Effect of zirconia and iron on the mechanical properties of Al₂O₃/TiC composites processed using combined self-propagating synthesis and direct consolidation technique

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Abstract

Self-propagating high temperature synthesis combined with direct consolidation technique was used to synthesize high density Al₂O₃/TiC composites from mixture of TiO₂, Al and graphite powders. The effect of controlled amount of zirconia and iron addition on the density, microstructure and the mechanical properties of the composites was investigated. The results revealed that, addition of either 1.0 mole zirconia or 5.0 wt% of iron metal powder led to a significant decrease in the sample porosity from 7.0 to less than 1.0 vol% together with a remarkable enhancement in the microhardness from 6.0 to 11.0 and 12.0 GPa with 1.0 mole zirconia and 5.0 wt% iron additions, respectively. Moreover, the fracture toughness increased from 3.5 to 6.0 and 7.0 MPa.m^{1/2} with 1.0 mole zirconia and 15 wt% iron additions, respectively. However, addition of 1.0 mole zirconia with 5.0 wt% iron powder led to a composite with higher porosity and reduced mechanical properties.

Keywords: TiC/Al₂O₃ composite; Self propagating high temperature synthesis; Microhardness; Fracture toughness

1. Introduction

The increasing demand for high speed machining requires the development of materials with higher hardness and toughness. Ceramic matrix composites (CMC) are regarded as one of the most promising materials that could fulfill these requirements. In composites, by incorporating one or more components into the base materials has the potential to improve properties such as, flexural strength, fracture toughness, thermal shock resistance, hardness and wear resistance. In recent years, Al₂O₃-TiC composites have been investigated for structural applications.. The attractive mechanical properties of the composites in this system include high hardness, good flexural strength and high wear resistance, make them suitable candidates in high speed machining tools application [1-3]. Commercially, pressure-less sintering and hot-pressing are the most common processing routes used for fabricating these composites [4]. However, pressure-less sintering results in high porosity and hot-pressing is expensive [5-7]. In addition, the high temperature needed for sintering and hot-pressing can lead to a reaction between Al₂O₃ and TiC which generates reaction gases (CO or CO₂) leading to additional porosity and reduced mechanical properties [4]. In contrast, *in situ* processing techniques are attractive for synthesizing some ceramic matrix composite due to their simplicity, economy, and flexibility [8-10]. Self propagation high temperature synthesizes (SHS) is one of these techniques. SHS which is also referred to as solid state combustion is used for *in situ* CMC production from reactive reactants relying on heat generated due to exothermic reactions [11]. Once the exothermic reaction starts, the reaction becomes self propagating and the combustion wave travels through

the whole reactant mixture completely converting the reactants to the final target composite. There are several advantages of this technique including, i) the ability to volatilize low boiling point impurities as a result of high temperature generated during the process and, therefore, a high purity material can be produced; ii) avoiding the need of expensive materials according to the simple exothermic nature of the SHS reaction; and iii) the reduction in processing time to seconds rather than hours resulting in lower operating and processing costs [4,12-13]. The main drawback is that it is an extremely violent and energetic process leading to uncontrolled reaction which produces porous materials [12,14]. The porosity can be reduced by applying mechanical compression immediately after SHS starts [14]. In this approach, self propagation high temperature synthesis is combined with dynamic consolidation (SHS/DC) to fabricate lower porosity composites in a single processing step.

The fabrication of TiC and its composite via SHS technique has been the topic of many investigations [15-27]. Al₂O₃-TiC composites were produced according to the exothermic reduction of TiO₂ with Al metal in the presence of carbon [18-27]. Although this composite material is characterized by attractive mechanical properties it suffers from low fracture toughness which limits its application in many practical fields [18,28]. Different approaches have been used to enhance the fracture toughness of ceramics including phase transformation toughening, ductile metal reinforcement, and fiber or whisker reinforcement [29]. Partially or fully stabilized tetragonal zirconia is the most widely used ceramic for phase transformation toughening in which the toughening is due to the tetragonal to monoclinic transformation [30]. Another common practice is the incorporation of ductile phase into ceramic matrix which can dissipate energy by the plastic deformation of ductile crack-bridging ligaments [31].

