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A350 LF5 CL 2, A CONVENIENT MATERIAL FOR CONTAINMENT OF TYPE B PACKAGING

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ABSTRACT

For the containment of Type B packaging it is necessary to demonstrate that there is no risk of brittle fracture. For ferritic carbon steel, the brittle facture risk assessment is based on toughness properties and the size of critical discontinuities which can be detected by Non Destructive Examination. Cryogenic carbon steels are very good candidates and their price is very competitive since the Nickel content is limited. A350 LF5 class 2 base material with a nominal Nickel content of 1.5% has been used for several decades in the manufacturing of casks with forged thick components such as the TN®12-2 transport cask or the TN®24 dual purpose cask (DPC). The grade performances of this material are well optimized: Dynamic fracture toughness at -40°C as well as tensile properties at maximum service temperature ensures an adequate resistance in accidental transport conditions. This performance has been demonstrated thanks to a material qualification which has been completed by a forging process qualification for each first-of-a-kind component and/or new forged master. The acceptance criteria for the quality control of the serial production is based on a minimal Charpy energy value of 140 J at -40°C which guarantees a sufficient minimal dynamic fracture toughness at -40°C compared to the usual values of Stress Intensity Factors in a containment vessel during a 9-m drop. This approach has been validated by the French Nuclear Safety Authority (ASN). Its weldability is also very good. The toughness and tensile properties of the shell-to-bottom weld are as good as that of the base material. Thanks to these unique properties, A350 LF5 class 2 is a very appropriate material for the containment of Type B packaging.

INTRODUCTION

Carbon steel thick forging is one standard solution for the containment of Type B transport and interim storage packaging for nuclear materials. The grades used are selected among cryogenic steel, including ASTM A 350 LF5 class 2, and are suitable for the manufacture of pressure vessels at the minimum service temperature below of -40°C (-40°F) due to their good toughness properties. For several decades ASTM A 350 LF5 class 2 has been used to manufacture parts which combine containment and gamma shielding properties. The assembly process of the cask is simplified as only one layer of material is used instead of two: one for the containment and one for the shielding. The number of welds is reduced to one full penetrated bottom-to-shell butt weld. For example, designs with thin containment have at least 3 relevant safety welds. The rolled plate is first welded longitudinally to create the shell which is circumferentially welded to a top and bottom ring at the two extremities. The reduction of the gap between the containment shell and the gamma shielding shell is also an advantage for thermal transfer.

ASTM A 350 LF5 class 2 is used on parts with a thickness of up to 300 mm. The finished weight of a shell is several ten of tons. Because of this, it is important to limit the cost per kilogram. A350 LF5 class 2 steel, with its limited content of a costly alloy element, such as Nickel, is in line with this expectation.

MATERIAL QUALIFICATION

Extended test programs have been conducted for several years on containment forging during which a forging process qualification for each new forging company and for each new forging dimensions is performed. Test rings at both extremities are used to verify the homogeneity of the properties in any location of the part (both extremities are essential). The top of the shell is a sensitive area because it is a highly loaded area fitted with threaded holes for the closure system. The bottom of the body is also a key area because of the bottom-to-shell weld.

Furthermore, The TN® 24 cask design generally requires extra-thickness at the top of the cask. This extra-thickness can generate a different cooling rate during the quenching operation, detrimental to material characteristics. To confirm the homogeneity, Charpy tests are taken at different thicknesses and in the directions parallel and perpendicular to the main working direction. The quality control acceptance criteria shall be met for all orientations.

CHEMICAL COMPOSITION

Typical example chemical compositions of ingots are presented in table 1. Low sulfur and phosphor can be achieved. The relative low carbon content is not detrimental to the tensile properties. Significant margin on yield strength and tensile strength are presented in figure 2.

Table 1 Example of heat chemical composition

	C	Mn	Si	P	S	Ni	Cr	Mo	Cu	Nb	V	Cr+Mo
ASTM A350	<0.3	0.6-1.35	<0.12	<0.035	<0.04	1-2	<0.3	<0.12	<0.4	<0.2	<0.3	0.32
Heat A	0.12	1.17	0.09	0.007	0.005	1.85	0.17	0.09	0.1	0.001	0.005	0.26
Heat B	0.15	1.04	0.12	0.004	0.001	1.81	0.17	0.03	0.15	0.003	0.003	0.2
Heat C	0.15	1	0.1	0.008	0.002	1.82	0.2	0.05	0.18	0.003	0.003	0.25

TENSILE PROPERTIES

For containment forging, ASN now requires a process qualification to be carried out. This qualification is done on the first piece in a series. They have shown no influence of the location and orientation of the test samples in the forging (see figure 1 example for a QHT thickness of 322 mm). The yield strength is not linked to the location in the thickness. No significant discrepancies appear between the top and the bottom. Tensile Test samples oriented in a transverse direction have similar characteristics to those in longitudinal direction.

