MATERIAL SELECTION AND CONCEPT FOR THE DRILL STRING OF THE GERMAN CONTINENTAL DEEP DRILLING PROJECT (KTB)

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1 INTRODUCTION

The investigation which is the subject of this report is the part of a study on the suitability of high-strength steel and light metal materials for drill pipe. This study describes the current state of research regarding the behaviour of materials to be considered for the drill string in a 14,000 m deep well.

The requirements on the materials are determined by the borehole parameters, particularly the high well temperature, and the extreme string length. A further aspect concerns the question, whether corrosion resistant materials are available to enable the drill cuttings to be extracted without contamination from corrosion products.

2 INVESTIGATION METHOD

From the large number of steels and light metals available, those high-strength materials were selected and combined in classes, whose properties appeared suitable regarding the requirements placed on the drill string (Fig. 1).

These requirements were classified in categories which cover the mechanical and technological properties including corrosion and wear behaviour as well as the features governing the suitability of materials for drill pipe manufacture. As a further assessment criterion, the behaviour in the case of multiple make-up was considered (Fig. 2).

For each class of materials, an individual qualitative comparison was made between material properties and the requirement categories. The results obtained were then summarized in a general assessment.

3 RESULTS

In the following, those material properties will be discussed which are of special importance and finally caused the elimination of the respective class of materials.

The assessment of the tensile properties was based on the worst-case condition resulting from the simultaneous loading by:

- the string weight including drill collars (in water),
- the margin of overpull, and
- the axial loads due to internal pressure according to closed vessel conditions.

Taking into account the expected high borehole temperature of up to 300 °C, the materials must possess adequate tensile properties not only at ambient temperature, but also at elevated temperatures. The high temperature yield strength of metallic materials decreases at higher temperatures (Fig. 3).

High-strength aluminium alloys exhibit a marked drop in the tensile yield strength (R_p 0.2) already in the temperature range between 100 and 200 °C. Therefore, the combined load from the relatively low string weight including the required margin of overpull and the mud pressure will overstrain the material at temperatures above 100 °C. Accordingly, aluminium alloys cannot be considered as suitable materials for the described application.

Similarly, the tensile strength of the high - alloy 20 % Cr. steels (class IV) is also not high enough to withstand the axial load. This class of materials was excluded from further considerations, especially since other corrosion resistant materials with adequate tensile properties are available.

All other classes of materials exhibit sufficiently high tensile properties. This result is represented in the so-called rupture length, which is understood to be the string length, at which the load due to the string weight equals the yield strength of the materials (Fig. 4).

In the course of drilling operations as the total sum of the individual drilling periods, the pipes are subjected to high temperatures plus high tensile loads for extended periods, with the tensile/temperature load combination varying for different string depths.

At temperatures below 350 °C, creep processes may take place in metallic materials and lead to strains of 0.2 % and higher within a relatively short period of time. For ferretic steels, the effect of these processes is negligible, so that the high temperature strength can be used in the design of components.

Titanium and titanium alloys are particularly susceptible to creep. At about 300 °C, the tensile properties of titanium alloys are governed by its creep behaviour. At a temperature of 315 °C and at a load of only 60 % of the high temperature strength, ß-titanium alloy, for instance, will fail after 1,100 hrs. Titanium alloys are therefore not suitable for applications at temperatures above approximately 200 °C. Nevertheless, this type of material can still be used in the upper part of the drill string, where the temperatures are lower, in order to reduce the total string weight.

Borehole deviations generate rotating bending loads in the drill string during rotary drilling. This load becomes the more critical, the higher the initial axial tension resulting from the string weight.

Although it is well known that the bending fatigue strength of material increases with increasing tensile properties, this relationship is true only under laboratory conditions (Fig. 5). Due to the surface condition related to production and application of components such as drill pipe, their bending fatigue strength is lower and almost entirely independent of the tensile properties.

The additional effects of a corrosive environment cause the bending fatigue strength to drop to an even lower level. During tests, the effect of drilling mud was simulated using tap water or a 20 % sodium chloride solution.

According to estimates, deviations in the borehole of 1.5°/100 ft may lead to rotating bending stresses of about ± 100 N/mm^2. Under these conditions, none of the materials examined proved resistant to fatigue. Theoretically, under the combined load of the total string weight and corrosive conditions, the drill pipes in the upper section of the drill string may reach their fatigue limit and have to be replaced after a few days of drilling operations.

