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PROPERTIES OF HIGH-STRENGTH VALVE STEELS

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ABSTRACT

Valves for compressors are made from a number of different high-strength strip steels. To aid the designers with the material selection five valve steels have been documented with respect to their material properties.

The steels studied are the martensitic AISI 1095 (1C steel), AISI 420 (13Cr, 0.2C) and UHB SS 716 (13Cr, 0.35C) and the austenitic AISI 301(18-8) and 17-7 PH.

The steels have been investigated with respect to composition, structure, cleanliness, general corrosion resistance, wear resistance, hardness, tensile strength in the temperature range -200 to 400°C, fracture toughness, creep rupture strength and bending fatigue strength.

INTRODUCTION

A number of high-strength strip steels are used for flexible reed valves and ring valves in compressors. The dominating grade as regards volume is the martensitic 1 % carbon steel, AISI 1095. Where there is need for better corrosive resistance the 13 % Cr steel, the 18-8 steel and the 17-7 PH are used. To aid the designer/producer with his materials selection this comparative study of properties was performed.

MATERIALS

The materials tested were strips taken from production lots, all 0.381 mm (0.015) in thickness. The chemical composition of each steel is given in Table 1.

TABLE 1. Chemical composition (wt %)

Grade	C	Si	Mn	Cr	Ni	Mo	Al
AISI 1095	1.0	0.3	0.4	-	-	-	-
AISI 420	0.18	0.37	0.49	13.2	0.41	-	-
UHB SS 716	0.37	0.45	0.45	13.5	-	1.0	-
AISI 301	0.10	0.37	1.0	17.9	7.3	-	-
17-7 PH	0.08	0.42	0.6	16.6	7.0	-	1.12

AISI 1095 was hardened from 900°C and tempered at 400°C, AISI 420 and UHB SS 716 from 1 020°C and tempered at 320°C. The austenitic AISI 301 was cold rolled and 17-7 PH was precipitation hardened by ageing for 4 h at 425°C to hardness.

Mechanical properties at room temperature as well as measured surface roughness are given in Table 2.

TABLE 2. Mechanical properties and surface roughness

Grade	$R_{p0.2}$ MPa	R_m MPa	A_5 %	HV	R_a m	R_{max} m
AISI 1095	1790	1940	6	560	0.08	0.9
AISI 420	1320	1710	9	525	0.05	0.6
UHB SS 716	1580	1870	8	570	0.12	1.2
AISI 301	1260	1290	23	415	0.07	0.5
17-7 PH	1220	1430	14	465	0.4	3.0

AISI 1095, AISI 420 and UHB SS 716 have a martensitic structure with 1, 5 and 9 percent retained austenite, respectively. The AISI 301 and 17-7 PH are austenitic. The material cleanliness is given in Figure 1 and 2 and in Table 3. Data are given only for oxide inclusions since they together with surface roughness constitute the dominating structural feature that may affect the properties of the valve. It has to be pointed out that these results are valid only for the investigated lots and that values depend heavily on the suppliers metallurgical practice.

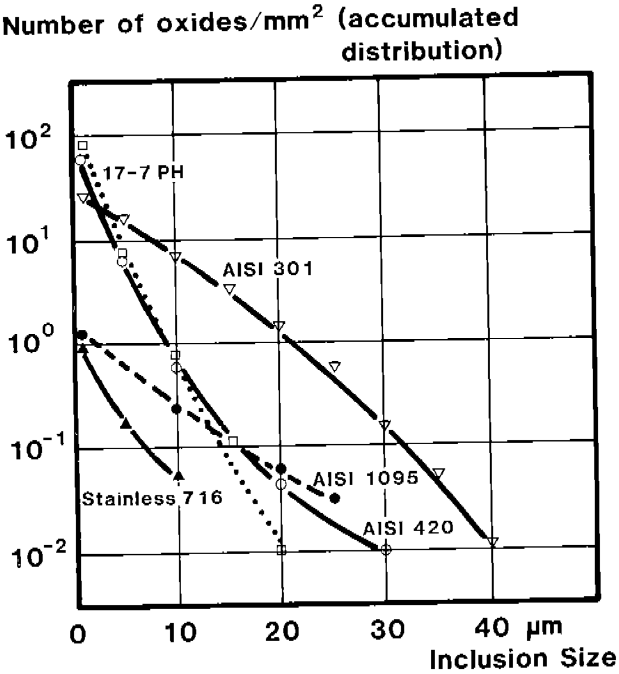

Figure 1. Number of oxides per mm² larger than indicated inclusion size.

TABLE 3. Cleanliness. Oxide inclusions.

