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SELECTION OF FLAPPER VALVE STEEL FOR HIGH EFFICIENT COMPRESSOR

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ABSTRACT

Due to the environmental, energy saving and economic requirements, development of very high efficient compressors is of great importance. Consequently, flapper valve material becomes a critical issue and a limiting factor for the development of compressor. This paper provides a discussion on the material selection of the flapper valve for the compressors with very high efficiency, based mainly on a basic research on the mechanisms of impact fatigue and a finite element method (FEM) simulation on the formation of stress concentration in the flapper valve during the impact process. Impact fatigue initiation is caused by the initial impact stress, but the fatigue crack propagation is caused by a wavy stress propagation. This causes the formation of secondary cracks at the stress concentration points where two stress waves have the same phase. The results indicate that the flapper valve materials for the very high efficient compressors should have both high impact fatigue strength for the initial stress, and high stress damping capacity to reduce the crack propagation rate. Most recent developed flapper valve steel, Sandvik Hiflex™, shows both higher impact fatigue strength and higher damping capacity comparing with other commercial flapper valve steels available. This flapper valve steel material has successfully been used in the newly developed high efficient compressors. Some case stories have been discussed.

1. 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 when small fragments are torn off from the edges, which is usually termed as edge chipping (Soedel, 1984; Svenzon, 1976; Dhar, 1988). 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 (Svenzon, 1976; Dhar, 1988). The earlier work considered that edge shipping occurs when two cracks propagate close to each other (Svenzon, 1976). 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. 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 and Chai, 2002).

2. STRESSS CONDITIONS IN FLAPPER VALVES DURING IMPACT

In order to analyze the formation of stress in the flapper valve during the impact, a FEM was done using a simulated flapper valve movement. All simulations were performed in the FE software MSC. Marc 2011r1. The impact stresses from the impact with the cast iron seat was sought. The stress distribution induced from the impact, on the cast iron seat, had stress components from all three directions with equal magnitudes and therefore a 3D-model was used for the simulation. As for element type, 8-noded solid elements were used. The flapper valve had five elements in the thickness direction, which gave a smooth change in stress values through the thickness direction. The table that the flapper valve hit against had to be able to deform in order to get correct values of stress in the flapper valve. Thus, the table was also meshed as a deformable body made of 8-noded solid elements. The largest stresses in the flapper valve, however, occurred at the circular part, which made it possible to simplify the table. Only the circular part of the table had to be deformable and the rest could be created as a rigid body. The flapper valve moved with different velocities in the simulations and therefore a dynamic transient analysis had to be used.

