SKF C-110, a high strength steel with high resistance to Sulphide stress cracking

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SKF C-110, A HIGH STRENGTH STEEL WITH HIGH RESISTANCE TO SULPHIDE STRESS CRACKING

Ovako has an extensive R&D since many years, an area that now is in an even higher intensity. Some of the R&D work is published in our technical reports.

Due to that Ovako of today has had a number of different company names and used various trade marks we have until now chosen to not have these reports publicly available. However, many of these technical reports contain valid data about material and steel grades that we still promote, but with other names etc

The following Technical Report from 1987 is about a product that was developed for a special Oil & Gas application. See also Ovako Archive technical report 6 1983 about an earlier stage in this development

Data and processes in this report represent state of art at time of publishing.

In this Technical Report there is used the following Company names and trade marks that no longer is used by Ovako AB

Ovako Steel AB; This company name is no longer used. The organization is now part of Ovako AB.

SKF C-110; this grade and product name is no longer in use.

Technical Report 1/1987

SKF C-110, a High Strength Steel with High Resistance to Sulphide Stress Cracking

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OVAKO STEEL AB

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1. Introduction

In oil and gas exploration and production, hydrogen sulphide (H_2S) is becoming an increasingly bigger problem as deeper wells are drilled and with increased use of sophisticated recovery methods. Severe and quick sulphide stress cracking (SSC), hydrogen induced cracking (HIC) and general corrosion are common results from the action of H_2S on steel. The deeper wells also call for higher strength material. Such material generally also has a higher tendency for SSC. (1,2,3). H_2S is also highly toxic and every step must therefore be taken to prevent H_2S leakages.

Extensive research and development work has been devoted to understand and find solutions to the problems caused by H_2S.

One of the most difficult problems to understand and combat is SSC. Through extensive testing and development work Ovako Steel has developed a new high strength steel grade, SKF C-110, which exhibits excellent resistance to SSC to stresses up to almost 100 % of the yield strength in all generally accepted corrosion tests.

2. Production Route

The production route for SKF C-110 is illustrated on the center spread. The most important steps for the final properties of the finished product are:

- Steelmaking
- Tube rolling
- Cold working
- Heat treatment
- Final inspection

2.1 Steelmaking

The most important properties of the steel grade are set already in the steel making stage. It will be shown later that among others the content of inclusions, both macro and micro, has a great influence on the SSC-resistance of the steel.

At Ovako Steel we have developed a steel making process, which makes sure that we meet the most stringent requirements, primarily from the bearing industry, but also from other demanding market segments.

The MR process comprises two production steps, one melting stage, M, under oxidising conditions and one refining stage, R, under reducing conditions, see **fig. 1**.

The melting operation produces a liquid raw steel which then is refined in an ASEA-SKF ladle furnace. More detailed explanations on our MR steelmaking technology are available in our technical litterature (4, 5). In the ASEA-SKF ladle furnace a number of operations can be performed as illustrated in **Fig. 1**. The MR steel is characterized by consistant chemical compositiv and very low contents of non-metallic inclusions - in fact the content of macroinclusions is almost nil (**table 1**).

