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Selecting the appropriate carbon source in the synthesis of SiC nano-powders using an optimized Fuzzy Model

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Abstract

Different sources of carbon in the synthesis of silicon carbide were evaluated using a multi-attribute group decision making fuzzy model. In this model, the aim was to find the carbon precursor which has the minimum price, highest carbon content, good water solubility, lowest synthesis temperature and the optimum crystallite size. Based on the model results, sugar was the best candidate. Therefore, sugar was selected as carbon source in the synthesis of SiC, also tetraethyl ortho-silicate (TEOS) used as source of Silicon. The XRD and SEM results showed that the SiC powder prepared by this method was fully crystalline and has the average crystallite size of 40 nm, and a flake-like morphology. The synthesis temperature was 800°C, which is a relatively low temperature for synthesis of crystalline SiC. To optimize the carbothermal process, microwave heating and just 15 minutes was enough to form crystalline SiC with this method.

Keywords*: Silicon Carbide; Sol gel; Fuzzy model; Microwave; Optimization.*

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1. Introduction

Final properties of SiC ceramics and coatings largely depend on the characteristic of the starting raw materials and precursors. Generally, the production of high-performance SiC ceramics requires ultrafine and pure SiC powders. To produce such an ultrafine and pure SiC powder, a number of alternative techniques, such as sol-gel method [1], thermal decomposition of silane compound [2, 3] and chemical vapor deposition [4], have been developed to eliminate the limitation of conventional Acheson process. However, the powders prepared by these methods has a lot of costs, due to expensive raw materials and low production rate of the methods and their demand for expensive equipments. Sol-Gel process has been established as a novel method for nano-powders synthesis with several outstanding features including, high purity [5], high chemical activity, enhancing powder sinterability, and the possibility for materials mixing at the molecular scale. A sol-gel process using metal alkoxides as precursors has been widely used for the synthesis of fine powders with homogeneous size and controlled shape [6]. Tetraethyl ortho-silicate (TEOS)

is an interesting precursor as a source of Si for production of SiC powder using sol-gel method. Aelion et al. were among the first researchers to evaluate the kinetics of hydrolysis and condensation of TEOS. The rate and extent of the hydrolysis reaction were found to be influenced firstly by the type and concentration of the acid or base catalyst while the temperature and solvent were of the secondary importance [7].

Although he investigate about TEOS, but there are only a few reports on the details of SiC powder preparation by a combination of sol-gel and carbothermal reduction route [8].

Selection of appropriate starting materials, including silicon and carbon sources as initial precursors, is vital for successful synthesis of ultrafine and pure SiC by sol-gel method, especially the difference in nature of carbon that is provided from the diverse sources can have an important effect on the characteristics of as prepared SiC nano-particles. As a result, optimum selection of the carbon sources plays an important role in the production process of SiC nano-powders by sol-gel technique.ع

TEOS is widely used as silicon source for synthesizing nanosized SiC by sol-gel route while the synthesis of SiC using sol-gel process largely depends on the appropriate selection of the carbon source as a precursor. There are different factors to be considered in the selection of a suitable carbon source including; carbon yield, reactivity, cost and nature of impurities. while various materials including Polyphenylene oxide–polystyrene [9], carbon black [10], phenolic resol [11], sucrose[12], and sugar[13] can be used as carbon source.

Traditionally, when selecting a material whose features are identified, experts usually apply trial and error methods or use previous experiences to find an optimized method of synthesis. However these methods do not cover all of the options for the synthesis process. This blind spot can be addressed by adopting a multi-factor decision-making model (MADM). On the other hand, the MADM approach can be used in the evaluation and selection problems, in which decisions include a set of options and a set of performance features [14]. So far, various MADM methods have been proposed to solve the selected issues. Literature review shows that while some researchers have proposed MADM methods for selecting materials for manufacturing systems, none of them have chosen the MADM selection method. In addition, group decision and materials selection in an uncertain environment are discussed in just a few studies. In this paper, we have chosen an

intuitionistic fuzzy multi-attribute group decision-making (IF-MAGDM) model to solve the problem of choosing the best source of carbon as a lead for the synthesis of SiC.

2. Proposed IF-MAGDM Model

IF-MAGDM method can deal with vague data, more effectively. This method has 11 steps, which should be done sequentially as follows (details of the method is included in appendix A):

Step 1: Identifying the attributes to be required and candidates have been identified based on features that are needed.

Step 2: Fuzzy decision matrix, decision makers create the intuition.

Step 3: Using an entropy weight method to determine the weight of each expert from the decision matrix.

Step 4: According to the expert opinion, an IF decision matrix is collected. After gaining weight values for experts, the assessment values that are provided by different experts can be obtained from the IFWG operator.

Step 5: Setting the entropy values of the traits, all traits may not be assumed to be of equal importance. W represents a set of degrees of importance. To obtain x, an intuitive fuzzy entropy is used [15].

Step 6: Building an IF weighting decision matrix. The decision-weight matrix of the IF weight is obtained based on the importance of characteristics.

Step 7: Determine intuitionistic fuzzy positive-ideal solutions (PIS) and negative-ideal solutions (NIS) as $\hat{r}_j^+$ j and $\hat{r}_j^-$ in appendix A.

Step 8: Defining an IF positive-ideal separation matrix (D^+) and negative-ideal separation matrix (D^-) fined and calculated the grey relational coefficient of each candidate from the PIS and the grey relational coefficient of each candidate from the NIS.

Step 9: Calculation of the Gray relational coefficient for each of the candidates.

Step 10: Calculating the Total Collective Indicator (CI) based on the Gray relational coefficient.

Step 11: Determining the priority of candidates $A_i(i = 1,2, \dots, m)$ by the proposed $CI_i(i = 1,2, \dots, m)$. If any of the candidate has the highest CI_ivalue, then, it is the most important candidate.

3. Materials and Methods

For silicon carbide synthesis, tetraethyl ortho-silicate (TEOS) was used as source of silicon and the hydrochloride acid (HCl) also was used to keep the pH of the solution at 4. The TEOS, carbon source, ethanol, and DI water were the mixed to prepare a solution. This solution was stirred at the speed of 250 rpm at temperature of 30°C for 4 hours. The resultant gel was kept in the hot air oven for 4 hours in 60°C. For the carbothemal process two different method was performed. The first

one includes microwave heating at power of 1200 W and frequency of 2.45 GHz for 10 and 15 minutes. The second method was annealing in a furnace at 700-800°C in flowing argon for 3 hours.

Five carbon sources are provided for the sol-gel process, which are denoted as CS_1, CS_2, CS_3, CS_4, and CS_5. The description of these carbon source candidates is given in Table 1.

Table 1. Carbon Source Candidates for Sol-Gel Synthesis of SiC Nano-powders

CANDIDATES	CARBON SOURCES	REF.
CS_1	Carbon black	[10]
CS_2	Polyphenylene oxide–polystyrene	[9]
CS_3	Sugar	[13]
CS_4	Sucrose	[12]
CS_5	phenolic resol	[11]

Grain size, cost, carbon content, water solubility and temperature of SiC formation can be attributed to the difference in the nature of carbon obtained from the various sources. Therefore, the attributes for selection of the carbon source were obtained as cost (A_1) of carbon source that has an important role in the sol-gel process of SiC. An interesting strategy for efficient sol-gel processing of SiC is using small amount of carbon source, so having high carbon content (A_2) is another important attribute. The system needs less water to reach optimum when the carbon source has a high water solubility (A_3). Increasing the water content leads to a corresponding increase in hydrolysis rate and the time to achieve stable sol is decreased at higher water/precursor rate. Therefore, the rate of polymerization reaction may be impaired under such condition. The primary advantage of the sol-gel process is that nano-powders can be synthesized at a considerably lower temperatures plus time and energy saving. Formation of SiC at low temperature (A_4) is necessary to obtain SiC nano-powders because at high temperature, the growth rate of nano-crystals is highly accelerated and large size of SiC powders is obtained. The most important properties of the as-synthesis SiC is the optimization of the grain size (A_5). The increased contact area between carbon source and silicon should make the reaction suitable for decreasing the grain size of SiC.