Grade	Number of oxides in each size class			
	-5μm	5-10μm	10-20μm	> 20μm
AISI 1095	0.56	0.43	0.28	0.06
AISI 420	55.0	4.5	0.60	0.04
UHB SS 716	0.3	0.12	0.05	-
AISI 301	11.0	9.1	5.2	1.37
17-7 PH	78.0	5.9	0.54	0.01

CORROSION RESISTANCE

The ability to withstand an aggressive environment was tested according to ASTM B 117-73. Test pieces 50 x 100 mm were sprayed with a 5 % NaCl water solution at 35°C for 2 x 24 hours. The result is shown in Figure 2. As expected, the austenitic grades are the most resistant ones. For the two 13 % Cr martensitic grades, AISI 420 is more resistant owing to its lower carbon content. A lower carbon content means less chromium carbides and thus a higher chromium content in the steel matrix.

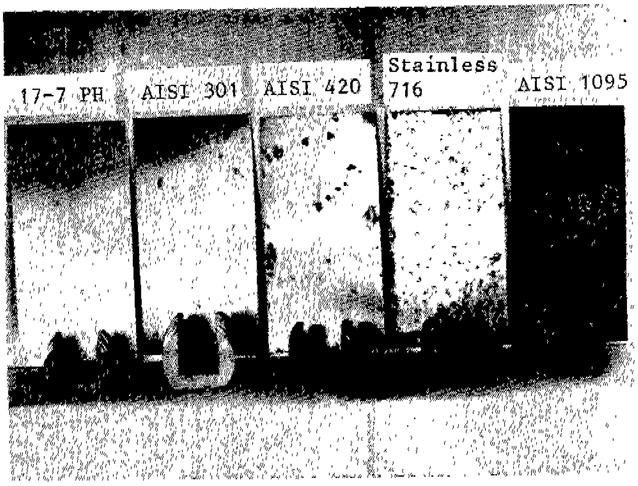

Figure 2. Corrosion test results

ELEVATED TEMPERATURE DATA

The ultimate tensile strength was determined for the temperature range -198 to 400°C. For the lowest temperature the specimens were immersed in liquid argon and for elevated temperatures they were heated with an infra-red multizone heater. The tests were performed at a deformation rate of $5 \cdot 10^{-3}$ sec^{-1}. The results are given in Figure 3.

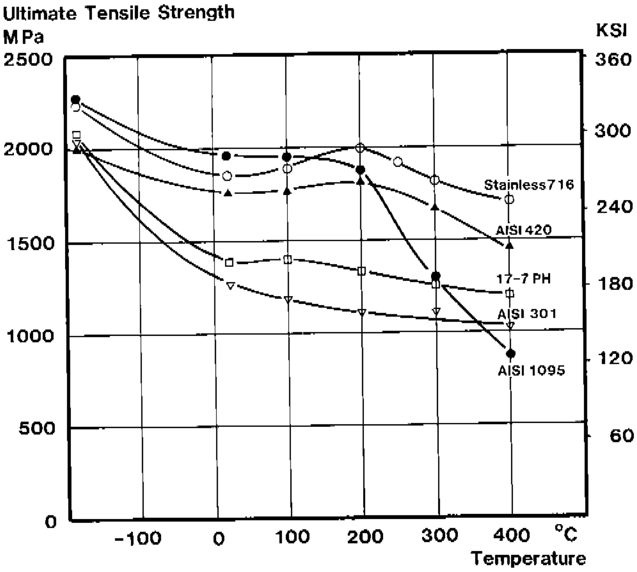

Figure 3. Ultimate tensile strength versus testing temperature.

All the stainless steels have good elevated temperature resistance but the plain carbon steel AISI 1095, shows a rapid decrease beyond 200°C.

The deformation of the valve across the discharge opening has been discussed in terms of low temperature creep. (Ref. 1) To make such an analysis possible creep rupture data in the temperature range 250 to 400°C has been collected. The results are given in Figure 4 and 5.

