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Advancements In Compressor Valve Steel For Enhanced Performance In Refrigeration And Freezer Applications

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ABSTRACT

This paper presents an exploration of the development of a new compressor valve steel variant (Freeflex® Versa) developed to elevate fatigue properties, catering to the rigorous demands of high-end household, commercial, and industrial segments within the refrigeration and freezer industry. The primary objective is to meet and exceed the performance requirements for compressors in the evolving landscape of HVACR applications, with a specific focus on energy efficiency.

Over the past decade, generic compressor valve steels have emerged to meet the latest energy efficiency standards across diverse HVACR applications. Our research presents Freeflex® Versa as a pioneering compressor valve steel, further improving mechanical properties, impact and bending fatigue resistance, residual stresses, and wear resistance. In the light of designs towards smaller and lighter compressors, the valve steel is not the only parameter to support this development but is essential to enable further pace and pressure with shorter, thinner and in general more complex valve geometries for future improvements in reliability and compressor Coefficient of Performance (COP). The importance of these developments has been discussed within the International Energy Association, IEA, and furthermore governmental directives on progress have been issued in several countries, with the aim to set future standards. While our company's previous version, launched in 2021, targeted the residential AC compressor market, the new version Freeflex® Versa, has been developed and presented with an even higher fatigue resistance then it’s precursors which together with an elevated wear resistance offers unique conditions to manage future compressor demand of reliability and increased COP in the Refrigeration Industry. The benefits with smaller and shorter valves, higher deflection to mention a few parameters, is to enhance miniaturization of compressors alone or in combination with improving the performance which is crucial for better utilization of our world’s resources. A miniaturization can follow, if the flow of cooling media can be retained because of the reed valves better performance, despite a smaller sized compressor. In the paper, the purpose of segmentation, the unique steel alloy together with information of the developing process and the steel performance in terms of mechanical properties, microstructure, impact and bending fatigue, residual stresses and wear resistance will be discussed. The findings of this paper hold significance for manufacturers, engineers, and stakeholders involved in the continuous improvement of compressor technologies to meet the evolving market demands.

1. INTRODUCTION

Energy and environmental concerns have prompted regulations to reduce energy consumption, leading to the development of more efficient cooling devices worldwide. Recent investments by manufacturers in designing newer, higher-performing cooling equipment have resulted in rapid technological advancements in the compressor industry.

New compressor platforms exhibit higher COP, lower weight and noise levels. Today's compressor systems require less energy to operate, thanks to superior raw materials, lighter weight and environmentally friendly cooling media, supporting reduced greenhouse emissions. Additionally, the share of refrigeration inverter-type compressors is expected to exceed 60% by 2030 (CHEAA 2019). Moreover, compressors for room ACs should be 10% lighter, driving miniaturization and sustainability efforts by reducing material usage. Meeting these demands will require innovative solutions from compressor manufacturers and the entire supply chain.

In this study, Alleima, an advanced steel material researcher and manufacturer of compressor valve steel, will present a new valve steel exhibiting a higher tensile strength and retained high ductility than any other existing valve steel on the market today. With the new material, the aim is to support the development of higher-performing compressors aligned with the future compressor industry demands.

2. MATERIALS

During the previous compressor conference 2021, a new alloy, consisting of C0.53 Cr14.0 Mo1.0 Cu0.70 wt%, was presented (Hoel et al., 2021). The focus area for that development was towards air conditioning applications. One important aspect for these applications, where the limitation of noise formation during impact besides the fatigue properties. In this report, the results of an investigation of a further development of the same grade, now with the target towards tougher application areas, are presented. The new Freeflex® Versa material is furthermore compared with three existing compressor materials. The investigated materials are presented in Table 1. The material thickness throughout this work is 0.178 mm.