The grain size of the reaction products of TEOS and best carbon source after the carbothermal process was measured from XRD patterns (Philips X-pert) by Cu-kα radiation. For the evaluation of agglomerates size and qualitative analysis of synthesized powders, FE-SEM equipped with EDX analyzer was used. Investigation of phase transformations at corresponded temperatures was carried out using thermal analysis (TG/DTA). In this case samples were heated with a rate of 20 °C/min.

4. RESULTS AND DISCUSSION

In this study, the presented IF-MAGDM model was employed to evaluate and select the best carbon source to synthesize SiC by a sol-gel process. At first, the attributes and carbon sources as candidates identified, a committee of three professional experts is formed to conduct the evaluation and to select the most suitable carbon source. The IF-value ratings of these five carbon source candidates by the linguistic variables and their respective IF-value are evaluated by the experts with respect to the attributes. In the next step, the IF-performance matrix is formed for each of the three experts. The aggregated IF-decision matrix is constructed based on the opinions of experts

by step 4. The obtained results are provided in Table 1. The weights in Table 2 is the seven attributes are calculated by step 5.

Table 2. The Aggregated Intuitionistic Fuzzy Set Decision Matrix Based on Opinions of Experts and Weights of the Attributes.

CANDIDATES	**ATTRIBUTES**				
	A_1	A_2	A_3	A_4	A_5
CS_1	⟨0.464,0.435⟩	⟨0.919,0.081⟩	⟨0.100,0.900⟩	⟨0.566,0.333⟩	⟨0.665,0.234⟩
CS_2	⟨0.778,0.122⟩	⟨0.400,0.500⟩	⟨0.100,0.750⟩	⟨0.594,0.306⟩	⟨0.656,0.244⟩
CS_3	⟨0.100,0.874⟩	⟨0.250,0.600⟩	⟨0.950,0.050⟩	⟨0.464,0.435⟩	⟨0.100,0.831⟩
CS_4	⟨0.100,0.831⟩	⟨0.250,0.600⟩	⟨0.950,0.050⟩	⟨0.566,0.333⟩	⟨0.110,0.839⟩
CS_5	⟨0.283,0.500⟩	⟨0.900,0.100⟩	⟨0.100,0.900⟩	⟨0.778,0.122⟩	⟨0.800,0.100⟩
WEIGHTS	0.178	0.176	0.363	0.07	0.212

Table 3. Weighted Aggregated Intuitionistic Fuzzy Set Decision Matrix

CANDIDATES	**ATTRIBUTES**				
	A_1	A_2	A_3	A_4	A_5
CS_1	⟨0.105,0.862⟩	⟨0.358,0.642⟩	⟨0.038,0.962⟩	⟨0.057,0.926⟩	⟨0.074,0.903⟩
CS_2	⟨0.236, .687⟩	⟨0.086,0.885⟩	⟨0.038,0.901⟩	⟨0.061,0.920⟩	⟨0.072,0.906⟩
CS_3	⟨0.019,0.976⟩	⟨0.049,0.914⟩	⟨0.663,0.337⟩	⟨0.043,0.943⟩	⟨0.007,0.987⟩
CS_4	⟨0.019,968⟩	⟨0.049,0.914⟩	⟨0.633,0.337⟩	⟨0.057,0.926⟩	⟨0.008,0.988⟩
CS_5	⟨0.058,0.884⟩	⟨0.333,0.667⟩	⟨0.038,0.962⟩	⟨0.100,0.863⟩	⟨0.107,0.851⟩
POSITIVE-IDEAL SOLUTIONS (R_+)	⟨0.019,0.976⟩	⟨0.358,0.642⟩	⟨0.663,0.337⟩	⟨0.043,0.943⟩	⟨0.007,0.988⟩
NEGATIVE-IDEAL SOLUTIONS (R)	⟨0.236,0.687⟩	⟨0.049,0.914⟩	⟨0.038,0.962⟩	⟨0.100,0.863⟩	⟨0.107,0.851⟩

The positive-ideal and negative-ideal solutions are computed according to the concept of IF values by step 7 that are given in Table 3.

The positive-ideal separation matrix is computed by step 8 (Eq. 12 in appendix A) and the negative-ideal separation matrix is computed by step 8 (Eq. 13 in appendix A). The grey relational coefficient of each candidate from PIS and NIS are calculated by step 9. The degree of the grey relational coefficient of each candidate is computed by. Step 10 and the results are listed in Table 4.

Table 4. Values of $(\xi_i^+)_1, (\xi_i^+)_2, (\xi_i^-)_1, (\xi_i^-)_2, \xi_i^+, \xi_i^-$ and CI_i by the Proposed Intuitionistic Fuzzy Multi-Attribute Group Decision-Making Model

CANDIDATES	$(\xi_i^+)_1$	$(\xi_i^+)_2$	$(\xi_i^-)_1$	$(\xi_i^-)_2$	ξ_i^+	ξ_i^-	CI_i	FINAL RANKING
CS_1	0.742	1.475	0.801	1.743	1.094	1.396	0.439	4
CS_2	0.655	1.266	0.801	1.863	0.830	1.493	0.357	5
CS_3	0.883	1.803	0.697	1.352	1.591	0.943	0.629	1
CS_4	0.882	1.803	0.697	1.353	1.590	0.943	0.627	2
CS_5	0.737	1.548	0.785	1.746	1.141	1.372	0.454	3

Proposed ranking index CI_i for all carbon source candidates is calculated by step 11 and is given in Table 4. The larger CI_i, means the higher the priority of the candidate. Therefore, the final ranking based on the IF-MAGDM model is as follows:

$$CS_3 > CS_4 > CS_5 > CS_1 > CS_2$$

5. Sensitive Analysis

In this section, each identification coefficient value ρ is employed to see whether each identification coefficient value have an impact on the results of the ranking order of the candidates using the proposed model. These variant identification coefficient values are employed to investigate the proposed model. The ranking order of the candidates and the values of ranking index CI_i based on variant ρ are depicted in Fig. 1. The results illustrate the variation of the ranking index value of each candidate using various identification coefficient values and also that the ranking orders of the five candidates are the same despite from the changes of a resolving coefficient value from $\rho = 0.1$ to $\rho = 1$. Hence, this article can confirm that the results of the ranking orders of all candidates using the proposed model is reliable. These results can help decision makers to evaluate and elect a suitable candidate. Moreover, the proposed model figures out that the gaps between CI_i values of various candidates become larger when the resolving coefficient value is reduced from 0.1 to 1. Through the gap between each CI_i value of each candidate, the decision maker can distinguish the differences among the candidates more efficiently. According to the above-mentioned analysis, this article figures out that the proposed model can result in satisfactory findings and provide appropriate information to help decision makers in the group decision-making problems.

