fatigue fracture mechanism

A typical cause of fracture in a flapper valve is "edge chipping" due to repeated impact loading, during which small fragments are torn off the edge (Soedel, 1984; Svenzon, 1976). Although much work has been done to find the crack initiation and propagation process, the mechanisms for edge chipping are still not fully understood. Recently, an explanation based on the experimental observations and the dynamic stress wave theory was proposed (Chai et al., 2002).

Crack initiation starts near the impact area (Figure 5a) or in a zone between the impact area and the specimen edge, due to localised damage by oblique impact. The crack propagates in the longitudinal direction first, but soon becomes unstable (or new cracks have initiated) due to the effect of Rayleigh waves. Then the crack propagates, not 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 stresses. Since the shear stress wave decays more quickly, the cracks will then propagate more radially with increasing wave travel distance, until they reach the edge of the specimen where edge chipping occurs (Figure 5b).

Since both the tension stress wave and the shear stress wave are generated at the front of the impact area, and each type of wave moves with the same velocity, the instantaneous energy input from each impact is always in the same phase. This indicates that dynamic stress concentrations can be formed in certain wave travel distances, which can initiate higher order cracks, as shown in Figure 5c. This observation can be compared with an earlier FEM simulation by Soedel (1984). These analyse indicate that a material with high impact fatigue strength should have:

1). High resistance to crack initiation and propagation by repeated impact loading

2). High stress decay rate with stress wave travelling so that the crack propagation becomes difficult.

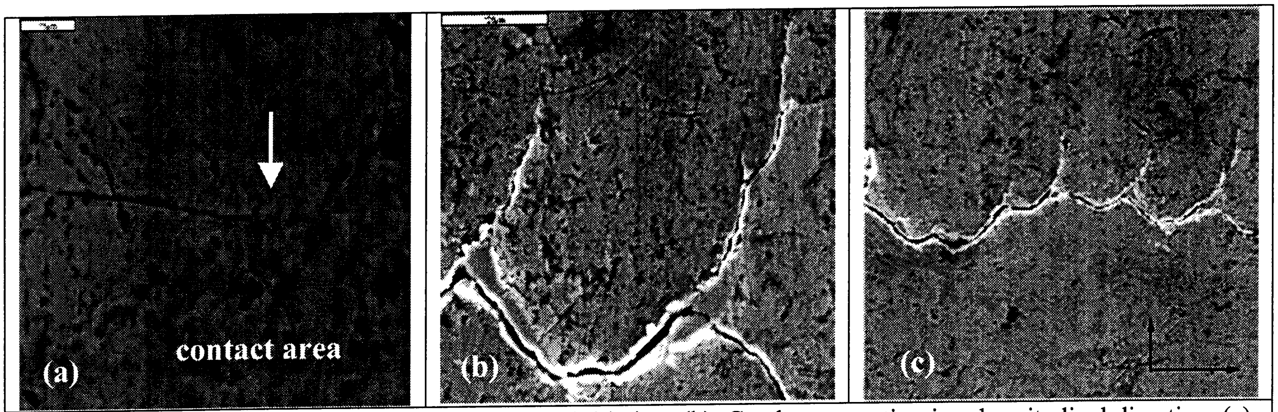

Figure 7: Formation of "edge chipping", (a). Crack initiation, (b). Crack propagation in a longitudinal direction, (c). Crack propagation in a transversal direction.

4.2 Parameters affecting the impact fatigue resistance of flapper valve steels

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 that propagate away as elastic waves at high speed through the specimen. The initial transformed stress can be:

$$\sigma_o = v_o\sqrt{E\rho} \tag{3}$$

where σ_0 is the initial induced stress, v_o is the impact velocity, ρ is the density of the strip, and E is the modulus of elasticity. This equation shows that high initial tensile and shear stresses at the impact area can be created by high impact velocity. A high performance flapper valve should, therefore, have high impact fatigue cracking resistance.

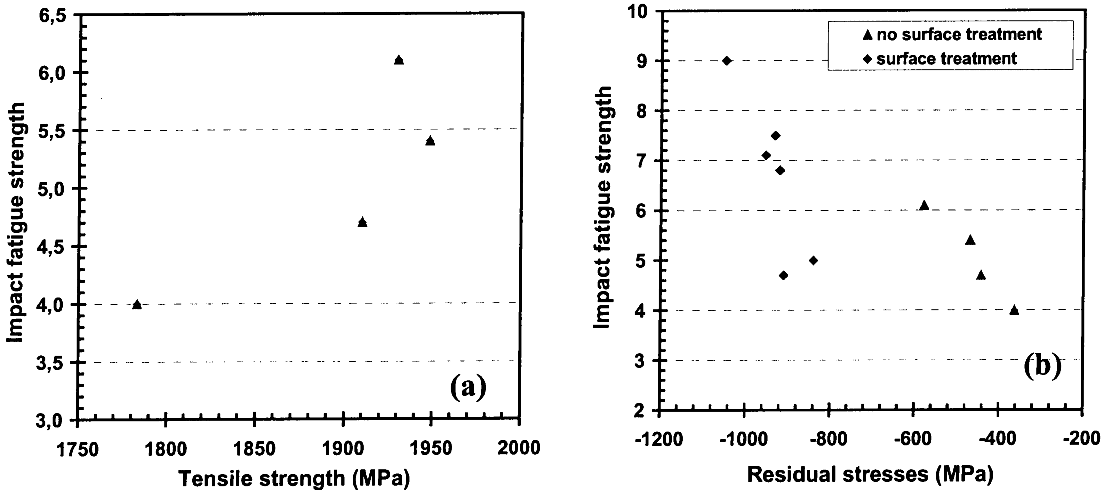

Figure 8: Influence of tensile strength and residual stresses on the impact fatigue strength of the AISI 420 type of flapper valve strip.