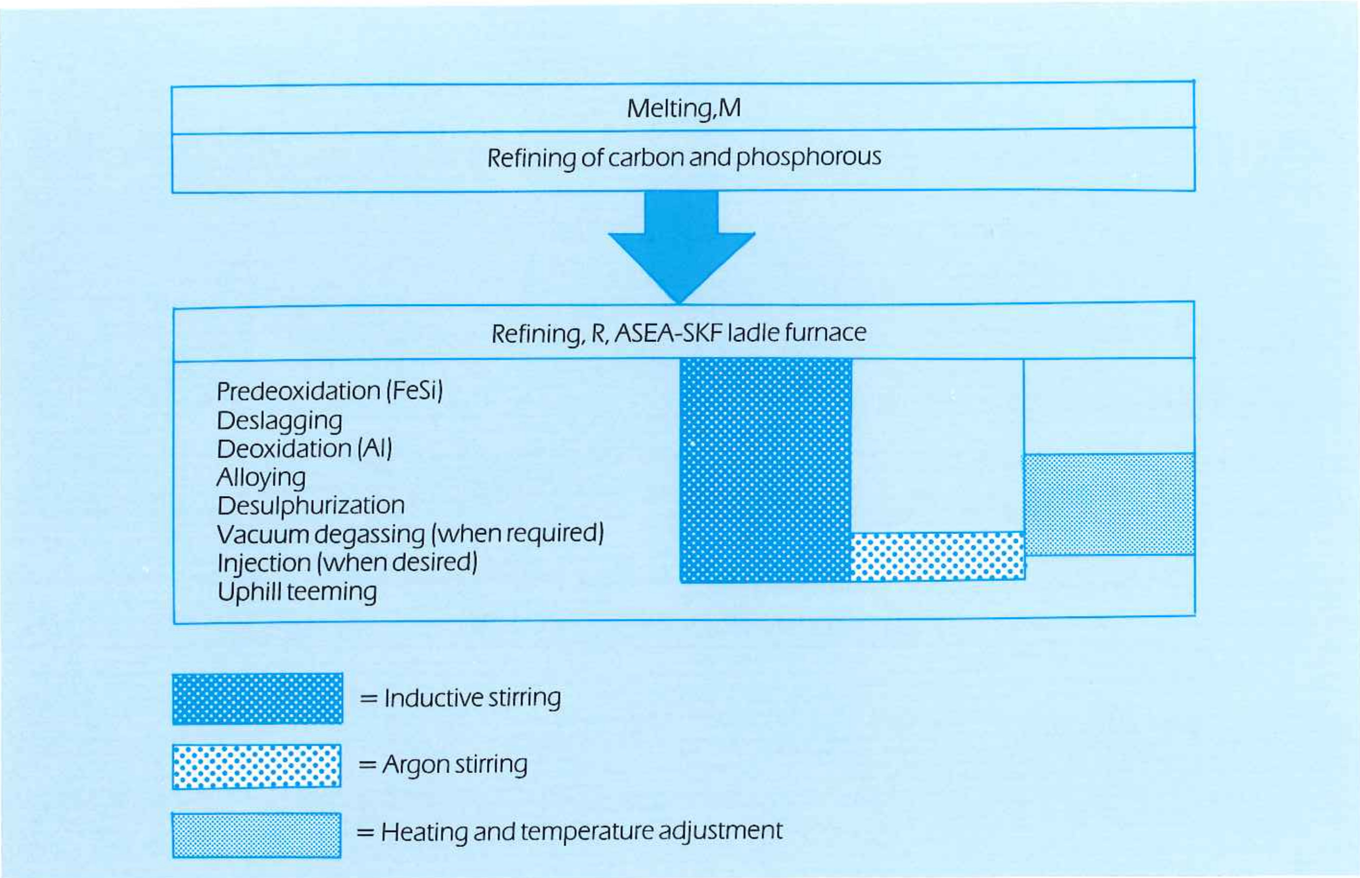

Fig. 1 The MR Process

Table 1
Content of non-metallic inclusions in SKF C-110.

	Guarantee value	Average value
Macro inclusions (down test)	5 mm/mm^2 0.02 inch/ft^2	0 mm/m^2 0 inch/ft^2
Micro inclusions (ASTM A295)		
A-type thin	1.5	0.8
heavy	1.0	0.6
B-type thin	1.5	1.0
heavy	0.2	0
C-type thin	0	0
heavy	0	0
D-type thin	0.5	0
heavy	0	0

2.2 Tube manufacturing

The tubes at Ovako Steel are made in a rotary piercer followed by processing in an Assel rolling mill. Tubes made this way have tight tolerances and small wall variations.

The cold working of the SKF C-110 tubes with area reductions of usually 40-65 % give them their high strength and conventional quenching and tempering is therefore not necessary. This cold working gives the tubes a microstructure with very low susceptible to SSC. This is contrary to quenched and tempered martensite structures which are very susceptible to SSC when the strength is above a certain level (1, 2, 3).

The advantages of this cold-working can be summarized as:
- tighter tolerances
- good concentricity
- smooth surfaces
- improved machinability
- high strength
- high resistance to SSC

2.3 Dimensions and tolerances

The standard dimensional range and the tolerances are presented in **fig. 2.** and **table 2**. This standard range covers the most frequent tubing and coupling stock sizes. On special request we also produce tubes outside this standard range. The closer tolerances compared to API can be used to increase the inner diameter of the tubing, which means increased production from the wall.

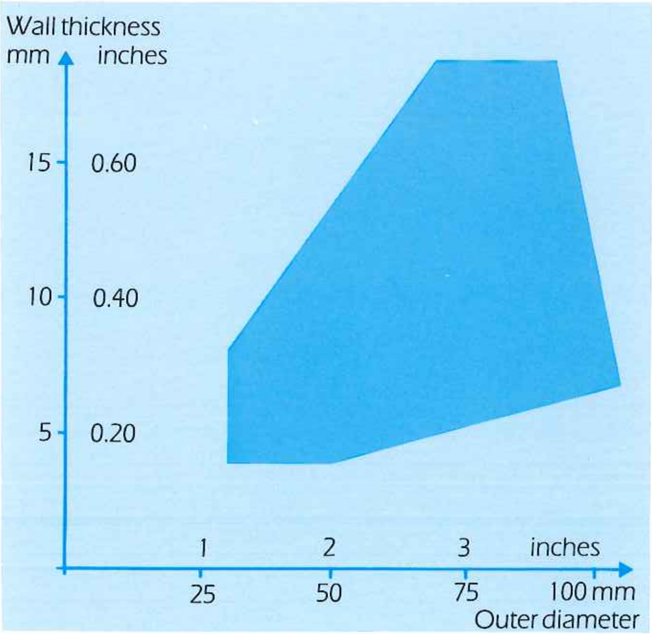

Fig. 2 Standard size range.

Table 2
Tolerances for SKF C-110

OD:	± 0.3 mm (± 0.012".)
Wall:	± 7 % or ± 0.4 mm (0.016") which ever is bigger
Out of roundness:	± 0.25 mm (± 0.010".)

The cold worked SKF C-110 tubes are stress relieve annealed at 400-600° C to increase their resistance to SSC, without essentially losing in strength. Temperatures above 600° C in the finished SKF C-110 tubes must be avoided. This would decrease the strength of the tubes.

2.4 Non-destructive testing

A final inspection is performed on all SKF C-110 tubes to verify their high quality. The tubes are inspected to 100 % for wall variations, macro inclusions, cracks and outer diameter (OD). The OD test is made by a laser scanner - the other inspections by ultrasonics. The ultrasonic system comprises 2 x 18 transducers for crack detection and 1 x 12 transducers for wall thickness, evaluating together more than 200 functions per pulse cycle in a fully computerized system.

All longitudinal surface or internal defects bigger than 0.25 mm (0.1 inch.) are detected by this device, which also covers angles from 0-30° to the longitudinal direction. Wall thickness and OD are measured to an accuracy of 0.05 mm (= 0.002 inch.). From every batch of tubes a histogram of the distribution of minimum wall is drawn on request. **(Fig 3).**

