CAST IRON AS STRUCTURAL MATERIAL FOR HOT-WORKING REACTOR VESSELS (PCIV)

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SUMMARY

Cast iron with lamellar graphite is best suited for prestressed structures, because its compressive strength is nearly 4 times its tensile strength. In comparison to room temperature, cast iron with lamellar graphite shows essentially no loss of strength up to temperatures of 400 °C.

Under the particular aspect to use cast iron for hot-working prestressed reactor pressure vessels (PCIV) (Prestressed cast iron vessel = PCIV) a materials testing program is carried out, which meets the strict certification requirements for materials in the construction of reactor pressure vessels and which completes the presently available knowledge of cast iron.

Especially in the following fields an extension and supplement of the present level of knowledge is necessary.

— Mechanical properties under compressive stresses:

Despite the fact that cast iron has substantial tensile strength, in comparison with concrete, the properties under compressive stresses are decisive for prestressed cast iron structures. Principal parameters are wall thickness, location of the specimen in the cast iron block, and temperature. The long-term properties of the material may have a substantial influence on prestressed vessels. Though significant influence is not expected (stress and temperature for the PCIV are relatively low) long-time tests will be performed. The changing loading conditions that occur during the life of prestressed reactor pressure vessels have been taken into consideration by fatigue tests.

— Material properties at elevated temperatures:

The testing program includes test of the mechanical and physical properties of cast iron at elevated temperatures. The compressive and tensile strength, relaxation, fatigue strength, thermal and physical properties will be studied at room and elevated temperatures up to 450 °C with emphasis on the operating temperature of the PCIV of 300 °C.

— Influence of irradiation on mechanical and physical properties:

Knowledge of the activation properties is of special interest with respect to the ease of inspections and repairs of the vessel and the dismantling of the vessel when the whole plant is taken out of service. These properties are determined analytically based on the measured rates of trace elements and, in addition, by irradiation samples. To determine the changes of the mechanical and physical properties tests with irradiated and unirradiated specimen are performed, though a significant influence is not expected because the neutron dose at the inside surface of the PCIV is relatively low.

— Production standards and quality control:

When grey cast iron is used as structural material for a reactor pressure vessel strict requirements must be met for its quality. To meet these requirements the following tests are suggested: Chemical analyses of the charge, destructive testing of specimen made from the same charge, and non-destructive testing methods. The non-destructive ultrasonic testing of the finished cast iron blocks is of special importance.

The state of the research and the available data of the material testing program are reported.

1. Introduction

For prestressed constructions cast iron with laminated graphite is very suitable due to the fact that its compressive strength is almost by the factor 4 higher than its tensile strength. Up to approx. 400°C cast iron with laminated graphite shows only slight reductions in strength in comparison with room temperature.

Under the special aspect of applying cast iron for hot-operated, prestressed reactor pressure vessels, a material testing programme (MTP) is being carried out which fullfils the increased proof requirements for the application of materials in the construction of reactor pressure vessels and adds to the knowledge about cast iron which has already been available for many yaers.

It is especially in the areas listed below that an addition to an extension of the present level of knowledge is required for the intended fields of application of the material.

- mechanical properties in the compressive area
- material properties at increased temperatures
- radiation and shielding behaviour
- manufacturing and quality control

2. Mechanical properties

Compared with concrete, cast iron has also got considerable strength in the area of tensile stress.

Fig. 1 shows tensile strength as a function of wall thickness. Samples were taken from a plate of 300 mm wall thickness. The first sample was taken 50 mm from the edge, the second 100 mm and the third 150 mm from the edge, i.e. in the centre of the 300 mm plate. The procedure showed that the strength drops from the outside to the inside by only 10 % from approx. 220 N/mm^2 to approx. 200 N/mm^2. But the decisive part for prestressed cast iron constructions is played by the behaviour of the material under compressive stress

Picture 2 shows compressive strength as a function of wall thickness. In this case the drop from the outer edge of a 300 mm thick plate to the centre of the plate was also only 10 % from approx. 860 N/mm^2; although cast iron with laminated graphite is generally regarded as unhomogenous material, a comparatively good constancy of strength values across the wall thickness could be proved in our material testing programme.