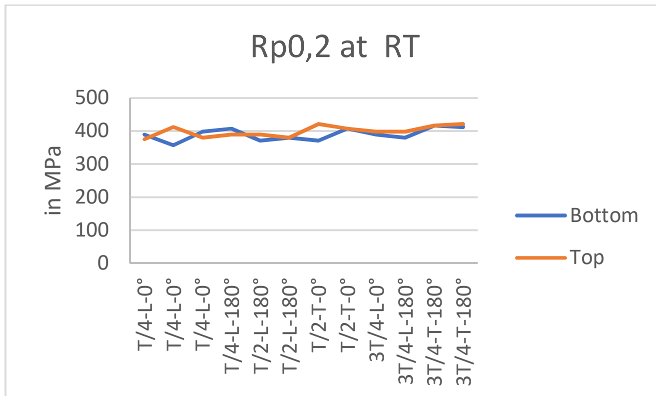

Figure 1 Variation of yield strength through thickness (Thickness 322 mm)

(T/4-L-0°: T/4 = depth : quarter thickness - L = longitudinal orientation to the main working direction - 0° = angular orientation along the circumference)

Tensile Tests carried out on a series of identical shells (thickness 215 mm) are presented in figure 2. They comply with the required ASTM A350 value at room temperature. They correspond to samples located at T/4. The results show significant margin for the minimum value. The margin is 28% for the yield strength. On the ultimate strength, the results are close to the standard criteria.

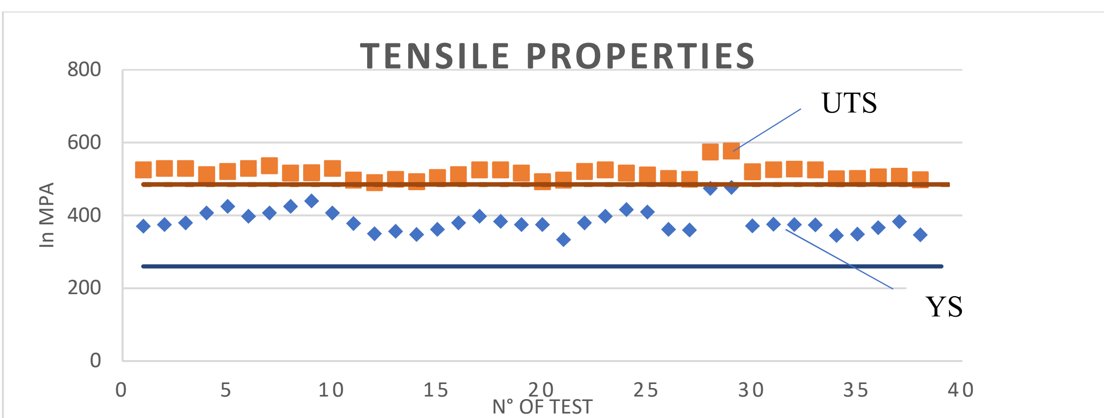

Figure 2 Reproducibility of the tensile properties for a type of cask

YS = Yield Strength - UTS = Ultimate Tensile Strength

CHARPY IMPACT TEST

The process qualification also includes verification of the toughness properties of the forging. Charpy impact test specimens are conducted in accordance with the ASTM A 370 standard with full thickness specimens of 10x10 mm. The axis of the samples is located at 3 different thicknesses (T/4, T/2 and 3T/4). Samples are oriented in longitudinal and transverse directions to the main working direction and testing temperature is -40°C. This temperature corresponds to the minimum regulatory service temperature for Type B(U) packaging. The screening through the thickness generally shows that the lower individual value is obtained at mid-thickness, see figure 3. This location is generally characterized at the weakest and it is selected for the toughness of the test samples.