There are some investigations of the effect of iron metal [26, 31, 32] or zirconia [33] addition on the mechanical properties of Al_2O_3 -TiC ceramic composites fabricated by SHS technique. Generally, these studies report positive effect of these additions on the mechanical properties of the ceramic matrix composite. However, to the best of our knowledge, no studies have reported the fabrication of these composites by the SHS/DC technique. The focus of this study is to apply SHS/DC technique to fabricate low porosity Al_2O_3 -TiC composites with controlled amounts of zirconia and iron metal. The effect of addition of different amount of zirconia on the properties of the composites was studied. In addition, the effect of addition of different amount of iron powder on the properties of the composites with and without zirconia was also systematically investigated.

2. Experimental

2.1. Materials

Titanium oxide (TiO_2), graphite (C), aluminum metal (Al), iron metal (Fe), zirconium oxide (ZrO_2) and alumina (Al_2O_3) were the reactant powders used in this investigation. The materials specifications of these powders, from the suppliers, are presented in Table 1.

2.2. Procedures

In order to synthesize the target composite (Al_2O_3 -TiC) and investigate the effect of zirconia addition (1-2 moles) and iron metal powder addition (5-20 wt%), the starting reactant powders were weighed in the required molar ratio according to the following reaction:

Where, M is zirconia or Fe and x, is their stoichiometric value. The weighed powders were dry mixed in agate mortar for 15 min then formed into cylindrical pellets (2 cm diameter and 2 cm length) using uniaxial hydraulic press at 78 MPa without binder, (Model KPD-50E Mega Melchor Gabilondo, Spain). The pressed pellet was transferred to an in-house fabricated combustion reactor. The reactor was evacuated to 10^{-3} bar and the temperature of the green compact was increased using a resistance coil around the compact till it reached the ignition temperature. When the reaction was triggered (the temperature data logger recorded a sudden jump in the temperature), the required load was immediately applied (using motorized hydraulic press). Additional details of the experimental procedure are in [27].

2.3. Characterization

The phases of the combustion products in the processed samples were identified by X-ray diffraction analysis using X-ray diffractometer (D8 Advanced Bruker AXS, GmbH, Karlsruhe, Germany). The sample porosity was measured using Archimedes method. A vacuum saturation technique was applied for such measurement which has been shown by Safiuddin and Hearn [34] to be more efficient than the cold-water or boiling-water saturation techniques for porosity measurement. In this research, the procedure described in Ref. 34 was followed.

For detailed backscattered SEM analysis and micro-hardness measurements a part of the sample was mounted in 32 mm phenolic hot mounts such that the largest flat surface of each specimen was exposed. The mounted specimens were ground using a diamond-impregnated pad and polished to a 1 μm finish using diamond suspensions. Vickers micro-hardness analysis was performed on each sample in accordance with the ASTM E384 using a micro-hardness testing system (AMH 43 Automatic Micro/Macro-indentation Hardness Testing System, LECO

Corporation, Michigan, U.S.). A total of five indentations were performed on each specimen using 1 kg indentation load. The dwell time for each indentation was 13 seconds. The micro-hardness testing system used for this investigation is fully automated and makes use of a 50x magnification to automatically measure indentation dimensions and calculate the micro-hardness.

After micro-hardness testing, the microstructure of the specimens was analyzed on a field emission SEM (Model JSM-7000F, JEOL, Tokyo, Japan) with an accelerating voltage of 15 kV and 10 mm working distance. Secondary electron images were used to assess the level and nature of porosity while backscatter electron images were used to reveal the different phases present in the samples. The chemical constituents of the phases seen under backscatter were determined using EDS. In addition to the micro-structural and compositional analysis, SEM was also used to analyze the nature of each indent. This analysis was performed in order to assess the presence and extent of micro-cracks extending from the corners of the indentation. Indents that had no micro-cracks were used to calculate the micro-hardness of the specimens while indents accompanied by micro-cracks were used to estimate the fracture toughness.