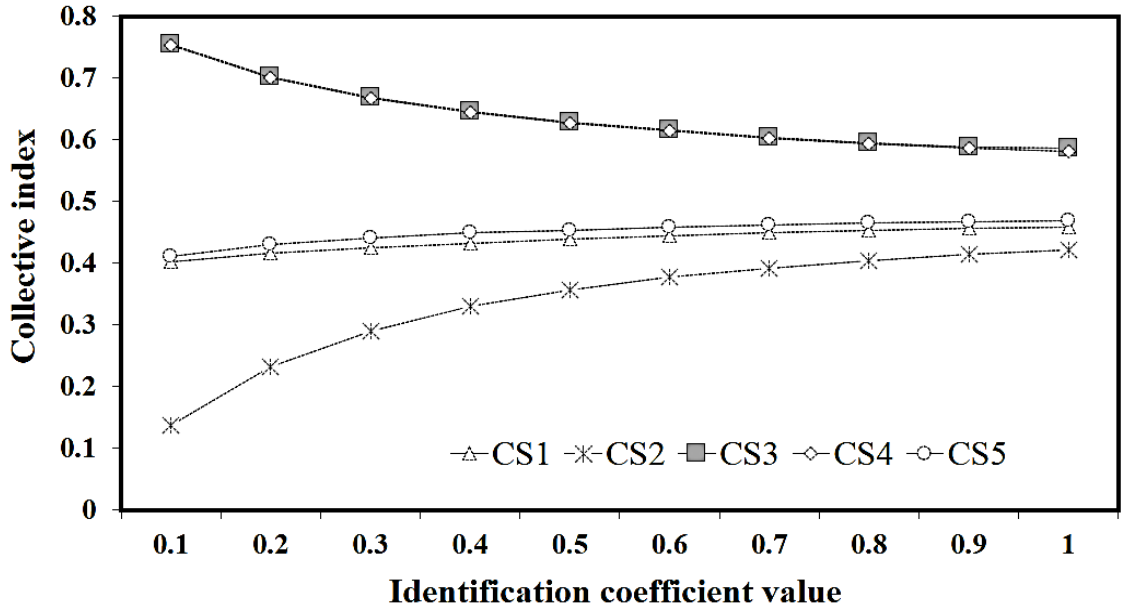

Fig. 1. Variation analysis of collective index values for the candidates using each identification coefficient value.

As noted above, it should be noted that the proposed model can simultaneously achieve the ideal candidate gap, ranking candidates, and priority points for improving each candidate. Regarding the sensitive analysis, it has been shown that this model can measure any value of the identification coefficient to evaluate the distance between the different CI values of the candidates, which can help the decision-makers. In this case, entropy method for direct use of information from the intuitional fuzzy decision-making matrix is used as a reasonable way for the features and experts in weight as well as for robust decision-making.

According, to the results of IF-MAGDM model and sensitive analysis it can be considering the attributes the best carbon source is the sugar. Wou et al. used the carbon black as a carbon source for synthesis SiC [16]. The reaction can be completed at 1550˚C for 2 h when the C/Si ratio is 5 and the grain size of the SiC particle is the 5–20 μm. in another study, Raman et al. used the Polyphenylene oxide–polystyrene as a carbon source and TEOS mixture was stirred well for about 2 h.
The sol-containing polymer was then allowed to gel at room temperature and dried at 60 C to obtain polymer incorporated with sol–gel derived silica and the SiC precursor prepared as above was carbonized at 1000℃ and analyzed for carbon and silica contents. The carbonized product was further heated at 1400℃ under argon atmosphere and the grain was the macro/ micro sized.

Ping Lu et al. Used polyphenylene oxide-polystyrene raw materials to make nano-porous SiC wires [17]. Their results showed that the nanowires prepared in different shapes are straight, bead and bamboo-like, and that most of the wires are of the straight type with a diameter of about 105 nanometers. They have found that all of these nanowires are made of coarse particles and

nanoparticles. On the other hand, they stated that this range has different dimensions and forms of pyrolytic behaviors

Shunlong Pan and colleagues used carbon black precursors to synthesize β-SiC nanocrystalline powder particles [10]. These nanoparticles were synthesized by spraying a mixture of sodium silicate and carbon black. Completion of the carbothermal reaction in this study was by storing the spray and dried material at temperatures of 1200 to 1700 ° C. The observations showed that the appropriate temperature for the process in which the BET parameter has the highest value is 1550 ° C for 2 hours. Apply to the material while the C / Si ratio is about 5 or more. From this perspective, this process requires a high temperature to complete the reactions.

A. Najafi et al. Also fabricated β-SiC powder nanoparticles using phenolic resol carbon precursor. The researchers also studied different temperatures to complete the synthesis process, and their results showed that the germination of β-SiC particles ends at 1400 ° C and ends at around 1500 ° C. The nanoparticles created in this study were less than 100 nm in size and had non-uniform morphology. However, observations made by TEM microscope showed that these particles are mostly round and their size is between 30 and 50 nanometers. The researchers did not study other properties for the particles present, and since the resulting particles are very small, they may agglomerate and make the properties uncontrollable [11].

Zhimin Li and colleagues also synthesized SiC nanopowder particles using sucrose precursor. The researchers performed the sol-gel process using TEOS as the silicone precursor, sucrose as the carbon material with tributyl borate as the dopant. The XRD results of these researchers showed that the formation of β-SiC started at 1600 ° C and ended at 1700 ° C. Of course, increasing the temperature to 1800 degrees Celsius has caused these powders to crystallize as well as possible. The powders created in this process were spherical particles about 70 nanometers in size, which were synthesized to form slightly needle-like particles at 1800 ° C. The sintering temperature in this method was also very high and from this point of view it is not a suitable method for synthesizing powders [12].

In this case, 3 g of sugar is dissolved in 5 mL of deionized water at room temperature. Then this solution is added dropwise to 15 mL TEOS and 5 mL ethanol. The rest of the process is described in the materials and methods part.

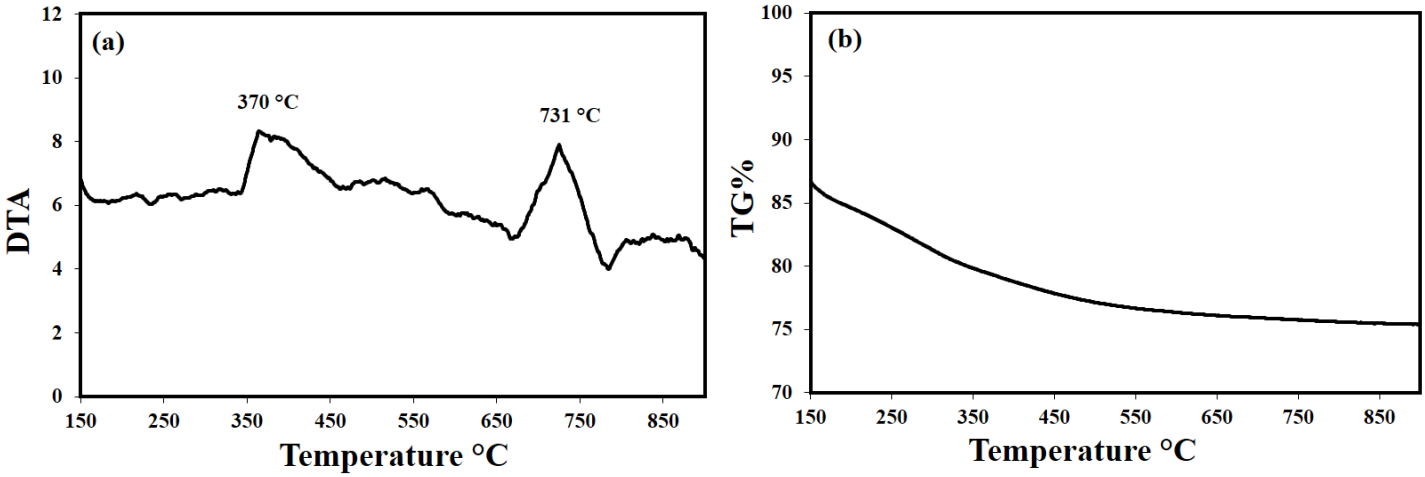

Fig. 2. The thermal analysis of the gel a) DTA analysis and b) TG analysis.

