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Prediction of the Mechanical Behaviour of Cladding Materials for Nuclear Reactor Pressure–Vessels Based on the Analysis of Technological Requirements

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Abstract

A prediction of the mechanical behaviour based on the analysis of standardized requirements is essential to optimize the technical characteristics of materials used in cladding automatic-processes for nuclear reactor pressure-vessels, being crucial to prevent failures. The aim of this work is to develop a quantitative analysis of requirements of the AISI 304 and AISI 347 materials, and their German equivalents, DIN X5CrNi18-10 and DIN X6CrNiNb18-10, respectively, in order to predict the mechanical behavior. To this purpose, we have carried out prediction studies based on the estimation of ferrite-δ content and its relationship with hot-cracking described in the literature. Additionally, chemical and mechanical requirements have been evaluated by the application of a deterministic algorithm based on Stringency Levels. Results show that steel DIN X6CrNiNb18-10 can be defined as the best option, because of its lowest hot cracking susceptibility and the high stringency of its requirements.

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Keywords: Cladding material; automatic process; algorithm; hot cracking; stringency levels

1. Introduction

A prediction of the mechanical behaviour based on the analysis of standardized requirements is essential to optimize the technical characteristics of cladding-materials for nuclear application, being crucial to prevent failures.

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Equivalences between different standardized specifications of materials are usually established [1, 2] with respect to their main chemical and mechanical properties. However, the technological requirements described by equivalent specifications sometimes exhibit significant differences between them [3]. Additionally, publications of key importance about the influence of the chemical composition on the mechanical behaviour of materials have not been typically taken into account [3, 4]. The reactor vessel is the most important structural-component for the safety of a nuclear power plant. The vessel of a nuclear reactor is a cylindrical component [5] constructed using low alloy steels with a cladding of austenitic stainless steels such as AISI 304 or 347 specifications, to avoid corrosion processes [6, 7]. Corrosion is often the cause of fractures and deformation [8]; thus, the advantage of austenitic stainless steels is its high corrosion resistant because of the alloying elements allow the formation of a passivating layer [9]. Cladding materials are susceptible to hot cracking and stress corrosion cracking phenomenon, combined with the pernicious effect of the neutron irradiation. Cracks in the cladding could generate a catastrophic failure due to the corrosion of the vessel, as happened in the U.S. Davis-Besse nuclear plant in 2002 [10]. This topic is of high interest at present [4], because cracks have recently been detected in the reactor vessel of the Doel III and Tihange II nuclear - power plants in Belgium [11, 12]. These failures could have been due to the manufacturing process or to materials defects. The aim of this work is to assess the suitability of different cladding-materials standards, such as American and German ones, based on the analysis of technological requirements. The standards analyzed are the AISI 304 and AISI 347 specifications, and their German equivalents, DIN X5CrNi18-10 and DIN X6CrNiNb18-10, respectively.

Nomenclature

BCC	Body Cubic Centered
Cr_{eq}	Equivalent Chromium
δ	Ferrite- δ. Solid solution of carbon in BCC iron
FN	Ferrite Number
IASCC	Irradiated-Assisted Stress Corrosion Cracking
L_e	Experimental limit (method of Stringency Levels)
L_s	Standardized limit (method of Stringency Levels)
$L_{s\ (Min)}$	Minimum value of the Standardized limits (method of Stringency Levels)
$L_{s\ (Max)}$	Maximum value of the Standardized limits (method of Stringency Levels)
Ni_{eq}	Equivalent Nickel
RPV	Reactor Pressure Vessels
SL	Stringency Level
$SL_{(Max)}$	Maximum value of Stringency Level according to the defined scale
UTS	Ultimate Tensile Strength

2. Methodology and initial considerations

For this purpose, chemical and mechanical requirements are evaluated by the application of a deterministic algorithm based on Stringency Levels [3, 4]. The table 1 shows the scale of Stringency Levels.

Table 1. Scale of Stringency Levels.

