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MODULUS OF ELASTICITY AND ITS INFLUENCE ON THE PERFORMANCE OF FLAPPER VALVE MATERIALS

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ABSTRACT

Modulus of elasticity of flapper valve material is an important parameter for compressor design since it can affect efficiency and life time of the compressor. Modulus of elasticity is usually considered as a material constant. Actually, it can vary with material orientations and conditions and even environments such as temperature will also affect this value. Therefore, the parameters that can affect the modulus of elasticity of flapper valve material have been concerned. This paper provides an investigation on the parameters that may affect the modulus of elasticity and also the fatigue properties of the flapper valve materials. The results show that the modulus of elasticity of flapper valve material can vary with the orientation of the sample due to the presence of texture in the material. This variation is also different between different materials such as AISI 1095 and AISI 420. For AISI 1095, the modulus of elasticity increases slightly when increasing the angle to the rolling direction. For AISI 420, the modulus of elasticity is higher at 0° and 90º to the rolling direction, and lowest at 45º to the rolling direction. The heat treatment such as tempering can also affect the modulus of elasticity, but not significant. Surface treatment such as tumbling and cyclic loading also have a small influence on the modulus of elasticity. Cold rolled strip has lowest modulus of elasticity and highest anisotropy. Increase in temperature decreases the modulus of elasticity. Increase in modulus of elasticity will increase the initial impact stress. Therefore, the impact fatigue strength of the flapper valve steel is related to both the tensile strength and the E-modulus. For bending fatigue, the fatigue strength is however mainly related to the tensile strength and the ductility of the material.

1. INTRODUCTION

As known, a flapper valve will undergo high frequency bending and impact stresses during its service (Soedel, 1984). The bending stress in the flapper valve depends on the maximum bending strain at the outside fibre of the strip and the modulus of elasticity. For a given bending strain, the material with higher modulus of elasticity can suffer from a higher bending stress.

When a flapper valve 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 speeds through the specimen. The initial transformed stress is as follows (Timoshenko, 1955; Soedel, 1984):

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

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

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

where σ_o and σ are the initial and damped stresses, v_o is the setting 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.

Equations 1 and 2 show that the modulus of elasticity of a flapper valve affects not only the initial stress, which causes the crack initiation, but also the damped stresses, which cause the crack propagation.

Modulus of elasticity is the ratio of the stress applied to a body to the strain produced. It is also called Young's modulus, named after the British physicist Thomas Young. Modulus of elasticity is generally believed to be a material constant. The influences of other parameters such as alloying elements and plastic deformation have been believed to be comparatively small. For example, the modulus of elasticity of a number of steels often found in literature is 210GPa. Elasticity in the nature is the property that enables certain materials to return to their original dimensions after an applied stress has been removed. On an atomic scale, however, macroscopic elastic strain is manifested as small changes in the interatomic spacing and stretching of interatomic bonds. Different metals have different crystal structures with different interatomic spacing and bonding forces. This indicates that different metals with different crystal structures can have different modulus of elasticity. Hence, the factors that affect the interatomic spacing and forces between atomic bands will also affect the modulus of elasticity of metals. Temperature, texture and cold working etc are the most common factors that can strongly affect modulus of elasticity of the material.

Martensitic carbon steel (AISI 1095) and martensitic stainless steel (AISI 420) are two commonly used flapper valve steels. They usually have a microstructure of martensitic phase together with small carbides in the as tempered conditions. The flapper valves are also surface treated by tumbling or shot peening. During service, flapper valves are subjected to cyclic loading. For flapper valve design or flapper valve performance, the influences of the production process, flapper valve manufacturing process and service are concerned.

In this investigation, the parameters that affect modulus of elasticity of flapper valve are discussed. It mainly focuses on the influence of texture in the strip, cold working, tempering process, tumbling and cyclic loading on the modulus of elasticity of the strip.

2. MATERIALS AND EXPERIMENTAL

2.1 Materials

The materials used are three flapper valve grades shown in Table 1. Both AISI 1095 and AISI 420 strip materials have high tensile strength and high fatigue strengths under bending and impact stress conditions (Sandvik, 2003). Modified AISI 420 type materials, especially Sandvik Hiflex™, show higher fatigue strength than AISI 1095 (Sandvik, 2004), 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 (Sandvik, 2004).

