1976

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Johansson, R. and Persson, G., "Influence of Testing and Material Factors on the Fatigue Strength of Valve Steel" (1976). *International Compressor Engineering Conference.* Paper 173.
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INFLUENCE OF TESTING AND MATERIAL FACTORS ON THE FATIGUE STRENGTH OF VALVE STEEL

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INTRODUCTION

Flapper valves are critical components of compressors, pumps and internal combustion engines, and have to be extremely reliable. To seal properly, they must conform to very high standards of surface finish and flatness. Above all, high resistance to repeated bending and impact loading is required of them. Thus, the fatigue strength of valve steels is of prime importance.

Measured fatigue strength is influenced by factors of two kinds, namely testing conditions, i. e. type of load and surroundings, and the internal and external properties of the test specimens, see Table 1. Some of the factors will be dealt with below with reference to SANDVIK valve steels, Table 2. SANDVIK 15M and 20C are straight carbon steels, whose nominal composition corresponds to AISI 1074 and 1095, respectively. SANDVIK 7C27Mo2 is a special stainless chromium-molybdenum steel. Fig. 1 shows the nominal tensile strengths and yield strengths of these grades. The tensile strength tolerance is ± 100 N/mm^2 (± 14 500 psi).

FATIGUE TESTING CONDITIONS

The testing procedure has to be carefully stated in order to assure relevant fatigue test results. In fact, ostensibly identical tests of a material in two similar machines can yield different results. Thus, the interpretation of fatigue data always requires a certain element of caution.

At Sandvik, the fatigue strength of valve steels is tested in three principal ways, namely under bending stress, under purely axial stress, and, thirdly, under impact stress. Since operational flapper valves are mainly subjected to bending and impact stresses, and in view of the fact that impact fatigue testing is described elsewhere (1), the present account will deal primarily with bending fatigue.

Strips up to 0. 75 mm (. 03") thickness are tested in so-called UMG-machines, Fig. 2, partly of our own design, while thicker gauges are tested in Sonntag equipment, Fig. 3. The bending test frequency is 25 Hz. In both cases, the test specimens have trapezoidal waists, Fig. 4, the object of this shape being to expose as large a portion of the test piece as possible to a well-defined stress.

Fatigue testing of strips under axial stress is performed in Amsler high frequency pulsators. A test specimen is shown in Fig. 4.

Bending and tensile fatigue test specimens are in general blanked from strips with their axis in the rolling direction. The edges are machine ground and subsequently polished.

In certain cases, e. g. for corrosion fatigue testing, rotating bending loading is employed. Test specimens are then taken from bar stock.

In the case of bending fatigue, the stress is defined as the longitudinal stress, calculated according to the elementary theory of elasticity, in the surface of the test specimen, neglecting any residual stress. Mean stress (= prestress) and amplitude figures are always quoted when referring to fatigue strength of SANDVIK valve steels.

Up to a point, fatigue fractures are a statistical phenomenon. Consequently the Wöhler S-N curve does not illustrate an absolute value beyond which fractures invariably occur. Curves are generally given for 50 per cent probability of fracture, in certain cases together with curves for lower and higher probability of fracture.

By way of example, the Wöhler S-N curve for SANDVIK 7C27Mo2 in reversed bending is shown in Fig. 5, where curves for 2. 3, 50 and 97. 7 per cent probability of fracture are shown.

Here, the fatigue limit is defined as the stress at which 50 per cent of the test specimens can stand up to 2 x 10^6 load cycles.

Practically speaking, the fatigue limit is often determined by the staircase method, whereby testing is discontinued after fracture or after 2 x 10^6 cycles. The next specimen is subjected to a predetermined stress one step lower or one step higher. Using about thirty test specimens, we obtain an accurate figure for the stress giving 50 per cent probability of fracture, but the assessment of the stress level for high and low fracture risks is less reliable. As a rule, however, the standard deviation for fatigue strength in valve steels amounts to about 8 per cent of the fatigue limit.