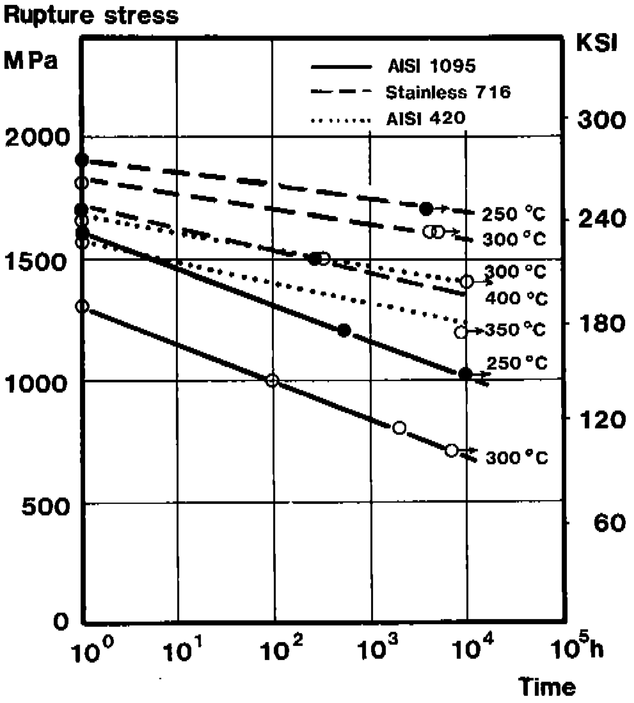

Figure 4. Creep rupture for the 1 % carbon steel and the 12 % chromium steels

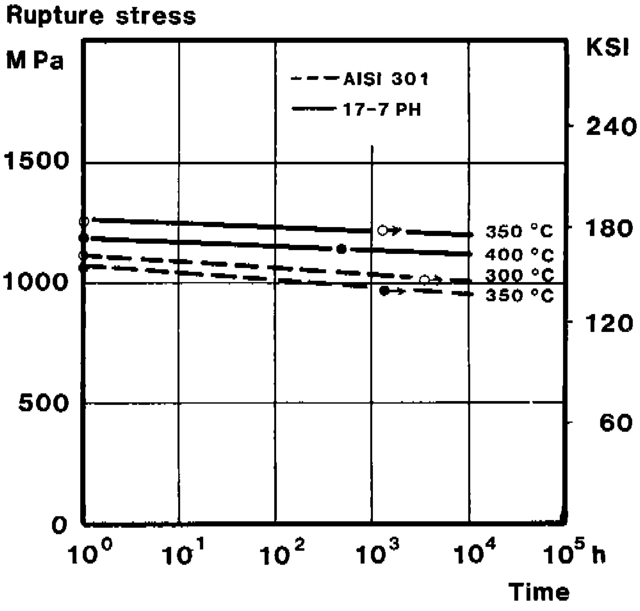

Figure 5. Creep rupture for the austenitic steels

The austenitic steels, AISI 301 and 17-7 PH, show almost no decrease in rupture strength with time whereas the martensitic steels, UHB SS 716 and AISI 420, lose some strength but only to such an extent that they always remain superior to the austenitic grades.

The AISI 1095 loses its strength so rapidly that after less than 100 hours it has lower rupture strength than the austenitic grades.

FRACTURE TOUGHNESS

The toughness testing was made on a center-cracked tension specimen with the principal dimensions as in Figure 6. Correction of K_{max} for the plastic deformation in the crack plane has been carried out according to the procedure given in Reference (2).

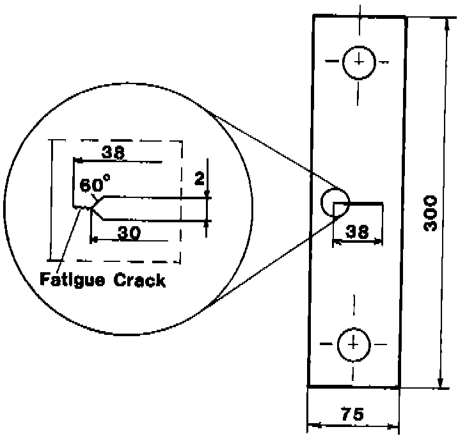

Figure 6. Center-cracked tension specimen for fracture toughness testing

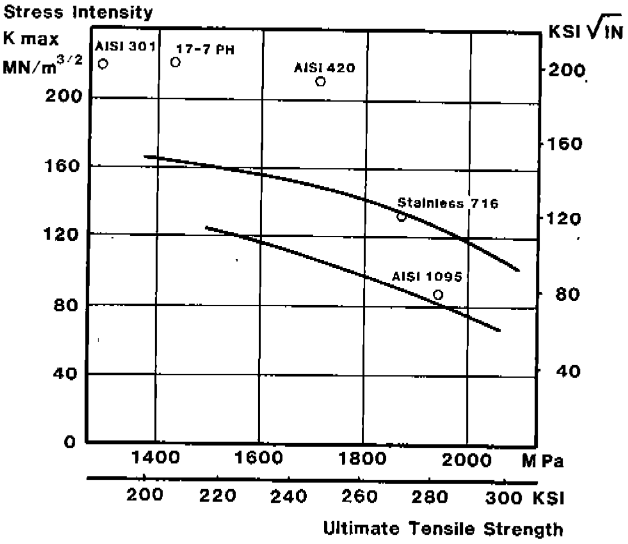

Figure 7. Fracture toughness, K_{max}, as a function of ultimate tensile strength