Table 1: Flapper valve grades

Materials	**Grades**	**C**	**Si**	**Mn**	**Cr**	**Mo**
AISI 1095	Sandvik 20C	1.00	0.3	0.4		
AISI 420 mod	Sandvik 7C27Mo2 Sandvik Hiflex™	0.38	0.4	0.6	13.5	1.0

2.2 Experimental

The modulus of elasticity is determined using a mechanical method with tensile stress, and evaluated using a software: Inersjö-Cyclic version. The strips used mainly have a thickness of 0,305mm. The followings are the testing matrixes.

2.2.1 Influence of tempering process on the modulus of elasticity: Table 2 shows the testing matrix for the influence of tempering process on the modulus of elasticity. The normal hardened and tempered state is used for flapper valves, named H/T in Table 2. The cold rolled material has a microstructure of ferrite together with carbides. By hardening and tempering, the hardness of the cold rolled material is increased. In order to see how tempering process affects the modulus of elasticity, some extra tempering have been done as shown in Table 2. In Table 2, A = 550°C for 5 minutes, B= 610°C for 5 minutes, C=700°C for 5 minutes for 7C27Mo2; and for 20C, A = 420°C for 5 minutes, B= 530°C for 5 minutes, C=600°C for 5 minutes

Table 2: Testing matrix for influence of tempering

Rolling direction	**Condition**	**20C**	**7C27Mo2**	**Hiflex**
Along	H/T	x	x	x
Along	H/T + Temp A	x	x	x
Along	H/T + Temp B	x	x	x
Along	H/T + Temp C	x	x	x
Along	Cold rolled	x	x	x
Along	Cold rolled + Temp C	x	x	x
Across	H/T	x	x	x
Across	H/T + temp A	x	x	x
Across	H/T + Temp B	x	x	x
Across	H/T + Temp C	x	x	x
Across	Cold rolled	x	x	x
Across	Cold rolled + Temp C	x	x	x

Along: parallel to the rolling direction; Across: vertical to the rolling direction.

2.2.2 Influence of material orientation or texture on the modulus of elasticity: A flapper valve may consist of several tongues with different orientations. These tongues can have similar cyclic impact and bending stresses simultaneously during service. In the flapper valve design, it is therefore important to know the modulus of elasticity of flapper valve strips in all orientations. The specimens with five orientations: 0º, 30º, 45º, 60º and 90º to the rolling direction were taken from the strips of AISI 1095 and AISI 420 mod flapper valve steels.

2.2.3 Influence of temperature on the modulus of elasticity: The flapper valve for carbon dioxide compressors for automotive air conditioning can undergo high temperature. Therefore, the modulus of elasticity at 20°C, 100°C, 200°C and 300°C was evaluated.

2.2.4 Influence of cyclic loading on the modulus of elasticity: The specimens were cyclic loaded first according to Table 3, and then the modulus of elasticity of the specimen was determined at room temperature (RT).

Table 3: Cyclic loading

Loading	**Number of cycles**
600±600	$>10^7$
640±640	$>2\text{x}10^6$
680±680	>500

2.2.5 Influence of cyclic loading on the modulus of elasticity: In order to investigate the influence of surface treatment such as tumbling and shot peening on the modulus of elasticity, a test matrix as shown in Table 4 was arranged. The modulus of elasticity of the flapper valve strips in the as delivered condition, surface treated condition and then fatigue tested condition (near fatigue limit for $2\text{x}10^6$ cycles) was determined.