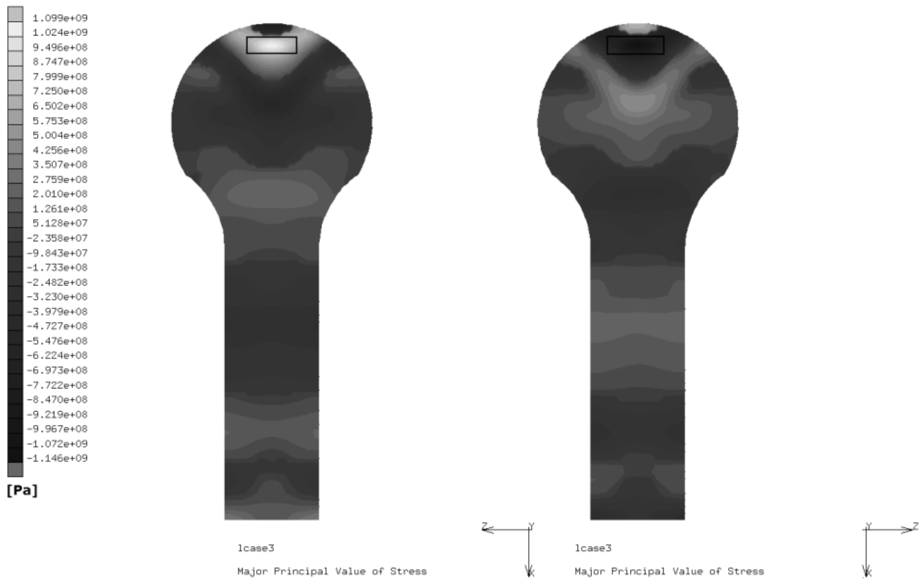

Figure 1: The left and right picture shows the top and bottom of the flapper valve, respectively. Both pictures were taken at a time where the maximum tensile – and compressive stresses occurred. The figures are from a 80 Hz case.

The maximum tensile- and compressive stresses where located at the top and bottom of the flapper valve, which can be seen in Figure 1. The extreme values are within the rectangular area on the upper part of each corresponding valve. The maximum stresses were in the elastic region of the material. It should be mentioned that damping was not taken into account for this simulation. This is because the Rayleigh damping coefficients were not known. If damping would have been introduced the tensile stresses induced by the impact would be smaller as the stress wave would be damped to a greater extend. The impact velocity of the flapper valve was around 7.7 ms^{-1} in this case. The physical properties of the flapper valve material used in the simulation can be seen in Table 1.

Table 1: Physical properties of the flapper valve steel.

Physical property	Value
Young's modulus, E [GPa]	210
Poisson's ratio, ν	0.3
Density, ρ [$kg \cdot m^{-3}$]	7700

3. IMPACT FRACTURE MECHANISM

3.1 Impact induced stresses

At the impact of a compressor valve specimen against the seat, high compressive stresses are formed in the seat as well as in the valve impact area. The formed stresses, located at the surface, are transformed into shear and tensile stresses and will be transported through the material as elastic waves. This can be expressed by (Dhar, 1988):

$$\sigma_o = v_o \sqrt{E\rho} \tag{1}$$

As a consequence of damping properties, the stress levels will decay as the waves propagate through the material:

$$\sigma = \sigma_0 e^{-tA\sqrt{E\rho}/M} \tag{2}$$

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

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 (Soedel, 1984). The velocities of longitudinal (tension) waves and shear waves in a solid are (Timoshenko, 1955; Kolsky, 1962):

$$C_1 = \sqrt{E/\rho}\,;\ C_2 = \sqrt{G/\rho}\,;\ \text{and}\ t = \frac{L}{Ci} \tag{3}$$

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 Equation 3 into Equation 2, we get:

$$\sigma = \sigma_0 e^{-LA\sqrt{E\rho}/MCi} \tag{4}$$

$$Tan(\alpha) = \frac{\sigma_{Tensile}}{\sigma_{Shear}} \tag{5}$$

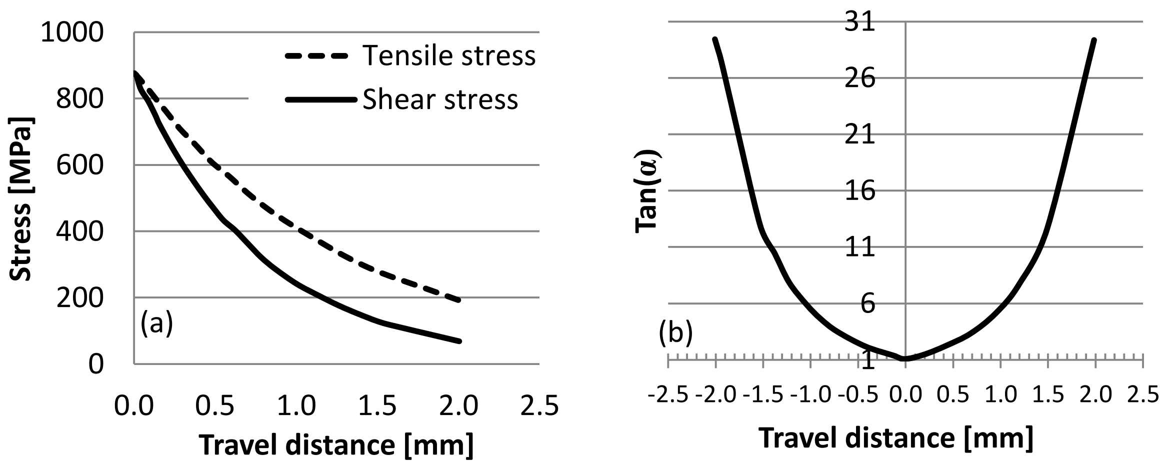

Figure 2: Stress initiation and travel during impact, (a). The tensile or shear stress versus travel distance, (b). A combination effect of the tensile stress and shear stress.

Equation 3 and Equation 4 show that both longitudinal (tensile) stress and shear stress decay with increasing wave travel distance, and the shear stress decays faster than the tension stress. Figure 2a shows the decay of the tensile stress and shear with stress travel distance during the impact. The shear stress decays faster than the tensile stress. Equation 5 shows a combination effect of the tensile stress and shear stress. Figure 2b shows the combination effect of Tan (α) versus travel distance, which shows an U type of curve.

3.2 Fracture mechanism

Edge chipping is a type of fracture commonly observed in the early stage of failure (Chai, Sandberg, 2002). To study the impact fracture mechanism, the fractures of the impact fatigue tested specimens were carefully investigated. In the early stage of impact fatigue, fatigue crack initiation can be observed as shown in Figure 3a. It started at the edge of impact area, and propagated towards the edge of the specimen. This crack split then into two cracks, but they still propagated towards the edge of the specimen (Figure 3b), and finally formed chipping (Figure 3c), which has the similar form as Figure 2b.

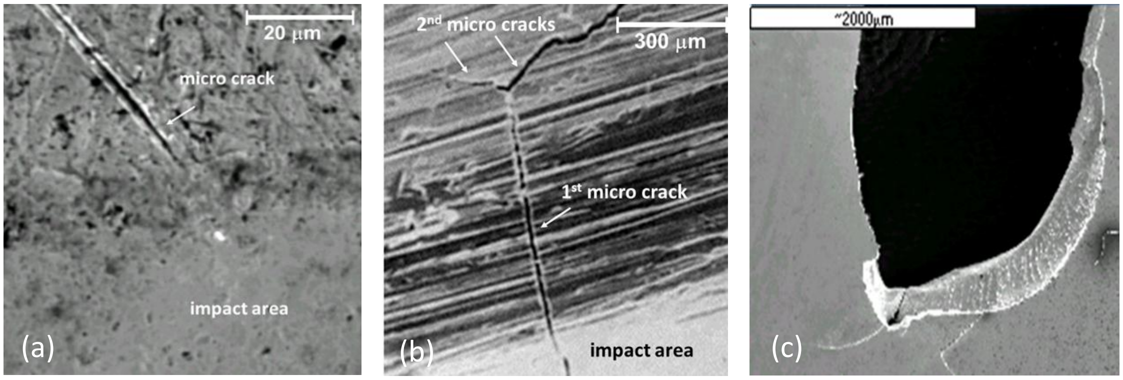

Figure 3: Fatigue crack initiation and propagation during impact, (a). Crack initiation, (b). Split of main crack, (c). Formation of chipping.

It was also observed that the cracks could propagate in the wave form in both radial and transversal directions (Figure 4a and b). At these crack wave peaks, high order cracks have been initiated. These high order cracks propagated towards the edge of the specimen and formed new small chippings.