WAY OF LOADING

From the literature (e.g. 2) it is known that reversed load gives a higher fatigue value than fluctuating load, and fatigue strength under bending stress is higher than under axial stress. For SANDVIK 7C27Mo2, data are given in Table 3 for the fatigue limit under various conditions. When compared with the fatigue limit in reversed bending, the amplitude is reduced by 10 per cent in fluctuating bending with prestress = amplitude. For fluctuating tensile stressing, the corresponding drop is 25 per cent.

A similar behaviour is observed for SANDVIK 20C, see Table 4.

The fatigue strength of steel at different prestresses is often presented in the form of a Goodman diagram, Fig. 6. For reversed loading, maximum stress, prestress and minimum stress are represented by the points A, B and C, and for fluctuating loading by D, E and F, respectively.

Fatigue testing is time consuming, and in many quarters efforts have therefore been made to bring down the time involved. One possible recourse is to raise the load frequency. This can be an acceptable method, at least for purposes of comparison, provided that the temperature of the test material is carefully monitored. On the other hand, if testing is conducted at such high stress levels as to come within the sloping portion of the Wöhler S-N curve, i.e. if the number of cycles preceding fracture is always far less than, say, 10^6, no conclusion can be drawn regarding the fatigue limit, which after all is the prime consideration where flapper valve steel is concerned.

INFLUENCE OF ENVIRONMENT

Temperature

Normally, fatigue strength data refer to 20°C. Fatigue strength increases with declining temperature, the effect, however, being relatively small for high strength steels. It should be mentioned that notch sensitivity also rises when the temperature is lowered (2).

Our tests on SANDVIK valve steels have revealed that at -200°C (-330°F) the fatigue strength is 15 to 20 per cent higher than at room temperature.

Fatigue strength declines at elevated temperature. For SANDVIK 15M and 20C it drops by about 10 per cent at 200°C (390°F) and 20 per cent at 400°C (750°F). SANDVIK 7C27Mo2 suffers only a slight loss of fatigue strength up to 400°C (750°F).

Atmosphere

The regular shape of the Wöhler S-N curve presupposes that no influence is exerted by a corroding atmosphere. In corrosive conditions the curve continues to decline as the number of load cycles increases even beyond $N = 10^6$.

The degree of reduction of the fatigue strength depends on the composition and the condition of the steel as well as on the corrosive agent. Carbon and low alloy steels are more sensitive than stainless steels. It has been found that the reduction of fatigue strength is more pronounced, the higher the hardness.

Already moist air is sufficient to diminish the fatigue strength. At 10^7 cycles as much as 35% reduction was reported for an AISI 4140 steel having a hardness of 52 HRC (3). The influence was less pronounced on a stainless spring steel tested under similar conditions (4). On the other hand, a maraging steel with a tensile strength of 1900 N/mm^2 experienced nearly a 90 per cent drop in fatigue strength when tested in water (5).

It is therefore to be expected that also the fatigue strength of valve steels is prone to be influenced by corrosive media. As an example, Fig. 7 shows a comparison between test results in air and water spray for SANDVIK 20C and 7C27Mo2. The polished specimens had a diameter of 7.5 mm and were tested under rotating bending condition, 50 Hz. To one litre of distilled water was added 36 mg $CaCl_2 \cdot H_2O$, 18 mg $CaSO_4 \cdot H_2O$ and 50 mg $CaCO_3$, giving a total water hardness of 6°d and pH = 7.6.

The static strength differed somewhat from the standard valve steel execution, which explains why the same fatigue strength was obtained for both grades in air. As shown in the figure, the fatigue strength of the carbon steel when tested in water was reduced by 85 per cent at 10^7 cycles. The fatigue strength of SANDVIK 7C27Mo2 was less influenced by the water: at 10^7 cycles it was three times as high as for the carbon grade.

INFLUENCE OF CERTAIN MATERIAL FACTORS

Composition

In dry air and at high tensile strength levels, alloy steels often have better fatigue properties than carbon steels. The advantage of SANDVIK 7C27Mo2 as compared with 20C in this respect is evident from the data given in Tables 3 and 4.