Table 4: Surface treatment

Materials	**Treatment**	**Materials**	**Treatment**
7C27Mo2	no	Hiflex	no
7C27Mo2	tumbling	Hiflex	Heavy shot peening
7C27Mo2	Tumbling+fatigue	Hiflex	Heavy shot peening+fatigue

3. RESULTS AND DISCUSSION

3.1 Influence of Tempering Process on the Modulus of Elasticity

Table 5 shows a summary of how extra tempering influences the modulus of elasticity of the three mostly used flapper valve steel strips. The strips in H/T condition are the same to that in as delivered condition. By considering the standard deviation, the differences in the modulus of elasticity of these three flapper valve steel strips are relatively small. However, they show differences in the anisotropy of the modulus of elasticity (the ratio of the modulus of elasticity in the rolling direction to that in the transversal direction). 20C has a higher anisotropy than the others. The anisotropy in the 7C27Mo2 strip is relatively small. The extra tempering can change the modulus of elasticity depending on the material. For 20C, the modulus of elasticity of the material can be decreased 5% by en extra tempering. For 7C27Mo2 and Hiflex, the modulus of elasticity slightly decreases with increased tempering temperature, but the influence of en extra tempering is small. The above discussion indicates that tempering may change the modulus of elasticity of flapper valve strip materials, but the change is not significant.

Since tumbling or shot peening can introduce some plastic deformation at the surface of flapper valve strip, cold rolled or cold rolled and then tempered strip has been investigated although it is not a flapper valve strip. The purpose of this investigation is to study the influence of cold work on the modulus of elasticity since tumbling or shot peening can also introduce some plastic deformation at the surface of flapper valve strip. As shown in Table 5, the cold rolled strips show both low modulus of elasticity and high anisotropy (E_L/E_T=0,84-0,87). The modulus of elasticity of 20C in cold rolled condition is 25% lower than that in H/T condition. As known, plastic deformation introduces amounts of dislocation in the material, which consequently introduces residual stresses that may introduce strain in the crystal structure and vacancies that change atomic distance in a micro scale. These factors can lead to a decrease in the modulus of elasticity. Another important factor is that plastic deformation introduces texture in the material. This leads to anisotropy in the material. Tempering can cause a recovery of plastic deformation, and consequently the modulus of elasticity.

The modulus of elasticity (E_L) shown in this investigation is slightly higher than those reported earlier (210GPa). One reason is that the method and software used in this study are different from earlier. Therefore, only the variation of the modulus of elasticity with the parameters investigated are discussed in this study.

Table 5: Influence of tempering on the modulus of elasticity of three flapper valve steel strips (GPa)

	20C				Hiflex				7C27Mo2			
	E_L	sd	E_T	sd	E_L	sd	E_T	sd	E_L	sd	E_T	sd
H/T	249	13	272	20	236	7	253	5	248	4	240	11
Temp A	235	4	232	2	236	4	244	10	237	2	248	4
Temp B	238	1	241	2	227	1	235	5	241	5	240	1
Temp C	231	3	228	1	220	8	227	1	228	4	230	2
CR	178	4	204	7	206	10	234	9	198	4	235	9
CR-Temp C	223	3	234	3	226	5	241	3	224	5	229	7

E_L: the modulus of elasticity in rolling direction, E_T: the modulus of elasticity in the vertical direction to the rolling direction, sd: standard deviation, CR: cold rolled.

3.2 Influence of Cyclic Loading on the Modulus of Elasticity

Cyclic loading even under elastic limit can cause not only fatigue damage, but also other effects such as residual stress relaxation and formation of vacancies by edge dislocation annihilation. Table 6 shows the influence of cyclic loading on the modulus of elasticity of 7C27Mo2 flapper valve strip. Under fatigue limit (life $N>2x10^6$), the influence of cyclic loading on the modulus of elasticity is little. This may be due to the fact that little plastic deformation can occur under these low stresses. When the applied stress is higher than the fatigue limit, the specimen has a limited life and local cyclic plastic deformation can occur. This is the case with a load of 680±680MPa. The modulus of elasticity of the strip slightly decreases after 500 cycles, but very small. These results show that the influence of cyclic loading near the fatigue limit on the modulus of elasticity is small.