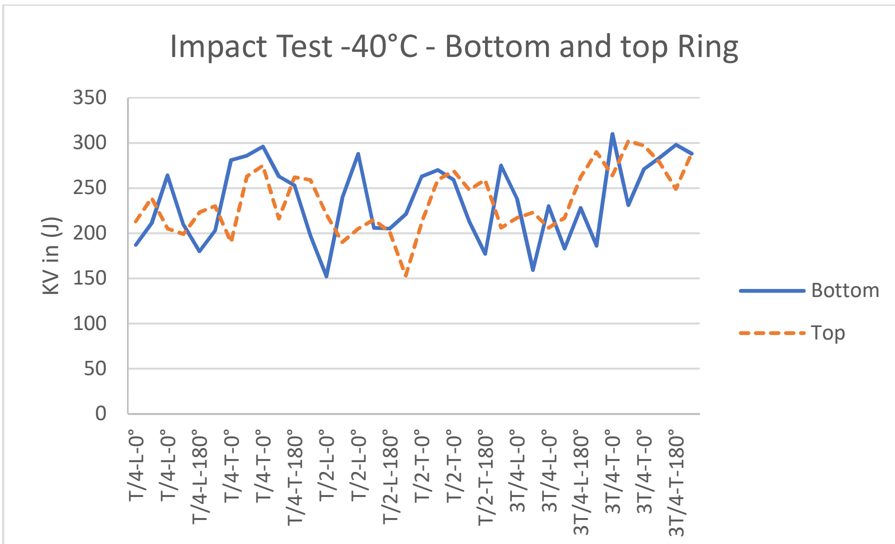

Figure 3 Impact test through thickness (Shell thickness of 322 mm at QHT treatment)

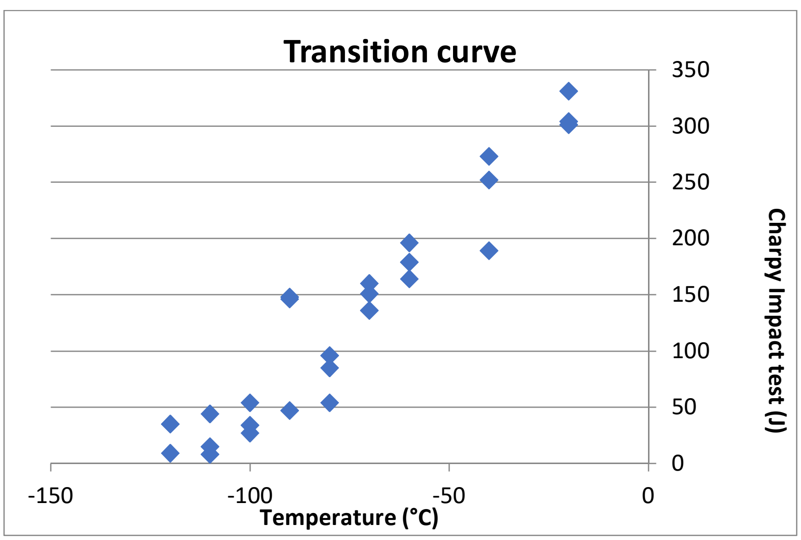

Figure 4 Typical example of impact test transition curve at mid thickness

(Shell thickness of 322mm at QHT stage)

FRACTURE TOUGHNESS

For the material qualification conducted prior to the process qualification, a dynamic fracture toughness test is done with SEB (25) samples in accordance with the ASTM E 1921 standard. If the samples thickness is defined as 'B' (25 mm), the width 'W' is 2B (50 mm) with a standard length of 2x2.25W. A notch is machined at the centre and then extended by generating a fatigue crack so that the total 'defect' depth(a) is half the width of the test piece (a/W=0.5).

Note that this sample thickness value (B=25mm) would certainly not be sufficient to get valid plane-strain fracture toughness results according to ASTM E399. Nevertheless, this thickness is conservative (superior) compared to the maximal crack front length of potential defects taking into account NDT performances. Indeed, ASN requires ultrasonic tests on forged components of the containment vessel with acceptance criteria as stringent as those of the EN 10228-3 (quality class 3) standard which allows the exclusion of defects in the component of 6mm in length and longer .

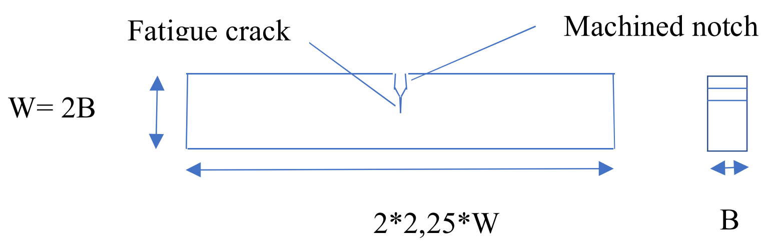

Figure 5 Dynamic toughness sample SEB(25)

The samples are bend bent between three points. The load versus the size of the crack opening is measured during the deformation.

