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ABSTRACT

In 2018 the International Energy Association IEA reported that air conditioning will be a major contributor for future electricity consumption (Birol, F. 2018). As recently seen in China, tougher legislation on energy efficiency for air conditioning and refrigeration is being introduced all the time. It is therefore crucial that new compressor models perform at the highest levels in terms of efficiency to reduce global energy consumption. The prerequisites to fulfill this legislation vary for the different applications such as rotary, reciprocating, scroll and linear compressors. However, to succeed in developing more energy efficient compressors, the ability to improve the performance of the flapper valves will play an important role. Furthermore, the current commercial alloys available for flapper valves may not be sufficient to meet these increasing demands. In the past, to improve the material fatigue properties, the development of high-performance flapper valve material has been focused around optimizing the metallurgical cleanliness, microstructure, surface finish and mechanical properties. Now research has been completed to develop a new alloy composition aiming to develop a material with further improved fatigue properties for flapper valve applications. The results from internal and external testing of the new alloy show significantly improved fatigue properties. Within this paper, some of the critical properties of the new alloy are presented and the test results are compared with other existing flapper valve steels on the market.

1. INTRODUCTION

Energy and environmental aspects have been the incentives for regulations to reduce energy consumption, which have led to a development of more energy efficient cooling devices globally. The past few years of increased investments by the manufacturers to design newer and better performing cooling equipment have made us witness some rapid technological breakthroughs within the compressor industry. New platforms show lower weight and noise as well as increased number of the highly efficient inverter technology. In general, todays compressor system needs a lower amount of energy to run with more environmentally friendly cooling medias which result in reduced green-house emissions and increased energy savings.

A technical roadmap for future compressor development has been formulated in China (CHEAA, 2019, CHEAA, 2019) For example, the road map states requirements for the future compressor development concerning compressor efficiency in terms of coefficient of performance COP, weight and fraction of inverter type of compressors where a variable speed is employed. Until year 2025 and improvement of the COP should be achieved with 25% and 10% for refrigeration and Room AC application, respectively. In addition, as inverter type of compressors generally has a higher COP in comparison to traditional compressors, an increased fraction of above 50% is demanded. Further-more, the weight of compressors in Room AC shall be reduced by 10% which is a driver for miniaturization and sustainability due to a reduced material need. These demands will only be met with innovative solutions from compressor manufacturers and all parts of the supply chain.

In this study Sandvik, a raw material researcher and manufacturer of flapper valve steel, has attempted to set a new direction for developing higher performing flapper valves which is in line with the future challenges for compressor development.

2. ALLOY DEVELOPMENT

2.1 Literature Review

Suction and discharge flapper valves are critical components for the function of a compressor. However, they will suffer from both cyclic bending stresses and impact stresses during service, which can cause the valves to fail (Soedel, 1984, Chai *et al.*, 2014). High bending fatigue strength and high impact fatigue strength are therefore the basic requirements for valve materials (Olsson, S., 1992). AISI 1095 and AISI 420 types of two martensitic steels are traditional flapper valve materials. These materials show both high tensile strength and high fatigue strengths under bending and impact stress conditions (Sandvik, 2003). Recent years, Sandvik Hiflex™ had been developed and has been widely used as flapper valve material for advanced compressors. 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 was initially designed particularly for use in carbon dioxide compressors for automotive air conditioning, where higher pressures and temperatures place increasing demands on the flapper valves (Chai *et al.*, 2004). Today, it is widely used within refrigeration and residential AC applications. To develop a compressor with even higher efficiency, however, the valve material is now becoming a limiting factor since even higher fatigue strengths are required due to the increase of the flapper valve lift or a shorter flapper valve with the same lift (Chai *et al.*, 2014).