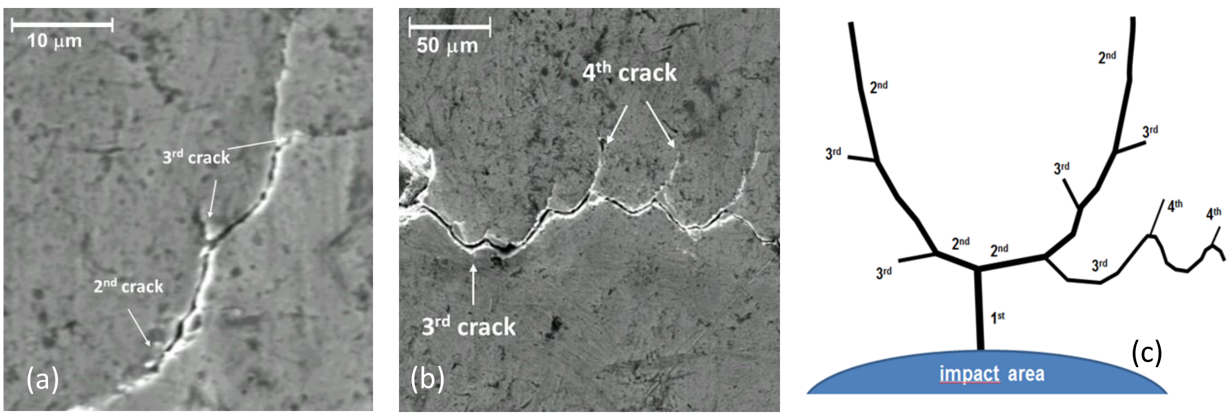

Figure 4: Crack propagation in wave form, (a). Along radial direction, (b). Along transversal direction, (c). A fracture model based on dynamic stress wave theory (Chai, Sandberg, 2002).

Based on the above analysis, an impact fracture mechanism using dynamic stress wave theory was proposed as discussed earlier (Chai, Sandberg, 2002) (Figure 4c).

a). Repeated impacts cause crack initiation at the edge of impact area and leads to the main crack that propagates towards the edge of the specimen. Localized damage by oblique impact (Svenzon, 1976; Dhar, 1988) is one of the main reasons.

b). This main crack (1st crack) propagates unstably due to the effect of Rayleigh waves (Soedel, 1984), and can split into two cracks, which propagate towards 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 as discussed in the previous chapter and shown in Figure 2b, and finally form a chipping as shown Figure 3c.

c). Since both the tensile stress and shear stress propagate in the wave forms, the repeated impacts with same wave velocity and same phase will cause the formation of stress leaks in certain wave travel distances. This can form dynamic stress concentrations, which will consequently cause the initiation of higher order cracks. This successive crack initiation and propagation process lead to the impact fracture with a waveform.

This analysis indicates that a material with high impact fatigue strength should have:

1). High resistance to crack initiations and propagations by repeated impact loading
2). High stress decay rate to stress wave travelling so that the crack propagation becomes difficult.

4. HIFLEX - A HIGH PERFORMANCE FLAPPER VALVE STEEL

The recent developed material for valves in high efficient compressors is Sandvik Hiflex™, which is an additionally modified AISI type of martensitic stainless chromium steel and in table 2 the nominal chemical composition is shown (Sandvik, 2014).

Table 2: Nominal chemical compositions of Sandvik Hiflex™ flapper valve steel (wt%)

Material	C	Si	Mn	P (max)	S (max)	Cr	Mo
Hiflex	0.38	0.40	0.55	≤0.020	≤0.010	13.5	1.0

As known, 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.

In Figure 5, (Chai et al., 2004) the tensile strength, impact fatigue strength and bending fatigue strength are shown for the different flapper valve material Sandvik 20C (below denoted AISI 1095), Sandvik 7C27Mo2 (below denoted modified AISI 420) and Sandvik Hiflex™, where the latter exhibits the highest values for all three properties. The material is, therefore, suitable in environments with high pressures or high valve lifts, and in addition an increased protection against corrosion is given.