Table 1 Typical chemical composition of the various investigated grades

Grades	Material	C	Si	Mn	P	S	Cr	Mo	Cu
Alleima® 7C27Mo2	1	0.38	0.40	0.55	<0.025	<0.010	13.5	1.0	-
Hiflex™	2	0.39	0.40	0.55	<0.025	<0.010	13.5	1.0	-
Freeflex® Core	3	0.53	0.40	0.68	<0.025	<0.010	14.0	1.0	0.70
Freeflex® Versa	4	0.53	0.40	0.68	<0.025	<0.010	14.0	1.0	0.70

3. EXERIMENTAL SETUP

3.1 Microstructure and wear

The materials are put into a mount and ground and polished carefully. The materials are furthermore etched in Kallings for microstructural depicting. Prior the images analysis, so called AxioVision investigation, the materials are color etched, depicted by SEM and image processed. The smallest particles are likely to be too small for detection which implies the number of particles is reasonably higher and thereby the average size is likely to be overestimated. It must be kept in mind that there are several factors influencing the results, such as chemical composition, individual heat treatments, etching of samples, manual threshold settings in the image processing to mention a few, so the data should be used as indications and not as specific values or quality measure.

The samples to be used for bending fatigue testing are also used to determine wear resistance. The weight has been measured prior and after the tumbling process. The number in each batch is 36 samples. There is an uncertainty in the method due to the deviations on the balance. Another uncertainty is likely to be the tumbling since the material is run in individual batches. Even if the process is conducted under conditions as similar as possible, variations could give rise to slightly different results. The applicability of the weight loss, as a measure of wear resistance within the compressor, could be discussed, as it is a method far from the application – although in this investigation the method is used to obtain a measure of the wear resistance.

3.2 Residual stress

The residual stress analysis of the samples was performed using XRD- Bruker axs D8 DISCOVER diffractometer (35kV,50mA) according to the $sin^2\psi$ -method with Cr - Kα (λ = 2.2879 Å) radiation. For a better overview, the average compressive residual stresses, based on the stresses in the rolling direction and transversal direction, are presented.

3.3 Tensile properties and hardness

The tensile testing is conducted according to standard ISO6892. Dog bone samples with a total length of 250 mm and a width of 20 mm on the parallel length have been used. The hardness measurements are conducted onto the surface by means of the standards ISO6507 and 6508. The relation between tensile strength and hardness is approximately 3.3 according to the standard ISO 18265:2013(E).

3.4 Fatigue testing

Samples are wire cut and tumbled to the proper surface finish as well as edge rounding. The sample design is shown in Figure 1. The fatigue testing is conducted in terms of staircase method and the fatigue limit is determined according to standard ISO 12107. The impact fatigue testing has been conducted using a compressed air system at a frequency of 200Hz to a runout level of 10 M cycles. The hardness of the utilized seats is in the range of 480 – 550 (HV1). The bending fatigue testing utilized a shaker induced set up operating at the resonance frequency of the sample, which on this thickness 0.178 mm, is about 200 Hz. The runout level for bending fatigue was set to 2 M cycles. These runout times are in line with the historical data.

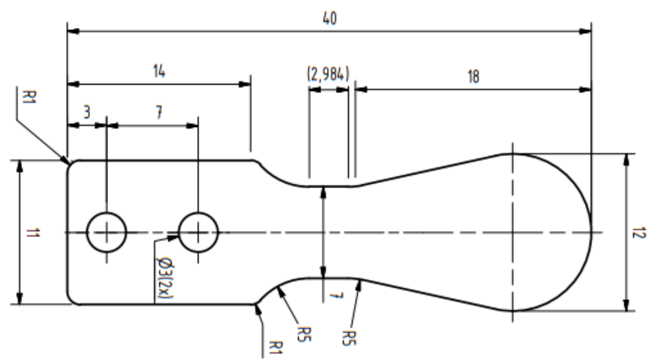

Figure 1 The Alleima design of the samples used for the fatigue testing.