It is known that the fatigue strength of a metallic material initially increases, more or less linearly, with increasing tensile strength. However, no further increase or even a decrease in fatigue strength is followed by further 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 (Forrest P. G, 1962). This observation indicates that it may be possible to have a further improvement of the fatigue strength of a material with a high tensile strength by retaining a low sensitivity to the stress-raising effect. Actually, this can be done by increasing the material´s strength and ductility simultaneously (Chai *et al.*, 2014). These properties are also the principles for the new alloy development presented in this paper. Strengthening was done by solid solution hardening with alloying elements and precipitation hardening with new stable nano-carbides. The ductility of the alloy was improved by refinement of the microstructure and introducing multiphases in the alloy.

2.2 Composition of the new alloy

In search for a higher strength material without significant need of changing the process parameters a material with higher amount of C is developed. In addition, the Cr – content is increased in order to follow the C – content and to allow additional carbides to be formed. Thereby the amount of free carbon can be limited which could lead to a brittle material. The composition for the new alloy, named Freeflex™, is given in Table 1. The typical chemical composition of a number of different flapper valve steels are also shown. A solid solution strengthening by use of Cu provides new possibilities to obtain superior properties.

Table 1 The typical chemical composition of the new alloy. For comparison other existing flapper valve steels are also given.

Sandvik Grades	Material	C	Si	Mn	S	P	Cr	Mo	Cu
20C	A	1.0	0.30	0.40	<0.010	<0.025	-	-	-
7C27Mo2	B	0.38	0.40	0.55	<0.010	<0.025	13.5	1.0	-
Hiflex™	C	0.38	0.40	0.55	<0.010	<0.025	13.5	1.0	-
Freeflex™	D	0.53	0.40	0.68	<0.010	<0.025	14.0	1.0	0.70

3. EXPERIMENTAL 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 AxioVision investigation, the materials are color etched, depicted by SEM and image processed. In addition, in search for Cu particles, the samples of material D are analyzed in SEM. The atomic number contrast is pronounced, and the images are further processed to be analyzed by AxioVision. As a complement to the image processing, the Cu – particle sizes are also determined manually. 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.

The wear testing is conducted by use of a CSM Instruments TRIBOMETER operating on a linear reciprocating path of 5 mm. The total length of wear is 150 m. The counter material is a cemented (tungsten) carbide ball of 5 mm diameter. The wear mark is being evaluated using an interferometer. The depth of the wear mark is determined at 5 positions along the path.

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.

3.3 Tensile properties and hardness

The tensile testing is conducted according to standard ISO6892. The hardness measurements are conducted onto the surface by means of the standards ISO6507 and 6508.

The thermal stabilities of hardened and tempered materials have been investigated by additional tempering at a temperature from room temperature and then 200 up to 450 C in step of 50C for 2h. When the additional tempering results in a change in hardness the thermal stability level is passed.

3.4 Fatigue testing

Samples are blanked and ground to the proper dimensions. Fatigue testing is conducted onto samples with different designs for different type of fatigue testing. The samples are tumbled in order to improve the edge condition and to build in the proper amount of residual stresses to ensure the material properties are tested. The different samples are shown in Figure 1.

