INTRODUCTION

The electric arc furnace processing of oxide ceramics is a well-established and widely-used industrial technology. Raw materials are readily melted together by joule and radiant heating to form substantially large liquid volumes. These are refined if necessary with carbon and additions of metal scavenging agents such as iron, and the product is then poured into molds for solidification. The castings can be used directly as fused cast refractories or, more commonly, are crushed down to fine sizes for use in a wide variety of applications.

Arc furnaces are less commonly used for manufacturing non-oxide ceramics. The melting points of most of these materials are well over 2273 K (2000 °C) and thermal conductivities are high, resulting in a condition where reaction products are more likely to freeze just outside of the arc zone than to flow away and form a surrounding liquid pool. Production is therefore limited to relatively small batch quantities. Furthermore, useful shapes cannot be directly made by the arc furnace process and downstream processing and consolidation are always necessary.

The patent and technical literature describe many attempts at developing arc-based manufacturing processes for non-oxide ceramics (Lipp, 1965). Successes exist, notably boron carbide (B₄C) for which production quantities are about 500,000 kg (1.1 MM lb) per year (Schwetz and Lipp, 1985). We will therefore discuss the manufacturing technology for this material in detail and then enumerate similar processes used for other commercial non-oxide ceramics.

BORON CARBIDE MANUFACTURING

Boron carbide (B₄C) is manufactured in electric arc furnaces by heating anhydrous boric acid (i.e., B₂O₃) together with graphite particles. The electric arc supplies sufficient thermal energy to melt the boric oxide (B₂O₃) and to react it with the graphite to produce B₄C:

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2B₂O₃ + 7C \rightarrow B₄C + 6CO \quad (5.1)
\]

The reaction occurs at temperatures slightly above the melting point of B₄C, 3036 K (2763 °C) (Thevenot, 1990). While the formation of B₄C is in theory easy to accomplish, the enormous volume of carbon monoxide (CO) that is liberated makes practical operations troublesome at best. Total energy productivity is quite low since 70–95 MW·s are required per kg of gross product (20–26 kW·h/kg) in comparison to the theoretical energy requirements of 14.7 MW·s/kg. However, arc furnace manufacture is almost twice as efficient as Acheson resistance furnace production of B₄C (Scott, 1964b).
RAW MATERIALS PREPARATION

Anhydrous boric oxide (B₂O₃), produced by the dehydration of boric acid (H₃BO₃), is readily available in the desired purity of 99.0% B₂O₃. Coarse sizes such as 4.76 mm (4 mesh) are preferred to minimize dust collector losses. Boric oxide should be purchased and stored in bags that have a moisture-resistant barrier since it is very hygroscopic and any hydration creates furnacing problems. For best results, the loss-on-ignition must be maintained below 1.5%.

Most final product specifications for boron carbide require purity in excess of 99% and therefore the preferred source of reactant graphite is machining chips from electrode turning operations. These are usually purchased as 2.38 mm (8 mesh) and finer particles. Purity exceeds 99.9% carbon.

A furnace mix formulated on a stoichiometric basis would contain 62.4% by weight anhydrous boric acid (i.e. B₂O₃) and 37.6% of graphite particles in order to yield a product which contains 78.3% boron. This proportion will vary depending on the molar ratio of carbon to boron that is specified for the final product; typically boron-rich B₄C is specified. However, a substantial portion of the graphite will be lost to oxidation with air and therefore mix formulations for stoichiometric B₄C are carbon-rich, typically in a ratio of 71% boron to 29% carbon. Each mix batch also contains from 20% to 40% ‘old’ mix reverted from previous furnace runs. Since the addition of the partially deoxidized revert requires less energy input for a given volume of mix and will result in less fume production, batches of mix that are designated for the bottom of the furnace charge will preferably contain up to 40% revert. Dust collector fines from crushing operations involving recycled mix and B₄C grain are also included in the mix in amounts up to 10% of the total to improve raw material productivity. Excess grits from crushing operations can also be included but it is usually more profitable to sell them as fine powders after milling, elutriation and acid leaching.

The total carbon, total boron and free B₂O₃ concentrations should be known for all of the raw materials to be used in each mix batch. The components for each batch are then weighed in proportions that will achieve the desired boron-to-carbon ratio. Mixing follows, typically in a ribbon blender, with the addition of sufficient kerosene to suppress dust losses, typically about 1%.

FURNACE DESIGN AND OPERATION

Boron carbide is made in open-top arc furnaces. The conventional three-electrode, three-phase power arrangement is preferred for energy productivity but single-phase furnaces have been successfully used. Electrode circles are small. Typically, the 0.30–0.35 m (11.8–13.8 in) diameter graphite electrodes used in a 1.8 m (5.9 ft) diameter, 2000 kVA furnace, are spaced from 0.30–0.35 m (11.8–13.8 in) apart. Their closeness is usually dictated by electrode holder configurations. The spacing will be less for lower power furnaces (Scott, 1964b). A three-phase transformer provides an output voltage to the electrodes that can be stepped from about 80 V to about 140 V.

The furnace structure is designed for easy disassembly. The slightly conical steel shell is set on a carbon base as shown in Figure 5.1. The assembly may be supported by a mold cart so that it can be pulled away from the electrodes. The shell is continuously water cooled on its outside walls.

A furnace run begins by lining the inside bottom surface of the furnace shell with a layer of petroleum coke. A layer of bottom mix, containing 40% revert, is spread over the petroleum coke and banked up around the periphery. A cavity matching the electrode configuration is scooped out from under the electrodes to a depth of about 0.1 m (3.9 in). This cavity is filled with 2.38 mm (8 mesh) graphite chips. The electrodes are then energized