Stringency Levels (numerical/quantitative)	Stringency Levels (qualitative)	Colour
1	Minimun	(dark red)
2	Low	(red)
3	Medium	(orange)
4	High	(olive)
5	Maximun (SL_{Max})	(green)

2.1. Case 1. Evaluation for chemical impurities requirements. No experimental limit considered

The case 1 is suitable for the evaluation of impurities requirements or chemical requirements that have upper limit. The mathematical set, called "standard limits", is defined as the set of maximum values specified by AISI 304, AISI 347, DIN X5CrNi18-10 and DIN X6CrNiNb18-10 specifications. This set is designed as {Ls (AISI, DIN)}. Thus, the Stringency Levels are calculated according to equations 1 and 2:

$$SL = 5.00 \text{ for } min\ \{Ls \text{ (AISI, DIN)}\} \tag{1}$$

The Stringency Levels of the rest of standard requirements are calculated according to equation 2:

$$SL = \frac{L_{s(Min)}}{L_s} SL_{Max} \tag{2}$$

2.2. Case 2. Evaluation for chemical impurities requirements. Experimental limit considered

The calculation is developed according to equations 3 to 7 [4] using the experimental limit considered (L_e):

$$SL = 1.00 \qquad (L_s \geq L_e) \tag{3}$$

$$SL = 2.00 \qquad (0.9L_e \leq L_s < L_e) \tag{4}$$

$$SL = 3.00 \qquad (0.8L_e \leq L_s < 0.9L_e) \tag{5}$$

$$SL = 4.00 \qquad (0.7L_e \leq L_s < 0.8L_e) \tag{6}$$

$$SL = 5.00 \qquad (L_s < 0.7L_e) \tag{7}$$

2.3. Case 3. Evaluation for mechanical and alloy-elements requirements

The case 3 is suitable for the evaluation of mechanical requirements and alloy-elements requirements.

$$SL = 5.00 \text{ for } max\ \{L_s \text{ (AISI, DIN)}\} \tag{8}$$

The Stringency Levels of the rest of standard requirements are calculated according to equation 9:

$$SL = \frac{L_s}{L_{s(Max)}} SL_{(Max)} \tag{9}$$

2.4. Ferrite - δ content and the relationship with hot cracking

We have carried out prediction studies based on the estimation of ferrite-δ content and its relationship with hot-cracking according to the criterions of different authors [13, 14]. Small amounts of ferrite-δ, accompanying the austenite, reduce hot cracking [15]. Also, a small amount of ferrite-δ is beneficial to mitigate the harmful effect of Sulphur, probably because Sulphur atoms are trapped into the ferrite [16].

Historical studies [17-20] have demonstrated that hot cracking increases when the value of equivalent Chromium and Nickel is modified to obtain a purely austenitic structure, without ferrite-δ. In order to ensure the reproducibility of results between different laboratories, the U.S. Welding Research Council defined the term called Ferrite Number (FN), to define the amount of ferrite measured by a calibrated instrument. Thus, design engineers usually require a minimum FN of 4-5 for cladding processes for RPVs. De Long diagram (figure 1) is frequently used to estimate the FN [14, 21]. FN coincides with the %wt content of ferrite- δ up to a FN equal to 6 [22]. The Chromium equivalent (Cr_{eq}) is calculated according to equation 10.

$$Cr_{eq} = \%\, Cr + \%\, Mo + 1.5\%\, Si + 0.5\, \%\, Nb \tag{10}$$

Whereas Nickel equivalent (Nieq) is calculated according to equation 11:

$$Ni_{eq} = \%\, Ni + 30\, (\%C + \%\, N) + 0.5\, \%\, Mn \tag{11}$$

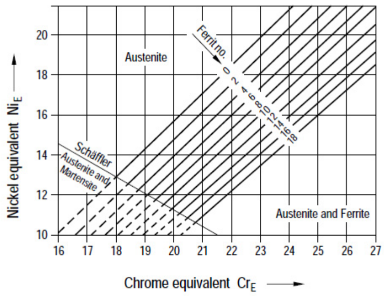

Fig. 1. Ferrite-δ estimation according to the De Long diagram [11].