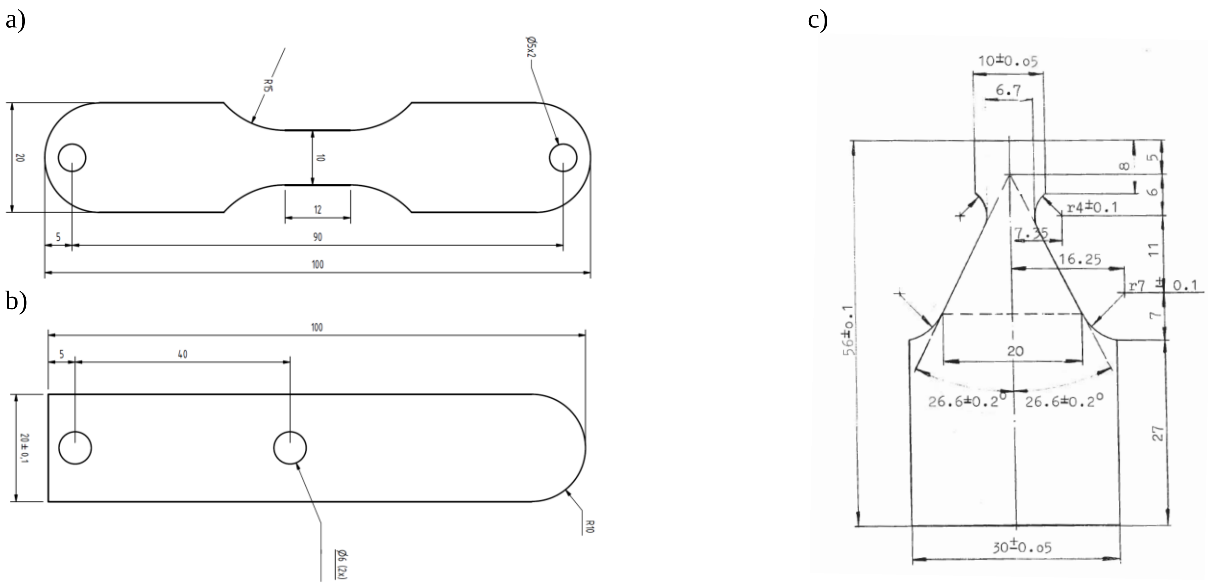

Figure 1 The design of the samples used for a) Fluctuating tensile testing b) Bending fatigue testing and c) Impact Fatigue testing, respectively.

4. RESULTS

4.1 Microstructure and wear

The microstructure of material C and D is given in Figure 2. For both alloys the microstructure consists of a martensitic structure with a fine dispersed distribution of carbides. The carbide distribution is investigated by use of image analysis using AxioVision. The distribution for material D is to be compared with the results from material B and C. The data is presented in Figure 3. A summary of the data is given in Table 2. The new alloy has a carbide density approximately twice of what is observed for material B and C. The maximum observed carbide is smaller, but this is however not a statistical measure. Instead, the volume fraction of carbides with a diameter above 0,70 µm is used as a measure. The volume fraction for carbides larger than 0,70 µm is 6-15 % for material D whilst 21-48 % for material C and B.

In addition to the effect of solid solution strengthening, an oversaturation of Cu, which is ensured in the interval around and above the composition of Cu for alloy D, enables a cluster strengthening and also a precipitation hardening. In the graph in Figure 5, an effect is observed where the A1 – transition temperature is reduced with addition of Cu for up to about 0.55 wt% after which the reduction is flattening out. The composition is chosen to be above the flattening threshold and furthermore to be kept low to avoid unnecessary addition of Cu for scrap handling reasons, possible limitations in hot processing as well as for economic reasons.

The A1 – temperature is the eutectoid temperature and defined as the minimum temperature for the austenite in equilibrium. This is illustrated in the Phase diagram in Figure 4. The presence of Cu – precipitates are shown in Figure 5b and the corresponding data is shown in Table 3, respectively. The Thermo Calc data is purely calculations and some deviations from reality is expected, however the results on A1 reduction from ThermoCalc – calculations are confirmed with dilatometry investigations even though the effect is not as pronounced. Whether there exist Cu – clusters as a pre-condition to precipitates or particles has not been confirmed but if there are Cu – particles it is reasonable that there are not yet formed particles, i.e. clusters and often referred to as Guinier – Preston or GP zones (Reed – Hill and Abbaschian, 1994). The Cu -particle density is found to be around 7 particles / 100 µm^2. The fine dispersed carbides together with the reasonably presence of Cu clusters, maximal solid solution strengthening, precipitates of Cu particles are indicators of an efficient pinning of dislocations resulting in elevated mechanical properties in comparison to the other alloys.

