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Experimental characterization of ceramic shells for investment casting of reactive alloys

Rui Neto[a], Teresa Duarte[a, *], Jorge Lino Alves[a], Francisco Torres[a]

[a]INEGI, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal

Abstract

The investment casting of reactive Ti and TiAl alloys requires the use of selected ceramics in the face-coat layer to prevent the reaction between the cast metal and ceramic shell, avoiding the formation of a hard layer at the metallic components surface. This work aims to study the influence of ceramic shells composition in some of its characteristics such as flexural strength, friability and dimensional accuracy. The microstructure of the shells was evaluated by SEM. Changes in the face-coat and back-up ceramic shells composition determines the ceramic shell strength to withstand the casting stage with adequate mould permeability and thermal conductivity, and a compromise resistance for knock-out. All the non-conventional ceramic shell systems with interest for reactive alloys, based on fumed alumina binder and alumina sand for the back-ups, present higher dimensional stability (low shrinkage or expansion) compared with traditional systems based on colloidal silica binder and zircon and aluminosilicates back-ups. In this work, better mechanical strength and lower friability were obtained with non-conventional face-coats of alumina and polymer binders, both with yttria flour and stucco, followed by alumina back-ups. Selecting the right ceramic shell composition, it is possible to achieve adequate properties for casting titanium alloys.

Keywords: Investment casting; friability; mechanical strength; ceramic shells; Ti alloys.

1. Introduction

The key requirements of a ceramic mould for investment casting are: enough green unfired strength to withstand wax removal without failure, sufficient fired strength to resist the metalostatic pressure, high thermal shock resistance to prevent cracking during metal pouring, high chemical stability and low reactivity with the metals being cast to reach adequate surface finishing and no alpha case formation on surface of Ti and Ti alloys parts. The mould also needs to present a level of permeability to be easily filled by molten metal, and a thermal conductivity to allow thermal transfer through the mould wall, allowing the metal to cool, and low thermal expansion to limit the dimensional changes and produce proper components. These requirements are mandatory to obtain metallic components without defects and with dimensional accuracy. Fig. 1 shows a production scheme to obtain a ceramic shell for investment casting and Fig. 2 depicts the generic structure of a ceramic shell.

Coating the pattern with the usual ceramic slurries [1] (based on silica, zircon or aluminosilicates) generates a reaction with the Ti alloys during casting and solidification, forming a 0.3-0.6 mm very hard (400-600 HV), cracked and weak reaction layer, called alpha case [2]. This surface layer is a result of the Ti reaction with the metallic oxides of the ceramic shells and is composed by brittle intermetallic compounds that significantly reduce the mechanical properties of the cast parts and raise machining problems [3].

To overcome this problem, titanium alloys should be poured into special ceramic shells that avoid or significantly reduce this type of reaction.

* Corresponding author.
E-mail address: tpd@fe.up.pt (Teresa Duarte)

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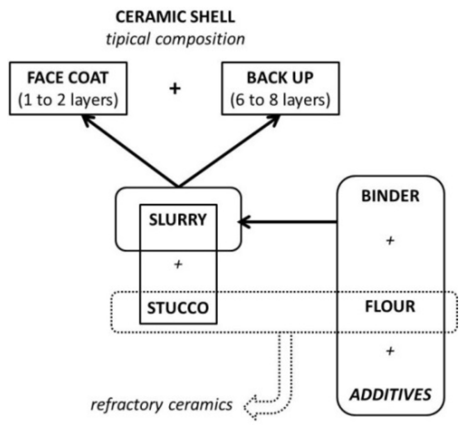

Fig. 1. Generic scheme to produce a ceramic shell.

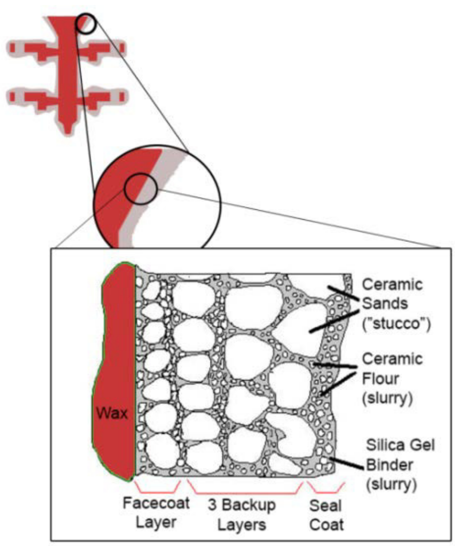

Fig. 2. Schematic of a ceramic shell for investment casting.

In this case, to select the most suitable ceramics one should take into account, as shown in Fig. 3, the standard free energy of formation of oxides (ΔGº). Ceramics such as CaO, ZrO_2 and Y_2O_3 must be adopted as mould materials and binders for the face-coat because their standard free energy of formation is more negative than that of TiO_2, preventing interface reactions [6]. Table 1 presents the main thermal properties and free Gibbs energy of formation of some ceramics used in shells production.

The melting temperature of the Ti and its alloys, 1400-1600°C [9], determines the temperature range to be analysed in the Ellingham diagram. As shown in Fig. 3, the lines related to the free energy of oxide formation in the lower part of the diagram (Al_2O_3, MgO, ZrO_2, CaO and Y_2O_3) mean that the oxide is thermodynamically more stable.

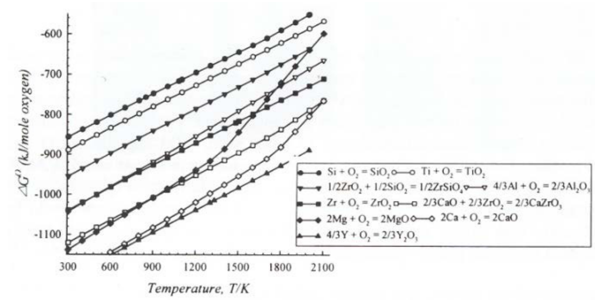

Fig. 3. Ellingham diagram for the more common oxides used in investment casting [4,5].

Table 1. Thermal properties and standard free energy of formation of different ceramic materials [7,8].

Ceramic	Thermal expansion coefficient ($x10^{-6} K^{-1}$)	Thermal conductivity (W/(m K)) 20-26°C	Gibbs Free Energy ΔG^O (kJ/mol O_2)	Softening temp. (°C)
Zirconia (ZrO_2)	10.0	2.5	-743 (at 1900 K)	2010
Yttria (Y_2O_3)	8.1	8.0-12.0	-989 (at 1469 K)	1855
Alumina (Al_2O_3)	8.0	28.0-35.0	-711 (at 1900 K)	1540
Silica (SiO_2)	0.5-0.8	1.2-1.4	-610 (at 1685 K)	1280
Zircon ($ZrSiO_4$)	4.5	8.0	not available	1815

With a softening temperature of 1855°C, above the melting temperature of the Ti alloys, and larger standard Gibbs free energy of formation than all oxides that could be used in the ceramic shells (-989 kJ/mol at 1469 K), yttria is undoubtedly the most promising refractory material for face-coat in terms of reactivity. Its use in ceramic shells only began to be more common in the last 15 years because, despite its potential, there were enormous difficulties in producing an yttria based slurry which did not gelify prematurely, preventing parts production in large series. In 1993, Horton [10] used successfully face-coat yttria slurries, applying colloidal silica as a binder and with the addition of hydroxide ions. This procedure avoided premature gelling of the slurry [11]. Different combinations of binders, flours (particle size and composition) and manufacturing techniques have conducted to the current state of the art of ceramic shells performance, where yttria, as described in reference [12], is the ideal ceramic with the lowest reactivity to cast reactive alloys.