The general trend in the toughness results are given in Figure 7. Increasing toughness from plain carbon steel to the martensitic 12 % Cr-steels and to the austenitic grades 301 and 17-7 PH is expected. A surprisingly large difference in toughness is noted between the two 12 % Cr-steels. A part of this difference is due to the larger amounts of chromium carbides in the UHB SS 716. When the material deforms plastically, voids are initiated in the carbide-matrix interface giving rise to a more favorable path for crack propagation. This effect is also seen in plane strain fracture toughness of tool steels with similar chemical compositions.

FATIGUE

From each material some 25 cantilever bend specimen were blanked and iso-finished according to the same procedure as for compressor valves. The specimens were fatigue tested in plane reversed (R= -1) bending in a Sonntag SF-2U machine at a frequency of 30 Hz. The fatigue limit was evaluated at $2 \cdot 10^6$ cycles of life by means of the stair-case method (Ref. 3). The results are given in Table 4.

TABLE 4. Plane bending, fatigue properties

Grade	Fatigue limit MN/mm²	Fatigue limit KSI	Standard deviation MN/mm²	Standard deviation KSI	Ratio Fatigue limit/ Tensile strength
AISI 1095	± 750	± 109	10	1.5	0.39
AISI 420	± 774	± 112	15	2.2	0.45
UHB SS 716	± 820	± 119	15	2.2	0.44
AISI 301	± 580	± 84	23	3.3	0.45
17-7 PH	± 600	± 87	24	3.5	0.42

The austenitic grades, 301 and 17-7 PH, show substantially lower fatigue limits owing to their lower tensile strength. These grades also show distinctly higher standard deviations giving rise to even lower design stresses for high survival rates. This is shown in Figure 8 where the stress for 95 percent survival at a confidence level of 97.5 percent is given for the investigated materials.

The stair-case method for the evaluation of fatigue properties was designed to give the best estimate for 50 percent survival i.e. the mean fatigue limit. It is well known to give less accurate estimates of standard deviations and thus a high degree of uncertainty when extrapolated to high rates of specimen survival.

In an earlier study, Ref 4, the results from a stair-case evaluation were compared with the more accurate, and much more test-piece consuming, probit method. This study was done on AISI 1095 in pulsating loading. Mean values as well as 95 percent survival at a 97.5 percent confidence level are shown in Figure 9. The difference between the two methods is at 50 percent survival less than one percent and has grown to some 8 - 9 percent at 95 percent survival. If the distribution function is known, or postulated, fatigue stresses for even higher survival rates could be calculated with an ever - increasing difference between the two evaluation methods.

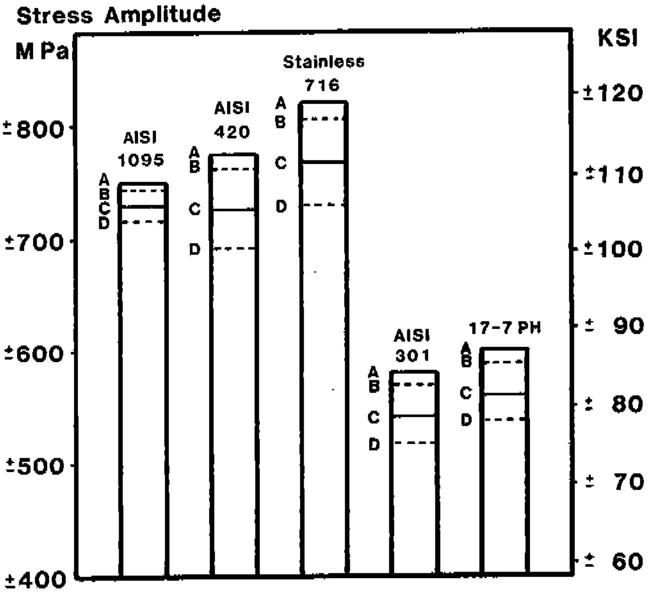

Figure 8. Mean fatigue limit (A) and fatigue stress for 95 % survival (C) at 97.5 % confidence level (B) respectively (D), for the steels investigated.