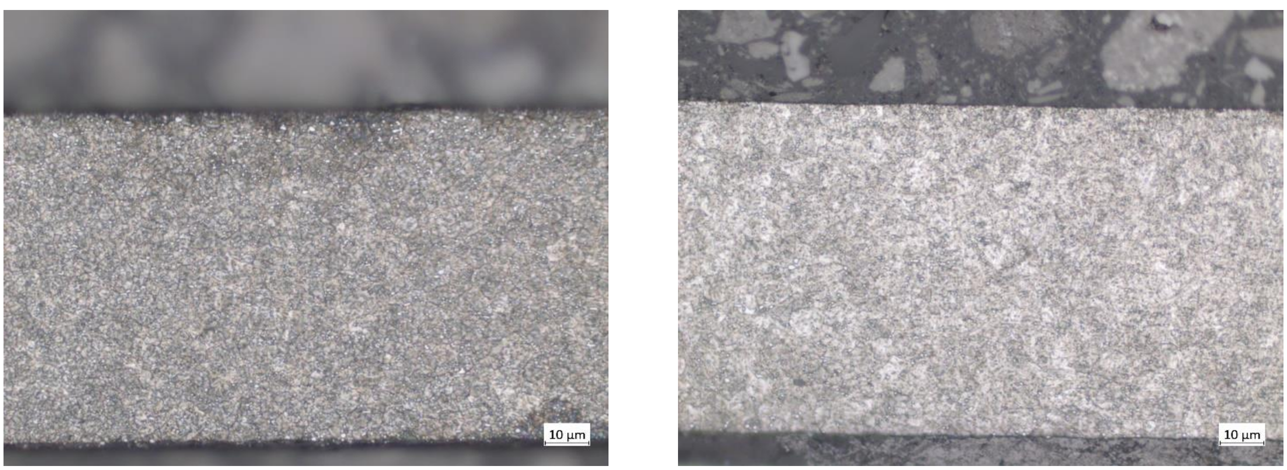

Figure 2 The microstructure of the materials a) C and b) D, respectively

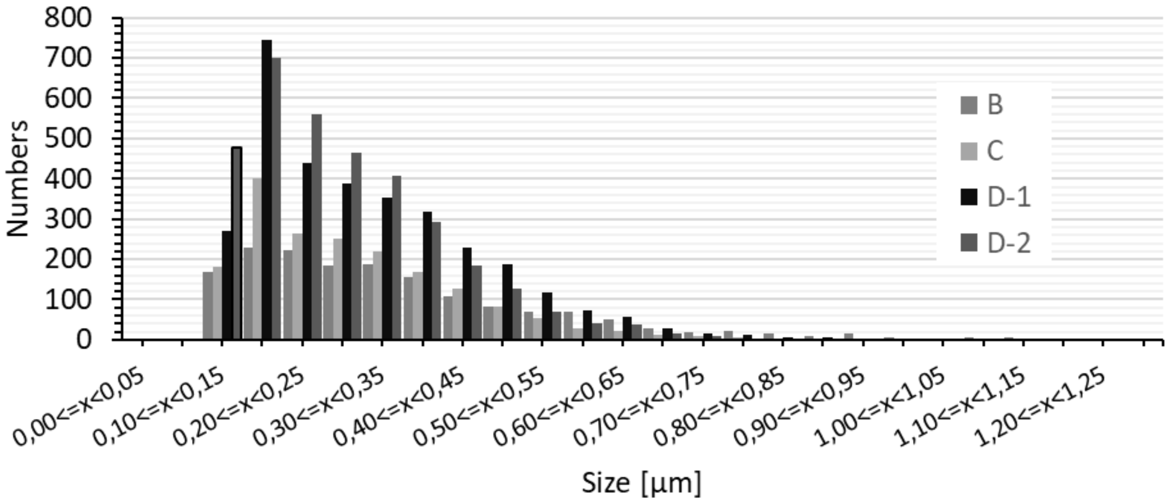

Figure 3 The carbide distribution for the different materials.