The dynamic toughness KJd is calculated according to the equation below using the Jd measurement which represented the absorbed energy (area below the curve). It is computed according to ASTM E 1921 assuming plane strain conditions.

$$KJ_d = \sqrt{J_d \cdot \frac{E}{1-\nu^2}}$$

E = Young modulus, ν =poison ratio = 0.3.

The target for the dynamic loading speed (dK/dt) was 10,000 MPa.√m/s in order to be representative of maximum loading speed in the structure during drop test conditions. The tests is conducted on two heats. 30 samples were tested. The lowest value was 182 MPa.√m and most of the curves show a ductile behavior.

The process qualification for each new type of forging or for each modification of major process parameters includes verification of the dynamic fracture toughness properties on a limited number of samples to confirm that the Charpy impact test criteria at -40°C is relevant. The tests are carried out in the area with the weakest impact energy results. In addition to the two heats used for the first material qualification, 5 heats of large forgings with a thickness greater than 200 mm were tested in the last few years, the lowest value being 282MPa.√m.

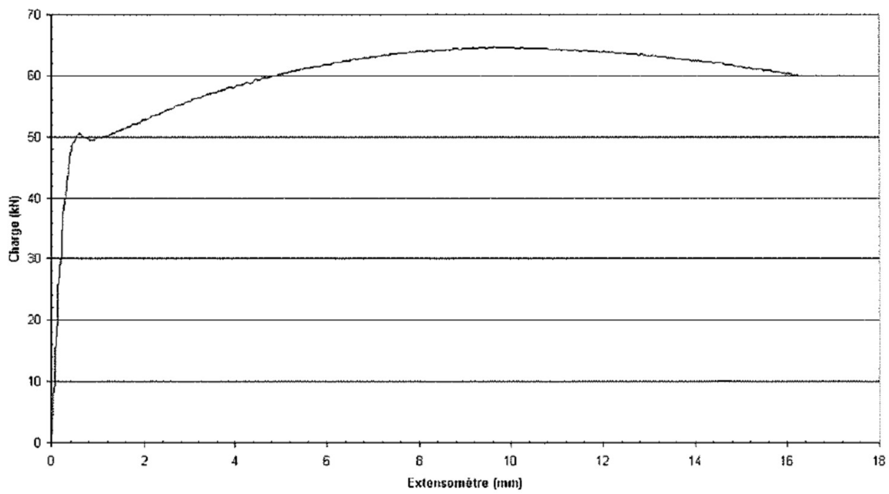

Figure 6 Example of SEB(25) curve with ductile behavior

Regarding irradiation influence on toughness properties, it is widely accepted that the neutron fluence level on a containment vessel of a used fuel DPC, such as the Orano TN TN®24, is significantly lower than those on a reactor vessel and do not affect mechanical properties.

WELDABILITY

As far as weldability is concerned, A350 LF5 Cl2 material is classified as P 9A in the ASME IX (9.1 according to ISO 15608). Several welding material manufacturers offer references which are adequate. Due to the considerable thickness of the weld, the SAW welding process is mainly used to get a high deposition rate. Since it is an automatic welding process the repair rate is very low. Post welding heat treatment is required by ASME III div 1 NB. This PWHT is convenient to limit residual stress in the weld.

Tensile tests conducted at room temperature in the weld deposit give a higher yield strength and tensile strength than the in the base metal.

The dynamic fracture toughness tests conducted in HAZ show a ductile behavior. In the weld deposit, seven samples out of twenty, exhibit brittle behavior and thirteen have ductile behavior. The minimal dynamic fracture toughness was measured at 190MPa.√m.

Table 2 Example of tensile test properties in weld metals

Tensile test at room temperature	Re (MPa)	Rm (MPa)
1	493	576
2	485	577
3	486	577
Average	488	577

CONCLUSIONS

A thick forging made of 350 LF5 class 2 material has homogeneous tensile properties which do not show a link to the thickness position or to the orientation (longitudinal versus parallel direction). The weld is as good as the base metal. Several qualifications of the forging process and the welding process show that sufficient dynamic toughness at -40°C, compared to the maximum Stress Intensity factor (SIF) expected in accidental conditions of transport, can be guaranteed in the containment boundary with this grade of steel.

ACKNOWLEDGMENTS
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REFERENCES

ASME III div 1 NB.

ASME IX Qualification Standard for Welding and Brazing Procedures, Welders, Brazers, and Weldingand Brazing Operators