Fig. 2 illustrate the thermal analysis of the gel samples. The first stage of weight loss occurs at 160°C which is corresponded to endothermic dehydration and removal of structural water, which is considered to be a physical process. This endothermic reaction is followed by two exothermic reaction at 370 °C and 731 °C that leads to SiC formation.

According to the result of DTA-TG analysis final SiC formation reaction happens at 731°C so we have choosen 700 °C and 800 °C for annealing temperature of the dried gel. Fig. 3 illustrate the XRD analysis of annealed sample at both of these temperatures.

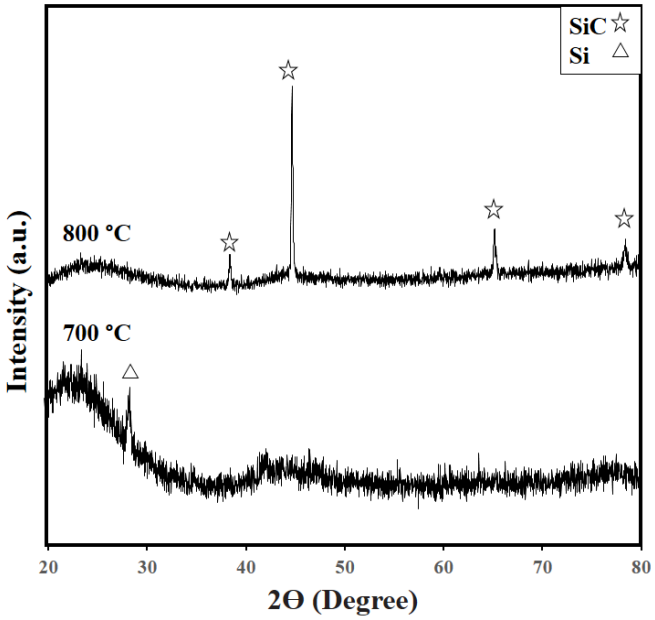

Fig. 3. XRD patterns of SiC samples prepared at 700 °C and 800 °C.

In the next set of experiment, the dried gel put on an alumina crucible and exposed to microwave heating for 10 and 15 minutes for carbothermal synthesis of SiC. Fig. 4 illustrate the XRD analysis of the samples.

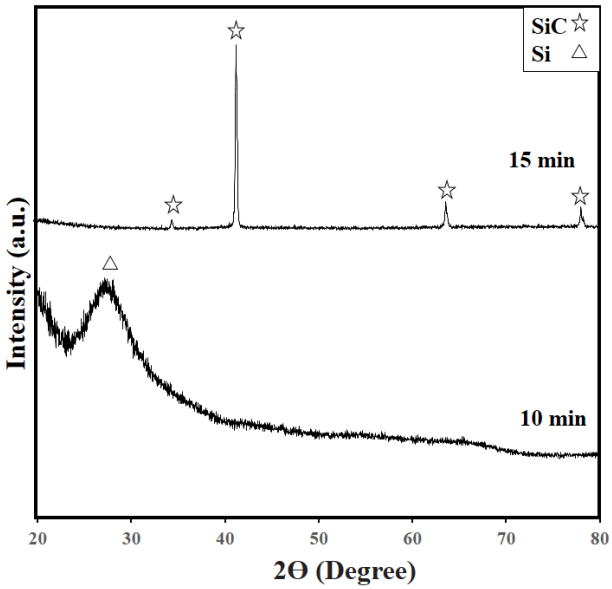

Fig. 4. XRD patterns of carbothermal SiC samples prepared by 10 min and 15 min.

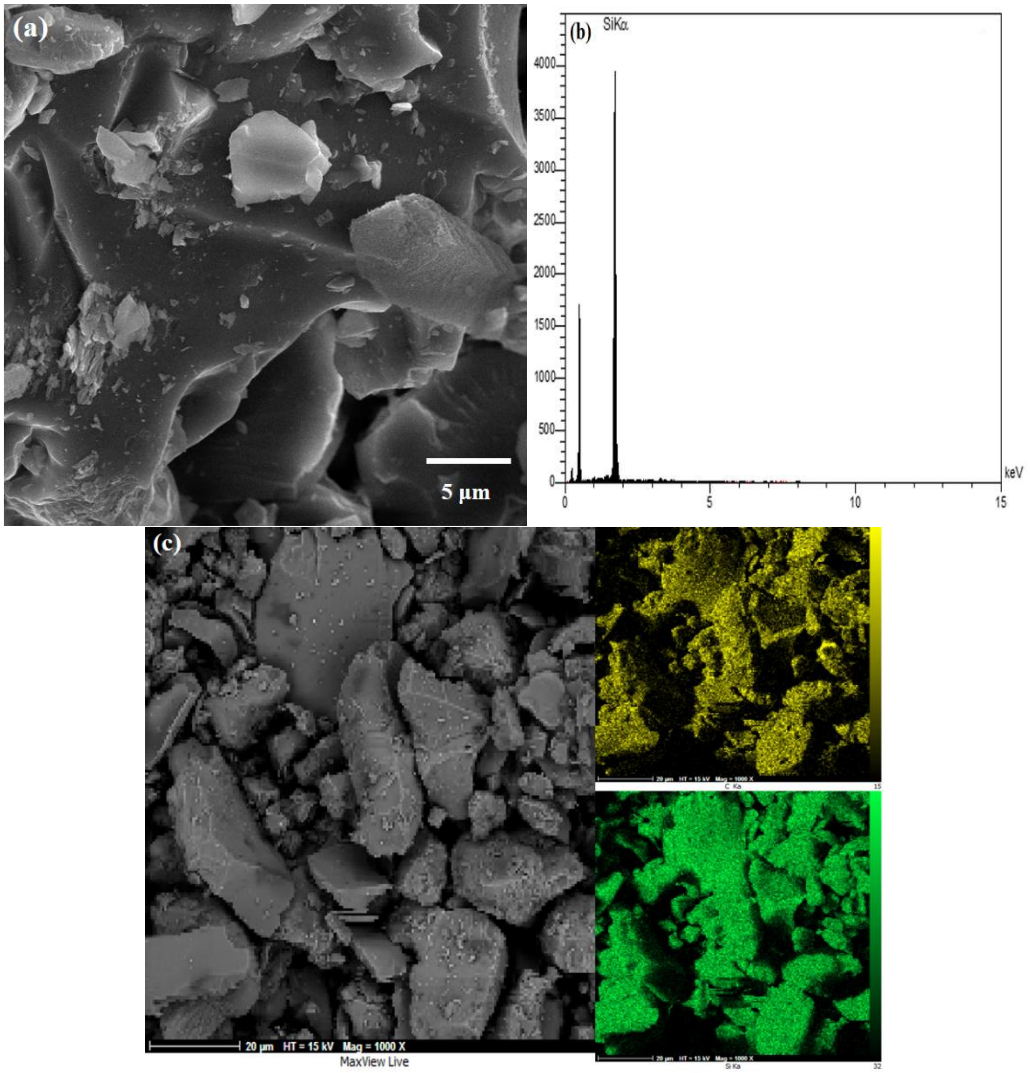

Fig. 5. The SEM analysis of SiC sample prepared in microwave furnace at 15 min a) SiC nanoparticles b) EDX and c) map of elements analysis.

The carbonization temperature is taken into consideration with a high priority. On the other hand, using microwave synthesis we reduced the time and energy needed for synthesis of SiC. The results showed that this method can be used in a short period of time and also cost without needing any specific type of atmosphere, as it is reported in some other literatures.