This means that the deviations in the upper section of the borehole must be kept extremely small, i.e. less than 1°/100 ft. In addition, the drill pipes must be inspected regularly at short intervals.

The material assessment with regard to corrosion resistance concerned two aspects. Firstly, the type of corrosive environment to be expected under actual drilling conditions must be considered. Secondly, as already mentioned, it was to be considered whether the drill cuttings could be extracted in their original condition - i.e. free from corrosion products - for geoscientific investigation purposes.

In the wall, sweet water can be extracted, with minor contents of salt and CO_2, from the rock. For the drilling mud, Ca-chloride solution may be used. Under these conditions, low-alloy steels according to classes I and III will suffer weightloss corrosion. Provided suitable measures are taken - this concerns especially the removal of dissolved oxygen in the drilling mud - corrosion processes can be kept within acceptable limits.

When aluminium materials are used, exact limits must be observed with regard to the pH-value and the salt content in the drilling mud, in order to avoid detrimental corrosion damage. Under drilling conditions, it is unlikely that the required stringent control of these limit values can be maintained.

For the case that the drilling string must be kept free from corrosion, high-alloy steels and nickel base alloy (classes IV/V) can be used.

In addition to the technological properties, another important aspect when assessing the suitability of a material concerns its processing behaviour for the manufacture of high-quality drill pipe. Furthermore, in view of the expected large number of round trips, the unproblematic multiple make-up/break-out behaviour is a factor of vital importance.

According to our knowledge, drill pipe in high-alloy corrosion resistant steels has not yet been produced. However, these materials have been successfully run as production tubing in highly corrosive gas wells.

High-strength titanium alloys have also been used for the manufacture of pipe. However, with these materials - similar to high-alloy steels - there are still some aspects to be solved regarding the shaping of drill pipe and the welding behaviour of weld-on connectors.

On the rig multiple break-out and make-up behaviour of the connections, when the drilling bit needs to be changed, or measurements must be taken, is an important factor. Low-alloy steel drill pipe has been sufficiently tested. With corrosion resistant steels and titanium alloys, no such experience is available. However, it is known from other application areas that special protective measures have to be developed, to decrease the galling tendency of these materials during make-up.

4 DESIGN CONCEPT FOR THE DRILL STRING

Based on the qualitative assessment of the individual material characteristics, the general assessment is differentiated between "suitable", "suitable with minor/major restrictions", and "not suitable" (Fig. 6).

Aluminium materials are ruled out, because of their low high temperature yield strength above 100 °C, and due to the additional problems of controlling the corrosion by salt solutions used as drilling mud.

The martensite precipitation hardening steel (class II), which exhibits the highest tensile properties, is also ruled out, because of its insufficient toughness.

The high-strength low-alloy steel (class I) largely complies with the requirements, but corrosion products must generally be accepted.

The high-alloy corrosion resistant materials (classes III/IV) meet the requirements to a great extent.

Because of their susceptibility to creep, titanium alloys (VI) are only suitable for depths in which, according to the temperature profile of the well, temperature stays safely below 200 °C.

Based on these results, the following alternatives are available for the design of a 14,000 m drill string:

- high-strength low-alloy steel as pipe materials with steel tooljoints, or
- Hastelloy C 276 nickel base alloy as pipe and tooljoint material, or
- a combination string with titanium alloy in the upper string section and high-strength low-alloy steel or a corrosion resistant material in the lower string section.

Given 14,000 m string length, this combination results in a total weight reduction of about 9 %.

Apart from the technical aspects, the material costs must also be taken into account.

According to the literature and market information, the following cost relations were established for plain-end pipe of comparable sizes:

High-strength low-alloy steel	Basis	Factor 1
High-alloy steel ≥ 20 % Cr		Factor 13
Hastelloy C 276		Factor 30
Titanium alloy Ti 6AL 4V		Factor 30

The materials discussed offer a number of alternative solutions which permit flexible decisions, which can be adapted to the actual requirements of the main well.

Finally, it should be pointed out that the study, on which this paper is based, has been prepared for the KTB project as the result of cooperative contributions from numerous authors of Mannesmannroehren-Werke and of the Mannesmann Research Center.

