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Issues in Reactor Pressure Vessel Materials
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Issues in Reactor Pressure Vessel materials

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Abstract

Reactor Pressure Vessel (RPV) is one of the most important structure in a VHTR. The choice of this material is therefore of a prime importance and necessitates significant work of validation.

The purpose of this paper is to make the status of knowledge on different vessel material candidates. The paper will be divided as follows:
- Definition of RPV material candidates,
- Status of RPV candidates with regard to Codes & Standards,
- Advantages and drawbacks of these materials.

The paper will explain in particular the background of the choice of Framatome ANP to use either SA508 / SA533 PWR material for the cold vessel option or SA 336 grade 91 (mod 9Cr1Mo) for the hot vessel option.

Another important issue in the choice of material is the capability to weld the material. The paper will present in the specific case of mod 9Cr1Mo the needs identified by Framatome ANP of welding processes and the status of work carried out so far in the welding of thick rolled or forged plates. The paper will recall the problems encountered at the beginning, in particular the problems of hot cracking met in the case of GTAW process applied to heavy sections, and the progress achieved since then will be pointed out.

The last item will concern R&D work needed to validate the choice of these materials. The paper will identify in particular work already launched in France or in Europe and specific points for which input from international collaboration would be helpful.

1. INTRODUCTION

Framatome ANP have decided to launch an extensive programme on Very High Temperature Reactors (VHTRs) to add this technology to its long term nuclear power plant design portfolio. Two concepts are studied in parallel: one which is aimed at meeting DOE NGNP (Next Generation Nuclear Plant) requirements and the other one which is Framatome ANP commercial plant.

The aim of this paper is to give the background of the choices made by Framatome ANP with regard to Reactor Pressure Vessel (RPV) materials and to provide the status of actions which need to be carried out to qualify the materials chosen for this application.

2. RPV MATERIAL CANDIDATES

The choice of RPV materials is to be made taking account of the following considerations:
- Industrial experience,
- R&D information available,
- Operating conditions.

From this point of view, there are three families of candidates which can be envisaged for RPV applications:

- The first one concerns manganese nickel molybdenum low alloy steel,
- The second one covers 2.25Cr1Mo steel grades,
- The last one concerns 9% Cr steel grades.

The first one is the grade used in PWRs for which the industrial experience is the most important. This material is known in France as 16MND5 and is covered by RCC-M code (ref. 1). It is also covered by American Codes and Standards and corresponds to ASME/ASTM A508 grade 3 class 1 for forgings and A533 grade B class 1 for plates.

As far as 2.25Cr1Mo materials are concerned, there is a large number of steel grades with differences in the required tensile strength at room temperature. The different levels of yield and ultimate strength are obtained by different heat treatments and particularly by different tempering temperatures.

A particular grade of 2.25Cr1Mo had been developed as an alternative to 16MND5 in French PWRs. A strength similar to 16MND5 was obtained by steel making practice and heat treatment but the final decision was to keep 16MND5 as PWR material.

The ASME/ASTM 2.25Cr1Mo grade for use at elevated temperature is a fully annealed grade known as grade 22 class 1. The levels of its tensile properties are far from those of grade 16MND5.

The RCC-MR code (ref. 2) is referring to other grades of 2.25Cr1Mo (10CD9-10 and 7CD9-10) which correspond to normalised and tempered or quenched and tempered grades. These grades are more resistant compared to the annealed one, at least in tensile and short term creep conditions but they were not characterised in heavy sections.

The last family concerns high chromium alloyed steels of the type 9Cr1MoVNb (or modified 9Cr1Mo). This material is known as ASME/ASTM SA 336 grade 91 and is also covered in RCC-MR code.

3. STATUS OF RPV CANDIDATES WITH REGARD TO CODES & STANDARDS

3.1 PWR grade

According to ASME, SA508 / SA533 grades are applicable for class 1 components. Rules are given in section III for temperatures below 700°F (371°C). It is possible to go above this limit in accidental conditions if the criteria given in Code Case N-499 are met. In any case, the limit of 1000°F (538°C) can not be exceeded.

This material can also be used according to RCC-M for class 1 components. It can not be used however for temperatures above 375°C.