4. RESULTS

4.1 Microstructure, carbides and wear

The microstructure of the material 1-4 are shown in Figure 2. All alloys exhibit a microstructure consisting of a martensitic structure with an appropriate fine dispersed distribution of precipitates. In the micrographs the majority of the precipitates are of the M23C6 -type which is the predominate precipitate phase. The Thermo -Calc graph is shown in Figure 3. Other phases such as Chromium – Vanadium – Nitride and Copper are also present in the phase diagram but to a lower amount. The Cu – precipitates are found in the materials 3 and 4, which is an outcome of the oversaturation of Cu. The possible contribution of Cu on solid solution strengthening, and cluster strengthening have been discussed earlier (Hoel et al. 2021).

The carbide distribution is investigated by image processing and the data is presented in Figure 4. The condensed information on the materials carbide distributions are given in Table 2. The materials 3 and 4, with the higher C – content, show clearly a higher particle density compared to the materials 1 and 2 with the lower level of C – content. The maximum size observed carbides are of low importance since it could be the contribution of a few or single individuals or could be a miss interpretation of the image processing of 2 adjecent carbides. The measure of volume fraction above 0.70 µm indicate the majority of the carbides being smaller than the 0.70 µm.

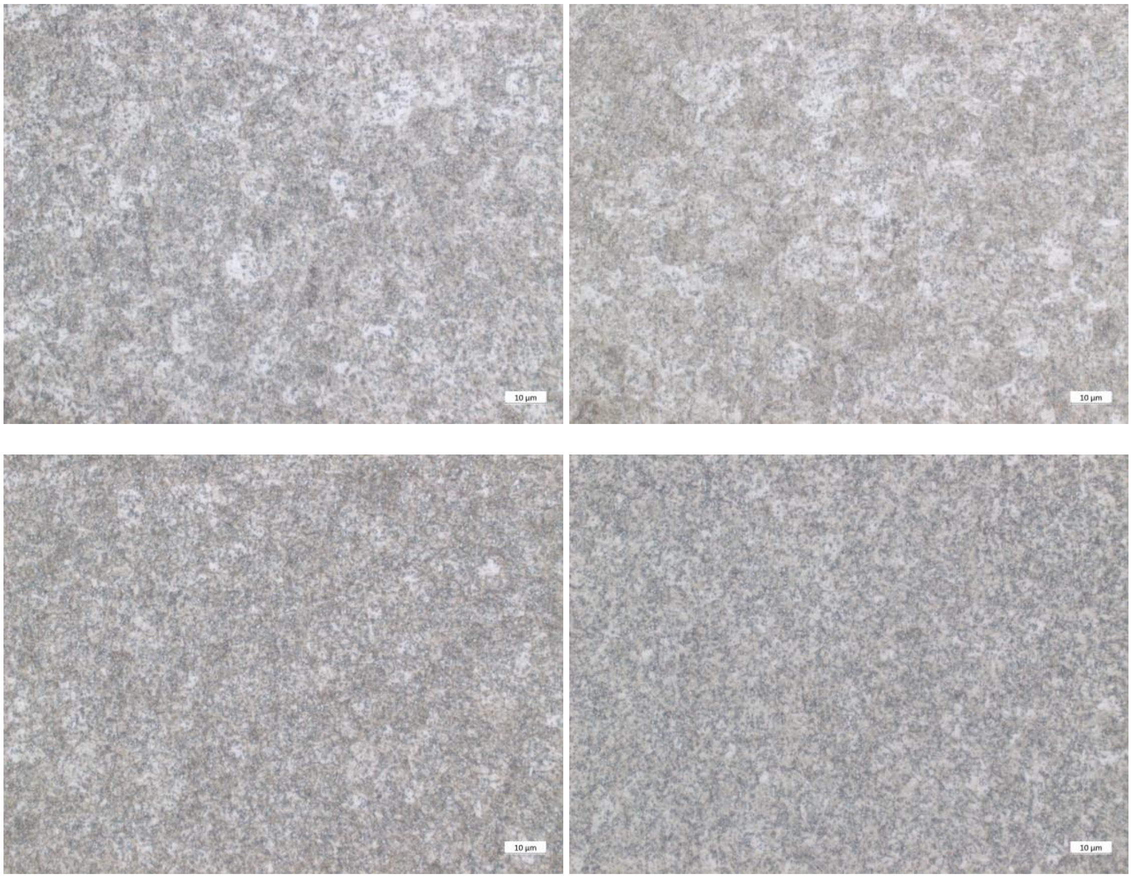

Figure 2 Microstructure of the materials 1 (upper left), 2 (upper right), 3 (lower left) and 4 (lower right). The images are taken at 1000X magnification.

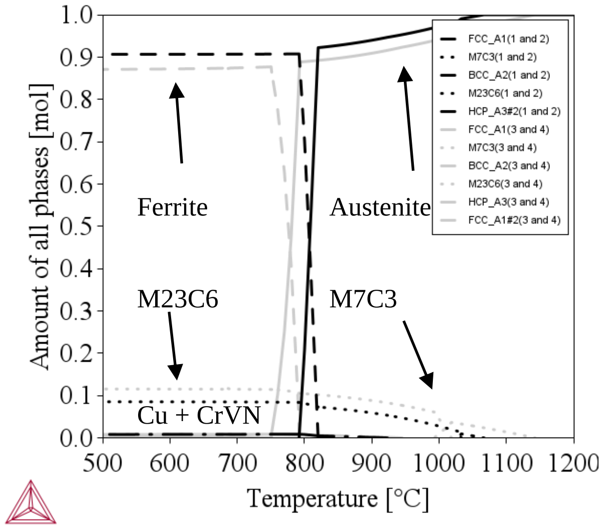

Figure 3 A ThermoCalc diagram showing the differences of the alloys based on material 1 and 2 compared to material 3 and 4.

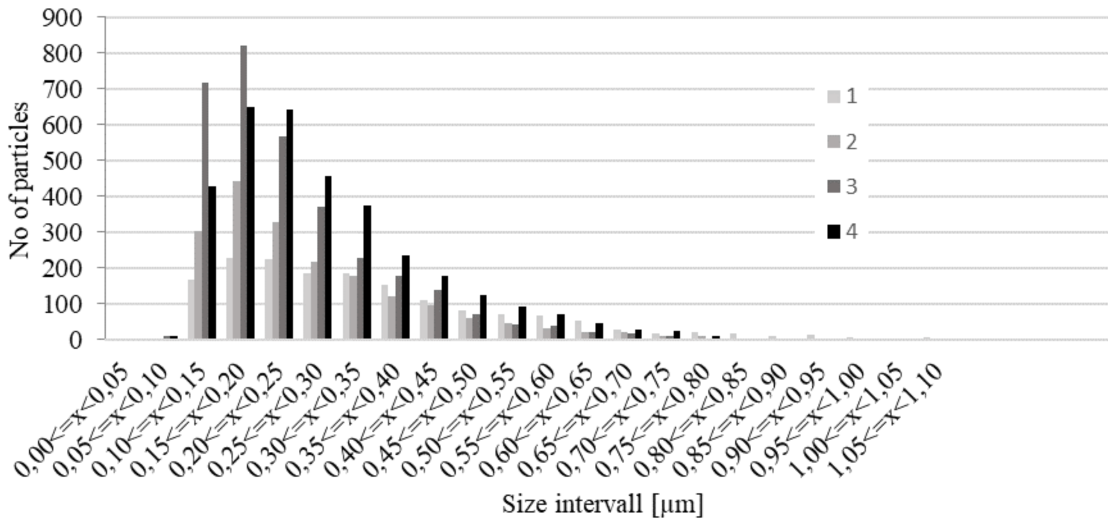

Figure 4 The carbide distribution for the dfferent materials 1- 4.

Table 2 A summary of the carbide distribution for the materials 1-4.