Table 2 A summary of the carbide distribution

ID	No of particles	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 %
Sample D-1	3249	56	5,0	0,30	1,07	0,03	15
Sample D-2	3393	58	4,1	0,27	0,97	0,02	6
Sample C	1839	32	2,6	0,29	1,36	0,02	21
Sample B	1663	30	3,7	0,35	1,30	0,05	48

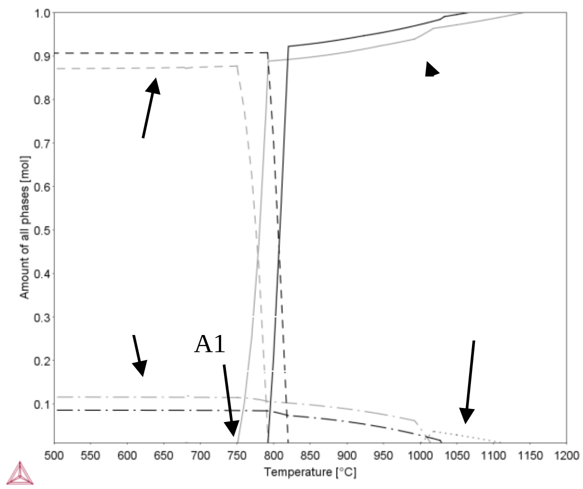

Figure 4 A ThermoCalc diagram showing the differences of the alloys based on material B/C and material D.

Table 3 A summary of investigation of Cu- particles.

Method	No of particles	Average Area [µm²]	Average Diameter [µm]	Inspected area [µm²]	Particles / 100 µm²
Image processing	92	0,012	0,12	1370	7
Manual	96	0,011	0,09	1370	7

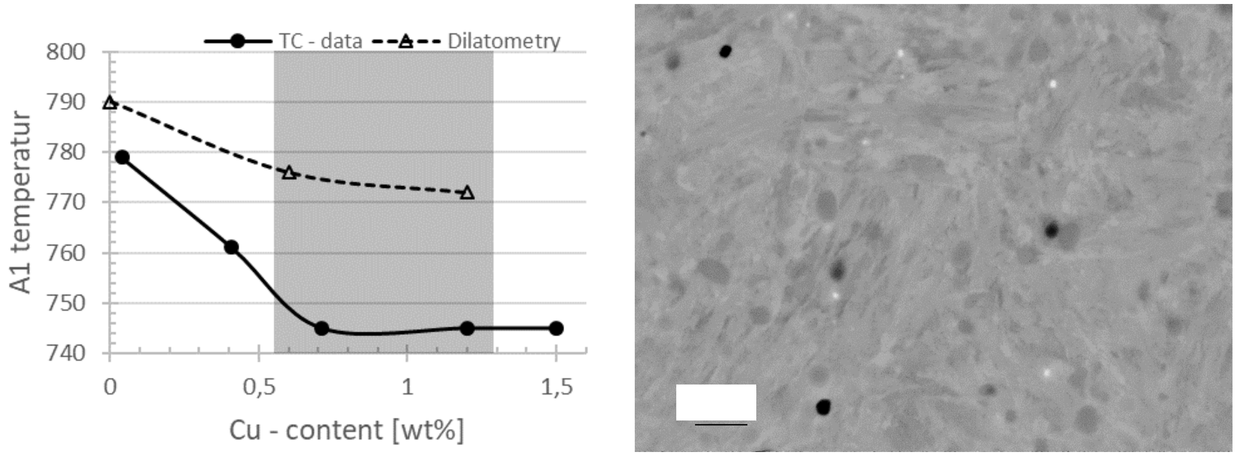

Figure 5 a) A diagram showing the decrease of A1 – temperature as a function of Cu – content as determined by Thermo – Calc as well as dilatometry, respectively. b) In the image, the presence of Cu precipitates (white) is observed besides Cr -carbides (grey).

The results from the wear mark analysis is shown in Figure 6. In a) the interferometry images are shown. In b) the average depth and the corresponding standard deviations are given. In c) a SEM image of material A is shown as an example. The ranking of the wear resistance according to this specific test is clear where material D exhibits the best wear resistance closely followed by C and then with a significant gap to material B and A.