Class	Material	Type
I	Low alloy high strength steel	30 Cr Ni Mo 8-170
II	Martensite precipitation steel	X2 Ni Co Mo Ti 18 12 4
III	Corrosion resistant steel >13 % CR	X20 CR 13 X 4 Cr Ni Mo 16 5 X 3 Cr Ni Mo Al 13 82
IV	High alloy steel >20 % CR	X 2 Cr Ni Mo N 22 5 X 1 Ni Cr Mo Cu 31 27
V	Nickel base alloy	Hastelloy G 2 Hastelloy C 276
VI	Titanium alloy	Ti 3Al 8V 6Cr 4Zr 4Mo (ß) Titanium Ti 6Al 4V (α+ ß) Titanium
VII	Aluminium alloy	Al Cu Si Mn Al Zn Mg Cu 1,5
VIII	Magnesium alloy	Mg Zn 6Zr

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CLASSES OF MATERIALS

Bild 1

Material requirements	**Drillstring requirement categories**
Tensile properties	Σ String weight + Margin of overpull (MOP) $\leq$ Tensile yield Total weight $\leq$ Permanent operating hook load
Impact strength	Absorbed impact energy $\geq$ 50 Joule at ambient temperature
Creep resistance	Rp 0,2 at 100 000 h and 300°C
Fatigue resistance	– Combined fatigue and tensile strength – Combined fatigue and corrosion resistance
Corrosion resistance	– Ca-Chloride based mud – Borehole media
Wear resistance	– Abrasion – Mud wear – Interaction of erosion and abrasion
Producibility	– Pipe – Tooljoint
Make and break behaviour	Comparable to API-drillpipe

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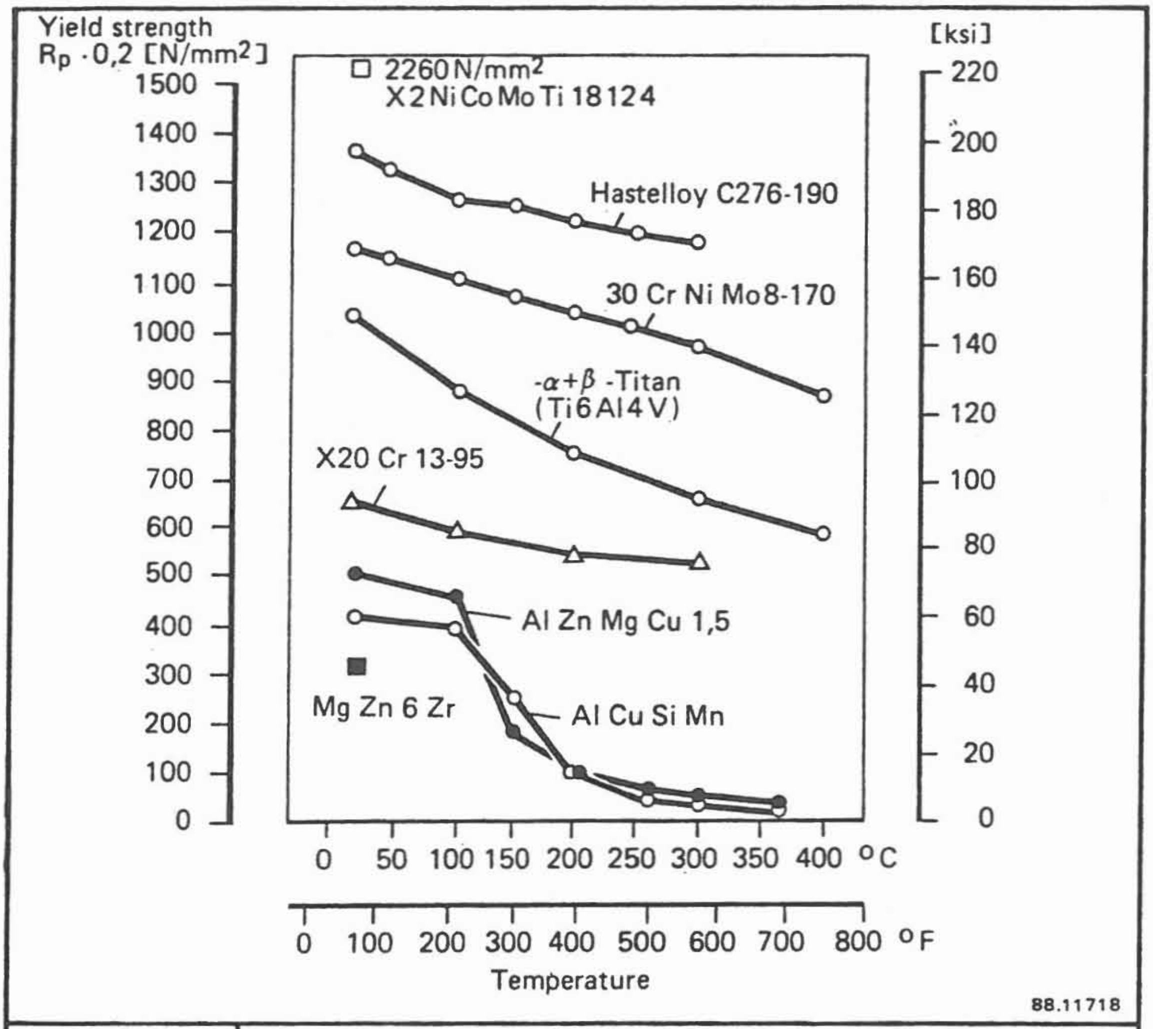
Bild 2