Microstructure

Fatigue strength increases with diminishing grain size, the latter being determined by the hardening and tempering procedure, among other things. It is impaired by inhomogeneities occurring in the form of segregation and surface decarburization. Literature data (6, 7) show that 10-50 per cent reduction of the fatigue limit can occur if ferrite appears in a surface layer. The effect is more pronounced, the higher the tensile strength. Therefore, it is essential that valve steels be fine-grained and without surface decarburization. Small carbides, evenly distributed in the structure, do not impair the fatigue strength.

Non-metallic Inclusions

Steel inevitably contains non-metallic inclusions, i.e. oxides and sulphides. Experience from our own testing and from literature shows that there are several parameters to be considered when discussing their possible influence on the fatigue strength, e.g. composition, shape, size, position and amount of inclusions. Only the initiation stage needs to be dealt with since fatigue crack propagation is of minor interest at high cycle fatigue.

No crack initiation has been found at sulphide inclusions (e.g. 8). In strip steel, sulphides are thin and have a favourable shape and orientation in relation to the ordinary stress direction. Recent investigations on experimental heats of SANDVIK 20C, show that there was no influence of the sulphur content in the range of 0.005-0.029 per cent on the fluctuating tensile and reversed bending fatigue strength, see Table 4.

Oxide inclusions may initiate fatigue cracks, provided that their shape is suitable, their size exceeds a critical value, and that they appear at a highly stressed position. This critical value declines with increasing fatigue stress applied, Table 5. For normally occurring stresses in a valve it is evident that the critical size is quite large, probably >50 μm (2 μinch). The values in the table are based on the assumption that all inclusions are spherical and of the same size and that their stress concentration effect is the same as for cavities (9, 10).

The risk of having a critical oxide inclusion at a highly stressed position diminishes with the total number of oxides, i.e. a low content of large oxides should give a high fatigue strength. The practical experience with our valve steels is that inclusions do not initiate fatigue fractures.

Static Strength

Higher tensile strength generally means higher fatigue strength, too. Thus, thin gauges of SANDVIK carbon valve steels have higher fatigue strength than thicker gauges, a consequence of the tensile strength curve, Fig. 1. The reversed bending fatigue strength/tensile strength ratio is close to 0.4 for the carbon grades.

Residual Stresses

Many investigations reported in the literature show that residual compressive stresses in the surface can considerably improve the bending fatigue strength while tensile stresses reduce it (2, 11). Compressive stresses can be introduced by different surface treatments, e.g. shot peening and tumbling. The stress distribution below the surface after a light tumbling of SANDVIK 20C is shown in Fig. 8. Higher compressive stress values at the surface and at least five times as deep a penetration has been observed after more intense tumbling.

Fatigue stresses as such can influence the state of stress (2). This is illustrated by Fig. 9, where we find that a certain stress relaxation occurs during fatigue testing. The compressive stress remaining at the specimen surface after fatigue testing is, however higher, the higher the original value.

Shape of the Test Specimen

Stress concentrations lead to a decline in the fatigue strength, as already mentioned in connection with inclusions. The influence of stress concentrations on valve steels has been studied in fluctuating tensile fatigue testing. A 5.5 mm (.22") hole was drilled in the centre of a 0.381 mm (.015") thick strip specimen with a waist of uniform width, 11.0 mm (.43"). The stress concentration factor K_t was greater than 2.2 which is the value for an ideal, polished hole of the size mentioned. Table 6 shows the effect on the fatigue strength at 2×10^6 cycles as determined by the staircase method.

The sheer size of the component under stress also has some, although only a slight, effect: the larger the volume which is put under the same stress, the higher the probability of fatigue fracture being initiated (12). Thin strips would be expected to show a somewhat higher fatigue strength than thick strips at a given tensile strength. However, in an actual application a thin valve may show a more complicated pattern of movement than a thick one, thus introducing additional stresses that may lead to a shortened life.

