Proceedings of the 15th International Symposium on the Packaging and Transportation of Radioactive Materials
PATRAM 2007
October 21-26, 2007, Miami, Florida, USA

USE OF ALCAN'S AL-B_4C METAL MATRIX COMPOSITES AS NEUTRON ABSORBER MATERIAL IN TN INTERNATIONAL'S TRANSPORTATION AND STORAGE CASKS

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ABSTRACT

Major issues in the area of transportation and/or storage of radioactive materials are reliability and safety of engineering components. Among the functions to be undertaken, transportation and storage systems shall allow the criticality control of the transported matter, the control of its temperature, as well as the capacity to withstand the mechanical stresses due to normal, incidental and accidental conditions of use.

In most cases, criticality control requires the use of an internal arrangement made of a neutron absorber material, which must also have high thermal conductivity properties to ensure the temperature control. When, as in many AREVA-TN International applications, the design takes credit of the neutron absorber material as a structural component, it must show high mechanical performances.

Alcan's Al-B_4C Metal Matrix Composites (Al-B_4C MMCs) meet all the above-mentioned requirements, due to their special capability of capturing neutrons, their lightweight, and their superior thermal conductivity and mechanical properties. The significant advantage of Alcan's technology is its flexibility with regards to a wide range of boron carbide contents and matrix alloys (from AA1XXX to AA6XXX). This enables the adjustment of the properties to the exact needs of the design. TN International presently uses extruded and/or rolled Al-B_4C MMC parts in several of its internal arrangements.

The present paper gives an overview of the manufacture processes of Alcan's Al-B_4C MMCs, from the mixing of B_4C into liquid aluminium to the extrusion and rolling operations. It describes the methods and results for the qualification tests in terms of the neutron absorption, thermal, physical and mechanical properties of the material. Finally, details are given on the use of Alcan's MMCs as a neutron absorber with enough credit for structural material in TN International's TN24 designs.

INTRODUCTION

Alcan's Al-B_4C Metal Matrix Composites are the composite containing boron carbide mixed in an aluminium matrix. The distinctive feature of this material is its manufacturing process; indeed, the boron carbide (B_4C) powder is here mixed into the liquid metal [1]. In the following, the material will simply be denoted as "Boron MMC". It allows to achieve a very uniform distribution of the B_4C particles in the aluminium matrix and maintains all the properties of the metal for the finished material, i.e.:

- Lightweight;
- Physical properties, especially thermal conductivity;
- Mechanical strength depending on the type of alloy selected for the matrix.

These properties, combined with the ability of B_4C to capture neutrons, makes Boron MMC a good candidate for the fabrication of baskets dedicated to receive spent fuels inside the cavity of transport and/or storage casks.

TN International started a close collaboration with Alcan in 2003 to tune up the finished product characteristics to the needs of the TN24^{TM} designs. The first casks, equipped with a basket made of Boron MMC, were loaded in 2007; several of them are under construction while Alcan has already delivered the material for more than 10 baskets.

FABRICATION OF BORON MMC

Generalities

The diagram in Figure 1 illustrates the main steps of the manufacturing process of Boron MMC. The aluminium matrix is melted in an induction furnace, where the B_4C powder is incorporated into the liquid metal. An appropriate mixing sequence permits to achieve a perfect distribution of the B_4C filler in the furnace.

The MMC is then poured into the DC caster to obtain either round billets or rectangular ingots, depending on the final transformation process foreseen. Both extrusion (as presented in the diagram of Figure 1) and rolling are the common methods used in the downstream to fabricate the final products.

Type of Aluminium Matrix

One of the main advantages of the Alcan's manufacturing process is that it allows the use of a various range of aluminium alloys, from AA 1XXX to AA 6XXX series.

Boron Content

The key parameter for the efficiency of the material to serve as a neutron absorber is its boron content. It is determined here by the quantity of B_4C powder mixed with the aluminium matrix, expressed as a fraction of weight (wt.%) or as a fraction of volume (vol.%)., Alcan currently manufactures Boron MMC materials with a B_4C range from 4 to 16 vol.% on a regular production basis. Although the upper limit of B_4C content in Alcan's process is to be determined, Alcan recently cast and fabricated a Boron MMC with 25 vol.% B_4C on a large industrial scale.