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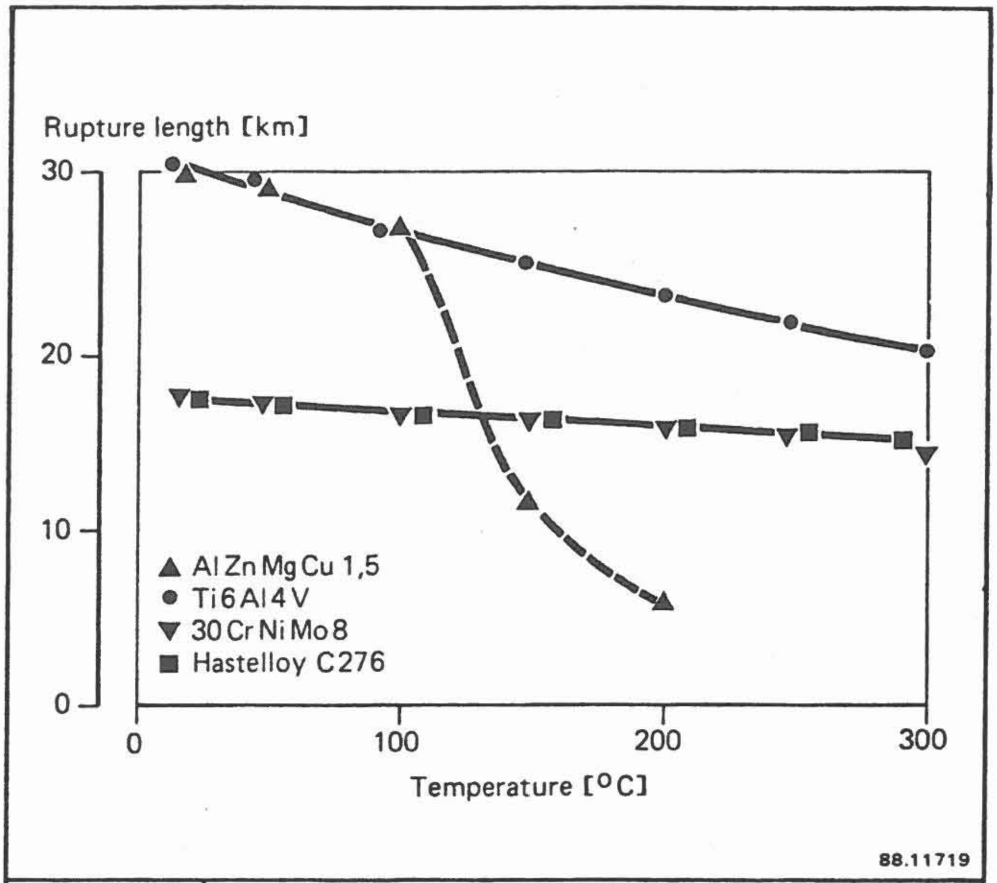
YIELD STRENGTH $R_p \cdot 0{,}2$ OF VARIOUS MATERIALS vs. TEMPERATURE