Positioning of the Test Object

A sample taken in the strip rolling direction will, as a rule, display a somewhat higher fatigue strength than a sample which is taken transversely. This may sometimes be due to slag inclusions, but it can also be a result of texture and surface topography, among other things. Experiments with SANDVIK valve steels have shown that the difference in fatigue strength between the two directions is approximately 5 per cent.

Surface Finish

The better the surface finish, the higher the fatigue strength up to a point where other factors dominate.

Although shot peening and tumbling generally are beneficial for the state of surface stress and thus for the fatigue strength, they may cause a rough surface, which in itself has a negative influence. Such a surface is also prone to corrosive attack. Excessive shot peening may lead to distortion.

Fig. 10 shows how surface defects shorten the life of 0.381 mm (.015") thick specimens of SANDVIK 7C27Mo2, tested under reversed bending. About 50 test specimens with intentionally introduced grooves and scratches were tested at a constant strain level. Each point in the figure is an average value for specimens with depth of grooves and scratches within a certain range. Only specimens with fatigue cracks initiated at surface defects were considered in the evaluation.

Edge Finishing

An even, rounded edge is an advantage in terms of fatigue strength. The purpose of tumbling a valve after blanking is in the first place to remove burrs and scratches from the edge. Furthermore, the blanked edge has a residual tensile stress, which will be replaced by a desirable compressive stress during this process.

The valve manufacturer can achieve maximum safety against bending fatigue fractures by designing the valve suitably, positioning it correctly in relation to the strip, avoiding surface defects, and by treating the edges in an appropriate way.

SIMULTANEOUS INFLUENCE OF SEVERAL FACTORS ON THE BENDING FATIGUE STRENGTH

Of the various factors mentioned above, strip thickness, tensile strength and surface finish have been varied in a number of reversed bending fatigue tests on SANDVIK 20C valve steel. All test specimens were given the same edge treatment, namely hand-polishing. The residual stress in the loading direction was determined. Table 7 shows the relevant data. It is no simple matter to draw instant conclusions from this table regarding the influence of individual parameters on the bending fatigue limit. For instance, relating bending fatigue strength to tensile strength, we obtain a considerable dispersion of measurements, as shown in Fig. 11. On the other hand, a multiple regression analysis gives a relatively good collection of measured and calculated fatigue data, Fig. 12, around a regression line having the following equation

$$\sigma_D = 319 + 0.208 \cdot R_m - 226 \cdot R_a + 0.390 \cdot \sigma_R - 171 \cdot t$$

$$(\sigma_D = 46\,300 + 0.208 \cdot R_m - 830 \cdot R_a + 0.390 \cdot \sigma_R - 630\,000 \cdot t)$$

where σ_D is the bending fatigue strength in N/mm^2 (psi) at 2×10^6 load cycles, 50 per cent probability of fracture

R_m = tensile strength in N/mm^2 (psi)
R_a = surface roughness in μm (μinch)
σ_R = residual compressive stress in N/mm^2 (psi)
t = strip thickness in mm (inch)

The multiple correlation coefficient is 0.89 and the standard error of the estimated fatigue strength is approximately 60 N/mm^2 (9 000 psi).

The analysis shows that, relatively speaking, the state of the residual stress has the greatest effect on the result. Thus, a high compressive stress in the surface is beneficial.

The influence of the tensile strength in the formula is perhaps less than anticipated. This may be due to the notch sensitivity factor making itself felt at the tensile strength considered and being included in the coefficient for R_m.

The coefficients of R_a and t have the anticipated sign, in other words a fine surface and a light strip gauge are advantages in terms of fatigue strength.

A good deal of uncertainty is attached to all coefficients resulting from the statistical calculation, which, accordingly, should not be given a general validity. However, the exercise clearly demonstrates the great influence on the bending fatigue of factors that are introduced partly during steel production, partly during component manufacture.