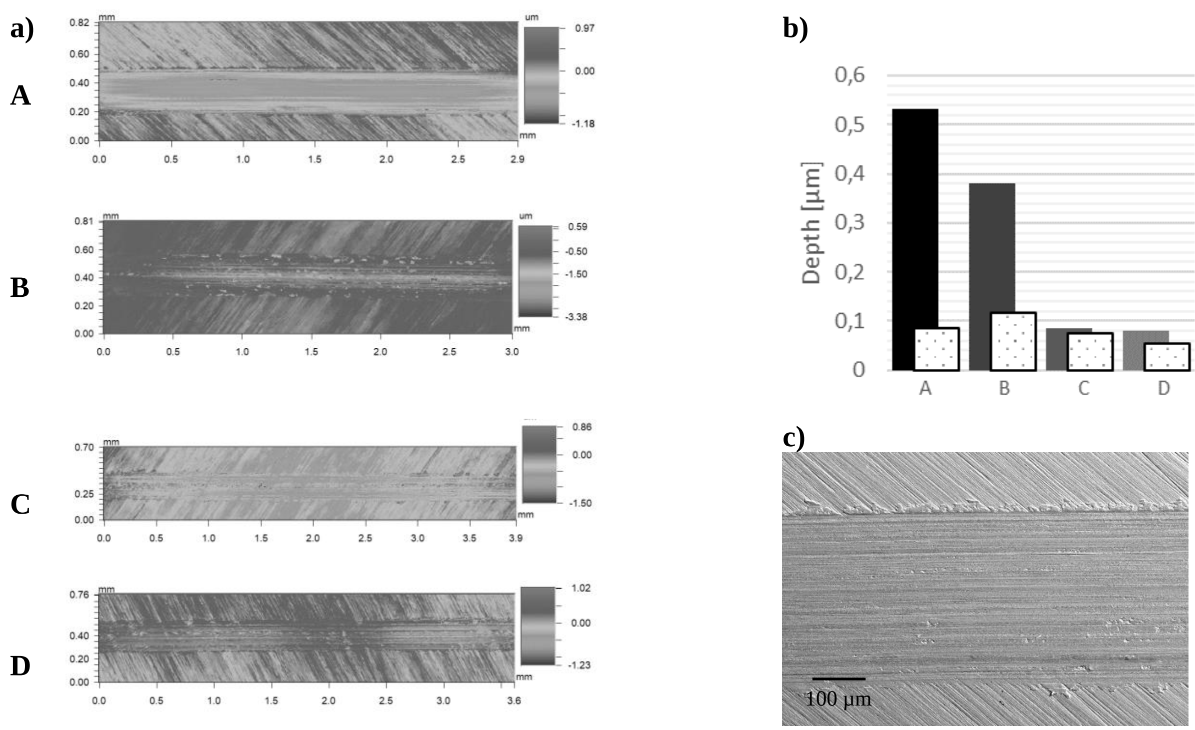

Figure 6 a) The wear mark from the interferometer for the different material A-D. b) The average depth and standard deviation of the wear mark. c) As an example, the wear mark of material A as seen by means of secondary electron microscopy in SEM.

4.2 Residual stress

The tumbling is conducted in a centrifugal tumbling unit in a batch of 30 samples. The residual stresses for as produced and tumbled material are shown in Figure 7. The values shown represents the average value of the components in the rolling direction and transversal direction, respectively.