Table 6: Influence of cyclic loading on the modulus of elasticity of 7C27Mo2 flapper valve strip (GPa)

Loading	**Number of cycles**	**E**	**sd**
600±600	$>10^7$	235	10
640±640	$>2x10^6$	239	13
680±680	>500	229	2
AD	-	236	5

E: the modulus of elasticity, sd: standard deviation

3.3 Influence of Surface Treatments on the Modulus of Elasticity

As known, some surface treatments are critical to improve the reliability and life of flapper valves. By surface treatment, the surface finish of the strip can be improved, which can reduce or eliminate a number of stress raiser and stress concentrators. Surface treatments can also introduce compressive residual stresses and increase the hardness near the surface of the strip, which can significantly improve the fatigue limit of the material. Tumbling and shot peening are two commonly used methods for surface treatment of flapper valves. Table 7 shows the influence of tumbling and shot peening on the modulus of elasticity of 7C27Mo2 and Hiflex. The influence of tumbling and tumbling + cyclic loading on the modulus of elasticity of 7C27Mo2 flapper valve strip is little. This is because tumbling causes little plastic deformation in the material, and stress relaxation for the tumbled strip during cyclic loading is very little [Chai, 2004]. In this study, a heavy shot peening was performed for Hiflex flapper valve strips, which caused a deep plastic deformation zone near the surface. This surface treatment has led to a small decrease in the modulus of elasticity. The influence of shot peening and then cyclic loading on the modulus of elasticity is similar to that with only shot peening.

Table 7: Influence of surface treatment on the modulus of elasticity of flapper valve strips (GPa)

Materials	**Treatment**	**E**	**sd***
7C27Mo2	no	225	12
7C27Mo2	tumbling	220	12
7C27Mo2	Tumbling+fatigue	221	12
Hiflex	no	231	12
Hiflex	Heavy shot peening	216	12
Hiflex	Heavy shot peening+fatigue	215	12

*: maximum standard deviation

3.5 Influence of Specimen Orientation on the Modulus of Elasticity

Figure 1 shows a summary of the influence of the specimen orientation on the modulus of elasticity (E-modulus) of AISI 1095, 20C and AISI 420 mod, 7C27Mo2 flapper valve strips. 7C27Mo2 shows a higher modulus of elasticity than that of 20C, but both materials show similar tendencies to the specimen orientations. Both materials show minimum modulus of elasticity at an orientation of 45^o to the rolling direction. 7C27Mo2 flapper valve strip shows similar E-modulus values in the rolling direction and in the vertical direction. For 20C, however, the E-modulus in the rolling direction is some what smaller than that in the vertical direction. The results can be compared with that in chapter 3.1.

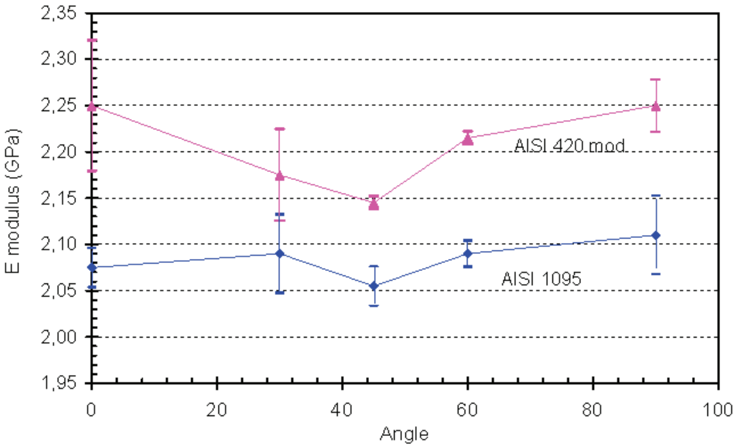

Figure 1: Influence of the specimen orientation on the tensile properties

As mentioned previously, cold working or rolling can lead to the formation of texture and cause the anisotropy of the material. Therefore, strip materials usually show strip texture. Figure 2 shows the texture structure in 7C27Mo2 strip. Three pole figures, (110), (200) and (211), and its diffraction intensities have been measured. Two of these are shown in Figure 2. The common strip texture components in cold rolled BCC steels: {100} <011>, {211} <01-1>, {111} <01-1> and {111} <11-2> can be observed in this material. From the (110) pole figure, diffraction intensity from all the above mentioned four texture components can contribute to the spread (110) poles centered at around alfa = 30 degrees. Some of the (110) poles of the {211} <01-1> are located at alfa =30 degrees and some of the {111} <11-2> at alfa = 35 degrees and the others shifted vertically. The {111} <11-2> seems to be stronger, which gives higher intensity of the poles at alfa = 60 degrees in the (200) pole-figure, but it was found that the {211} <01-1> component is weaker from the (211) pole density at alfa = 0, and the higher pole density could mean a stronger {111} <01-1>.