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Table 1
Factors influencing the measured fatigue strength

Testing conditions	Material parameters
Way of loading	Internal factors
stress distribution	composition
rate of loading	microstructure
frequency	non-metallic inclusions
	static strength
Environment	internal stresses
temperature	
atmosphere	External factors
	shape of specimen
	specimen orientation
	surface condition
	edge preparation

Table 2
Grades

SANDVIK	Chemical composition (nominal), % C	Si	Mn	Cr	Mo
15M	0.75	0.2	0.75	-	-
20C	1.00	0.25	0.45	-	-
7C27Mo2	0.38	0.4	0.6	13.5	1.0

Table 3
SANDVIK 7C27Mo2. Fatigue limit under various loading conditions

Way of loading	Fatigue limit N/mm²	1000 psi	rel. amplitude
Reversed bending	±860	±125	100
Fluctuating bending	770±770	112±112	90
Fluctuating tension	650±650	96±96	75

Table 4
SANDVIK 20C, experimental heats. Influence of sulphur content on the fatigue limit.

Heat	Thickness mm	inch	Sulphur %	Tensile strength N/mm²	1000 psi	Residual compressive stress N/mm²	1000 psi	Tensile fatigue limit N/mm²	1000 psi	Reversed bending fatigue limit N/mm²	1000 psi
A	0.381	.015	0.010	2000	290	155	23	650±650	94±94		
B strip 1	0.381	.015	0.029	2090	303	220	32	655±655	95±95		
B strip 2	0.381	.015	0.029	2100	304	225	33	640±640	93±93		
C	0.381	.015	0.005	1850	268	155	23	575±575	83±83	±760	±110
D	0.381	.015	0.012	1790	260	215	31	575±575	83±83	±780	±113
E	0.305	.012	0.011	1825	265	170	25	595±595	86±86		

Table 5
Critical cavity size in µm at different tensile strengths and fatigue limit/tensile strength ratios

σ_D/R_m	K_f	Tensile strength, N/mm² (1000 psi) 1000 (145)	1500 (218)	2000 (290)	2500 (363)
0.28	1.78	700	350	200	130
0.30	1.67	400	200	110	70
0.32	1.56	250	115	70	45
0.34	1.47	170	80	50	35
0.36	1.39	110	60	35	25
0.38	1.32	80	40	25	18
0.40	1.25	60	30	18	12
0.42	1.19	40	20	12	8
0.44	1.14	25	15	8	6
0.46	1.09	15	10	5	4
0.48	1.04	7	5	2	<1

Table 6
Influence of stress concentration on the fluctuating tensile fatigue strength

SANDVIK	K_t	Tensile strength N/mm²	1000 psi	Fatigue strength N/mm²	1000 psi
20C	1 *)	1890	274	550±550	80±80
20C	>2.2	1890	274	205±205	30±30
7C27Mo2	1	1960	284	690±690	99±99
7C27Mo2	>2.2	1960	284	220±220	32±32

*) standard, unnotched specimens

Table 7
SANDVIK 20C
Simultaneous influence of several parameters on the fatigue limit.

Strip thickness		Surface condition	Direction of stressing	Tensile strength		R_a (CLA)		Res. compr. stress before fatigue test		Reversed bending fatigue limit	
mm	inch			N/mm^2	1000 psi	µm	µinch	N/mm^2	1000 psi	N/mm^2	1000 psi
0.381	.015	Polished	Long.	2000	290	0.05	2	160	23	±680	±99
0.381	.015	Polished	Long.	2100	304	0.05	2	230	33	±800	±116
0.381	.015	Polished	Transv.	2100	304	0.08	3	250	36	±740	±107
0.381	.015	Polished	Long.	2090	303	0.05	2	220	32	±840	±122
0.381	.015	Polished	Transv.	2090	303	0.08	3	260	38	±720	±104
0.381	.015	Fine ground	Long.	1800	261	0.15	6	450	65	±790	±114
0.381	.015	Polished	Long.	1820	264	0.09	4	130	19	±660	±95
0.381	.015	Fine ground + tumbled	Long.	1800	261	0.23	9	500	73	±790	±114
0.381	.015	Polished + tumbled	Long.	1800	261	0.19	7	350	51	±700	±101
0.787	.031	Fine ground	Long.	1790	260	0.07	3	230	33	±610	±88
0.787	.031	Fine ground	Transv.	1770	257	0.27	11	350	51	±580	±85
0.787	.031	Fine ground + tumbled	Transv.	1760	255	0.35	14	540	78	±780	±113
0.787	.031	Coarse ground	Transv.	1610	233	0.65	26	200	29	±430	±62
0.787	.031	Shot peened	Transv.	1760	255	0.69	27	680	98	±580	±84
0.787	.031	Shot peened + tempered	Transv.	1740	252	0.69	27	280	41	±570	±83