In addition, Brooks and Thompson [13] demonstrated that stainless steels with a Cr_{eq}/Ni_{eq} ratio greater than 1.5 are considered hot cracking immunes.

3. Results and discussion

Table 1 shows the chemical requirements specified for AISI 304 and AISI 347 austenitic stainless steels, and their German equivalents, DIN X5CrNi18-10 and DIN X6CrNiNb18-10, respectively.

Table 1. Chemical composition required for AISI 304, DIN X5 Cr Ni 18-10, AISI 347 and DIN X6 CrNiNb 18 – 10 [1, 19].

Specification	Chemical requirements maximun Wt %								
	C	Mn	Si	Cr	Ni	P	S	N	Nb
AISI 304	0.08	2.00	0.75	18.00-20.00	8.00-10.50	0.045	0.03	0.10	-
DIN X5 Cr Ni 18-10	0.07	2.00	1.00	17.00-19.50	8.00-10.50	0.045	0.015	0.11	-
AISI 347	0.08	2.00	0.75	17.00-19.00	9.00-13.00	0.045	0.03	-	10%C-1.00
DIN X6 Cr Ni Nb 18-10	0.04	2.00	1.00	17.00-19.00	9.00-12.00	0.035	0.015	-	0.65

The analysis of Carbon and Sulphur requirements and their influence, as well as the analysis of mechanical requirements and the FN estimation is developed in subsections 3.1 to 3.4, as follows.

3.1. Influence and Stringency Level of Carbon content

Carbon is the essential ingredient in the formation of Chromium carbide, which is known to precipitate in the grain boundaries, producing intergranular corrosion. One method to avoid this type of corrosion process is to reduce the carbon available for the formation of Chromium carbide.

The calculation of Stringency Level of Carbon requirement is developed according to equations 1 and 2 (case 1) and it is shown in table 2:

Table 2. Carbon requirement and its Stringency Level.

Specification	C maximum wt% content required	SL (C)
AISI 304	0.08	2.50
DIN X5 Cr Ni 18-10	0.07	2.86
AISI 347	0.08	2.50
DIN X6 Cr Ni Nb 18-10	0.04	5.00

The material DIN X6CrNiNb18-10 exhibits the maximum Stringency Level of the analyzed group (5.00), followed by the DIN X5CrNi18-10 (2.86) AISI 304 (2.50) and AISI 347 (2.50).

3.2. Influence and Stringency Level of Sulphur content

The irradiation embrittlement is a complex phenomenon that depends of the chemical composition, neutron flux and operation temperature [23]. Experimental results have shown that Irradiation-Assisted Stress Corrosion Cracking (IASCC) is dramatically increased when the Sulphur content is greater than 0.03% [16].

The calculation of Stringency Level of Sulphur requirement is developed according to equations 3 to 7 (case 2) and it is shown in table 3:

Table 3. Sulphur requirement and its Stringency Level.

Specification	S maximum wt% content required	SL (S)
AISI 304L	0.030	2.00
DIN X5 Cr Ni 18-10	0.015	5.00
AISI 347	0.030	2.00
DIN X6 Cr Ni Nb 18-10	0.015	5.00

The Sulphur requirements specified by DIN are more stringent (5.00) than requirements specified by AISI (2.00).

3.3. Stringency Level of minimum requirement of Ultimate Tensile Strength

A high value of Ultimate Tensile Strength (UTS) compensates thermal distortions [24]. That is the reason why it is convenient an elevated value of this requirement.

The calculation of Stringency Level of UTS requirement is developed according to the equations 8 and 9 (case 3) and it is shown in table 4:

Table 4. UTS requirements and its Stringency Levels.