3.2 2.25Cr1Mo grades

According to ASME, the grade 22 class 1 (annealed grade) can be used for class 1 components. Applicable rules are given in section III for temperatures below 700°F and in Subsection NH (ref. 3) for temperatures above 700°F, up to 1100°F (593°C) for rules involving long term properties and up to 1200°F (649°C) for rules involving short term properties.

2.25Cr1Mo grades are not covered in RCC-M code. The normalised and tempered or quenched and tempered grades are however covered by RCC-MR code (16S material) and can be used for class 1 components.

3.3 Modified 9Cr1Mo

Grade 91 is covered by ASME for class 1 components up to 700°F (371°C). There was a will at a time to include this grade within Subsection NH for application above 700°F and a draft has been written (ref. 4) but not yet incorporated in the recent issues of addenda.

Figure 1 compares the curve of Ultimate Tensile Strength S_u versus temperature, given by the draft Subsection NH, with the data gathered in Europe:
- data from past Fast Reactor R&D programmes,
- recent data obtained on a 200 mm thick forged plate for VHTR R&D actions.

A non negligible number of European data appear to be lower than ASME S_u lower bound curve in the temperature range 200-500°C. The corresponding points were obtained in majority on thick section products : 300 mm thick rolled plate and 200 mm thick forged plate. Figure 1 shows that design data will need to cover fully representative thick parts. In addition, these data will need to include the effect of representative Post Weld Heat Treatment.

Modified 9Cr1Mo is also covered by RCC-MR code (18S material) and can be used for class 1 components, up to 600°C for rules involving long term properties and up to 650°C for rules involving short term properties.

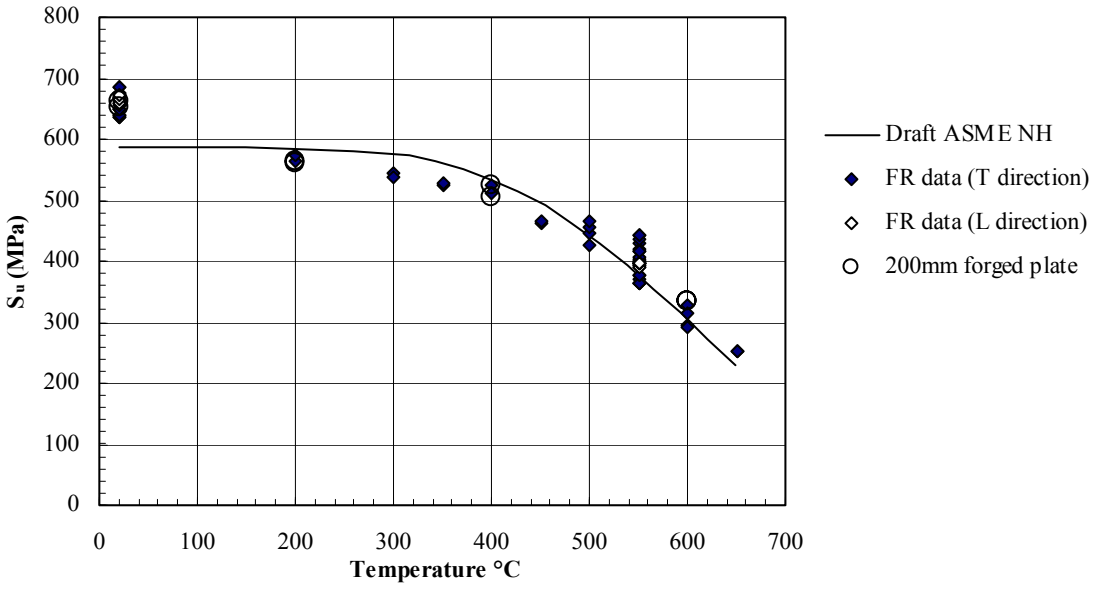
4. ADVANTAGES AND DRAWBACKS OF RPV CANDIDATES

Table 1 lists the advantages and drawbacks of the different RPV candidates for application to VHTRs.

The choice made by Framatome ANP is to use either PWR grade or modified 9Cr1Mo depending on the loading in normal and accidental conditions.