Bild 3



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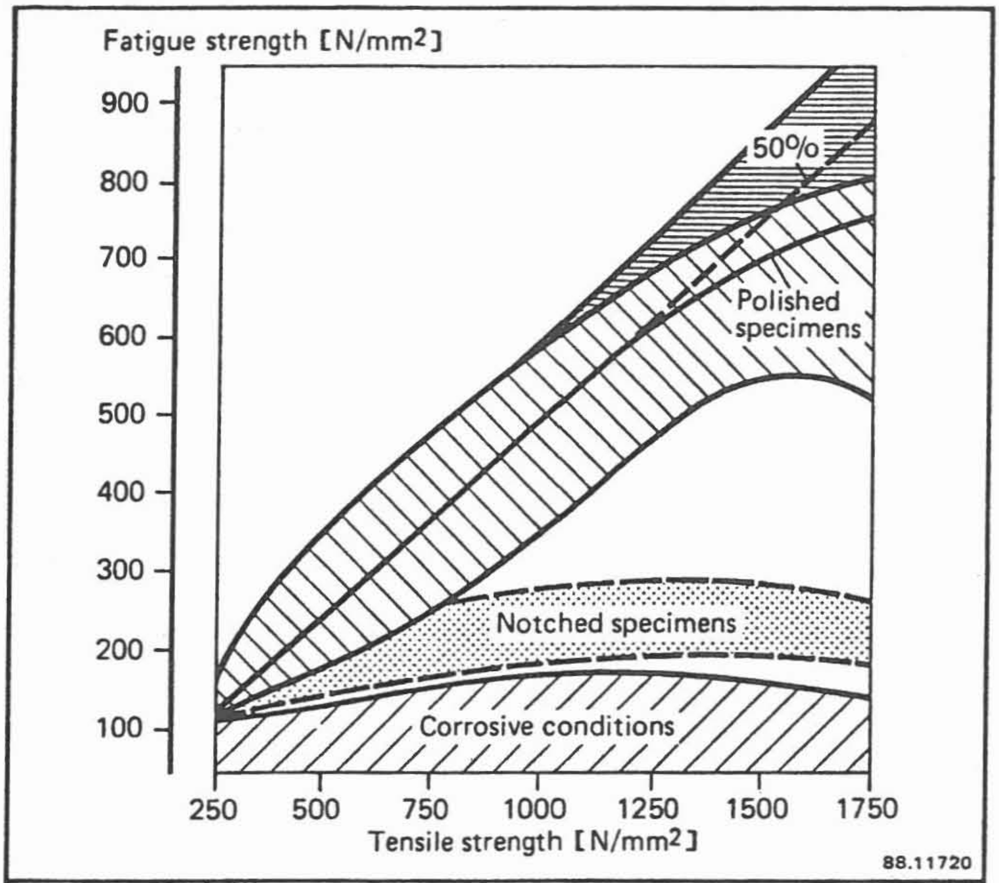
RUPTURE LENGTH vs. TEMPERATURE
(Related to yield strength and under consideration of boyancy)

Bild 4



MANNESMANN RÖHRENWERKE	**FATIGUE STRENGTH vs. TENSILE STRENGTH ACC. TO BULLENS FOR POLISHED AND NOTCHED SPECIMENS IN LABORATORY AIR AND UNDER CORROSIVE CONDITIONS**

Bild 5

Material properties Material groups		Tensile strength	Impact strength	Creep resistance	Fatigue resistance	Corrosion resistance	Wear resistance	Producibility	Make and break behaviour	Total valuation
I	Low alloy steel	●	●	●	■	■	■	●	●	●
II	Martensite steel	●	☐	●	■	■	■	■	?	☐
III	Corrosion resistant steel (>13 % CR)	●	■	●	■	■	■	■	?	■
IV	High alloy steel (>20 % CR)	▲	●	●	■	●	■	■	?	▲
V	Nickel base alloy	●	●	●	■	●	■	■	?	■
VI	Titanium alloy	●	▲	▲	■	■	■	■	?	▲
VII	Aluminium alloy	☐	▲	☐	▲	▲	☐	●	?	☐
VIII	Magnesium alloy	☐	?	☐	☐	☐	☐	?	?	☐

● suitable for use
▲ with major restrictions
? unknown
■ with minor restrictions
☐ not suitable for use

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VALUATION MATRIX FOR PIPE AND TOOLJOINT

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