The fracture toughness, K_{Ic} , of the composite specimens was calculated using Vickers indentation fracture technique used by Fukuhara, et al to calculate the fracture toughness of similar ceramic and ceramic composite materials [35]. This technique was applied to the micro-indentations in which radial cracks were induced. From the Vickers indents, the micro-hardness, H , the indentation diagonal length, $2a$, and micro-crack length, $2c$, are measured. These values are then substituted into equation 2 to yield fracture toughness in units of $\text{MPa.m}^{1/2}$

$$K_{Ic} = \frac{0.203Ha^{1/2}}{(c/a)^{3/2}} \quad (2)$$

The values reported for hardness and toughness are averages of a minimum of five measurements on each sample.

3. Results and Discussion

3.1. Effect of zirconia dilution

3.1.1. Approximate thermal analysis for combustion synthesis of TiC/Al₂O₃/ZrO₂ composite

Thermal calculations of the systems TiC/Al₂O₃/ZrO₂ and TiC/Al₂O₃/Fe were conducted based on equation (1) and the available data published by Barin et al [36]. The adiabatic temperatures, the molten fractions of the different phases and the total liquid phase were calculated using the following equation:

$$\begin{aligned}
 -\Delta H_{r,298} = & 3 \int_{298}^{T_{ad}} C_p(\text{TiC})_s dT + 2 \int_{298}^{2303} C_p(\text{Al}_2\text{O}_3)_s dT + 2\alpha \int_{2303}^{T_{ad}} C_p(\text{Al}_2\text{O}_3)_l dT + x \int_{2139}^{T_{ad}} C_p(\text{eutectic40\%ZrO}_2)_l dT \\
 & + y \int_{298}^{T_{ad}} C_p(\text{ZrO}_2)_s dT + z \int_{298}^{1809} C_p(\text{Fe})_s dT + y\beta \int_{1809}^{T_{ad}} C_p(\text{Fe})_l dT + 2\alpha \Delta H_{f,\text{Al}_2\text{O}_3} + \gamma \Delta H_{f,\text{Fe}} \quad (2)
 \end{aligned}$$

Where, $\Delta H_{r,298}$ is the enthalpy change of reaction, T_{ad} is the calculated maximum temperature (assuming no heat loss) and C_p is the specific heat capacity. In the most general case, it is anticipated that the adiabatic temperature is higher than the melting point of Al₂O₃ (2303 K) but less than the melting point of TiC (3433 K) and melting point of ZrO₂ (2988 K). As a result, equation two assumes that a certain fraction (α) of Al₂O₃, and a certain fraction (β) of Fe melts. x, y and z are, respectively, the amounts of eutectic mixture, ZrO₂ and Fe, and ΔH_f is the enthalpy of fusion. This equation is solved in an iterative manner to obtain x, α , and β .

Addition of zirconia in the presence of alumina will contribute to an expected formation of a eutectic mixture between alumina and zirconia. The amount of the eutectic depends on the maximum temperature achieved and the amount of zirconia addition. According to Jerebtsov et

al [37] this eutectic mixture is formed at a weight ratio of 40:60 of Al_2O_3 to ZrO_2 and has a melting point of 2139 K. In case of no ZrO_2 additions, the calculated adiabatic temperature was 2374 K with a liquid phase of 53.2 wt% due to melting of the entire alumina content. The effect of zirconia additions on the calculated adiabatic temperature and molten fractions are shown in Fig. 1. Addition of zirconia up to 0.75 moles leads to a gradual decrease in the adiabatic temperature to 2250 K with a liquid phase content of 48.5 wt% due to melting of the eutectic mixture. For samples with 1.0 mole ZrO_2 , the adiabatic temperature dropped to the melting point of the eutectic (2139 K) and remained constant at this temperature up to 2.0 moles zirconia additions. Up to 1.0 mole zirconia addition leads to a gradual increase in the amount of liquid phase due to the formation of ZrO_2 - Al_2O_3 eutectic with a maximum value of liquid phase of 58.1 wt% at 1.0 mole zirconia. For zirconia addition up to 1.0 mole, the alumina content (2.0 moles) consumes the entire zirconia amount in the formation of eutectic mixture. Further addition of zirconia (greater than 1.0 mole) leads to the formation of the eutectic mixture and increasing amounts of residual zirconia due to the depletion of alumina content. At 2.0 moles of ZrO_2 , the amount of residual zirconia is 0.9 moles which is equivalent to 17.4 wt% of the total sample weight and the total liquid phase reaches its minimum value of 11.8 wt%.