The choice was not made to recommend one of 2.25Cr1Mo grades for the following reasons:
- The grade for which the material data base is the most important (annealed grade) is the one which is the less tensile and creep resistant
- The effort in terms of R&D and technological development is of the same order of magnitude of that needed for modified 9Cr1Mo
- The ultimate tensile strength (and therefore the allowable stress limit S_m) being lower compared to other candidates (see figure 2), an increase of thickness from 1.25 to 1.5 (depending on the grade) should be envisaged for the same loading conditions.

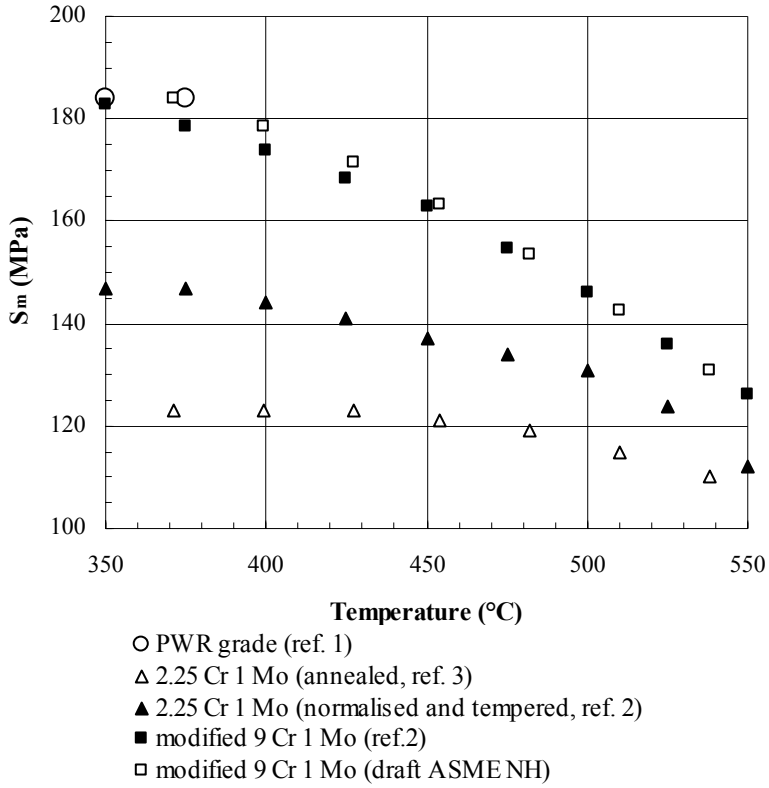
FIG.1. Ultimate Tensile Strength S_u of modified 9Cr1Mo



TAB. 1. Advantages and drawbacks of RPV candidates

Material	Advantages	Drawbacks
PWR grade	• Material for which feedback from experience in nuclear industry is the larger • Material data file is already available • Technological developments are limited • R&D work needed is limited	• Resistance to creep is limited • Resistance to corrosion in He environment is likely to be lower compared to Cr-Mo grades • Presently limited to maximum temperature of 1000°F (538°C) according to ASME
2.25Cr1Mo grades	• Resistance to creep is better compared to PWR grade	• Feedback from experience limited • Tensile properties are low compared to those of PWR grade • Necessitate larger thickness compared to other candidates (for the same loading conditions) • Material data file to write • Technological developments needed (included definition of welding parameters and products)
Modified 9Cr1Mo	• Resistance to creep is better compared to other candidates • Tensile strength is similar to that of PWR grade	• Feedback from experience mainly for non nuclear industry with lower thickness products • More difficult to procure large size ingots compared to other candidates • Material data file to write • Technological developments needed (included definition of welding parameters and products) • Post weld Heat Treatment temperatures larger compared to PWR grade

FIG.2. Comparison of allowable stresses S_m



5. WELDABILITY OF MOD 9Cr1Mo THICK PLATES

The particularity of welding mod 9Cr1Mo in HTRs compared to conventional industry is in the thickness of the products to weld. Framatome ANP has worked in the frame of the European Fast Reactor (EFR) project on the welding of Steam Generator Units parts and activities for HTRs started from this experience. The first welded joint with heavy thickness was a 150 mm thick joint performed with GTAW process on a rolled plate with a filler material whose chemical composition is given in table 2. Metallographic examination carried out indicated the presence of microcracks about 200 μm long in the weld metal, not detectable by production NDE (figure 3). Those microcracks were attributed to hot cracking and attempts to reduce the energy of welding enabled to reduce the number of cracks but not make them completely disappear. It was therefore decided to launch a programme on the one hand to explain the reasons of the phenomenon and on the other hand to help in the selection of a filler material which would avoid this problem.