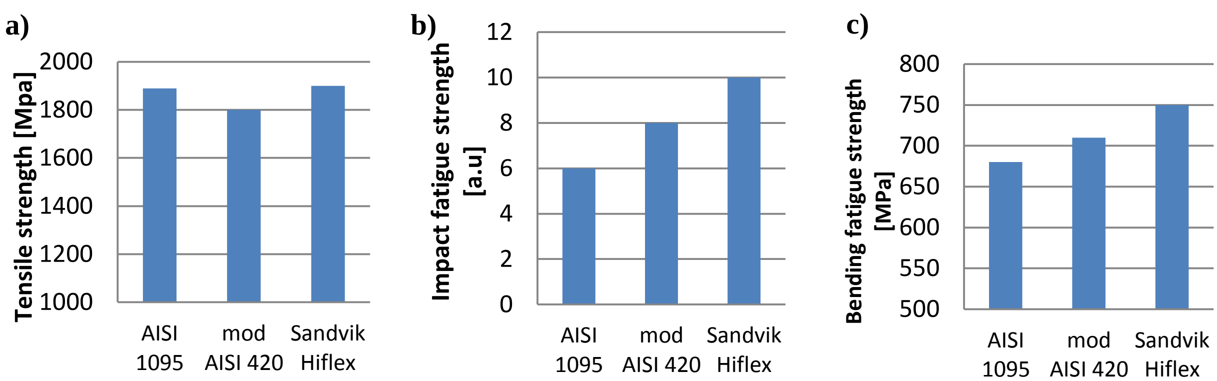

Figure 5: Comparison of tensile strength (a), impact fatigue strength (b) and bending fatigue strength (c) of flapper valve steel strips: AISI 1095, modified AISI 420 and Sandvik Hiflex.

The Figure 6a (Chai et al., 2004) shows the combined effect of tensile strength σ_{TS}, elongation A and constant k (between 18.8 and 25.1 depending on material) on the bending fatigue strength of flapper valve steels. A straight line can be fitted to the data and Sandvik Hiflex represents the right upper set of data (non – filled triangles) due to both higher ductility and higher tensile strength.

As formulated in Equation 1, the impact fatigue properties increase with increased tensile strength. Experimental data thereof is shown in Figure 6b (Chai et al., 2004) for modified AISI 420 – type of material, however tensile strength is not the only property to influence the impact fatigue strength. Similar results were shown by Svenzon for AISI 1095 type of material (Svenzon, 1976).

At the impact of the flapper valve to the seat, compressive stresses are induced within the impact area. These stresses are transformed into wave forms in longitudinal and transverse directions. Due to damping the amplitude will decay with increasing distance of travel, as described in Equation 3 and 4. The decay rate of the stress waves is strongly dependent on the damping capacity of the material. The materials properties influence on the materials damping is still not fully understood. Investigations on impact fatigue properties are performed on materials with similar properties in respect of density and elastic modulus but with different damping. In Figure 7a, the impact fatigue versus damping is shown (Auren, Chai, 2002). Figure 7b present, the damping index of three different flapper valve steels (Chai et al., 2004). The highest damping index and impact fatigue strength of these materials is found for the Sandvik Hiflex.