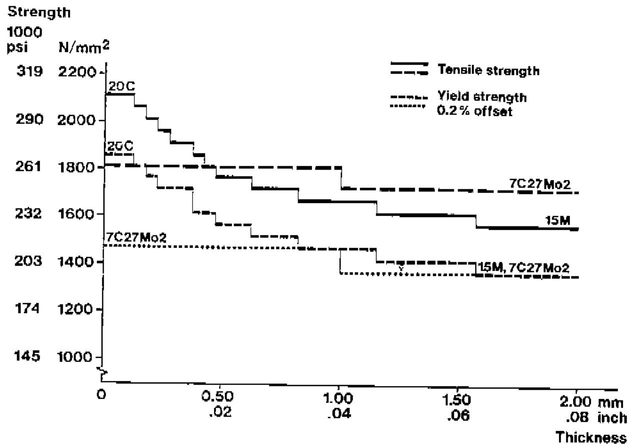

Figure 1
SANDVIK valve steels, static strength, nominal values at 20°C (68°F). SANDVIK 20C in thicknesses ≤1.00 mm (.039") and SANDVIK 15M in thicknesses >1.00 mm (.039").

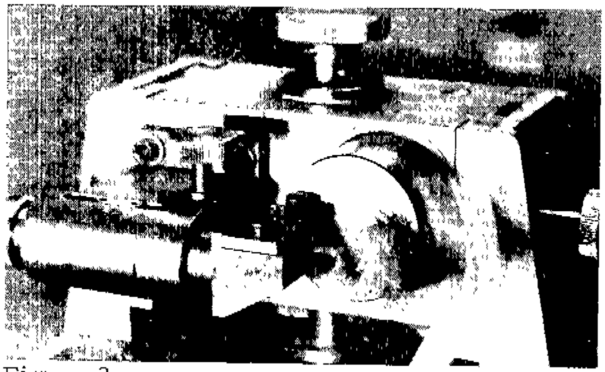

Figure 2
Bending fatigue testing machine, type UMG, used for strip thicknesses of max 0.75 mm (.03").

Figure 3
Sonntag bending fatigue testing machine, used for strip thicknesses >0.75 mm (.03").

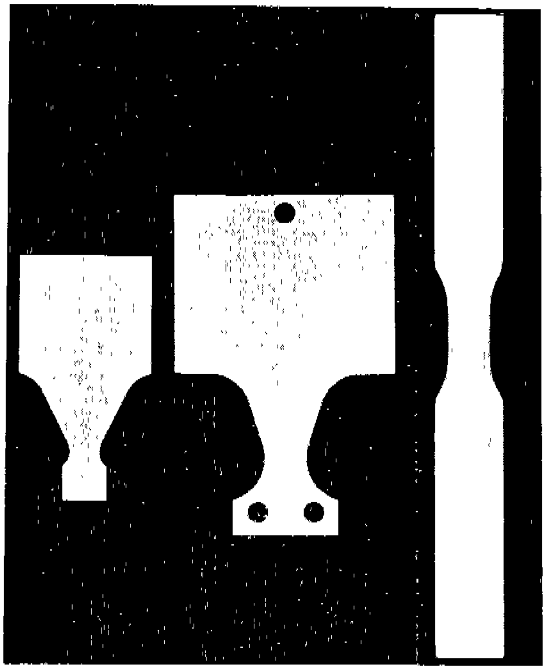

Figure 4
Specimens for bending fatigue testing in UMG (left) and Sonntag (middle) machines, for axial fatigue testing in Amsler high frequency pulsator (right). 0.7x