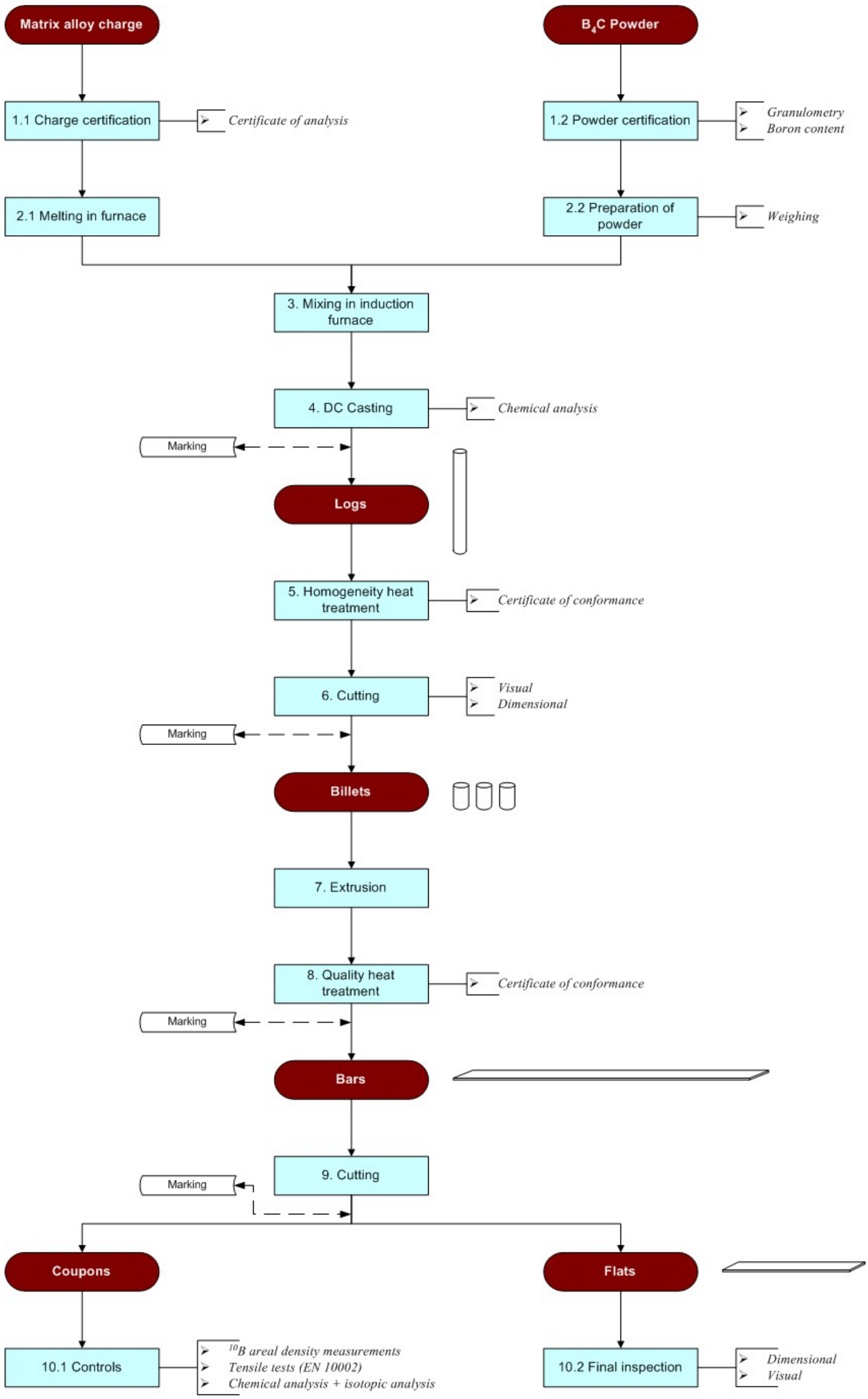

Figure 1. Diagram of Boron MMC Manufacturing Schedule

Final Product

Alcan's Boron MMC can be fabricated in the form of extruded bars (Figure 2) or rolled sheets (Figure 3), depending on the conditions of use. Fabrication of profiles presenting a more elaborated section has been demonstrated to be possible, but has not been produced yet on an industrial scale.

Inspection

The main inspections performed along the manufacturing process are:

- Chemical analysis of the aluminium matrix and checking of the material certificate of B_4C powder.
- Control of neutron absorption properties and good distribution of boron by neutron transmittance measurements on samples cut from the flats.
- Verification of mechanical properties at the design temperature of the cask, by tensile tests performed on samples cut from the flats.
- Dimensional and visual inspection of the finished product.

A Quality Assurance Program based on TN International's requirements is implemented all along the different steps of the manufacturing schedule.