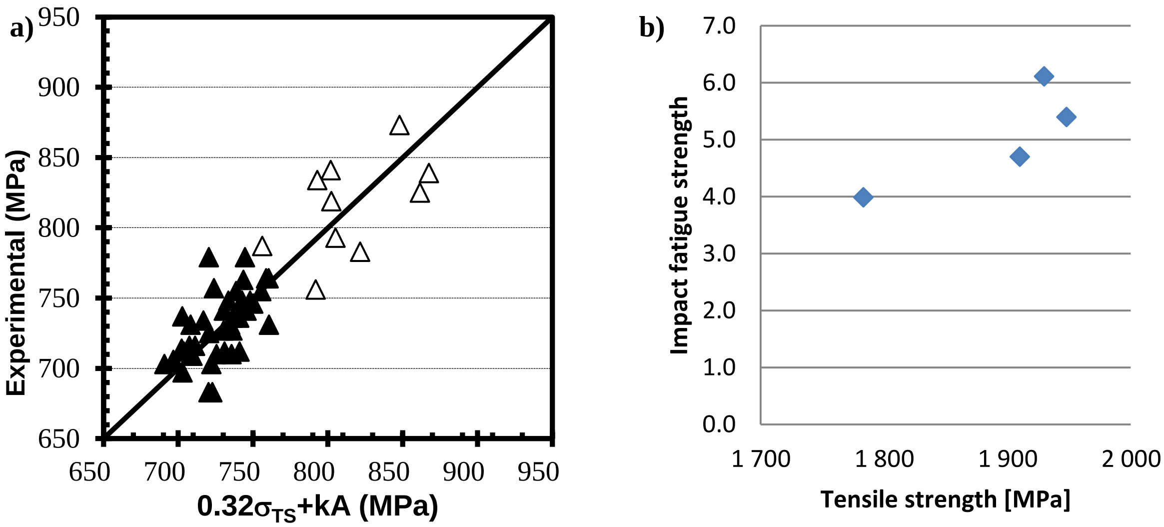

Figure 6: (a). Bending fatigue strength of the flapper valve steel strips versus tensile strength σ_{TS} and ductility/elongation A (k is the constant between 18.8 to 25.1 depending on the material) (b). Impact fatigue strength versus tensile strength for the modified AISI 420 type of flapper valve strip.

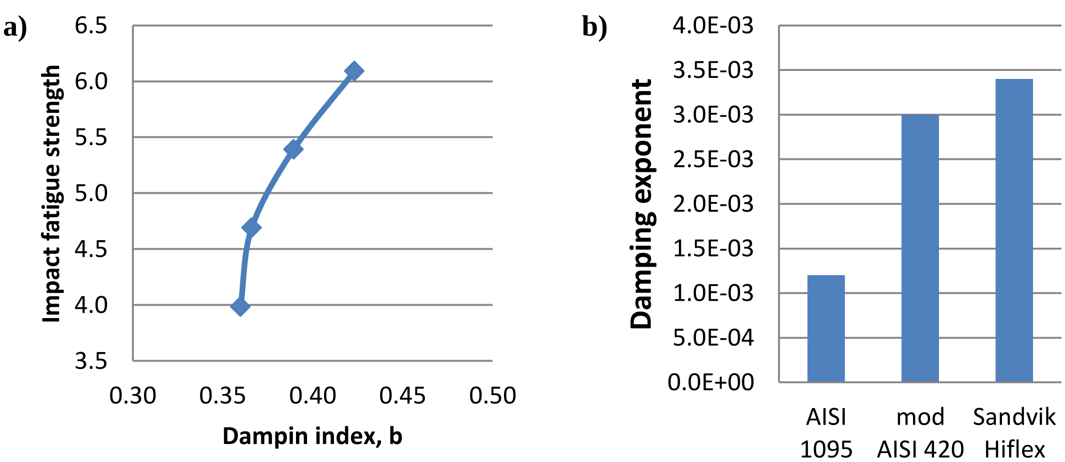

Figure 7: a) Influence of damping capacity and material on the impact fatigue strength of the flapper valve strips. b) Damping exponent for the different material AISI 1095, modified AISI 420 and Sandvik Hiflex™

5. CASE STUDIES

The strive towards more environmental friendly and efficient compressors leads to increased demands on the ingoing parts in a compressors. Since the flapper valve properties are essential for the performance and durability of the compressor this implies also new requirements for the flapper valve. A number of new operating conditions that flapper valves will have to handle are

- Higher pressure
- Higher temperature
- Higher operating frequency
- Higher discharge volume
- Higher valve lift
- Reduced thickness
- Reduced valve length
- Less noise

In Figure 8a an overview of how the coefficient of performance (COP) is affected by increased valve lift. The COP increases with increasing valve lift due to the reduced losses around the valve and in Figure 8b the difference is shown, for a compressor working with R22 –refrigerant, more specifically for valve lift 1.97 and 2.8 mm, respectively.