Material	Particle density No/100 µm²	Particle area fraction %	Average particle diameter µm	Max particle diameter µm	Average particle volume µm³	Volume fraction above 0,70 µm %
1	41	5,0	0,34	1,30	0,04	27
2	33	2,4	0,27	1,16	0,02	24
3	55	3,3	0,24	1,01	0,01	13
4	58	4,6	0,28	0,99	0,02	15

The wear properties are determined by use of weight loss upon tumbling. The weight of 36 samples are measured prior to and after the tumbling. The results are presented in Figure 5 and indicate a material with a higher resistance to the wear abrasion caused by the tumbling. The measurment indicated a slight mass uptake for material 4, which is not to be defined as a valid measure, and implies a uncertainty of the results. This is shown with the error bar of 0,07 g. The used weight loss method is, as mentioned, far from the application. It is although without doubt that the additional hardness and carbide density of material 4 in comparison to the other materials imply an improved capability to withstand wear. This is of importance in the application where the valve impact repeatedly to the seat and with time will form a wear mark and subsequently lead to a high stress concetration and eventually cause a failure of the valve.

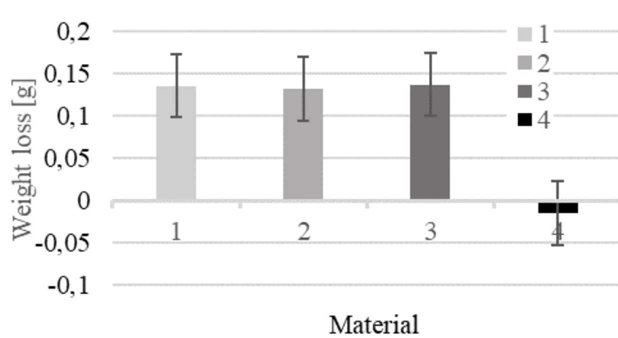

Figure 5 The weight loss of 36 samples determined through abrasion via tumbling

4.2 Residual stress

The residual stresses are measured by means of X – ray diffraction. The samples have been tumbled in order to obtain the proper edge rounding to remove possible stress increasing defects. These defects could be a consequence of blanking or as in this case from the wire cutting process. The effects of surface scratches from the polishing or from the material handling could also be reduced by the tumbling. A standard industrial tumbling is conducted for the impact fatigue testing. For the bending fatigue testing an additional tumbling by use of a centrifugal tumbling process is conducted to ensure the removal of the set defects. The average compressive residual stresses, calculated from the stresses in rolling direction and in transversal direction, are presented in Figure 6. When correlating the average compressive stress with the material tensile strength (see Figure 7), it becomes clear that the capability to form compressive residual stresses, in this type of material, follow with the tensile strength of the material – the higher the tensile strength – the higher the achievable compressive stress given sufficient energy is put into the surface by the surface treatment method. The relation between tensile strength and compressive residual stress has been elaborated in earlier work (Chai et al., 2004). As can be seen in the graph, with the different tumbling methods follow different energy levels and thus different compressive stresses.