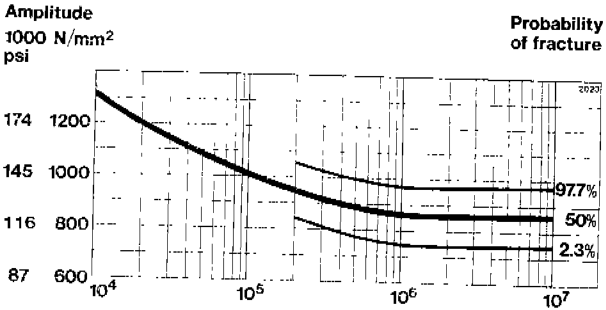

Figure 5
Wöhler S-N curve for SANDVIK 7C27Mo2 in reversed bonding. Tensile strength 1810 N/mm^2 (262 000 psi). Thickness ≤1 mm (.039").

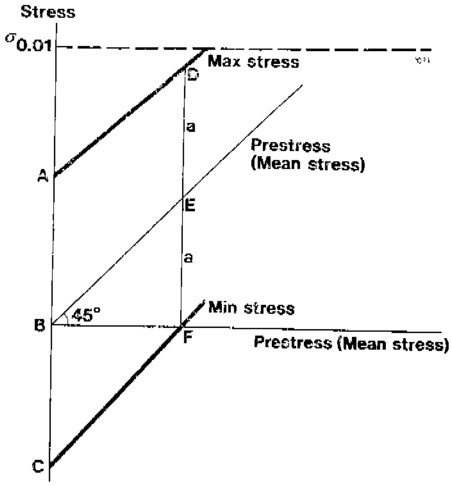

Figure 6
Goodman diagram, principle

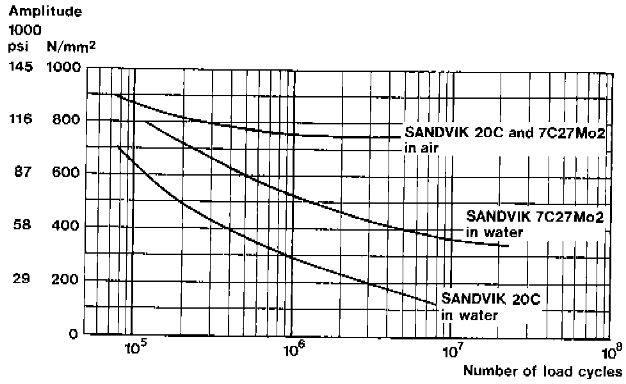

Figure 7
SANDVIK 20C and 7C27Mo2. The influence of corrosion on fatigue strength.

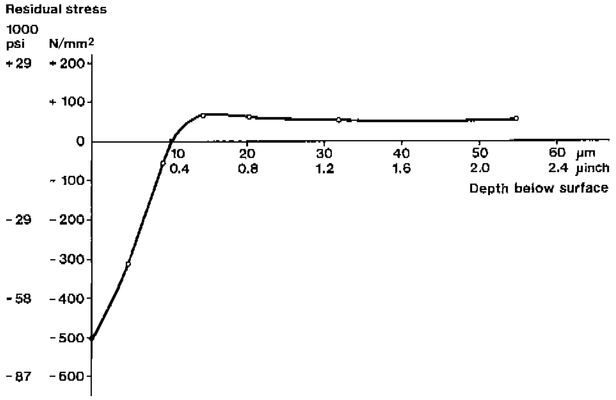

Figure 8
SANDVIK 20C. Residual stress distribution.