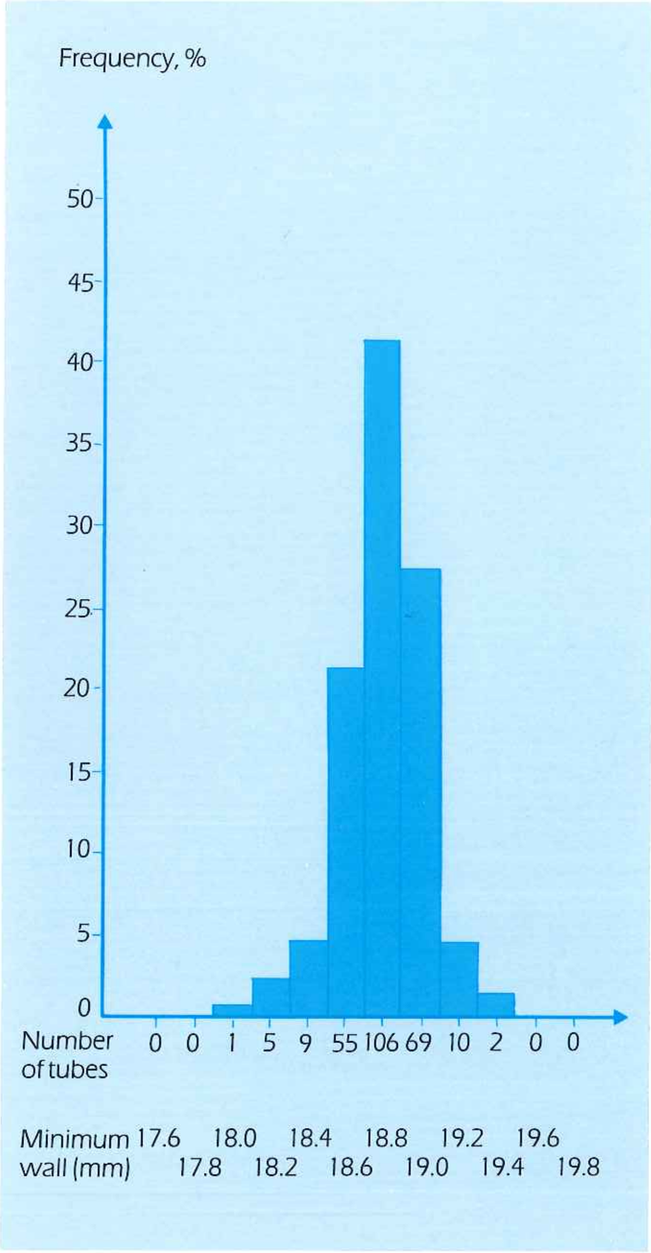

Fig. 3. Histogram of minimum wall distribution for 257 tubes.

3. Material Properties

3.1 Chemical composition

SKF C-110 is a low-alloy CMn-steel microalloyed with vanadium and balanced amounts of chromium and copper, **table 3**.

The vanadium contributes substantially to the strength of the steel by forming very fine vanadium carbo-nitride precipitates all through the steel. Copper and chromium contribute to the resistans to SSC and HIC (6, 7).

The residual elements sulphur and oxygen are kept on low levels in order to minimize the contents of non-metallic inclusions, **table 3**.

Table 3
Average chemical composition of SKF C-110

C	Si	Mn	V	Cr	Cu %
.20	.30	1.50	.10	.20	.20
P max 0.015 % S max 0.010 % O max 15 ppm					

Due to the low amounts of sulphur and oxygen the contents of non-metallic inclusions can be kept at very low levels, which is of great importance for the resistance to both SSC and hydrogen induced cracking (8 – 12), see **table 1**.

3.2 Microstructure

SKF C-110 has a ferrite-pearlite microstructure **(fig. 4)**.

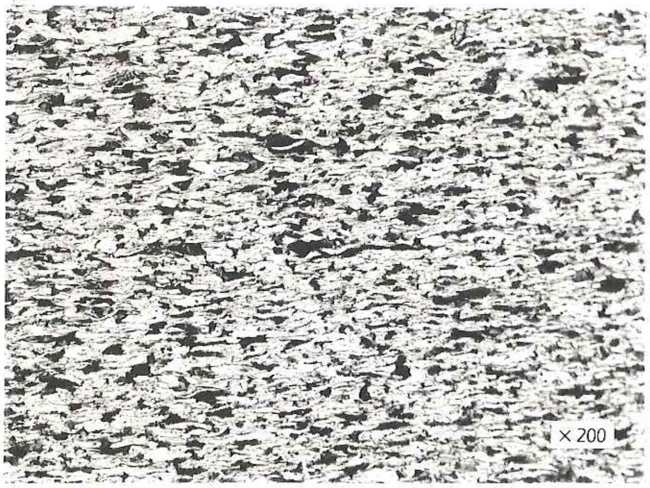

Fig. 4. Ferrite-pearlite microstructure of SKF C-110.

The total absence of martensite is one of the major reasons why SKF C-110 has very low susceptibility to SSC. The transmission electron microscope reveals a substructure with distinct subgrains formed during the cold-working and subsequent stress relieve annealing **(fig. 5)** There is a low dislocation density within these subgrains. The microstructure deviates clearly from common cold worked structures such as those after drawing or heavy straightening where the degree of cold deformation is much less than in SKF C-110.

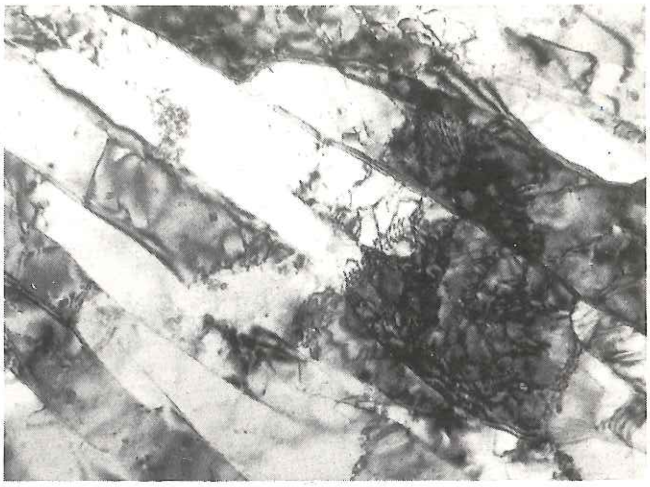

Fig. 5. Transmission electron micrograph. Low dislocation densities within subgrains. ~ × 12000.