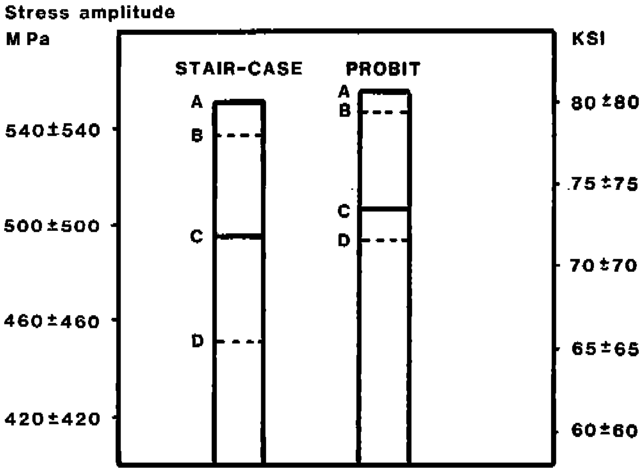

Figure 9. Mean fatigue limit (A) and fatigue stress for 95 % survival (C) at 97.5 % confidence level, (B) respectively (D), estimated from two different testing procedures.

TECHNOLOGICAL PROPERTIES

Some properties, less accurately defined than those reported so far, are important for a valve material. The blanking ability, the straightness of the valve, the wear resistance and the impact fatigue are discussed under this heading in an effort to relate these properties to the strength, ductility and structure of the valve material.

Blanking ability and valve straightness

The blanking ability of a material defined either by the wear of the punch or by the burr height is clearly related to tensile strength and ductility. A high yield-strength to tensile-strength ratio and a low ductility improves the quality of a blanked part, with a smaller burr height and a smoother blanked edge.

Of the materials investigated, AISI 1095 and UHB SS 716 have the best combination of these properties.

The geometrical quality of the valve is governed by the same basic properties. A low yield stress and high ductility lead to deformation of the blanked part. This was also observed in this study where the specimens from the austenitic grades 301 and 17-7 PH were heavily deformed.

Wear resistance

The ability of the steels to resist abrasive wear was investigated in a comparative test. Test pieces from each steel were tested in a rotating tumbling unit with 10 mm Al_2O_3-chips, SiC3-compound and water. The weight loss after different tumbling times was recorded and given in Figure 10.

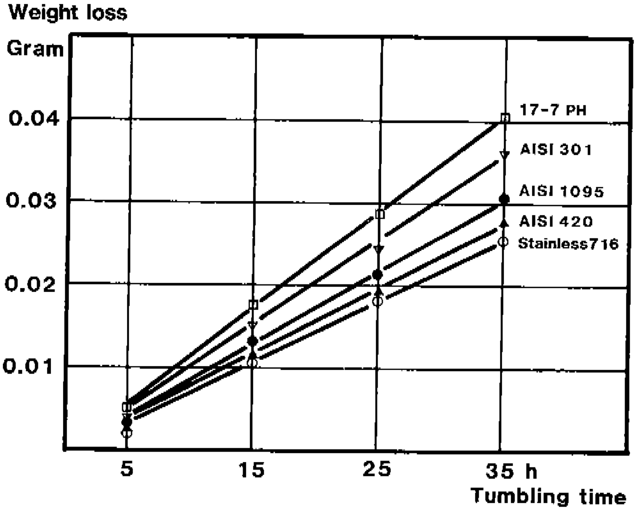

Figure 10. Weight loss versus tumbling time

The results indicate that a high volume fraction of primary carbides especially chromium carbides and high tensile strength are important for a high resistance to abrasive wear.

The wear resistance of a material is very sensitive to the environment in which the material is working. The introduction of different corrosive media may drastically change the comparative results from one test or working condition to another.

Impact fatigue

A typical failure appearance for valves is small fragments torn off from the edges due to stresses which are created when the valve hits the seat. Extensive fractographic studies (Ref 5) and laboratory simulations (Ref 6) show that this failure mechanism, impact fatigue, can be treated as conventional fatigue regarding the valve material. The main difference between the loading types is that critical impact fatigue stresses have very short duration and are very limited in extension. As for conventional fatigue the impact fatigue strength increases with mechanical strength of the material.

CONCLUSIONS

A summary of positive and negative factors for the different material/property - combinations are given in Table 5.

TABLE 5

Steel	Strength	Toughness	Fatigue	Corrosion	Wear	Blankability	Geometrical quality
AISI 1095	++	-	+	-	+	++	++
AISI 420	+	++	++	+	+	-	+
UHB SS 716	++	+	++	+	+	+	+
AISI 301	-	++	-	++	-	-	-
17-7 PH	-	++	-	++	-	-	-

The conclusions are that the overall optimum material selection are the martensitic stainless steels with preference for the UHB SS 716. For use in a non-corrosive environment AISI 1095 is the second best selection.

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