Figure 2 illustrated the effect of addition of different wt% of iron metal powder (5-20 wt%) to the reaction mixture on the adiabatic temperatures, molten fractions and total liquid phase. Increasing the iron content of the reactants up to 20 wt% produced a gradual decrease in the adiabatic temperature from 2374 K to the alumina melting point (2303 K). Although increasing the iron content decreases the adiabatic temperature, it is still above or equal to the alumina melting point. In contrast to ZrO_2 , addition of iron metal powder (5-20 wt%) does not significantly affect the total liquid phase fraction. The total liquid phase (fraction of molten

alumina and molten iron) is almost constant (55.4 wt% and 54.1 wt%) in the investigated iron addition range (5-20 wt% Fe).

3.1.2. Properties of sintered samples

The effect of zirconia addition (1.0 and 2.0 moles) on the properties of the fabricated samples was investigated. During sample machining, it was observed that sample containing 1.0 mole zirconia was harder to machine compared to the sample with 2.0 mole zirconia. This could be an indication of the higher density of the sample produced with 1.0 mole zirconia addition. The effect of zirconia addition on the apparent porosity of the samples is shown in Table. 2. Sample with 1.0 mole zirconia shows a minimum apparent porosity compared to both samples with 0.0 and 2.0 mole zirconia addition.

Due to the very short processing time of typical SHS, the diffusion phenomena responsible for sample shrinkage and densification in other processes (like e.g. hot pressing) are very limited [38]. Therefore, the densification of the material in this case could only be attributed to the applied compressive load. It is clear that the higher volume fraction of liquid in the sample with 1 mole ZrO_2 favors compaction and densification. The adiabatic temperature in case of 1.0 and 2.0 moles ZrO_2 addition is kept constant at the melting point of Al_2O_3 – ZrO_2 eutectic (2139 K). The calculated liquid phase in case of 1.0 mole ZrO_2 additions due to the formation of Al_2O_3 – ZrO_2 eutectic is the highest at 58.1 wt% of the sample weight. Increased density due to formation of Al_2O_3 – ZrO_2 eutectic in the SHS products was previously reported [39]. However, increasing zirconia addition to 2.0 moles leads to a decrease in the sample density and an increase in the apparent porosity. Although addition of 2.0 moles ZrO_2 did not decrease the adiabatic temperature (2139 k), it decreased the liquid eutectic content to 11.8 wt% (Fig. 1). Therefore, at

2.0 moles ZrO_2 , the efficiency of compaction load was lower due to the smaller amount of liquid phase. It is also possible that the excess ZrO_2 could reduce the extent of the reduction of TiO_2 leading to a lower temperature [40].

For further clarification of the effect of zirconia on the SHS/DC reaction, the microstructure of the samples was investigated. Both SEM and backscattered SEM with EDS analysis was performed and the results are shown in Fig. 3. Overall, the structure revealed that the elemental distribution is homogeneous through the whole structure. Also, it confirms the increase in the sample porosity with increasing zirconia addition, as evidence from the appearance of large pores in the samples with 2.0 mole excess zirconia (Fig. 3c & d). Elemental analysis was performed to investigate the different phase's present in the two samples. In the case of the sample with 1.0 mole zirconia (Fig. 3b), TiC (Tc) represents the matrix while alumina is isolated in large (A) and small islands (A') embedded in the matrix. Zirconia (Z) sometimes has the same grain shape as alumina (without the formation of large islands) and most of the time surrounds the alumina grains due to the formation of Al_2O_3 - ZrO_2 eutectic (E). With increasing zirconia addition (Fig. 3d) the matrix is composed of both zirconia (Z) and TiC (Tc) while alumina (A) becomes much finer than in the samples with 1.0 mole zirconia addition. Alumina was found to surround the TiC grains and only small part of it (A') forms small islands. Some of the TiC is embedded in the zirconia large grains. Also, large pores (P) (more than 20 μm) are clearly observed in the microstructure of the sample with 2 mole zirconia.