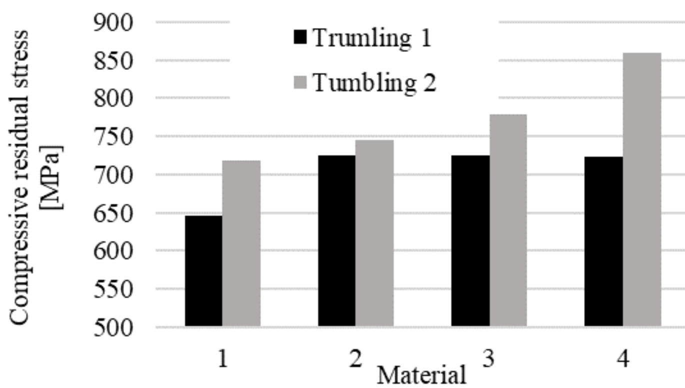

Figure 6 The average compressive residual stress after tumbling

4.3 Tensile properties and hardness

The mechanical properties for the different materials in terms of tensile strength, yield strength, hardness and minimum elongation A25% are shown in Figure 7. The material 4 exhibits a nominal tensile strength of 2150 MPa which is higher than other compressor valve steels of today. The hardness follows a staircase relation in line with the increasing tensile strength. The nominal value of tensile strength is related to the center value of hardness through a factor around 3.3 (ISO 18265:2013(E)). The combination of high strength and high ductility has earlier been discussed (Chai et al., 2004 and Hareland et al., 2014). The area or integral of tensile strength σ_{TS} with respect of displacement ε, see Equation 1, is a measure of the associated energy required when pulling the sample during tensile testing (Beer et al., 2006).

$$W = \int \sigma_{TS} \, d\varepsilon \quad (1)$$

For simplicity, the measure of tensile strength multiplied with the min elongation, as presented in Figure 8, can be used for the ranking of the material's high strength and high ductility properties. The figure shows a large variety in the minimum required energy needed when pulling the said materials 1 - 4.

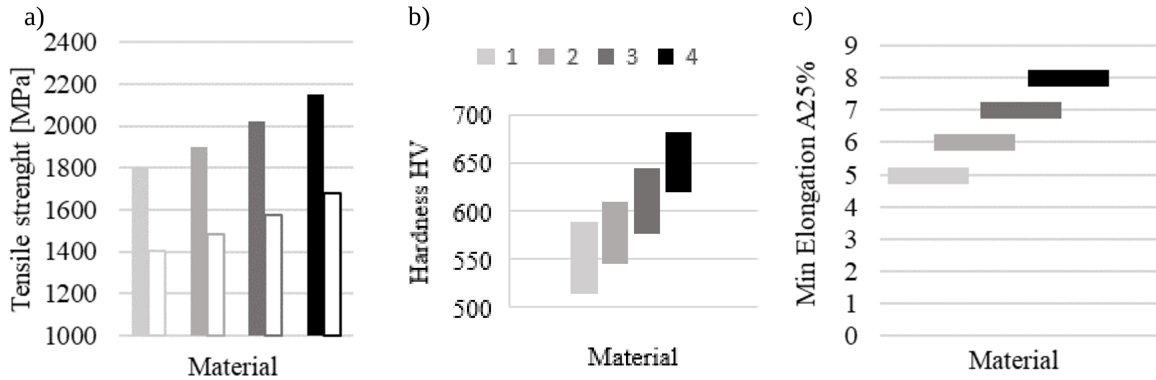

Figure 7 The mechanical properties in terms of a) tensile strength (filled columns) and yield strengh (open columns), b) hardness HV1 and c) minimal elongation A25%

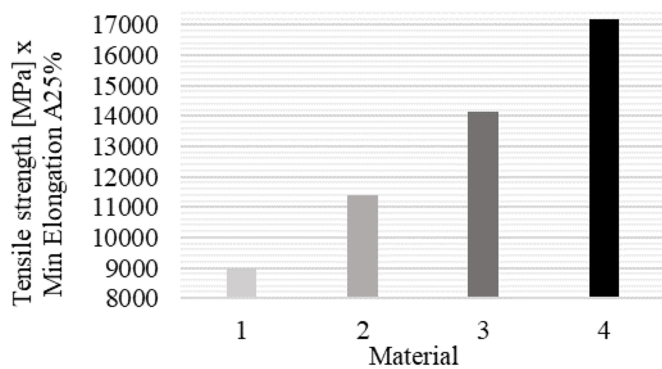

Figure 8 The measure of tensile strength multiplied with Minimum Elongation

4.4 Fatigue testing results

The fatigue properties of the above-mentioned materials are shown in Figure 9 for bending fatigue and Figure 10 for impact fatigue. The presented values are based on staircase method results with a probability to failure of 50 %. The results on bending fatigue are to a high extent depending on the capability to build compressive stresses. The results on impact fatigue are shown for velocity but also for kinetic energy with the definition, using mass *m* and velocity *v*, according to Equation 2.

$$W = m\, v^2 /2 \qquad (2)$$

The results are indexed compared to material 2 (Hiflex). This implies that the design aspects of mass will be avoided. In this evaluation, the design and density of the samples are to be defined as equal.