6. Conclusion

The optimum carbon source for the synthesis of silicon carbide nanoparticles were selected using an intuitional fuzzy decision-making matrix. Based on this selection some SiC samples prepared experimentally using microwave and conventional mode of heating. The optimum condition for annealing was calculated based of a thermal analysis (TG/DTA) and the results showed that 800°C is the minimum temperature required for conventional mode of heating in an argon atmosphere. However, using microwave synthesis, crystalline SiC nanoparticles were formed in a short period of time, 15 minutes, without any special type of atmosphere.

Appendix A:

Constructing the intuitionistic fuzzy decision matrices of decision makers. Assume that the rating of the candidate $A_i(i \in M)$with respect to attribute $C_j(j \in N)$given by the λh decision maker $D_l(l \in T)$is linguistic variable, which can be expressed in intuitionistic fuzzy values $\ddot{x}_{ij}^{(l)} = \langle \mu_{ij}^{(l)}, v_{ij}^{(l)} \rangle$ [18]. Then $\ddot{x}_{ij}^{(l)}$ provided by the expert Dl as an IF-decision matrix is obtained as the following form.

$$\ddot{X}^{(l)} = \left(\ddot{x}_{ij}^{(l)}\right)_{m\times n} = \begin{bmatrix} \langle \mu_{11}^{(l)}, v_{11}^{(l)} \rangle & \langle \mu_{12}^{(l)}, v_{12}^{(l)} \rangle & \cdots & \langle \mu_{1n}^{(l)}, v_{1n}^{(l)} \rangle \\ \langle \mu_{21}^{(l)}, v_{21}^{(l)} \rangle & \langle \mu_{22}^{(l)}, v_{22}^{(l)} \rangle & \cdots & \langle \mu_{2n}^{(l)}, v_{2n}^{(l)} \rangle \\ \vdots & \vdots & \ddots & \vdots \\ \langle \mu_{m1}^{(l)}, v_{m1}^{(l)} \rangle & \langle \mu_{m2}^{(l)}, v_{m2}^{(l)} \rangle & \cdots & \langle \mu_{mn}^{(l)}, v_{mn}^{(l)} \rangle \end{bmatrix} \quad (1)$$

To determine the weights, a method of entropy weights[15] is presented as follows:

$$\lambda_{ij}^{(l)} = \frac{1 - I_{ij}^{(l)}}{t - \sum_{k-1}^{t} I_{ij}^{(l)}} \quad (2)$$

Where $\lambda_{ij}^{(l)} \in [0,1], \sum_{k-1}^{t} \lambda_{ij}^{(l)} = 1,\ i = 1,2,\dots,m, j = 1,2,\dots,n,\ l = 1,2,\dots,t$ and $I_{ij}^{(l)}$ calculated by the following entropy measure:

$$I_{ij}^{(l)} = \frac{1}{\sqrt{2}-1} \times \left\{ \sin\frac{\pi \times \left(1 + \mu_{ij}^{(l)} - v_{ij}^{(l)}\right)}{4} + \sin\frac{\pi \times \left(1 + \mu_{ij}^{(l)} + v_{ij}^{(l)}\right)}{4} - 1 \right\} \quad (3)$$

Where $0 \le I_{ij}^{(l)} \le 1, i = 1,2,\dots,m, j = 1,2,\dots,n,\ l = 1,2,\dots,t.$

Constructing an aggregated IF-decision matrix based on the opinions of the experts. After weights values for the experts are obtained, the evaluating values provided by different experts can be aggregated based on the IFWG operator as follows:

$$\hat{\mathrm{r}}_{ij} = \left(\ddot{\mathrm{x}}_{ij}^{(1)}\right)^{\lambda_{ij}^{(1)}} \otimes \left(\ddot{\mathrm{x}}_{ij}^{(2)}\right)^{\lambda_{ij}^{(2)}} \otimes \ldots \otimes \left(\ddot{\mathrm{x}}_{ij}^{(t)}\right)^{\lambda_{ij}^{(t)}} \quad (4)$$

$$\hat{\mathrm{r}}_{ij} = \langle \mu_{ij}, v_{ij} \rangle = \langle \prod_{l=1}^{t} \left(\ddot{\mathrm{x}}_{ij}^{(l)}\right)^{\lambda_{ij}^{(l)}}, 1 - \prod_{l=1}^{t} \left(1 - v_{ij}^{(l)}\right)^{\lambda_{ij}^{(l)}} \rangle \quad (5)$$

The aggregated IF-decision matrix can be defined as follows:

$$\hat{\mathrm{R}} = \begin{bmatrix} \langle \mu_{11}, v_{11} \rangle & \langle \mu_{12}, v_{12} \rangle & \cdots & \langle \mu_{1n}, v_{1n} \rangle \\ \langle \mu_{21}, v_{21} \rangle & \langle \mu_{22}, v_{22} \rangle & \cdots & \langle \mu_{2n}, v_{2n} \rangle \\ \vdots & \vdots & \ddots & \vdots \\ \langle \mu_{m1}, v_{m1} \rangle & \langle \mu_{m2}, v_{m2} \rangle & \cdots & \langle \mu_{mn}, v_{mn} \rangle \end{bmatrix} \quad (6)$$

Obtaining the entropy weights of the attributes. All attributes may not be assumed to be of equal importance. W represents a set of grades of importance. To obtain x, intuitionistic fuzzy entropy will be used [15]:

$$G_j = \frac{1}{m} \sum_{i=1}^{m} \left(\sin \frac{\pi \times \left(1 + \mu_{ij} - v_{ij}\right)}{4} + \sin \frac{\pi \times \left(1 + \mu_{ij} + v_{ij}\right)}{4} - 1 \right) \times \frac{1}{\sqrt{2} - 1} \quad (7)$$

Where $0 \leq G_j \leq 1,\ i = 1,2,\ldots,m, j = 1,2,\ldots,n.$ The entropy weight of the jth attribute is defined as follows:

$$\omega_j = \frac{1 - G_j}{n - \sum_{k=1}^{t} G_j} \quad (8)$$

Where$\omega_j \in [0,1], \sum_{k=1}^{t} \omega_j = 1,\ j = 1,2,\ldots,n.$

Constructing a weighted aggregated IF-decision matrix. The weighted aggregated IF-decision matrix is determined based on the different importance of attributes as follows:

$$\bar{\mathrm{y}}_{ij} = \omega_j \hat{\mathrm{r}}_{ij} = \langle 1 - \left(1 - \mu_{ij}\right)^{\omega_j}, {v_{ij}}^{\omega_j} \rangle \quad (9)$$

Determining intuitionistic fuzzy positive-ideal solutions (PIS) and negative-ideal solutions (NIS) as $\hat{\mathrm{r}}_j^+$ j and $\hat{\mathrm{r}}_j^-$ by:

$$\hat{\mathrm{r}}_j^+ = \langle \mu_{\hat{\mathrm{r}}_j^+}, v_{\hat{\mathrm{r}}_j^+} \rangle = \langle \left(\left(\max_i \mu_{ij} \middle| j \in J_1 \right), \left(\min_i \mu_{ij} \middle| j \in J_2 \right) \right), \left(\left(\min_i v_{ij} \right) \middle| j \in J_1 \right), \left(\max_i v_{ij} \middle| j \in J_2 \right) \rangle \quad (10)$$

$$\hat{\mathrm{r}}_j^- = \langle \mu_{\hat{\mathrm{r}}_j^-}, v_{\hat{\mathrm{r}}_j^-} \rangle = \langle \left(\left(\min_i \mu_{ij} \right) \middle| j \in J_1 \right), \left(\max_i \mu_{ij} \middle| j \in J_2 \right) \right), \left(\left(\max_i v_{ij} \right) \middle| j \in J_1 \right), \left(\min_i v_{ij} \middle| j \in J_2 \right) \rangle \quad (11)$$

Let J_1 and J_2 be benefit attribute and cost attribute, respectively.