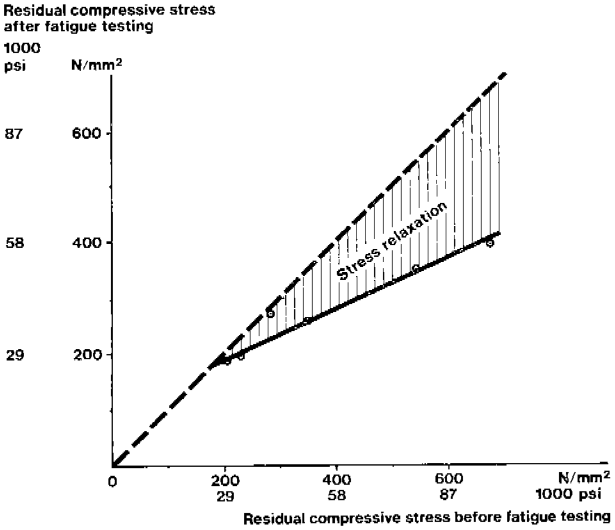

Figure 9
SANDVIK 20C. Change in residual stress due to fatigue loading.

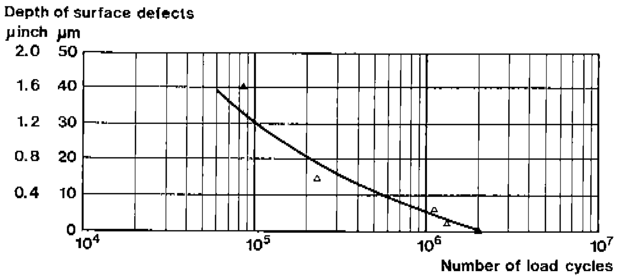

Figure 10
SANDVIK 7C27Mo2. Effect of grooves and scratches on the fatigue life.

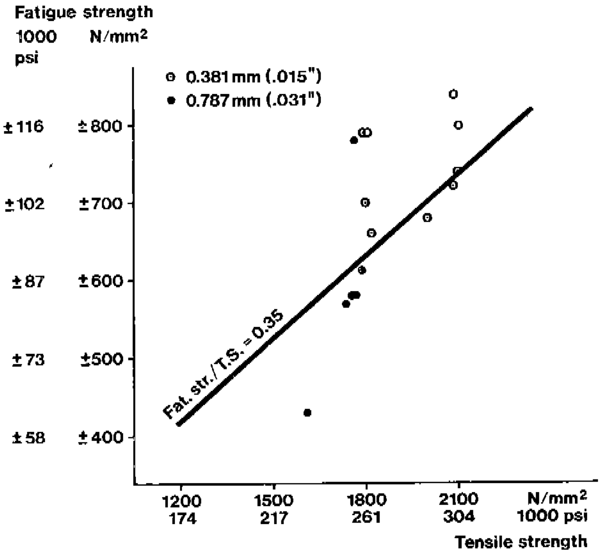

Figure 11
SANDVIK 20C. Fatigue limit in reversed bending versus tensile strength.

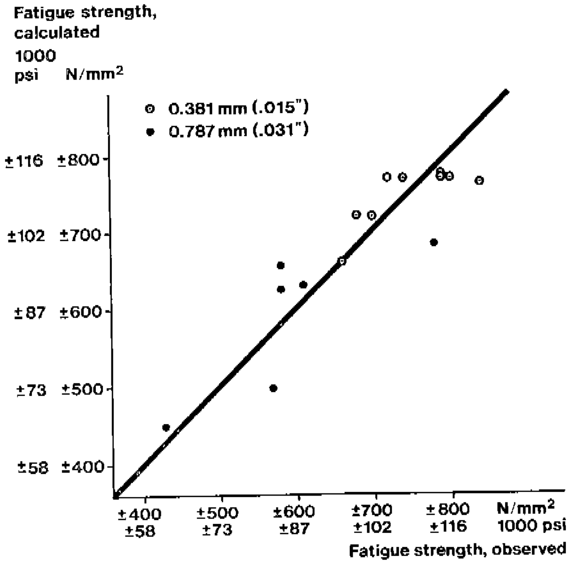

Figure 12
SANDVIK 20C. Observed and calculated fatigue limit in reversed bending.