3.3 Mechanical properties

3.3.1 Tensile, hardness, impact

The mechanical properties of SKF C-110 are given in table 4.

Table 4
Mechanical properties of SKF C-110

Yield strength	758 – 862 MPa 110.000 – 125.000 psi
Ultimate tensile strength	793 – 965 MPa 115.000 - 140.000 psi
Elongation	A5 = min 15 %
Hardness	240 – 320 HV 19 – 32 HRC
Impact strength KV at + 20° C (+ 68° F)	min 27 J " 20 ftlb
For half size specimens 5 x 10 mm KV 150/5	min 16 J " 12 ftlb
For special requirements we offer KV at –40° C (– 40° F)	min 27 J " 20 ftlb
For half size specimens 5 x 10 mm KV 150/5	min 16 J " 12 ftlb

Other low-alloy steels intended for use in H_2S environments are restricted in hardness to a certain max value. The commonly used max value is HRC = 22. This value is based on results from numerous corrosion tests on quenched and tempered steels, i.e. steels with a martensitic structure. Such steels, having HRC readings above 22 are susceptible to SSC (13.14).

For SKF C-110, which is a ferrite-pearlite steel, the upper hardness limit is not set by corrosion. However, there is a limitation for practical reasons. This upper limit is HRC = 32 (320 HV). The hardness variation within each delivery of tubes is extremely small. **Fig. 6** is an example of this. In a delivery of 650 tubes the hardness was tested on 76 tubes, two from each heat treatment lot, and 12 Vickers indentation per tube. The total variation from the highest to the lowest reading of these 912 indentations was only ± 9 Vickers, corresponding to ± 1.4 HRC and the standard deviation was only ± 3.5 HV units (± 0.6 HRC)!

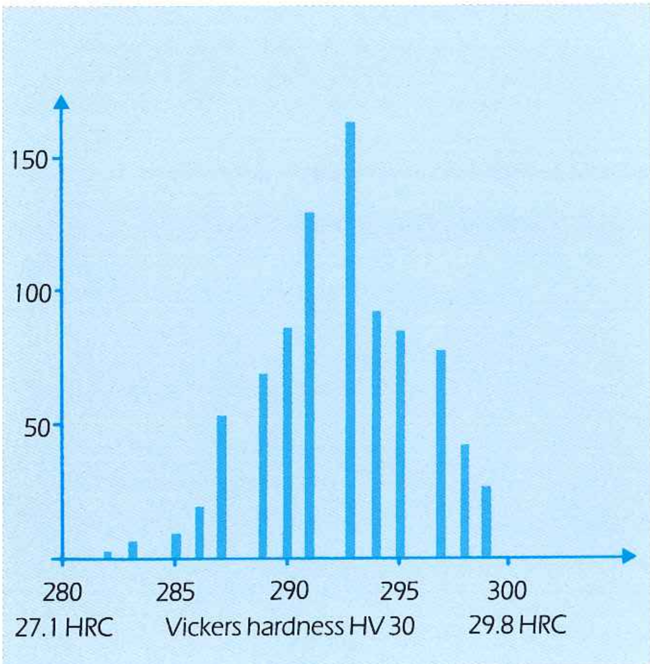

Fig. 6. Hardness distribution of 912 identations from 76 tubes SKF C-110

3.3.2 Isotropy

Because of the proposed usage of SKF C-110 tubes in high pressure applications, special attention has been given to prove that the material is isotropic, i.e. its mechanical properties are the same in all directions and all through the material. This was verified by three types of tests:

– hardness measurements over the wall section
– tensile tests in hoop (= transverse) direction
– pressure tests with strain gauges.

The hardness across the wall of SKF C-110 tubes normally does not vary more than ± 5 HV (about ± 0.7 HRC) **(fig. 7)** which is much less than can be expected in quenched and tempered tubes.

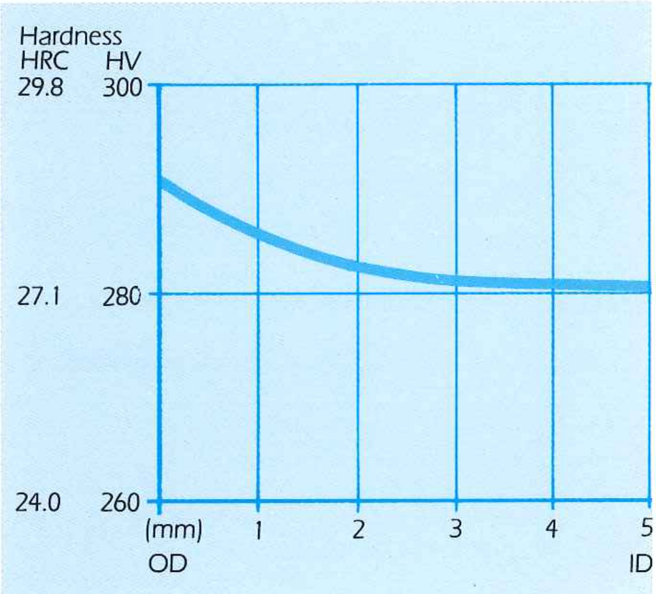

Fig. 7. Hardness through the wall of 2.900 x .217" (73.0 x 5.5 mm) SKF C-110 tubing.

Small tensile test bars, 3 x 4 mm in cross section, were cut in the transverse (hoop) direction. Strain gauges were attached on both sides, and the samples were tested in a tensile machine. The yield strength in the hoop and axial directions were compared and an isotropy factor, Ø, was defined:

$$Ø\,(YS) = \frac{YS\,(hoop)}{YS\,(axially)}$$

Oil country tubular goods (= OCTG) of various grades and from varous origins were tested in this way. The results show that you have to be aware of the anisotropy when dealing with standard OCTG, but for SKF C-110 the anisotropy is negligible, the isotropy factor being 0.975 (**table 5**).