To confirm that with zirconia additions the reaction is going to completion, XRD analysis was conducted for both samples with 1.0 and 2.0 mole zirconia and the results are shown in Fig. 4. The patterns reveal that both samples were composed of Al_2O_3 , TiC and tetragonal ZrO_2 . No

residual TiO_2 , Al and C or other phases were detected indicating that the combustion reaction processed to a high degree of completion.

The effect of addition of zirconia on both micro-hardness and fracture toughness of the samples is shown in Table 2. It was found that the addition of 1.0 mole zirconia enhanced the micro-hardness and the fracture toughness. The increase in the micro-hardness is attributed to the significant reduction in the apparent porosity, and also to the much more uniform and finer grained microstructure. The increase in the fracture toughness is attributing to the reduction in the porosity and transformation toughening. However with further zirconia addition (2.0 moles) the mechanical properties of the produced samples are reduced primarily due to the increase in porosity.

3.2. Effect of iron addition

The effect of different amounts of iron (5.0 to 20.0 wt%) on the phase composition and the properties of the samples was investigated. It was noticed that all samples with different amounts of iron were quite hard to machine indicating that these samples had low porosity. The apparent porosity of the samples is shown in Fig. 5. It was observed that the addition of iron lead to a sharp decrease in the apparent porosity of the SHS samples to less than 1.0 vol%. It should be noted that even with 5% iron metal addition the sample porosity is less than 1.0 vol%. This is because the total liquid phase fraction (molten alumina and molten iron) calculated for 5-20 wt% iron additions ranges from 55.4 to 54.1 wt% (figure 2). This large amount of liquid phase improves the efficiency of the compaction step. Although samples without and with Fe have roughly the same amount of total liquid, in the case of sample with iron, some of that liquid is

molten iron which has a lower viscosity than molten alumina. This lower viscosity liquid helps reduce the porosity in samples with iron.

The phase formation during the SHS/DC reaction with the addition of iron was investigated using XRD analysis. Figure 6 compares the XRD patterns of the samples produced with 0, 5 and 20 wt% iron metal additions. It was found that for all levels of iron, the desired composite of TiC/Al₂O₃ is obtained without the presence of any impurity phases. The only extra phase present is the un-reacted iron. This indicates that the presence of metallic iron as one of the constituents of the starting precursors did not perturb the SHS reaction. In addition, it is important to mention that with increasing amount of iron metal addition the alumina phase becomes the predominant phase as shown in the XRD pattern of the sample with 20.0 wt% Fe addition.

The detailed microstructures of the samples containing 5.0 and 15.0 wt% iron metal addition using SEM and backscattered SEM analysis with EDS was carried out and is shown in Fig. 7. These micrographs revealed that, for sample containing 5.0 wt% iron (Fig. 7b), the matrix is composed of fine grains of TiC (Tc) surrounded by a thin film of metallic iron (F). In addition, some of metallic iron forms very small islands. Small and large grains of alumina (A) are isolated and surrounded by a mixture of iron and TiC (Fig. 7b). The microstructure is quite different when the amount of metallic iron is increased to 15.0 wt% (Fig. 7d). In this case the matrix is composed of continuous alumina (A) while TiC (Tc) formed as islands. This observation of increasing alumina phase with increasing iron metal addition is consistent with the results of XRD analysis (Fig. 6). As in the case of sample containing 5.0 wt% iron, the fine grained TiC is surrounded by a thin film of metallic iron (F). However, as expected, the volume % of iron grains is much higher than in the samples containing 5.0 wt% iron. Finally, the microstructures confirm low residual porosity in these samples. These microstructural changes

with metallic iron addition are expected to have a significant impact on the mechanical properties of the composites.