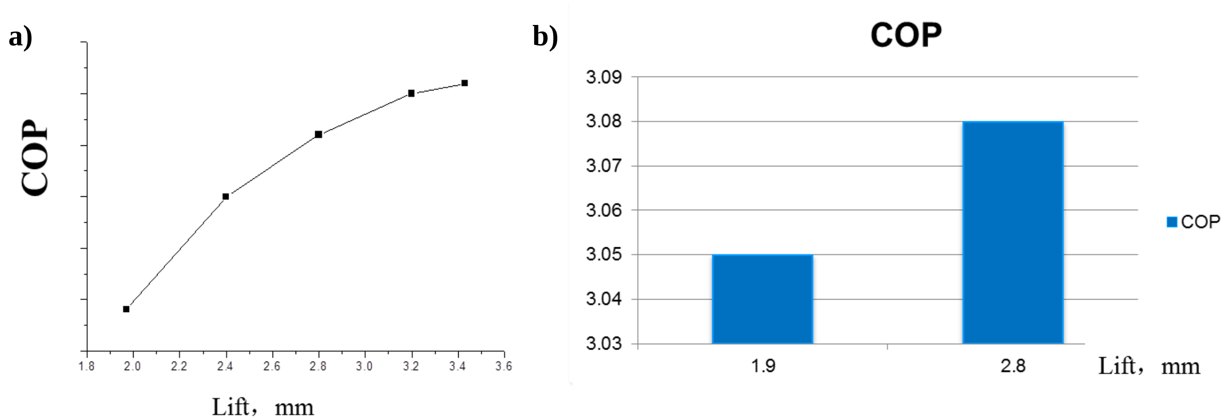

Figure 8: In a) an overview of COP as a function of valve lift is shown. In b) the specific difference in COP as the valve lift is increased from 1.97 mm to 2.8 mm in a medium of R22.

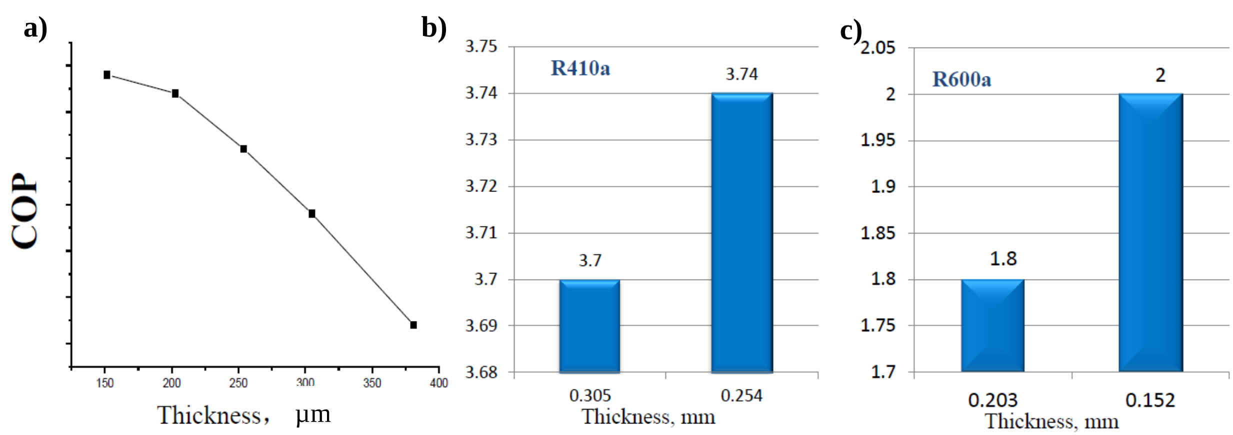

Figure 9: In a) an overview of COP as a function of valve thickness is shown. In b) and c) the specific difference in COP as the valve thickness is reduced for the different media R410a and R600a, respectively.