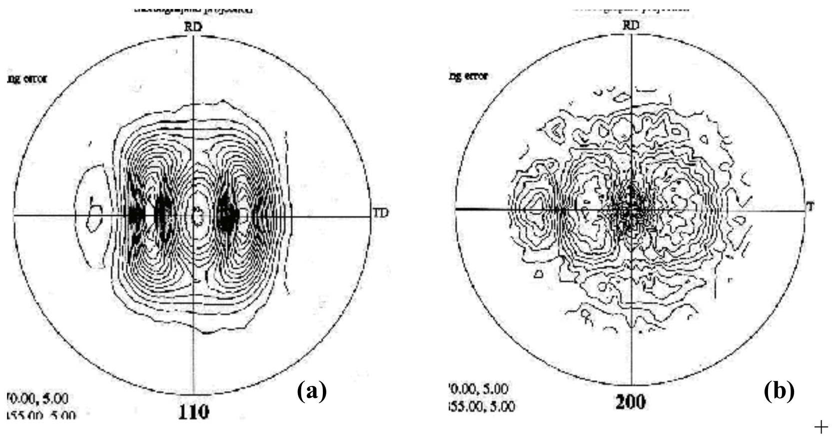

Figure 2: Pole figures and its diffraction intensities

3.6 Influence of Temperature on the Modulus of Elasticity

Figure 3 the influence of temperature on the modulus of elasticity of 7C27Mo2 flapper valve strip materials. As expected, the modulus of elasticity decreases with increases temperature. The decrease rate is about 5GPa/100°C. Increase in temperature in the4 metal material can increase the vibration of atoms in the crystal structure, which will increase the atomic distance and decrease the atomic force. This can lead to a decrease in the modulus of elasticity of the material.

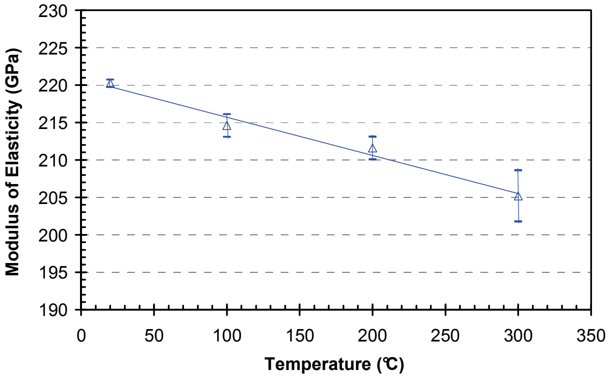

Figure 3: Influence of temperature on the E-modulus of 7C27Mo2 flapper valve strip

3.6 Influence of Modulus of Elasticity on the Fatigue Properties

Table 8 shows an example how influence of modulus of elasticity on the bending and impact fatigue properties of 7C27Mo2 flapper valve strip. As known, texture can strongly affect the modulus of elasticity of material, and also causes a texture hardening. This can also be seen in Table 8. Earlier investigations show that the bending fatigue properties of flapper valve are related to a combination of tensile strength and ductility of materials and the surface conditions (Auren et al. 2002, Chai et al. 2004). In this investigation, however, it can be found that the bending fatigue strength is mainly related to the tensile strength (Figure 3a). The influences of the elongation or ductility and surface residual stresses on the bending fatigue strength are relatively small. This indicates that the influence of the specimen orientation on the bending fatigue strength is mainly due to the texture hardening.