The effect of addition of iron on both the micro-hardness and fracture toughness of the samples is shown in Table 3. With iron addition a significant improvement in the mechanical properties of the composites was clearly observed. The highest micro-hardness was found for compact with 5.0 wt% iron metal which is attributed not only to the very low porosity but also to the fine grained microstructure [4]. Although, the porosity of sample produced with 15.0 wt% iron is very close to that of 5.0 wt% iron, its micro-hardness is lower than 5.0 wt% iron sample. This was attributed to the fact that the amount of hard components (TiC and alumina) is reduced and the amount of the softer metallic component (Fe) increases. In addition, the XRD analysis indicates that increasing the iron increases the softer alumina phase compared to the harder TiC phase. These changes in the relative phase volumes fraction with iron addition are the reasons for decrease of the micro-hardness value with increasing iron addition [4]. In contrast, the fracture toughness increases with increasing iron metal content. The presence of ductile iron especially on the grain boundaries of TiC, leads to ductile phase toughening due to bridging of the cracks. This bridging effect increases with increase in the iron content which improves the fracture toughness [41-42].

3.3. Effect of iron with zirconia dilution

Finally, the combined effect of both 1.0 mole of zirconia and 5.0 wt% iron addition on the properties of the composites was investigated. For this case, the measured apparent porosity of the samples was found to be 15.6 vol% which is higher than all the other samples. This could be attributed to the general increase in the total dilution amounts. It is well know that increasing the

diluents level lowers the actual combustion temperature [21]. Due to the dilution, it is possible that the temperature was below melting point of the alumina phase leading to reduced liquid phase and a composite that is not easily densified by the compaction. Also due to the lower temperature, the reaction may not proceed to completion [43]. In order to support this interpretation phase analysis via XRD and microstructural investigation was carried out. The XRD pattern of the sample produced with 1.0 mole of zirconia and containing 5.0 wt% iron metal is compared to the diffraction patterns of samples with only 1.0 mole zirconia and only 5.0 wt% iron is shown in Fig. 8. The XRD patterns revealed that, the samples with only 1.0 mole of zirconia and those with only 5.0 wt% iron did not show any impurity phases. In contrast, the sample with both additions has undesired phases including titanium oxide and iron carbide. The formation of iron carbide implies that some of carbon needed for desired composite formation was consumed in a side reaction with iron. In addition, a considerable amount of un-reacted titanium oxide was found in the final product. The presence of both iron carbide and titanium oxide implies the incompleteness of the reaction.

The backscattered SEM with its EDS analysis for the sample produced with the addition of both 5.0 wt% iron and 1.0 mole zirconia is shown in Fig. 9 and confirm the XRD observations. The matrix is composed of TiO_2 (Ti) with alumina (A) and zirconia (Z) grains embedded in the matrix with minor amount of iron carbide (Fc) and a considerable amount of both eutectic phase (E) and porosity (P). In addition, TiC (Tc) phase was hard to find in the microstructure which supports the observation from XRD that it is a minority phase leading to the conclusion that in this system, the reaction is not complete. Metallic iron (F) in this case does not surround the TiC grains (as in case of sample without zirconia dilution) but is present as aggregates in the microstructure reducing its effectiveness as a ductile crack bridging reinforcement. The

measured micro-hardness and fracture toughness of these samples were found to be 3.18 GPa and $4.61 \text{ MN/m}^{3/2}$, respectively. These values demonstrate a significant reduction in the mechanical properties with addition of both diluents. This is attributed to the sharp increase in the apparent porosity of the composite and also to incomplete reaction.