Specification	UTS [MPa] Min	SL (UTS)
AISI 304L	515	4.95
DIN X5 Cr Ni 18-10	520 – 720*	5.00
AISI 347	515	4.95
DIN X6 Cr Ni Nb 18-10	510-700*	4.90

*Maximum value specified

3.4. Ferrite-δ estimation

Table 5 shows FN according to equations 10 and 11 and De Long diagram.

Table 5. Cr_{eq} , Ni_{eq} and FN estimation according to De Long diagram.

Specification	Hot cracking prediction			
	Cr_{eq}	Ni_{eq}	Cr_{eq}/ Ni_{eq}	FN according to the De Long Diagram
AISI 304L	20.13	15.65	1.29	0
DIN X5 Cr Ni 18-10	19.75	15.65	1.25	0<FN<2
AISI 347	19.58	14.4	1.36	0<FN<2
DIN X6 Cr Ni Nb 18-10	19.83	12.7	1.56	4<FN<6

The obtained range of FN is between 4 and 6 for the DIN X6CrNiNb18-10 according to the De Long diagram, therefore this material is more suitable with respect to hot cracking; AISI 347 and DIN X5CrNi18-10 exhibit FN less than 2, while AISI 304 does not contain ferrite-δ. In addition, DIN X6CrNiNb18-10 is immune to hot cracking, because the Cr_{eq}/Ni_{eq} ratio is greater than 1.5. The Cr_{eq}/Ni_{eq} ratio for rest of materials is less than 1.5, and therefore they are prone to hot cracking, according to Brooks and Thompson criterion [13].

3.5. Additional considerations. Influence and of Niobium content

Niobium presents a high affinity for Carbon; therefore Niobium carbides are formed [25]. Bywater and Gladman [26] studied the effect of 0.1% Niobium addition on AISI 304 and AISI 347 tensile test samples and they concluded that Niobium improves ductility and prevents intergranular cracking. The materials AISI 347 and DIN X6CrNiNb18-10 contain Niobium; therefore they are more suitable to prevent intergranular cracking.

3.6. Comparison of obtained values

Table 6 shows a comparison of calculated Stringency Levels, the Cr_{eq}/ Ni_{eq} ratio and FN estimation according to the De Long diagram. In addition, a colour code is assigned, according to scale of table 1.

Table 6. Comparison of obtained values and its assigned colour code.

Specification	SL (C)	SL (S)	SL (UTS)	Cr_{eq}/ Ni_{eq}	Medium value of FN (ferrite – δ)
AISI 304L	2.50	2.00	4.95	1.29	0
DIN X5 Cr Ni 18-10	2.86	5.00	5.00	1.25	1
AISI 347	2.50	2.00	4.95	1.36	1
DIN X6 Cr Ni Nb 18-10	5.00	5.00	4.90	1.56	5

4. Conclusions and future works

As a general conclusion, the analyzed DIN-requirements are more stringent than analyzed AISI-requirements. Specifically, the Carbon Stringency Level of the DIN X6CrNiNb18-10 material corresponds with the maximum of the group analyzed (5.00), followed by DIN X5CrNi 18-10 (2.86), AISI 304 (2.50) and 347 (2.50). In addition, the Sulphur requirements are also more stringent in the case of DIN materials.

We can conclude that DIN X6CrNiNb18-10 is the best option, because of its lowest hot cracking susceptibility (5% of ferrite-δ content) and intergranular corrosion susceptibility (Niobium content) and the high stringency of its requirements. The advantage of the proposed methodology in this work is to compare quantifiable values such as the Ferrite Number (FN) and Stringency Level (SL), using the requirements of evaluated materials. The results allow us to select the best material option based on a prediction of crack behaviour and a comparative assessment of requirements according to a methodology based on Stringency Levels.

Our wish for the future is applying the methodology to different standardized specifications of materials with industrial interest, carrying out a previous selection of requirements with higher influence on mechanical behaviour of materials for the energy and aerospace industries.

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