Defining an IF positive-ideal separation matrix (D^+) and negative-ideal separation matrix (D^-) as follows:

$$D^{+} = \left[D_{ij}^{+}\right] = \begin{bmatrix} d\left(\hat{\mathrm{r}}_{11}, \hat{\mathrm{r}}_{1}^{+}\right) & d\left(\hat{\mathrm{r}}_{12}, \hat{\mathrm{r}}_{2}^{+}\right) & \cdots & d\left(\hat{\mathrm{r}}_{1n}, \hat{\mathrm{r}}_{n}^{+}\right) \\ d\left(\hat{\mathrm{r}}_{21}, \hat{\mathrm{r}}_{1}^{+}\right) & d\left(\hat{\mathrm{r}}_{22}, \hat{\mathrm{r}}_{2}^{+}\right) & \cdots & d\left(\hat{\mathrm{r}}_{2n}, \hat{\mathrm{r}}_{n}^{+}\right) \\ \vdots & \vdots & \ddots & \vdots \\ d\left(\hat{\mathrm{r}}_{m1}, \hat{\mathrm{r}}_{1}^{+}\right) & d\left(\hat{\mathrm{r}}_{m2}, \hat{\mathrm{r}}_{2}^{+}\right) & \cdots & d\left(\hat{\mathrm{r}}_{mn}, \hat{\mathrm{r}}_{n}^{+}\right) \end{bmatrix} \quad (12)$$

$$D^{-} = \left[D_{ij}^{-}\right] = \begin{bmatrix} d(\hat{\mathrm{r}}_{11}, \hat{\mathrm{r}}_{1}^{-}) & d(\hat{\mathrm{r}}_{12}, \hat{\mathrm{r}}_{2}^{-}) & \cdots & d(\hat{\mathrm{r}}_{1n}, \hat{\mathrm{r}}_{n}^{-}) \\ d(\hat{\mathrm{r}}_{21}, \hat{\mathrm{r}}_{1}^{-}) & d(\hat{\mathrm{r}}_{22}, \hat{\mathrm{r}}_{2}^{-}) & \cdots & d(\hat{\mathrm{r}}_{2n}, \hat{\mathrm{r}}_{n}^{-}) \\ \vdots & \vdots & \ddots & \vdots \\ d(\hat{\mathrm{r}}_{m1}, \hat{\mathrm{r}}_{1}^{-}) & d(\hat{\mathrm{r}}_{m2}, \hat{\mathrm{r}}_{2}^{-}) & \cdots & d(\hat{\mathrm{r}}_{mn}, \hat{\mathrm{r}}_{n}^{-}) \end{bmatrix} \quad (13)$$

Calculate the grey relational coefficient of each candidate from the PIS as below:

$$\xi_{ij}^{+} = \frac{\min\limits_{1\le i\le m}\min\limits_{1\le j\le n} D_{ij}^{+} + \rho \max\limits_{1\le i\le m}\max\limits_{1\le j\le n} D_{ij}^{+}}{D_{ij}^{+} + \rho \min\limits_{1\le i\le m}\min\limits_{1\le j\le n} D_{ij}^{+}}, \quad i = 1,2,\dots,m, j = 1,2,\dots,n \quad (14)$$

Similarly, the grey relational coefficient of each candidate from the NIS is given as below:

$$\xi_{ij}^{-} = \frac{\min\limits_{1\le i\le m}\min\limits_{1\le j\le n} D_{ij}^{-} + \rho \max\limits_{1\le i\le m}\max\limits_{1\le j\le n} D_{ij}^{-}}{D_{ij}^{-} + \rho \min\limits_{1\le i\le m}\min\limits_{1\le j\le n} D_{ij}^{-}}, \quad i = 1,2,\dots,m, j = 1,2,\dots,n \quad (15)$$

Where the identification coefficient $\rho = 0.5$.

Calculate the degree of the grey relational coefficient of each candidate using the following equation:

$$\xi_{i}^{+} = (\xi_{i}^{+})_1 \times (\xi_{i}^{+})_2 \quad (16)$$

$$\xi_{i}^{-} = (\xi_{i}^{-})_1 \times (\xi_{i}^{-})_2 \quad (17)$$

Where

$$(\xi_{i}^{+})_1 = \sum_{j=1}^{n} \omega_j \xi_{ij}^{+},$$

$$(\xi_{i}^{+})_2 = \sum_{j=1}^{n} \omega_j / \xi_{ij}^{-},$$

$$(\xi_{i}^{-})_1 = \sum_{j=1}^{n} \omega_j \xi_{ij}^{-}, \quad (18)$$

$$(\xi_{i}^{-})_2 = \sum_{j=1}^{n} \omega_j / \xi_{ij}^{+}, i = 1,2,\dots,m$$

Calculate collective index (CI) based on the degree of the grey relational coefficient of each candidate by:

$$CI_i = \frac{\xi_i^+}{\xi_i^+ + \xi_i^-}, i = 1,2,\dots,m \quad (19)$$

Determine the priority of candidates $A_i(i = 1,2,\dots,m)$ by the proposed $CI_i(i = 1,2,\dots,m)$. If any of the candidate has the highest CI_ivalue, then, it is the most important one.

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Conflict of Interest

The authors declare no conflict of interest in this study

Author contributions

Dr. Zeraati: Conducted researches and writing paper.
Dr. Barani: Designed research and analyed of data and
writing paper.
Dr. Sargazi: Analyzed data and writing paper.