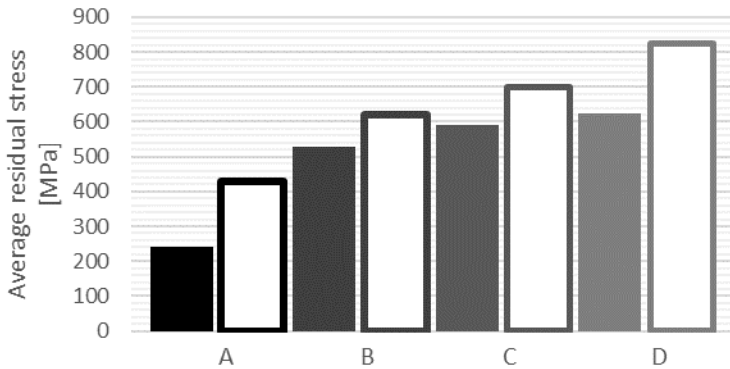

Figure 7 Residual stress for the different materials. The filled column corresponds to samples in as produced condition whilst the open column corresponds to tumbled condition, respectively.

4.3 Tensile properties and hardness

The mechanical properties are shown in Figure 8. For the materials C – D the values are of general measure for thicknesses in a wide range up to 1.0 mm. For material A, the tensile strength varies from 1650 – 2200 MPa depending on thickness. The shown values are valid for a material of thickness 0.305 mm. In a) the tensile strength is given together with the corresponding value for yield strength. In b) the hardness interval for the different materials are given. In c) the average elongation is defined by A25%.

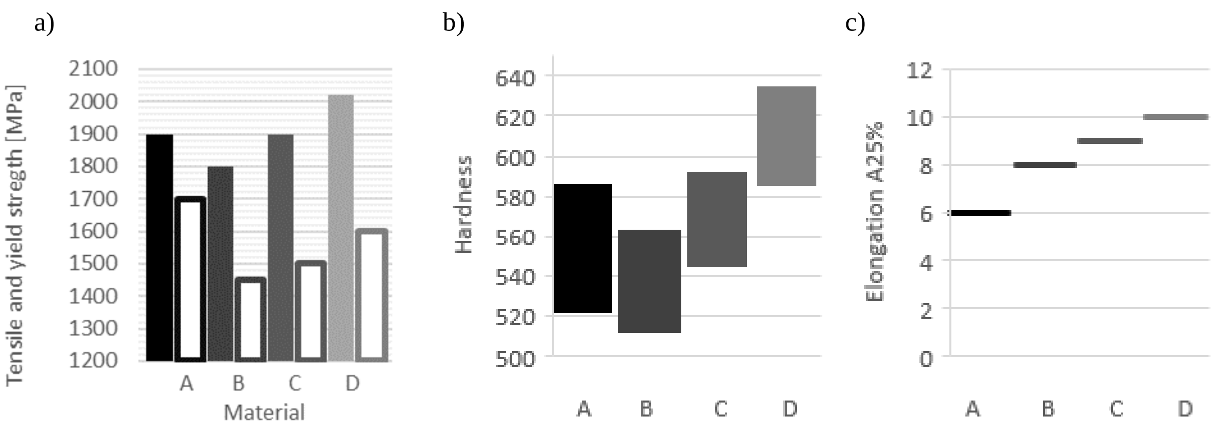

Figure 8 The mechanical properties in terms of a) Tensile strength R_m and yield strength $R_{p0.2}$ b) Hardness HV and c) Average Elongation A25%, respectively.

The thermal stabilities of the materials are evaluated. The results are shown in Figure 9. The chromium steels are almost unaffected by the additional tempering at these different elevated temperatures. The carbon steel on the other hand becomes softer as the temperature exceeds 300 ºC. The maximum utility temperature recommended for the carbon steel is 150 ºC. For the chromium steels discussed in this paper the corresponding temperature is up to 300 ºC. It is reported that the temperature in commercial compressors can exceed up to 240 ºC which indicate the need for a high thermal stability.