An essential aspect for the structural material of a prestressed vessel is not only the strength but, due to the close coupling with the other vessel components (tensioning system, liner), to a very high degree also the expansion behaviour. The prestressing and operational behaviour of the vessel depends greatly on the expansion behaviour of the material.

Picture 3 shows Young's Modulus, also as a function of wall thickness. Just like in the case of tensile strength and compressive strength it could also be proved for this factor that the Young's Modulus does not drop more than by approx. 10 % towards the centre of the plate. In order to fullfil the requirements of a prestressed construction, special emphasis was placed on the examination of expansion behaviour in the compressive area in addition to the examinations of the expansion behaviour in the tensile section. In some cases the test requirements could only be fullfilled by the usual testing machines after they had undergone structural alterations.

In the mentioned material testing programme, compressive stress values were recorded in stress-expansion diagrams in addition to the tests in the tensile stress section, in order to obtain as qualified as possible results on the prestressing behaviour of cast iron with laminated graphite.

Picture 3a shows the relationship of E_0-modulus and expansion limits for the tensile and compressive stress sector. The investigations showed that the values for the E_0-modulus for the tensile and compressive stress sectors were almost indentical. For the expansion limits the values in the pressure section lie above those of the tensile stress section.

An essential part with prestressed vessel constructions may possibly be played by the long-term behaviour of the material. For this reason long-time rupture tests were carried out in the tensile and compressive stress sections. In determinating the parameters for the long-time rupture tests special attention was paid to the compressive stresses and temperatures to be expected in the reactor vessel.

Picture 4 shows long-time expansion curves in the tensile stress section for room temperature. In the curves total expansion ($_{\text{elastic}}$ + $_{\text{plastic}}$) is compared with stress duration. Although the individual load stages were bigger than 85 % of the tensile strength, only a slight creep value has to be expected at room temperature.

The changes in stress occurring in the course of the service life of a prestressed reactor pressure vessel are taken into consideration by continuous vibration tests (permanent vibration stress).

Picture 5 shows a Smith diagram compiled of stress-number curves and prepared at room temperature for 30 000 cycles. The sample for this Smith diagram were taken from the centre of 300 mm thick sample plates. When this went into print the tests for the compressive stress section had not yet been completed. This diagram shows that the tensile-compressive stress reversal strength amounts to approx. 40 % of the tensile strength.

3. Mechanical properties with increased temperatures

The comparatively good strength properties of cast iron with laminated graphite in comparison with concrete were an essential reason for the concept of a hot-operated reactor pressure vessel. For this reason , the tests regarding mechanical and physical properties of cast iron were carried out at increased temperatures in the material testing programme (MTP). The tests covered in detail: tensile and compressive strength, long-time rupture strength, the physical and nuclear properties of the material at increased temperatures.

The top limit of the examined temperature range was set to be 450°C. This top limit was determined by the temperatures of the reactor vessel to be expected in cases of trouble, on the one hand, and by the expected limit of reasonable loads possible for the material. The emphasis of the tests lies with the probable operating temperatures of a hot-operated reactor vessel of 300°C, the minimum of the tested temperature range lies at room temperature.

Picture 6 shows the tensile strength as a function of temperature. It can be seen that the material passes through a minimum in its strength behaviour at approx. 200°C and that the strength rises again almost up to the maximum value above this temperature threshhold. Above 400°C a constant reduction in strength values must be expected.

Picture 7 shows Young's Modulus also as a function of temperature. In this case as well, a noticeable drop in Young's modulus must be expected above 400°C. In view of these facts it seems unproblematic to employ this material up to this temperature range of 400°C.

Picture 8 shows long-time expansion curves at different temperatures. We can see a comparison of long-time expansion curves with a load of 220 N/mm^2 at room temperature and at 300°C and with a load of 200 N/mm^2 at 450°C.

While there is only slight creep tendency at room temperature or 300°C, the creep tendency increases noticeably above 400°C. Here again, the findings established in short-time tests were ully confirmed. The material also shows in the long-time rupture behaviour its tendency towards application up to a temperature of 400°C.