Conclusion

From this study, the following conclusions can be drawn:

1. Low porosity composites of $\text{Al}_2\text{O}_3/\text{TiC}$ were successfully processed via combined SHS/DC technique with addition of either zirconia or iron metal powder.
2. The addition of 1.0 mole zirconia proved to be highly beneficial for both the physical and mechanical properties of the composites. This was reflected in the significant reduction of the sample porosity from 7.0 to less than 1.0 vol% as well as the remarkable enhancement in both microhardness (from 6.0 to 11 GPa) and fracture toughness (from 3.5 to $6.0 \text{ MPa.m}^{1/2}$).
3. Increasing zirconia addition to 2.0 moles led to an increase in porosity and decrease in the hardness and toughness.
4. The addition of iron was also found to be beneficial in enhancing both the physical and the mechanical properties of the composites. The addition of 5.0 wt% iron lead to a significant reduction in the porosity to less than 1.0 vol% and increase of both microhardness to 12 GPa and fracture toughness to $4.5 \text{ MPa.m}^{1/2}$.
5. Samples with 15.0 wt% iron addition had the highest fracture toughness ($7.2 \text{ MPa.m}^{1/2}$).
6. Adding both diluents (1.0 mole zirconia and 5.0 wt% iron metal) led to a significant increase in porosity, incomplete reaction and lower hardness and fracture toughness.

Acknowledgement

We gratefully acknowledge support for this work from the US National Science Foundation grant No. 0612063 and Science and Technology Development Fund (STDF), Egypt, Grant No. 323.

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Table 1: Specification of the starting reactant powders

Table 2: The effect of zirconia additions on the properties of synthesized samples

Table 3: Micro-hardness and fracture toughness of synthesized samples with different iron metal additions

Fig. 1 Effect of ZrO_2 additions on the calculated adiabatic temperature, eutectic molten fractions and total liquid phase fraction during self propagating combustion synthesis of $\text{TiC-Al}_2\text{O}_3$ composites

Fig. 2 Effect of iron additions on the calculated adiabatic temperature, eutectic molten fractions and total liquid phase fraction during self propagating combustion synthesis of $\text{TiC-Al}_2\text{O}_3$ composites

Fig. 3 Microstructure of samples with 1.0 (a and b) and 2.0 moles (c and d) of zirconia addition. (a) and (c) are secondary electron micrographs and (b) and (d) are backscattered. The different phases in the backscattered images are: Aluminum oxide (A), Titanium carbide (Tc), Zirconia (Z), Eutectic phase (E) and Pore (P).

Fig. 4 XRD patterns for samples with 0, 1.0 and 2.0 moles of zirconia addition

Fig. 5 Effect of iron metal amount on the apparent porosity of the $\text{TiC-Al}_2\text{O}_3$ composites

Fig. 6 XRD patterns for sample produced with different amounts of iron additions

Fig. 7 Electron images of sample produced with 5.0 and 15.0 wt% iron additions. (a and b) secondary and backscatter electron modes for sample containing 5.0 wt% iron; (c and d) secondary and backscatter electron modes for sample containing 15.0 wt% iron. The different phases in the backscattered images are: Aluminum oxide (A), Titanium carbide (Tc) and iron metal (F).

Fig. 8 XRD patterns for sample produced with addition of 5.0 wt% iron metal and 1.0 mole zirconia

Fig. 9 Backscattered SEM for sample containing 5.0 wt% iron and 1.0 mole of zirconia. The different phases in the backscattered images are: Aluminum oxide (A), Titanium oxide (Ti), Zirconia (Z), Eutectic phase (E), Iron metal (F) and Pore (P).

Fig. 1 Effect of ZrO₂ additions on the calculated adiabatic temperature, eutectic molten fractions and total liquid phase fraction during self propagating combustion synthesis of TiC-Al₂O₃ composites

Fig. 2 Effect of iron additions on the calculated adiabatic temperature, eutectic molten fractions and total liquid phase fraction during self propagating combustion synthesis of TiC- Al_2O_3 composites

Fig. 3 Microstructure of samples with 1.0 (a and b) and 2.0 moles (c and d) of zirconia addition. (a) and (c) are secondary electron micrographs and (b) and (d) are backscattered. The different phases in the backscattered images are: Aluminum oxide (A), Titanium carbide (Tc), Zirconia (Z), Eutectic phase (E) and Pore (P).

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