Table 5
Isotropical behavior of some OCTG

Grade	Tube size OD x ID (mm)	Longitudinal yield strength (MPa)	Hoop yield strength (MPa)	Isotropy factor Ø
N-80	73.1 x 61.2	676	640	0.95
L-80	73.4 x 57.4	569	522	0.92
L-80	194.0 x 154.0	747	615	0.82
P-105	61.0 x 49.1	875	742	0.85
SKF C-110	73.5 x 62.5	824	803	0.97

C110 TUBE MANUFACTURING AND INSPECTION

STEELMAKING

Raw material test and control of heat analysis.
Certificate.

BILLET ROLLING

Sampling for tests of cleanliness (macro and micro).
Heat number stamping.

TUBE ROLLING

Heat number identification.
Dimension checking.

BILLET CONDITIONING

Magnetic powder inspection.
Grinding and visual inspection.

INSPECTION

Surface and straightness.
Dimensions (O.D. and wall).
Steel grade.
Marking.

COLD ROLLING

Dimension checking.

STRESS RELIEF ANNEALING

INSPECTION

Dimensions (O.D. and wall).
Suraface defects.
Straightness.
Steel grade.
Marking.
Oiling.
Mechanical testing.

FINISHING – STOCK

SHIPPING

Heat number identification.
Marking (tags).
Delivery approval.
Personal responsibility sign.
Certificate.

Another way to verify the isotropy of SKF C-110 was by pressure tests with strain gauges both inside and outside the tube. The tests were performed with a floating plug to make sure there were no axial forces on the tube. In calculations of the internal pressure for yielding the yield strength in the hoop direction should be used. Lacking this information we have used the normal yield strength in the axial direction. The ratio between theoretical and experimental results can therefore be considered as the ratio between the yield strengths in hoop and axial direction, i.e. an estimate of the isotropy factor.

The pressure that will just cause yielding at the inner surface (ID) of the tube is evaluated as a small bend on the strain versus pressure curve. Here we have evaluated the average of four strain gauges and consequently the average wall was used in Ford's formula (15). Here we found isotropy factors of 0.98 – 1.03 **(table 6)**. This scatter in the isotropy factor at ID and values above 1.00 are due to the difficulty of an exact evaluation of this small bend on the strain-pressure curve.

A gross yielding starts as the minimum wall goes fully plastic, i.e. the stress is at the yield strength from ID to OD. The minimum wall thickness is therefore used in formula 2. By comparing experimental results with the theoretical pressure for gross yielding based on the yield strength value in axial direction we find the isotropy factors 0.98 – 0.99 **(table 6)**. Please also notice that we use ID in the nominator in formula 2, whereas API has OD in the nominator in the corresponding formulas (16). The API formula will therefore give a gross yielding at a lower pressure and therefore has a build in safety factor (15 percent in this case), wheras our formula is more realistic as shown in **table 6**. We claim that we do not need this built in safety factor since our material is almost fully isotropic. Our solution is also theoretically more correct. Since the internal pressure acts on the ID and the expanding force per length unit will be:

$$ID \times P_i$$

to be compared with the counteracting force from 2 walls:

$$2\,wall \times YS$$

which gives the equation:

$$ID \times P_i = 2\,wall \times YS$$

A finite element method (FEM) analysis gave an isotropy factor of 0.98 which agrees closely to the above results.

The burst pressure for SKF C-110 is more than 40 % above the API burst rating for standard 2"7/8 × .217 P-110 tubing as found in the bottom of table 6. The average outer diameter of the SKF C-110 tubes were 2.900 with a tolerance range 2.883–2.906. This is within the API range for standard 2"7/8 tubing 2.875 ± 0.031".
The SKF C-110 tubing will have a 2% bigger internal cross section area, meaning a 2% higher production from the wall.

Table 6
Internal pressure test with strain gauges.

		Tube I	Tube II	Tube III
Dimensions				
OD	inch	2 900	2 900	2 900
minimum wall	inch	.201	.202	.210
average wall	inch	.207	.210	.220
Yield strength	psi	113 053	113 053	121 175
Yielding at ID				
Experimental result,	psi	15 336	16 209	17 718
Ford's formula 1),	psi	15 481	15 556	16 674
Isotropy factor at ID		**.98**	**1.03**	**1.01**
Gross yielding				
Experimental result,	psi	17 923	18 074	20 189
Calculated 2),	psi	18 193	18 299	20 522
Isotropy factor		**.99**	**.99**	**.98**
Burst				
Experimental result,	psi	20 641	20 681	22 225
Pipe body minimum wall burst rating (16, 17) psi	psi	14 530	14 530	14 530
FEM analysis				
Isotropy factor		**.98**	**.98**	**.98**

Formulas used.

1. Ford - pressure for start of yielding at the ID of a thick walled tube, open ends (15).

$$P_i = \frac{YS}{3}\left(1 - \frac{1}{K^2}\right)\sqrt{\frac{1}{1 + \frac{1}{3K^4}}}$$

$$K = \frac{OD}{ID}$$

2. Pressure for gross yielding through the entire wall.

$$P_i = YS \cdot \frac{2\,wall}{ID}$$

The ductility that come out from these tests is high as can be seen from the bulging of the tubes in **fig. 8**

