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Utilization of Coal Fly Ash for the Production of Glass-ceramics With Unique Performances: A Brief Review

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Coal fly ash is an industrial by-product generated during the combustion of coal for energy production. Due to the increasing annual consumption of coal power and the serious potential environmental threats of coal fly ash, a considerable amount of research on the utilization of coal fly ash has been undertaken worldwide. Vitrification seems to be one of the most promising options for reusing this industrial waste. This paper presents a short overview of the production of unique high performance glass-ceramics using coal fly ash as a raw material. A detailed description of the methodologies for the synthesis of glass-ceramics from coal fly ash and the principal crystal phases, corresponding property and possible usage of those materials are introduced. Investigations revealed that converting coal fly ash into high performance glass-ceramic materials is a promising new approach to improve the utilization of this industrial by-product. This conversion not only alleviates the problems with disposal but also converts a waste material into a high value-added marketable commodity.

KEY WORDS: Coal fly ash; Glass-ceramics; High value-added utilization; $CaO-Al_2O_3-SiO_2$; $MgO-Al_2O_3-SiO_2$

1. Introduction

Coal is currently a significant source of fuel worldwide. Coal-fired power plants are in most countries the main source of electrical energy, accounting for about 40% of the worldwide electricity production. Coal fly ash, generated during the combustion of coal, is an industrial by-product whose current annual production is estimated to be more than 500 million tons[1], a number that continues to increase to account for the growth in power demand. This large amount industrial waste can cause significant environmental and ecological problems if not treated properly. Research has been undertaken worldwide on the potential reuse and effective utilization of this waste due to its ecologic and economic importance. In recent years, many investigations on the utilization of fly ash for glass-ceramics production have been reported[2–6]. The results are encouraging for it was found that the toxic trace elements were completely destroyed and the heavy metals were successfully solidified into the glass matrix during the process of high temperature vitrification and the consequent nucleation and crystallization heat-treatments[7,8]. Therefore, the glass-ceramics produced from coal fly ash are non-hazardous, valuable materials showing promising potential applications.

From the perspective of power generation, coal fly ash is a waste by-product, while from a coal utilization point it is a resource yet to be fully utilized. As a fine-grained powder, fly ash is mainly composed of spherical glassy particles that contain valuable mineral resources such as SiO_2, Al_2O_3, CaO, Fe_2O_3 and other oxides. The chemical composition and fine-grained powder morphology of fly ash makes it suitable for use as the raw material for glass-ceramics, a valuable material that is not only suitable for replacing many traditional materials, but is also useful in entirely new fields where no alternative material can satisfy the technical demands[9].

In this paper this promising new approach to utilizing fly ash was reviewed with an emphasis on the new, high infrared radiance glass-ceramics produced from coal fly ash. In addition, a new area or field that could expand the positive reuse of fly ash was sought, thereby seeking to reduce the environmental and economic impacts of disposal. The results of this investigation are not strictly confined to coal fly ash, and the fly ashes of other fuels, such as oil shale[10] and municipal solid waste incinerator fly ashes, may be utilized as raw materials for this glass-ceramics production[11–13].

2. Synthesis of Glass-ceramics from Coal Fly Ash

There are two traditional methods to produce glass-ceramics – the crystallization approach, and the sintering approach, both of which are shown in Fig. 1[14,15].

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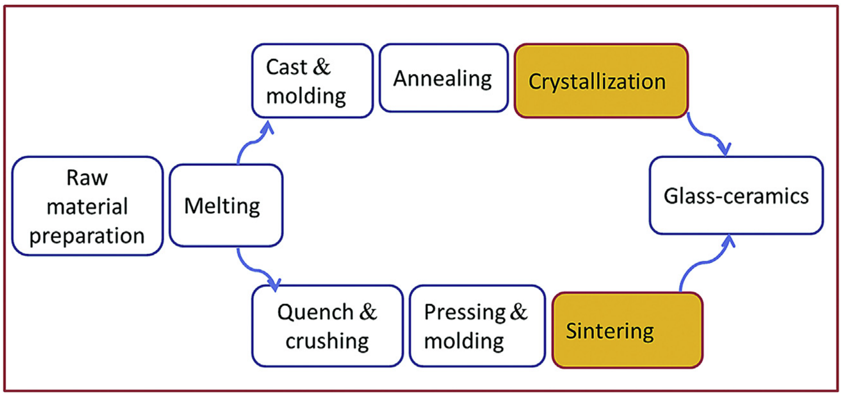

Fig. 1 Production procedure of fly ash glass-ceramics.