Figure 2. Extruded Bars of Boron MMC

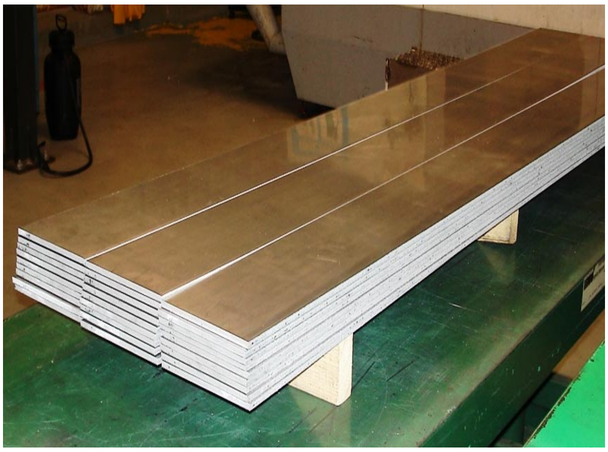

Figure 3. Rolled Sheets of Boron MMC

QUALIFICATION OF BORON MMC

Qualification of Alcan's Boron MMC was carried out for various B_4C contents. In the following section, results of an extruded material containing 4 vol.% B_4C are exemplarily presented here. This grade is used by TN International for building the TN24BH/BHL baskets. The manufacturing schedule of the qualification batches was strictly the same as that one implemented in large-scale productions.

Neutron Absorption Properties

Scope of the Testing

The acceptance and qualification testing of the material in terms of neutron absorption properties are performed by neutron transmission measurements. The average value of the ^{10}B areal density is determined on test pieces sampled from the production run. The sampling may vary with the dimension of the flats and the cutting schedule. The main purpose of the qualification is to demonstrate that the material in the entire batch is capable of reaching the target ^{10}B areal density, which assures the appropriate neutron absorption [2, 3].

Introduction to Neutron Transmission Measurement

A thermalized, collimated neutron beam from a research reactor is used for this verification. The measurement of ^{10}B areal density is made by comparison of the neutron count after the beam passes through the test piece to the count after the same number of neutrons pass through calibration standards of known uniform ^{10}B areal density. As the reactor flux is not constant, it is necessary to have neutron detectors not only after attenuation by the test piece, but also for the incident neutron beam, in order to normalize the counting. If the areal density is too high to be measured in a reasonable period of time, samples with reduced thickness can be prepared by machining. The number of counts must be high enough to obtain the desired degree of accuracy, that is, to reduce the standard deviation to the desired level; the time to achieve this number of counts increases with increasing ^{10}B areal density.

Results of the Neutron Absorption Qualification

The qualification of neutron absorption properties was implemented on a full-size batch of Boron MMC flats of 23 mm in thickness. For this material, the target ^{10}B areal density A can be determined with the formula:

$$A = W \times \rho \times E \times t$$

where:

W is the expected total weight percent (% wt.) of boron in the material
ρ is the bulk density of the material (see above)
E is the ^{10}B content (i.e. $^{10}B/B_{total}$ in percentage)
t is the thickness of the samples

The results of the neutron transmission measurements performed for the qualification tests are given in Table 1.

Table 1. Neutron Absorption Properties of Boron MMC

	^{10}B Areal Density Boron MMC Thickness (t) : 23 mm
Target boron content (mg $^{10}B/cm^3$)	13.74
Target areal density A (mg $^{10}B/cm^2$)	31.6
Number of samples	140
Mean areal density (mg $^{10}B/cm^2$)	36.02
Minimum areal density (mg $^{10}B/cm^2$)	32.944
Std. Dev.	0.77

The results show that the neutron absorption of the full-size batch meets and exceeds the target ^{10}B areal density, since among 140 samples, the minimum ^{10}B areal density is far above that of the target ^{10}B.

Thermal and Physical Properties

Generalities

One of the main purposes of TN International transport/storage casks is to enable the heat exchange between the cask cavity and the outside. Therefore, thermal conductivity between 25°C and 300°C is of high interest for TN24™ applications. The conductivity is determined by measurement of the thermal diffusivity, thermal expansion, density and specific heat.

Specific Heat

Values at different temperatures are given in Table 2.

Table 2. Specific Heat of Boron MMC

Temperature (°C)	23	100	200	300
Cp (J/kg/K)	870	920	970	1010

Thermal Diffusivity

Thermal diffusivity was measured by laser flash method (ASTM E1461). Values at different temperatures are given in Table 3.

Table 3. Thermal Diffusivity of Boron MMC

Temperature (°C)	23	100	200	300
D (cm²/s)	0.792	0.757	0.719	0.689

Thermal Expansion

The mean thermal expansion coefficients of the materials at different temperatures are reported in Table 4.