Several filler materials have been tested, either for direct welding of thick plates or for the welding of plates used for Varestraint tests carried out in CEA. The different investigations enabled to draw the following conclusions:

- Sulphur is an important parameter in the hot cracking phenomenon. This is confirmed by the presence of manganese sulphides along and inside the cracks. A filler material with very low sulphur content (a few ten of ppm) is needed to avoid cracking.
- Another important parameter is the manganese to sulphur ratio, a high value of this parameter being favourable to avoid hot cracking.

A 200 mm thick joint has been welded on the basis of forged plates with a new filler material with sulphur content of 10 ppm and manganese to sulphur ratio of 500 (compared to 50 ppm and 200 respectively for the first joint). Several metallographic cuts have been performed and no cracks were detected. Further investigations are presently underway to improve impact properties for which more margins would be preferable. It is expected that a reduction of the carbon content can achieve this improvement but the range to be specified must be optimised taking also into account the creep strength of the weld metal.

In parallel to actions on GTAW, Framatome ANP welding programme covers other processes likely to be used for welding in workshop or on site. Investigations concern mainly SAW and SMAW. For SAW, commercial welding products have been found to give no cracks in a 200 mm thick joint and with impact properties nearly as good as those of the base material.

For SMAW process envisaged for repair and tested therefore with half thickness (100 mm), commercial products studied so far did not lead to hot cracking but gave impact properties too low. Further investigations are presently underway to test new welding products.

TAB. 2. Chemical analysis of the GTAW filler (%)

C	Mn	P	S	Si	Ni	Cr	Mo	Nb	V	N_2	Cu
0.08	1.00	0.004	0.005	0.18	0.71	9.03	0.90	0.04	0.18	0.0189	0.17

FIG.3. Typical defect observed after GTAW (length : 200 μm)

6. R&D NEEDS ON RPV MATERIALS

R&D needs depend on the candidates. For PWR grade which has been already extensively studied, R&D needs are limited. In the context of HTRs, the main question which needs to be solved is how SA 508/ SA 533 material behaves in VHTR He environment (He + impurities). This material do not contain chromium and will not therefore develop an oxide layer to protect itself against carburisation and decarburisation.

For mod 9Cr1Mo, the effect of He environment need to be checked but there is no particular concern about it. Points which need particular investigations are listed below:

- Creep behaviour of weldments
- Creep-fatigue interaction diagram
- Aging behaviour at long term but moderate temperatures (450-500°C)
- Irradiation behaviour

For the latter, a programme has already been launched in the frame of the fifth framework programme of the European Commission (HTR-M, see ref. 5) and mechanical tests on irradiated specimens are in progress. It should be known at the end of 2004 if irradiation effects for the fluences expected at end of life in HTRs are negligible or whether further irradiations will be needed.

Another important point to investigate in relation to RPV materials is the values of emissivity. This parameter is very important for decay heat removal calculations and it is necessary to evaluate values which can be justified for the whole life of the reactor. The values depend on the material but also on the surface state (machined, oxidised…).

7. CONCLUSIONS

The choice made by Framatome ANP is to use either PWR grade or modified 9Cr1Mo depending on the loading in normal and accidental conditions.

For PWR grade, a few R&D work is needed to confirm the applicability of this material to VHTR. It concerns essentially the verification of the compatibility of this material with VHTR He environment.

Modified 9 Cr has the advantage compared to PWR grade of being more creep resistant and should be less susceptible to environmental effects. Technological developments are needed for this material, in particular with regard to welding. Problem of hot cracking met in the welding of heavy section products are now solved and investigations still underway are focusing on the improvement of impact properties. Further R&D actions needed to fully qualify this material are also listed.

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