Availability of data and material

The authors confirm the Availability of data and material

Compliance with ethical standards

The manuscript is compliance with ethical standards

Consent to participate

All of authors confirm the consent to participate

Consent for Publication

All of authors confirm the consent for Publication

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Figures

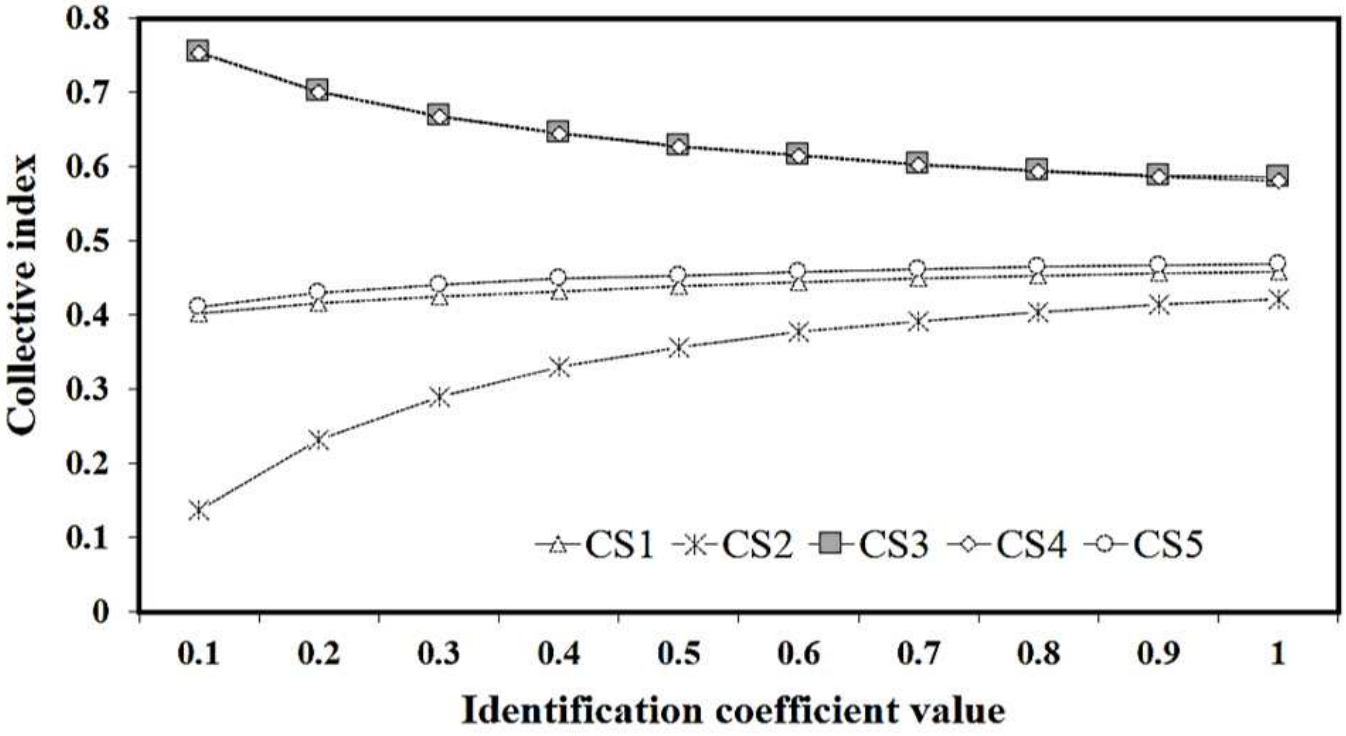

Figure 1

Variation analysis of collective index values for the candidates using each identification coefficient value.

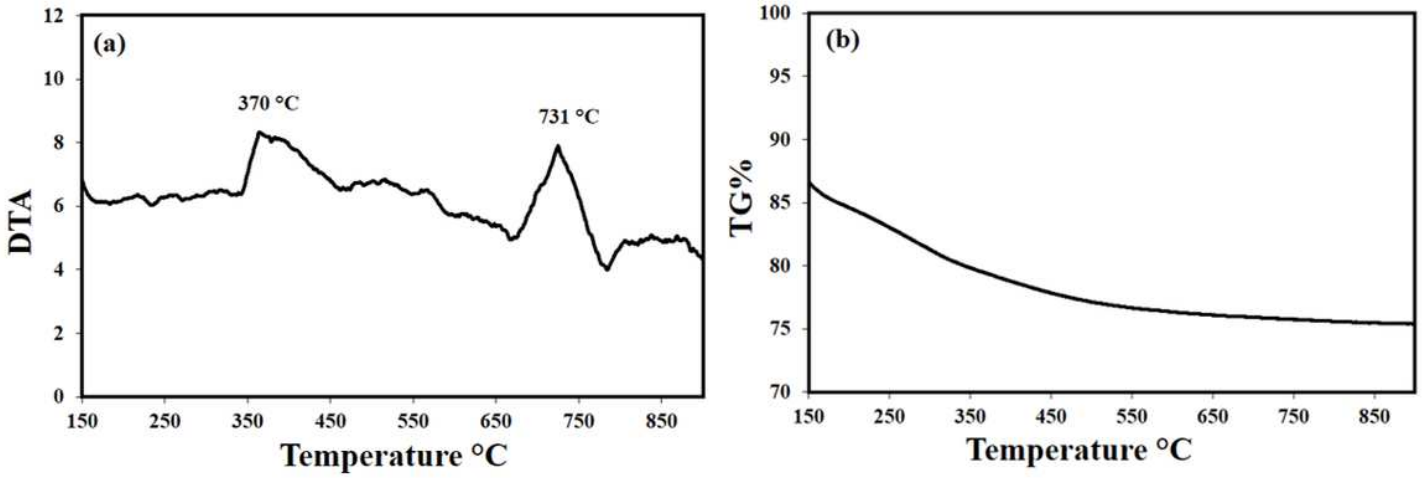

Figure 2

The thermal analysis of the gel a) DTA analysis and b) TG analysis.

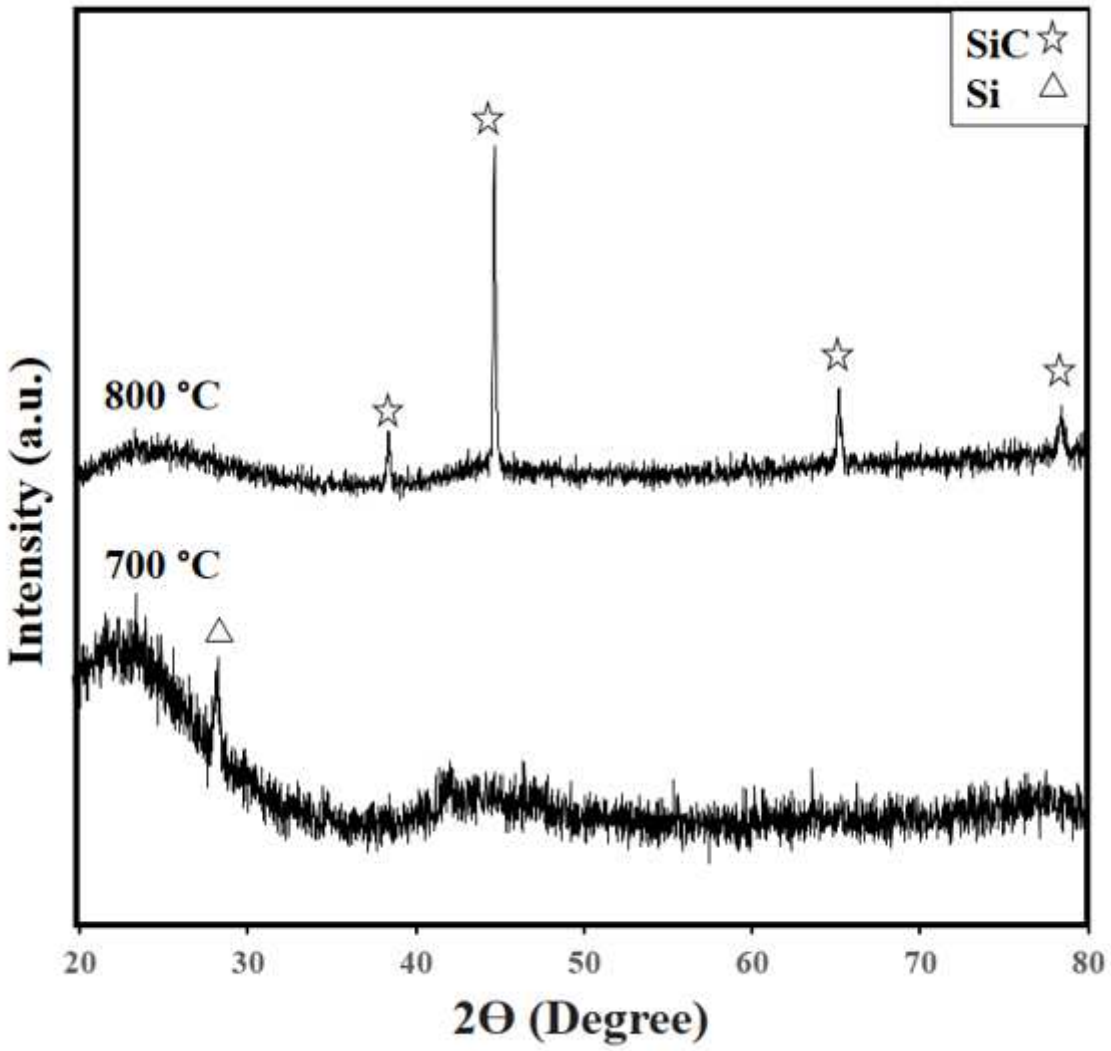

Figure 3

XRD patterns of SiC samples prepared at 700 °C and 800 °C.