Table 4. Thermal Expansion of Boron MMC

Temperature (°C)	100	200	300
Thermal expansion α (10^{-6} K^{-1})	20.6	22.9	24.3

Bulk Density

The bulk density at 23°C was measured using the ISO1183 standard. It was equal to 2.700 g/cm^3. From this result, the density at various temperatures can be evaluated with the formula:

$$\rho_T = \frac{\rho_0}{\left(1 + \alpha_L\right]_{T_0}^{T} \left(T - T_0\right)\Big)^3}$$

where: α_L is the linear thermal expansion coefficient of the material, at the concerned temperature, given in Table 4. The calculated densities are given in Table 5.

Table 5. Bulk Density of Boron MMC

Temperature (°C)	100	200	300
Bulk density ρ (g/cm^3)	2.69	2.67	2.65

The B_4C itself has a density of 2.52 g/cm^3, which is slightly lower than the density of aluminium alloys, i.e. about 2.7 g/cm^3. B_4C additions thus lead to a reduction of density. Nevertheless, this effect is barely detectable experimentally in this material.

Thermal Conductivity

Values of the thermal conductivities at the different temperatures are given in Table 6. They were calculated from the results above using the relation:

$$D = \frac{\lambda}{Cp \times \rho}$$

Table 6. Thermal Conductivity t of Boron MMC

Temperature (°C)	23	100	200	300
λ (W/m.K)	187	188	187	184

Thermal conductivities of Alcan's Boron MMC are in good agreement with TN International's requirements. This material enables a reasonable thermal gradient between the centre and the edge of the baskets.

Mechanical Properties

The mechanical properties of Boron MMC were determined throughout several tensile tests at various temperatures performed according to EN 10002. The minimum values obtained are reported in Table 7.

Table 7. Minimum Mechanical Properties of Boron MMC

Temperature (°C)	Minimum Values Obtained		
	Yield Strength Y.S (MPa)	Tensile Strength T.S (MPa)	A (%)
130	250	266	17,5
175	236	241	6,1
200	217	226	8,8
300	59	68	16,7

Repeatability of the Mechanical Properties

The capability of the manufacturing process has been verified on a qualification batch of Boron MMC sampled from a single heat from which 20 ingots were cast. An appropriate sampling schedule has been applied after extrusion into flats to verify that the mechanical properties were repeatable from ingot to ingot, billet to billet and flat to flat. This evaluation was made at the design temperature of the TN24 BH cask (175°C) by tensile tests performed according to EN 10002. Results are given in Table 8 below.

These results show that the mechanical properties are kept homogeneous within a production run. The level of mechanical strength is also in good agreement with the structural requirements for TN24™ designs.

Table 8. Mechanical Properties at 175°C from the Qualification Batch of Boron MMC

Origin of the Coupons	Number of Tests	Mechanical Property Evaluated					
		Yield Strength Y.S. (MPa)		Tensile Strength T.S. (MPa)		Elongation A (%)	
		Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Log #12 Billet #4	10	258.8	7.3	259.8	7.36	8.49	1.22
Log #12 Billet #1 to 5	10	255.2	4.91	257.6	3.82	8.36	1.36
Log #5 Billet #1 to 6	12	249.4	4.12	250.8	3.72	8.13	0.81
Log #8 Billet #1 to 6	12	251.3	8.24	253.8	6.68	8.92	1.53
Log #4 Billet #1 to 6	12	256.7	2.82	257.4	2.73	8.57	1.02

USE OF BORON MMC IN TN24BH/BHL DESIGN

Machining of Boron MMC

For the fabrication of TN24 BH/BHL baskets, the Boron MMC is delivered in the form of bars of 7 meters long, which are cut into flats of the appropriate length. Notches, chamfers, threaded holes and others are machined in the flats to obtain the desired finished parts that will constitute the basket. The material can be machined by all the conventional processes such as milling, drilling, turning, provided that adequate tools and speeds are used. Advanced processes such as electro-erosion and water-jet cutting can also be used.

Basket Assembling

The parts obtained are interlocked and piled up to build the alveolar structure of the basket.

Figure 4 shows different types of baskets for TN24 casks. On the left side is a TN24BH/BHL built up with Boron MMC.

CONCLUSIONS

The TN24 designs take credit for the mechanical strength of the neutron absorber material for the structural behavior of the baskets. For this reason, TN International specified adequate mechanical properties for the procurement of that kind of material. Alcan’s Boron MMC met all these requirements and the results of the mechanical testing on products were in conformity. The material also achieved the desired neutron absorption properties confirmed by the neutron transmittance measurements on the full-size batch. Various boron contents, from 4 vol.% to 16 vol.% B_4C, have been produced in a large variety of flats sections. Alcan's Boron MMC is used today for building the baskets of all TN24 design family casks.


Figure 4. Different Types of TN24 Baskets

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