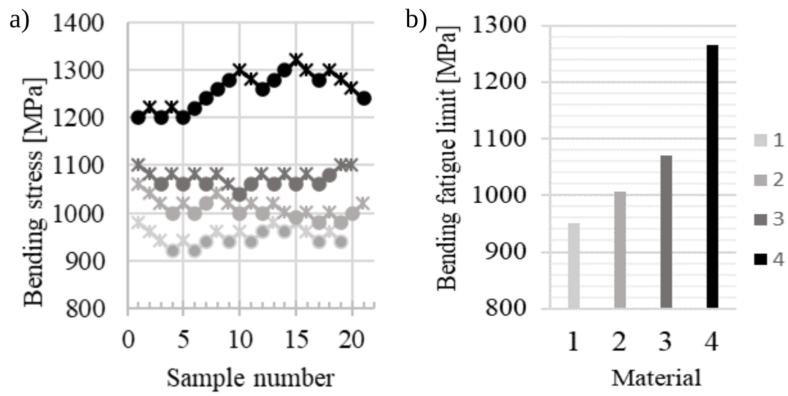

Figure 9 The bending fatigue properties presented in terms of a) staircase evaluation and b) bending fatigue limit for the different materials 1-4.

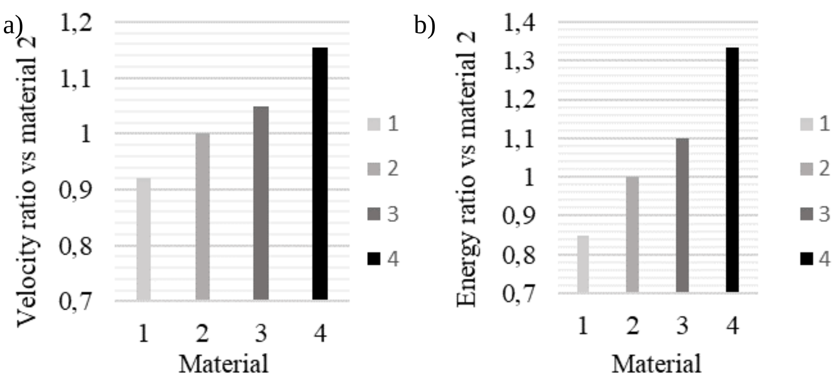

Figure 10 The impact fatigue properties in terms of a) velocity ratio and b) energy ratio

4.5 Potential for miniaturization

The bending fatigue results are used to calculate the corresponding bending radius by use of the relation between bending fatigue stress σ_{bf} *(MPa)*, elasticity modulus *E (GPa)*, thickness *t (m)* and radius *R (m)* as described by the Equation 3.

$$\sigma_{bf} = Et/(2R) \Leftrightarrow R = E*t/(2\sigma_{bf}) \qquad (3)$$

The bending stress is assigned to the area <5 mm where the bending fluctuations occur during the bending fatigue testing. The results are illustrated in Figure 11. The dashed horizontal line indicates the same deflection for the different materials 1- 4. An arc is used to indicate the potential for miniaturization of the valve with a consistent deflection. This is also illustrated by the appropriate scaling of the valve size in the figure. Sample 1 is depicted in natural size and 2 - 4 with the possible reduction in size.

An effort, to discribe the effect of different bending fatigue properties on the possible amount of circulated cooling media during one single cycle, is conducted by means of volume between the valve and the seat (D = 10 mm). There will be unavoidable flow losses around the valve and through the seat, but for simplicity the volume of the thought cylinder volume between seat and valve is calculated. The results are presented in Figure 12 with the volume (left axis) and the index ratio versus material 2 (right axis). The theoretically calculated volume increase for different lift with constant valve length should be related to the achievable COP of a compressor. As can be seen, the material 4 exhibit an increased capability related to the other materials.