4. Radiation and shielding behaviour

If a material is subjected to radiation with neutrons, 2 effects have to be taken into consideration. On the one hand, the activation of the material and, on the other hand, the change in mechanical and physical properties. Knowledge about the activation behaviour of the material are of special interest, particularly with regard to ease of inspection and repair of the vessel and with regard to final disposal.

These properties are, based on the knowledge of the chemical trace analyses, analised by means of calculations and additionally by means of radiation tests.

Recording of the changes in properties requires extensive tests with samples subjected to radiation and samples not subjected to radiation. In the radiation process the neutron dose and the radiation temperature are of special interest.

The first tests in this matter were carried out on the impact-bending samples having been and not having been subjected to radiation. For this purpose impact-bending samples were subjected to radiation at 300°C up to a neutron fluency of approx. 1×10^{19} n/cm^2. In subsequent tests the impact-bending tenacity was determined at various temperatures.

Picture 9 shows that a systematic change in the impact-bending tenacity temperature curve can be found except for the 300°C value. The impact-bending tenacity is about 1 Nm/cm^2 lower on the average after radiation.

5. Production and quality control

If cast iron with laminated graphite is used as construction material for a reactor pressure vessel, the requirements regarding quality and its reproducebility have to be very exacting. These requirements can only be fullfilled if constructions are designed which suit the foundry process, if the production plant has a high technical standard and if practicable and reliable production checks and non-destroying test processes are available.

Proposed are quanto-metric full analyses of the melt, accompanying destroying tests on separately cast special samples and ultrasonic tests. Of special significance in this context is the non-destroying test of the finished cast iron blocks with ultrasonic methods. This testing method is comparatively easy to use and is therefore to be perfected to such an extent that the use of only perfect cast iron blocks can be guaranteed.

At the closing time for this article no results from the ultrasonic test programme were yet available.

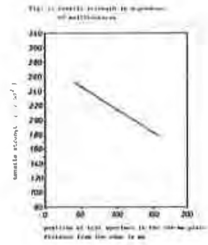

Fig. 1

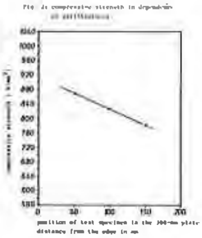

Fig. 2

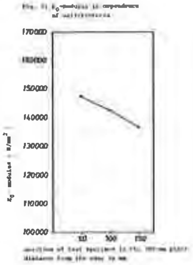

Fig. 3

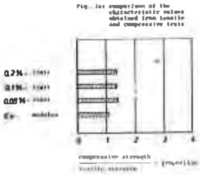

Fig. 3a

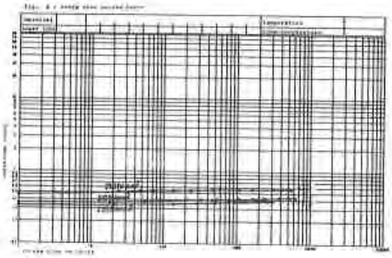

Fig. 4

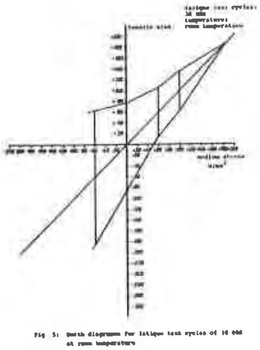

Fig. 5

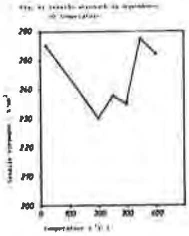

Fig. 6

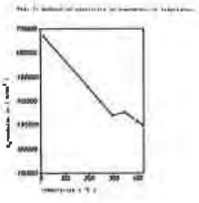

Fig. 7

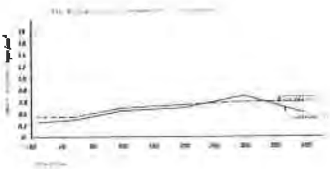

Fig. 8

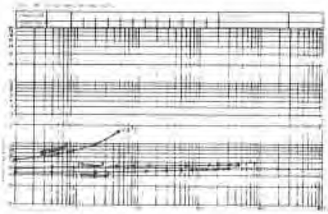

Fig. 9