The impact fatigue strength is not related to the tensile strength since it increases with the orientation angles as shown in Figure 4a. The high impact fatigue strengths at 30°, 45° and 60° (comparing with low bending fatigue strength) may be attributed to the comparatively low E-modulus (Figure 4b). The high impact fatigue strength at 90° may be due to the high tensile strength. As we know, the initial stress increases with increasing E-modulus or the impact velocity (equation 1). Consequently, a material with high tensile strength and a low E-modulus can lead to a high impact fatigue strength. Since texture can significantly affect E-modulus, it can also affect the impact fatigue strength of the strip. The above discussion leads to a conclusion that at the specimen orientation angle of 90º, a combination of highest bending fatigue strength and highest impact fatigue strength can be obtained.

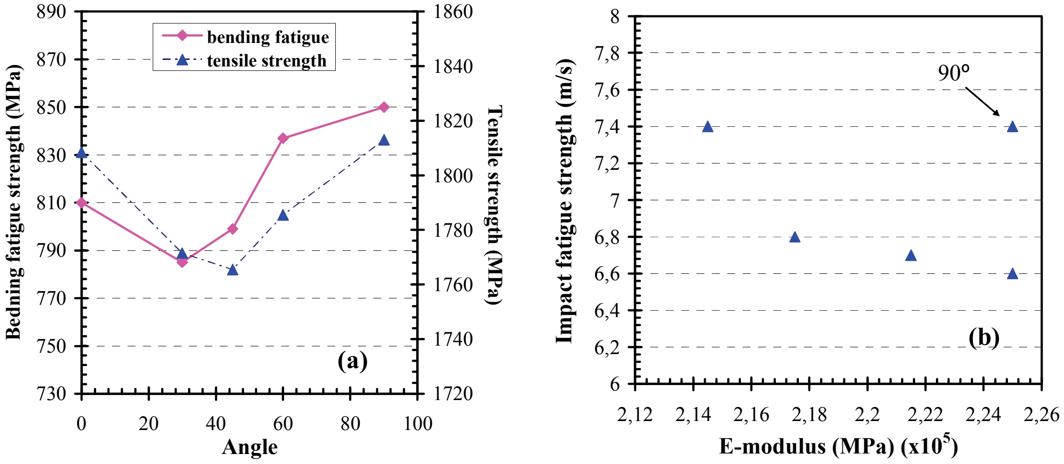

Figure 4: Influence of the specimen orientation or E-modulus on the bending and impact fatigue strength of 7C27Mo2 flapper valve strip

Table 8: Influence of the specimen orientation on the fatigue properties of 7C27Mo2 flapper valve strip

Angle	Rm	Rp0,2	A	E	σ_{ub}	sd	σ_{ui}	sd
	(MPa)	(MPa)	(%)	(GPa)	(MPa)	(MPa)	(m/s)	(m/s)
0	1812	1455	7,7	225	810	33	6,6	0,3
30	1771	1427	8,0	218	785	23	6,8	0,5
45	1765	1431	7,2	215	799	29	7,4	0,4
60	1785	1433	7,4	222	837	67	6,7	0,6
90	1813	1441	6,4	225	850	30	7,4	0,4

σ_u: fatigue strength, σ_{ub}: bending fatigue strength, σ_{ui}: impact fatigue strength, sd: standard deviation

4. CONCLUSIONS

Modulus of elasticity of the three mostly used flapper valve strip materials and its influence on the fatigue properties have been investigated. The following conclusions can be obtained.

- The differences in the modulus of elasticity of these three flapper valve materials are relatively small, but they have different anisotropy.
- The modulus of elasticity can vary with the orientation of the sample due to the presence of texture in the material. The modulus of elasticity at 45° to the rolling direction is lowest.
- Cyclic loading or fatigue performance near or lower the fatigue limit has a relatively small influence on the modulus of elasticity is relatively small.
- For a flapper valve steel, the influence of tumbling and fatigue performance on the modulus of elasticity is small.
- Increase in temperature decreases the modulus of elasticity.
- Generally, impact fatigue strength of the flapper valve steel is related to both the tensile strength and the E-modulus, but increases in E-modulus will decreases impact fatigue strength. For bending fatigue, the fatigue strength is however mainly related to the tensile strength and the ductility of the material.

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