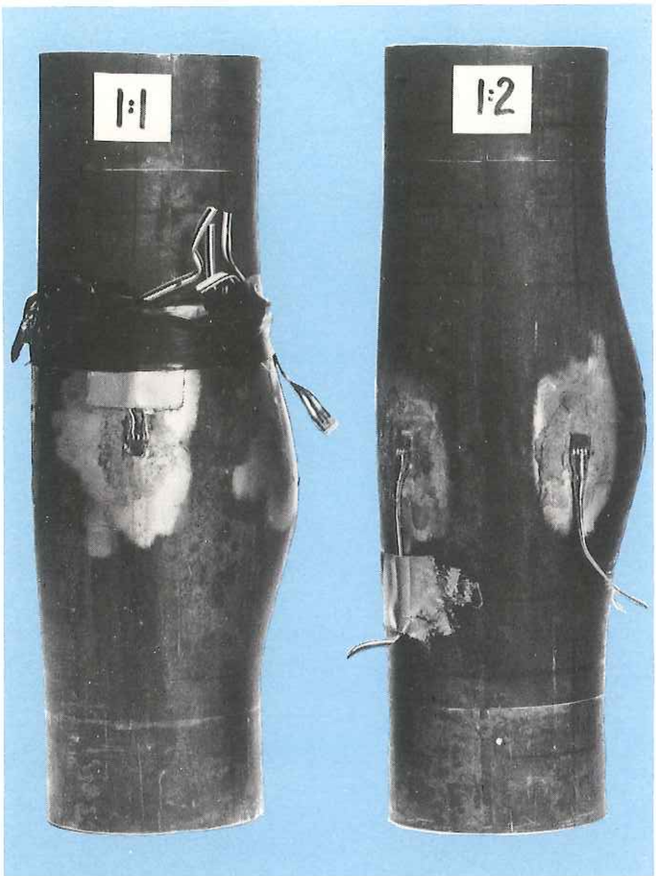

Fig. 8. Tubes from burst test. 4 strain gages outside and 4 inside each tube.

The conclusion of this test is that SKF C-110 behaves exactly as you can expect and scientific formulas without built in safety factors can be used. The real safety factor for SKF C-110 is 1.00 + 0.03 (grom isotropy and burst tests) which is higher than for conventional OCTG. Reasons for this are an isotropic material and extremely low contents of stress raisers such as nonmetallic inclusions, microcracks from quenching and surface defects.

3.3.3 Burst and collaps tests

Other types of burst tests with closed ends were performed. Unfortunately the accuracy in dimensions and strength data do not permit a scientific analysis of these test data. However, the results again surpass the API recommendations substantially (**table 7**) and they also agree fairly well with the results from **table 6**.

Table 7. Burst test on C-110 tubing

	tube dimensions inch	gross yielding psi	burst pressure psi	API (16, 17) psi
2"7/8	2.875 x .308	–	28500	20620
2"7/8	2.900 x .217	21400	21700	14530
	2.900 x .217	19700	20700	14530
	2.900 x .217	19400	20250	14530
	2.900 x .217	20000	21000	14530

Collaps tests from external pressure on 2" 7/8 × .217 show a surprisingly good agreement between experimental results and the Barlow formula **(table 8)**. Notice that we here use the Barlow formula from API (16) with OD in the nominator. The simple theoretical explanation is that the external pressure acts on the OD. The small differences (± 3%) can be explained by wall thickness variations. These results also greatly exceed the API recommendations for standard 2" 7/8 tubing.

Table 8. Collaps test on 2" 7/8 tubing (2.900 x .217).

Tube No	Yield strength psi	Collaps pressure psi	Barlow* formula psi	API recommend. psi (16, 17)
1	118600	17625	17750	14320
2	121800	18600	18230	14320
3	121800	18650	18230	14320
4	113100	16400	16930	14320

*) Barlow formula for collaps: $P_e = YS \times 2\,wall/OD$

The high performances in both these tests can be explained by: tight tolerances, small wall variations, high strength and an isotropic material.

The Barlow formula is usually used for calculation of burst from **internal** pressure (16). Here we can see that the Barlow formula correlates closely with test results from **external** collaps tests which also is expected from a theoretical interpretation of the formula.
By the proposed usage for the Barlow formula and of the other formulas above, tubes can be used to higher pressures than the standard API formulas predict (16). This however requires a sound and isotropic material as SKF C-110.

3.4 Engineering properties
3.4.1 Machinability

SKF C-110 has excellent machinability. A cutting speed of 200 m/min (= 600 ft/min) is recommended for standard carbided tools and this is about 50 % higher than recommended for quenched and tempered 4130-type steels of the same strength. For coated tools the cutting speed can be increased even more. Machinability is further discussed in (18).

3.4.2 Threading test (make and break)

The threading and the galling properties have been tested for VAM-threads. The test samples included 8 connections for 2" 7/8, 8.6 pounds per foot (12.8 kg/m) tubing.

The threading properties were excellent and also emphasized by the threaders. Owing to the better tolerances than standard API-tubes more threads than normal could be cut. The couplings were phosphated and pins were treated with zinc silicide.

The connections were subjected to make- and break tests 10 times at maximum torque (3300 ft-lbs = 4476 Nm) and 3 times at 33 % over maximum torque (5000 ft-lbs = 6782 Nm). The torque for break-out varied from 1800 to 2300 ft-lbs (2400 – 3100 Nm) for normal loading and 3100 – 3500 ft-lbs (4200 – 4700 Nm) for 33% overload.

The connections were taken completely apart every other time and visually inspected. All samples withstood the tests and were fully approved.

3.5 Corrosion properties

Sulphide Stress Cracking (SSC) is one of the most delicate problems in oil and gas production from deep sour wells.

For test purpose a very aggressive solution, the NACE solution, is often used. It is much more aggressive than the brine solutions in most sour wells. The NACE solution consists of: 5% NaCl, 0.5% HAc, water, saturated continuously with bubbling H_2S gas.

3.5.1 General corrosion

The general corrosion properties are determined by the chemical composition i.e. SKF C-110 has about the same corrosion rate as other low-alloyed OCTG, e.g. L-80, C-90 etc. Data from weight loss corrosion experiments in NACE solution are presented in table 9. All specimens evindenced the same appearance after 30 days exposure, namely a heavy black sulphide scale. The attack was primarily general with little or no evidence of significant pitting.

Table 9
Corrosion in NACE solution

corrotion rates
36.3 MPY
40.0 "
39.6 "
38.5 "
average 38.6 ± 1.7

MPY = Mils (=0.001") per year

3.5.2 SSC tests

The most important feature of SKF C-110 is its ability to withstand SSC in H_2S environments. The following test data illustrate the excellent test results this material has achieved.