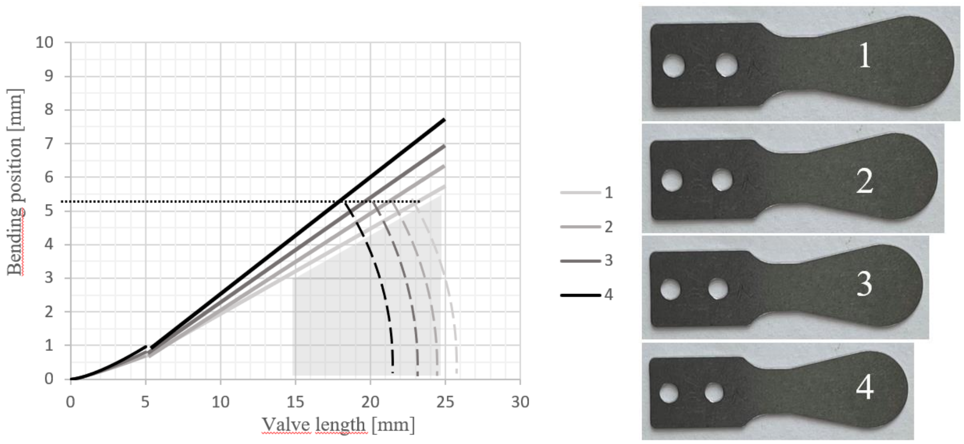

Figure 11 A schematic illustration of the effect of different bending fatigue limits. The arc indicate the capability for miniaturization when going from one material to the other with withheld deflection. To the right an illustration of the possible reduction of the valve length.

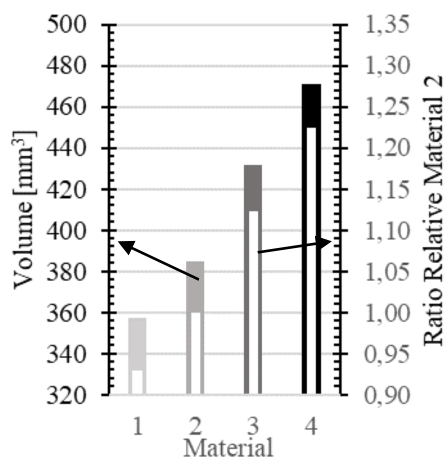

Figure 12 The volume between the valve at the upper most position and the seat based on the bending fatigue limit. The right axis correlate to the ratio relative material 2

5. CONCLUSIONS

In this paper, the results are presented from an investigation of a further development of the compressor valve steel within the Freeflex® - family, which was presented during Purdue 2021 (Hoel et al., 2021). The new Freeflex® Versa has shown to outperform the other chromium steels of the Alleima valve steel portfolio in terms of bending fatigue and impact fatigue properties. The material is designed towards an increased tensile strength, which as expected also influence the hardness as well as the achievable level of compressive stresses after tumbling. The higher level of C and Cr affect the carbide distribution in a positive way, which together with the overall increased hardness enable an improvement of the materials wear resistance. In addition, as discussed earlier, the Cu – content has a positive influence on the mechanical properties regarding solid solution strengthening effects and possible clustering effects compared to the traditional compressor chromium steel with C0.37% and Cr 13.5%. Based on the bending fatigue and the related bending radius, a geometrical determination, of the volume between the valve and seat indicates an accessible volume during valve movement. This volume is related to the transportation of cooling media and is thereby related to the energy efficiency or COP of a compressor. The new material exhibits the largest volume and appears to be an interesting candidate for future compressor development and furthermore in the strive for miniaturization. The material could be an important tool in the work to fulfill the present and future demands on compressor performance.

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