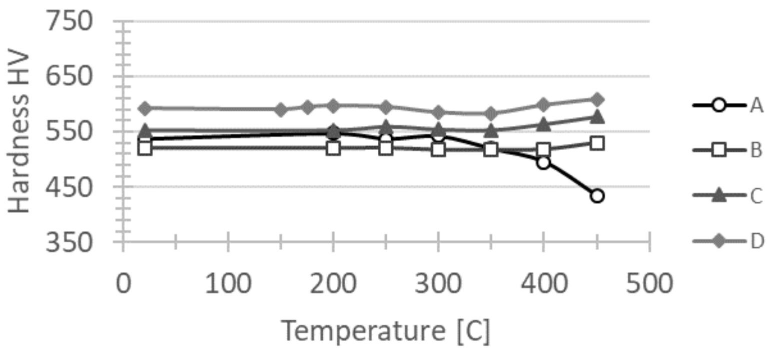

Figure 9 Thermal stability in terms of tempering resistance upon 2 h treatment.

4.4 Fatigue testing results

The fatigue properties of the above-mentioned materials are shown in Figure 10. The presented values are based on staircase method results with a probability to failure of 50 %. For fluctuating tensile strength, the load condition of R=0.1 is applied with a run out level of 5 M cycles. The maximum value is given. For bending fatigue testing the load condition R=-1 is applied with a run out level of 2 M cycles. For the fluctuating tensile strength and for the bending fatigue the capability to build surface residual stress is essential for the results. For impact fatigue a run out level of 10 M Cycles are used and the fatigue limit is given in terms of index normalized to 10 for material C.

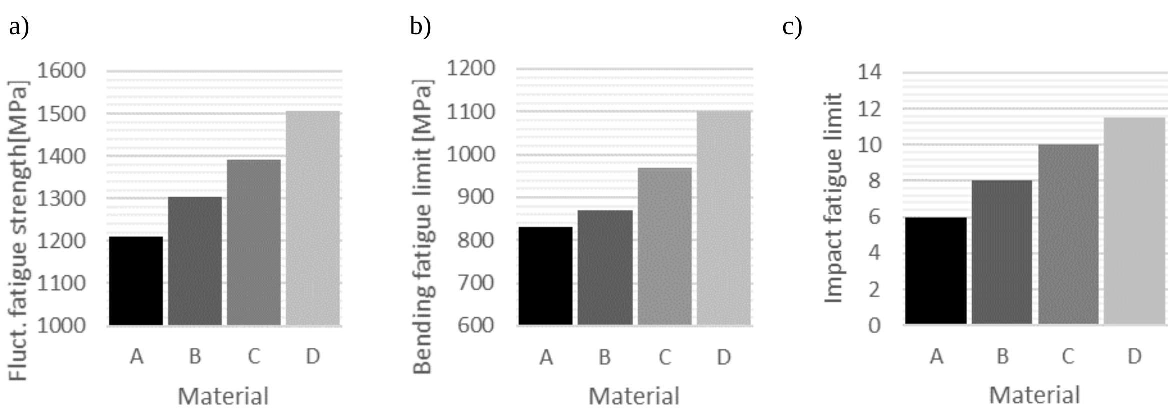

Figure 10 The fatigue properties of the various materials. a) Fluctuating fatigue strength b) Bending fatigue strength and c) Impact fatigue strength by index.

5. CONCLUSIONS

In this paper a new material is presented. The material is a further development from the well-known AISI 420 -based chromium steels. The modifications of the chemical composition enable an enhanced capability to pin the dislocations by use of solid solution strengthening, possible cluster strengthening and hardening effects by use of various precipitates. The new composition enables an increase of carbide particle density with slightly smaller sizes leading to a high wear resistance which is believed to be a crucial property for a superior performance in lifetime perspective in the compressor application. The increase of the surface residual stress acts as a further protection against surface related fractures. The development of the new material enables elevated material properties in terms of tensile strength, yield strength and elongation. These properties lead to a further increase of reliability through the improved fatigue properties, which in general terms can be stated to be about 10 % higher in comparison to the second-best material presented in this paper. The new material is clearly believed to be an important tool to allow further development of the compressor technology through enabled miniaturization and by further design developments increasing energy efficiency (COP) and thereby meeting the needed improvements to fulfill the continuously stricter legislations.

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