3.5.2.1 Bent beam tests

In this test the specimen is subjected to a three point bending at constant strain (**fig 9**). Different stresses are obtained by adjustment of the screw. Usually a set of test rigs with specimens stressed to 100%, 80%, 60% of YS etc are tested simultaneously. They are immersed in NACE solution for 30 days and evaluated for the highest stress that did not cause cracking.

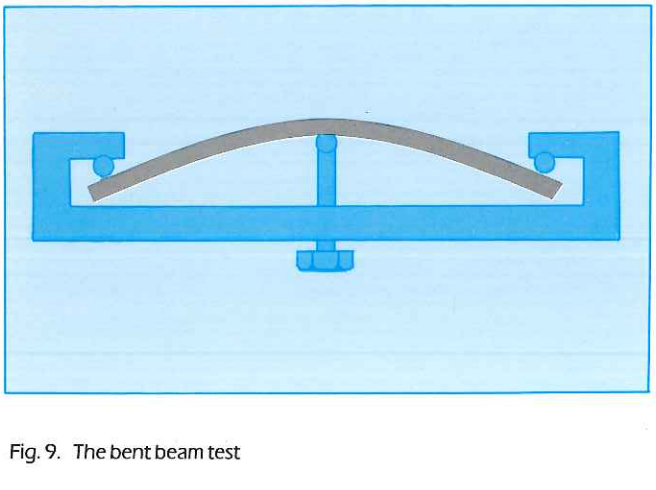

Fig. 9. The bent beam test

Results from a large number of bent beam tests on different types of steel grades of OCTG are summarized in **figure 10**. The yield strengths of the steel grades are given on the abscissa and the maximum stress which did not cause cracking on the ordinate. Those data points on the 45° line indicate material that is not susceptible to SSC. SKF C-110 was found to be the strongest of all those steel grades that are not susceptible to SSC. For other types of OCTG the resistance to SSC starts to decline at about 90 000 psi (620 MPa) in yield strength.

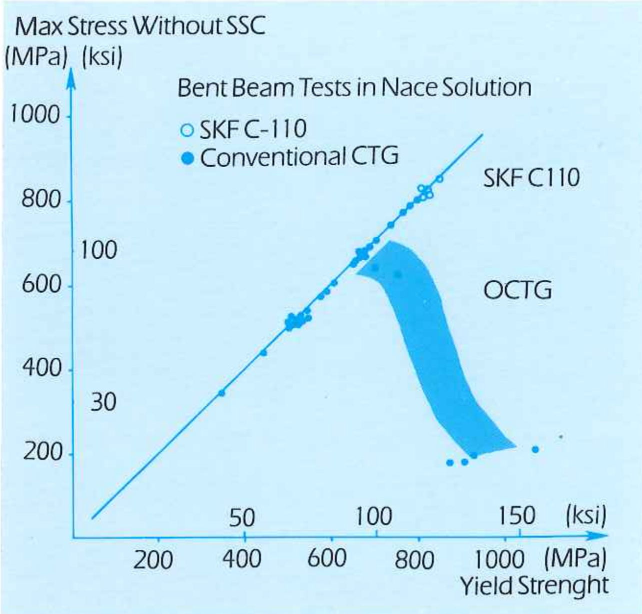

Fig. 10. Test results from bent beam tests.

3.5.2.2 Shell's Bent Beam tests

A variant of the above described test method is the Shell Bent Beam test. It differs from the Standard Bent Beam in that two holes are drilled in the middle of the beam and therefore a more complex stress situation occurs.

The stressed beams are exposed to a 0.5% acetic acid solution saturated with H_2S at 1 atmosphere pressure and 70° F (21° C). The duration of the test is four weeks.

A "critical stress" (S_c), which is the stress value (psi × 10^4) corresponding to 50% probability of failure, is calculated from the results obtained at varying beam deflections. This Sc-value is an artificial value and it is used only to rank different materials or the order of cracking resistance. The acceptable and non-acceptable Sc-values are based on correlation between field experience and laboratory data. The lower limit for acceptance in oil field applications has been set to $S_c = 10$.

Tests on SKF C-110 have given S_c-data between 15 and 18 whereas OCTG in the same strength level range, P-105 and P-110, give S_c values between 3 and 10.

3.5.2.3 Tensile bar tests

The NACE tensile bar, NACE TM-01-77 is the most frequently used method to evaluate the susceptibility to SSC. The test bar is immersed in NACE solution under tensile load (**fig. 11**). The stress levels are usually 70, 80, 90 and 100% of YS and the time to failure (= TTF) is evaluated. Test duration is 30 days (720 hours).

A general acceptance level, for use in H_2S environment, is that the material does not develop any SSC up to a stress level of 80% of the YS. A number of different heats of SKF C-110 have been tested by using this method, all with positive results as shown in **table 10**.

Table 10
NACE tensile bar TM-01-77 test results.