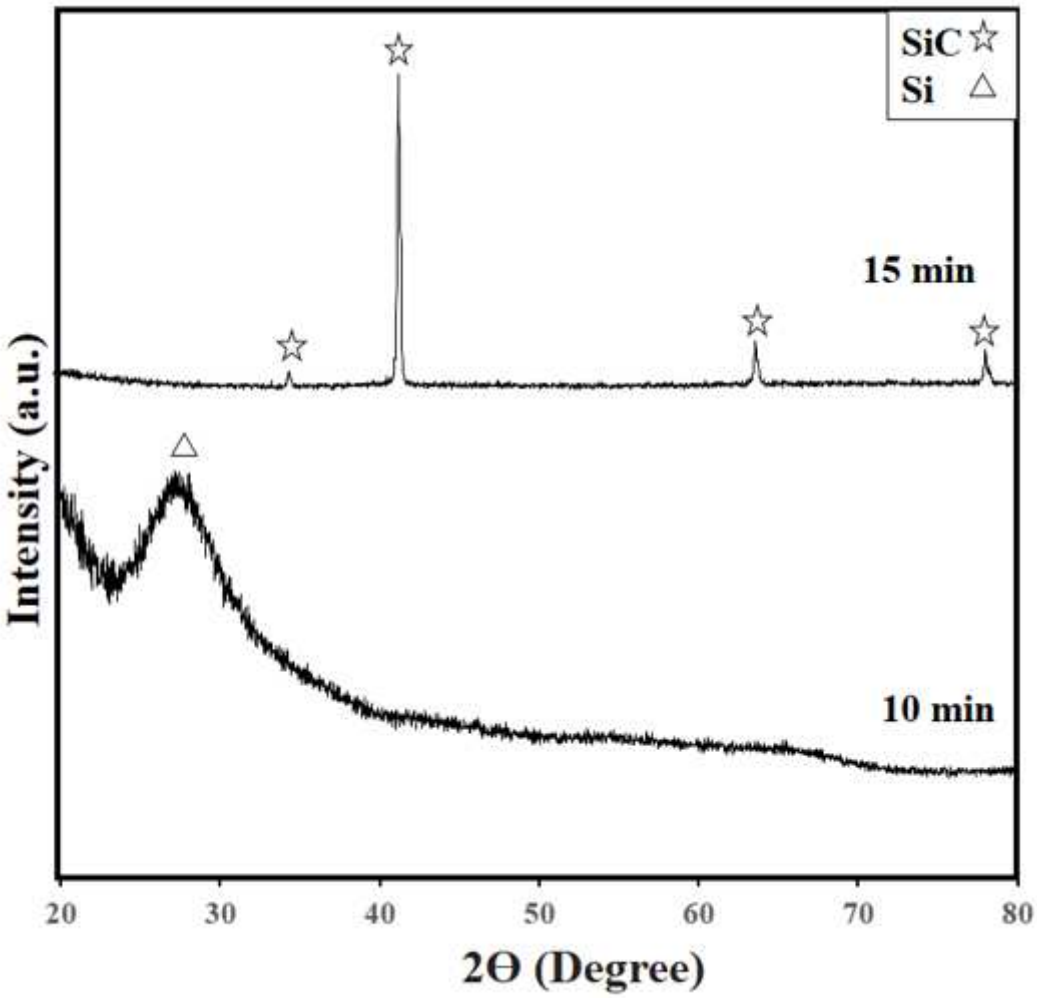

Figure 4

XRD patterns of carbothermal SiC samples prepared by 10 min and 15 min.

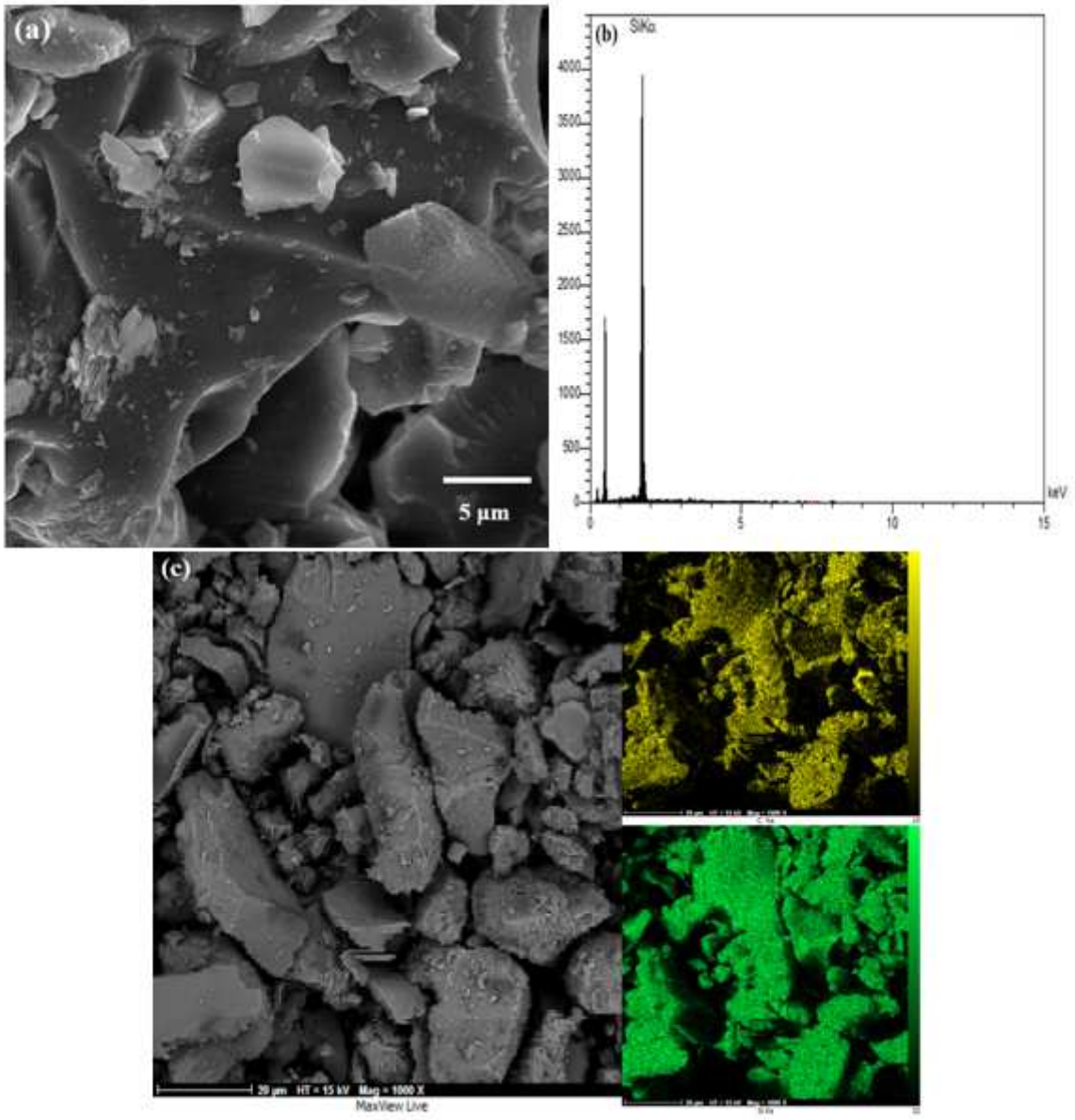

Figure 5

The SEM analysis of SiC sample prepared in microwave furnace at 15 min a) SiC nanoparticles b) EDX and c) map of elements analysis.