In Figure 9a an overview of the COP as a function of valve thickness is shown. The COP is increased as thickness is reduced. In Figure 9b and c the differences for different thicknesses in R140a and R600a are shown, respectively.

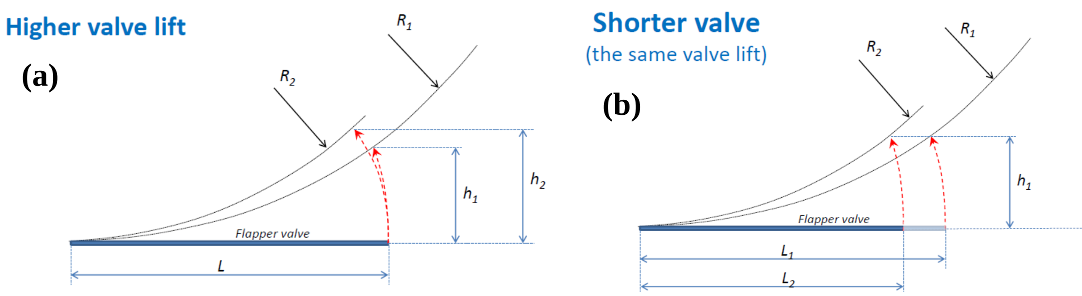

Figure 10: The a) higher valve lift and b) shorter valve lengths will result in higher bending stress as well as higher impact speed.

Figure 11: a) A failed valve in modified AISI 420. b) A well-functioning valve in Sandvik Hiflex™.

Refrigerant: R410a		
P_d P_s	3.40 MPa 0.55 MPa	3.40 MPa 0.55 MPa
Operating frequency	120 Hz	180 Hz
Discharge volume	80 cc	80 cc

Figure 12: Two different operating condition in a compressor with AISI 420 type of material in respect of discharge pressure P_d, suction pressure P_s, operating frequency and discharge volume, respectively

Efforts with the tougher operating conditions have been made with traditional flapper valve steel materials, but too often resulting in failure of the valve. As illustrated in Figure 10 higher valve lift or shorter valve lengths will cause higher bending stress levels as well as higher impact levels. In Figure 11 typical image of a) a failed valve with a modified AISI 420 type of material and b) a well-functioning valve. In Figure 12 two cases with tougher operating criteria (with refrigerant R410a) with modified AISI 420 material is shown.

In addition, Sandvik Hiflex™ has shown to be very responsive towards tumbling and shot peening compared to both AISI 1095 and modified AISI 420. This means beneficial residual compressive stress can be introduced to the flapper valve surfaces (Chai et al, 2004). This is a very important property to withstand the arisen impact stress levels and is together with the superior bending and impact fatigue levels as well as elevated damping properties a major advantage towards modified AISI 420. A consequence of these properties is that compressors employing Sandvik Hiflex can handle the tougher conditions where modified AISI 420 cannot. The capability to damp out the introduced stress waves upon impact are crucial for well –functioning flapper valves in high demanding compressors. Good durability is obtained as the flapper valve material is replaced from modified AISI 420 to Sandvik Hiflex.

6. CONCLUSIONS

The stresses that cause the fatigue damage or fracture are the tensile stress wave and shear stress wave induced by repeated impact loading. 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.

A flapper valve material with high performance or fatigue strength should have; high resistance to crack initiations and propagations by repeated impact loading and high stress decay rate with stress wave travelling so that the crack propagation becomes difficult.

Sandvik Hiflex™ shows high tensile strength, high bending and impact fatigue strength and high damping capacity, which shows excellent performance in the newly developed high efficient compressors.

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