Tube No	Yield strength	Stress	Stress % of YS	Result TTF*	Comments
1	754 MPa	640 MPa	85	NF	
	754	720	95	NF	
	754	760	101	NF	
2	766 MPa	690 MPa	90	NF	
	766	766	100	NF	
	766	766	100	NF	
3	756 MPa	616 MPa	81	NF	
	756	652	86	NF	
	756	680	91	NF	
	756	688	91	590 hr	
	756	724	96	NF	
	756	724	96	NF	
	756	760	101	199 hr	
4	795 MPa	600 MPa	75	NF	dead weight
	795	700	88	NF	"
	795	750	94	24 hr	"
5	800 MPa	680 MPa	85	NF	

*) TTF = time to failure
The test duration is 720 hours.
NF means no failure within 720 hours

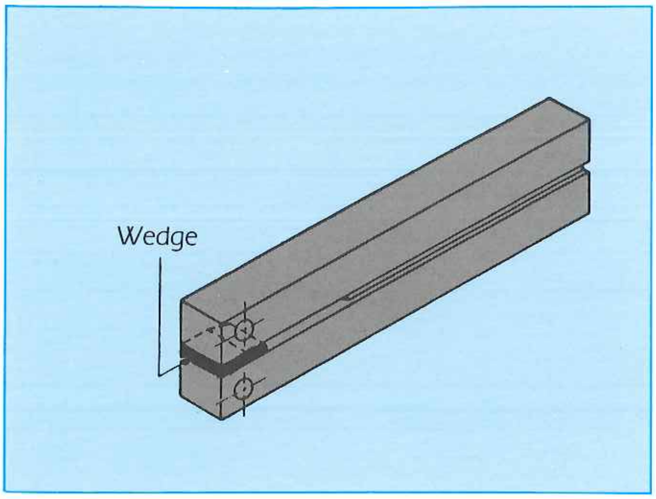

Fig. 12. DCB-specimen.

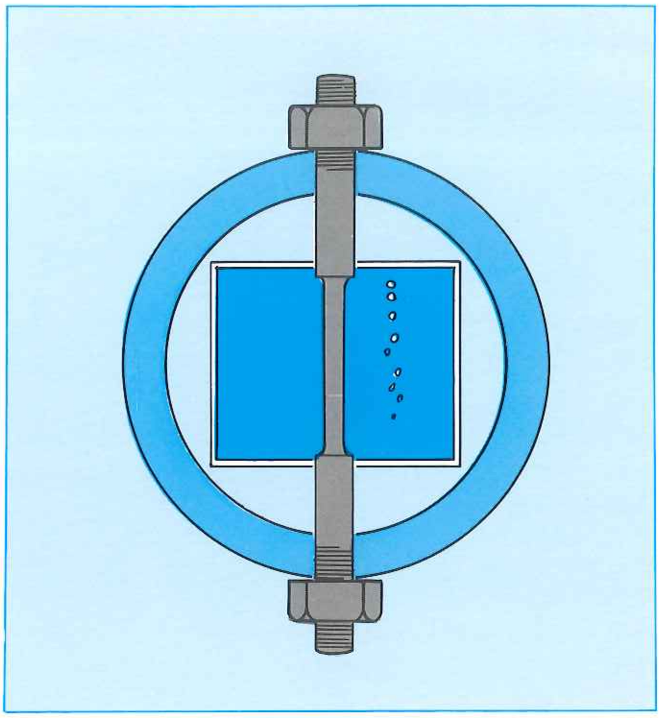

Fig. 11. NACE tensile bar device.

3.5.2.4 DCB-tests

The DCB-test is performed on a type of fracture toughness specimen. The specimen is stressed by introduction of a wedge and is immersed in NACE-solution for 14 or 28 days **(fig 12)**. During this period the crack grows. The stress intensity in the fracture tip decreases as a result of the decreasing influence of the wedge. At a certain stress intensity the crack growth stops. This stress intensity is measured by loading the specimen in a general tensile testing machine until it ruptures.

The DCB specimen is cut in the longitudinal direction of a tube and the load will accordingly be perpendicular to the fiber direction.

The results from some DCB-tests are presented in **table 11**. The K-values vary between 20 and 29 ksi $\sqrt{\text{inch}}$. Today there is no standard minimum K_{ISSC}-value, but these figures agree with K_{ISSC}-results from some molybdenumrich steel grades with good resistance to SSC (19, 20).

Table 11
Results from DCD tests.

YS	HRC	K_i	K_{Issc}
ksi (MPa)		ksi $\sqrt{inch}$	ksi $\sqrt{inch}$
124 (835)	26.1	40	25
		32	20
		52	24
		50	24
118 (812)	24.4	30	23
		32	23
		51	29
		47	27

Testing duration 28 days
K_i = initial loading
K_{Issc} = test result
Convert to MPa $\sqrt{m}$ by multiplying with 1.10.

3.5.2.5 Other SSC tests

SKF C-110 tubes have also been subjected to some customized, in-house designed, SSC-tests. These have been variants of DCB-tests and tensile bar tests. In all these tests the material behaved extremely well and withstood loadings up to 100 % of YS without any signs of SSC.

3.5.2.6 General comments regarding SSC

As seen above there exists a number of tests to verify a materials susceptibility to SSC. None of these is absolutely determining and each user has his own preference. Most users can relate laboratory test results to field experience to gain confidence in the test methods. It is evident from all tests that SKF C-110 has very high resistance to SSC.

4. Theoretical Explanations

Earlier in this paper we have touched upon the questions "Why is SKF C-110 so outstanding?" and "How can this strong steel withstand H_2S without cracking?" During our development work we have found some answers:

- There are no microcracks in the cold-worked structure of SKF C-110
- Different types of non-metallic inclusions can act as stress raisers and play an important role in SSC (8–12). Macro-inclusions and D-type microinclusions can here be considered as the most disadvantageous. SKF C-110 has virtually no inclusions of these types and therefore is less sensitive to SSC.
- The total absence of martensite is important since high strength martensite is very susceptible to SSC (1–3).
- The cold worked SKF C-110 exhibits a favorable cellular sub microstructure that is totally different from the low-deformed structures. This structure has been shown much superior to quenched and tempered structures (21).

5. Conclusions

SKF C-110 is a high strength, low alloy steel with excellent resistance to sulphide stress cracking (SSC). No other steel grade currently available has this combination of high strength and sulphide stress cracking resistance. Quenched and tempered grades such as L-80 and C-90 fall far short of the critical qualities shown by SKF C-110. Due to close tolerances, small wall variations, an absence of stress raisers such as macro inclusions and surface defects and the isotropic nature of the steel; SKF C-110 tubes can take maximum advantage in design. The consistant, reliable properties allow a judicious use of available safety factors and let you design with confidence.

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