Generally, regardless of which approach is pursued, the properties of glass-ceramics are determined by the main crystallization phases and their microstructures, which depend on the composition of the parent glass as well as the thermal treatments. It is therefore important to design the composition and time-temperature schedules to achieve the desired crystal phase, microstructure, and corresponding properties[16].

2.1. Composition design of coal fly ash glass-ceramics

It is difficult to synthesize glass-ceramics from fly ash directly without any additives, for in most conditions, the fly ash does not contain proper ratios of components for the formation of a glass. The addition of glass network modifiers is needed to fully achieve vitrification of fly ash. Na_2O is the most effective glass modifier, as it can decrease the melting temperature and melting viscosity of the parent glass and make the processing operations easier. However the addition of Na_2O can also decrease the chemical durability and compressive strength of the obtained glass[17,18]. B_2O_3 are network-forming elements in glass structure, and a proper amount of B_2O_3 in the glass matrix can promote nucleation of the glass[19]. Aside from addition of glass network modifiers, the main contents, such as CaO and MgO, and nucleating agents, such as TiO_2 and ZrO_2 are typically also required. Trace contents such as V_2O_5 and BaO also have great influences on the processing operations and the final properties of the fly ash glass-ceramics[20−24].

According to the American Society for Testing Materials[25], the ash containing more than 70 wt% $SiO_2 + Al_2O_3 + Fe_2O_3$ that is also low in lime is defined as class F fly ash, while ash with a $SiO_2 + Al_2O_3 + Fe_2O_3$ content between 50 and 70 wt% that is high in lime is defined as class C fly ash. The chief difference between Class F and Class C fly ash is in the amount of calcium and the silica, alumina, and iron content in the ash. Due to the varying chemical compositions of different classes of coal fly ash, normally there are two main categories of coal fly ash glass-ceramics[26], $CaO-Al_2O_3-SiO_2$ (CAS) system coal fly ash glass-ceramics and $MgO-Al_2O_3-SiO_2$ (MAS) system coal fly ash glass-ceramics.

2.1.1. $CaO-Al_2O_3-SiO_2$ system coal fly ash glass-ceramics. Class C coal fly ash is much more suitable for synthesizing $CaO-Al_2O_3-SiO_2$ system glass-ceramics. This system glass-ceramics have many excellent properties such as high mechanical strength, excellent dimensional stability, and abrasion, corrosion resistance, demonstrating potential for a wide range of application on construction. The main phases of this system glass-ceramics usually include anorthite ($CaAl_2Si_2O_8$), wollastonite ($CaSiO_3$), gehlenite ($Ca_2Al_2SiO_7$) and diopside ($CaMgSi_2O_6$). The various phases are related to the differences in composition (Fig. 2)[27].

To synthesize CAS system glass-ceramics from coal fly ash, addition of CaO is required during the composition design process. Some researchers reported that the addition of CaO can be accomplished by using shell and other CaO-rich materials as raw materials, which can decrease the cost of final glass-ceramics production further[28]. The ratio of CaO/SiO_2 can influence the processing operations and the final properties of the glass-ceramics decisively[29]. Experimental results show that an increase of CaO amount can decrease the crystallization activation energies and promote the crystallization of glass-ceramics. However, when there is an increase of CaO content, the range of the sintering temperature is decreased, which in this case has a negative effect on the sintering, leveling and compacting processes[30].

2.1.2. $MgO-Al_2O_3-SiO_2$ system coal fly ash glass-ceramics. Differing from class C coal fly ash, class F coal fly ash is not suitable for the production of CAS glass-ceramics and cement additives due to its relatively high MgO and Fe_2O_3 content. However the class F coal fly ash can be used to synthesize $MgO-Al_2O_3-SiO_2$ system coal fly ash glass-ceramics[31−34], whose main phases are usually cordierite ($2MgO\cdot 2Al_2O_3\cdot 5SiO_2$) or mullite ($2Al_2O_3\cdot SiO_2$). Due to its many outstanding properties such as an elevated thermal stability, good chemical durability,

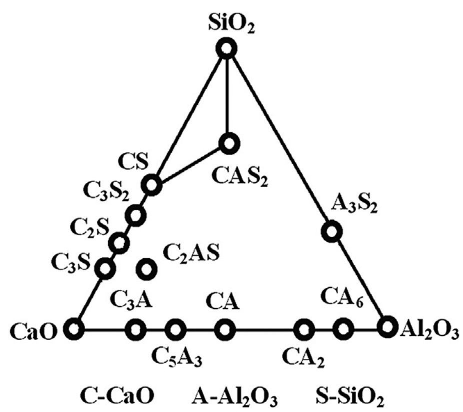

Fig. 2 Phase diagram of CAS system glass-ceramics.