According to Eq. 3, an increase in tensile strength of the material seems to improve its impact fatigue properties. However, this correlation is not distinct. Figure 8a shows the correlation between the tensile strength and impact fatigue strength for the AISI 420 type of flapper valve strip. Similar results were reported for the AISI 1095 type of flapper valve strip. Impact fatigue strength is not dependent on the tensile strength (Svenzon 1976).

Surface treatments have a great influence on the impact fatigue strength (Svenzon, 1976, Auren et al., 2002). However, the investigation on the surface roughness of AISI 1095 strip material, introduced by polishing, coarse grinding, shot peening, eletrolytical polishing and tumbling, shows that surface roughness has only a moderate effect on the impact fatigue strength. However, the residual stresses introduced by the surface treatments have a significant effect on the impact fatigue strength. Figure 8b shows the influence of residual stresses on the impact fatigue strength of AISI 420 type strip materials (Auren et al., 2002). The compressive residual stresses, introduced by the surface treatments, will compensate the tensile stresses introduced by impact, as shown in Eq. 3. The hardness increment near the surface created by the surface treatments can also increase the resistance to the impact crack initiation. Furthermore, it was found that the relaxation of residual stresses during impact fatigue testing is small.

4.2 Influence of damping capacity of flapper valve steels on the impact fatigue strength

As mentioned earlier, the impact stresses propagate in waveforms in both longitudinal and transversal directions. However, the stress amplitude will gradually decrease due to damping:

$$\sigma = \sigma_o e^{-LA\sqrt{E\rho}/MCi} \tag{4}$$

and

$$C_1 = \sqrt{E/\rho}\,;\ \ C_2 = \sqrt{G/\rho} \tag{5}$$

where σ is the stress at a wave travel distance L, C_1 and C_2 are the velocities of the longitudinal waves and the shear waves, G is the shear modulus, M is the mass and A is the impact area. 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. Obviously, the stress decay rate strongly depends on the damping capacity of the material. The influence of material parameters on its damping capacity is not well understood. Recently, the influence of damping capacity on the impact fatigue strength was investigated by using materials with similar elastic modulus and density, but different damping capacities. The results show that high damping capacities can lead to high impact fatigue strengths (Figure 9a) (Auren, 2002). It was explained that the stress waves decay more quickly in the material with higher damping capacity, which lowers the induced peak stress, and consequently reduces the risk for both high order crack initiation and propagation. This increases the impact fatigue strength. It was also found that the damping capacity varies with the material (Figure 9b). Sandvik Hiflex™ shows the highest damping capacity, which is one of the reasons for the highest impact fatigue strength among these flapper valve materials.

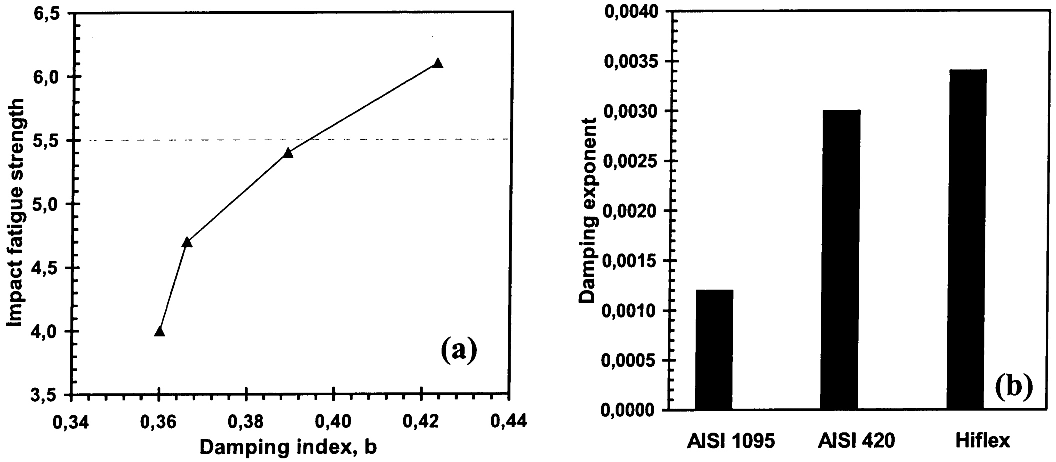

Figure 9: Influence of damping capacity and material on the impact fatigue strength of the flapper valve strips.

6. CONCLUSIONS

A flapper valve steel with high bending fatigue strength should have a high tensile strength with high ductility. The surface after surface treatments should show a very good finish and high compressive residual stresses with a low stress relaxation rate.

A flapper valve steel with high impact fatigue strength should have a high tensile strength with high ductility and high damping capacity. The surface can be treated with high compressive residual stresses.

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