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Research Article

Appraisal of Thermomechanical Performance of Aluminum Metal Matrix Composites Using Stir Casting Technique

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The advance of aluminum alloy-based matrix composites is becoming indispensable in several applications like automobiles, aerospace, electronics, and structural industries due to the benefits over conventional materials such as lightweight, high strength, and high hardness value. The main aim of the work is to study the thermomechanical characteristics (heat transfer rate, convective heat transfer coefficient, and tensile strength) of an aluminum (AA7075) alloy nanocomposite containing 0 wt%, 3 wt%, 6 wt%, and 9 wt% of nano SiC particles (50 nm) by the stir casting technique. The thermomechanical performance of AA7075 alloy nanocomposite is obtained by pin fin apparatus and followed by ASTM test standards. The composite contained 9 wt% nano SiC and was found to have superior thermomechanical characteristics.

1. Introduction

Generally, metal matrix composites (MMCs) are developed with the constitutions of more than one material chemically bonded by conventional techniques to obtain specific characteristics [1]. The composite contains major and minor elements called matrix and reinforcement, respectively. Currently, researchers are continuing their research on aluminum alloy matrix composites of more than one reinforcement for superior properties like good hardness, strength, thermal conductivity, low wear rate, and better coefficient of friction [2]. The properties mentioned above vary due to the phase constitution ratio, amount of reinforcement, particle shape, size, and processing technique [3]. Miracle et al. [4] and Surappa et al. [5] studied and reported that the aluminum-based matrix composites (AMC's) are synthesized with fiber and particulates. Specifically, the ceramic particle reinforced aluminum alloy composite has good thermal expansion, high thermal stability [6], high strength, and light weight compared to traditional materials [7]. The aluminum based AMC's are developed by solid state processing [8], deposition or vapor state processing [9], and liquid state processing [10]. Among the different techniques for AMC's processing as listed above, the liquid state (stir cast) processing has most prevailing and cost-effective technique for mass production [11]. While compared to solid/vapor state processing, the liquid state processing has enhanced the wettability, particle distribution and limits the pores during composite casting. Balasubramaniam et al. [12] developed SiC reinforced aluminum alloy (AA6063) composite by stir casting. They reported that the addition of hard ceramic particles in the AA6063 alloy matrix resulted in an increased tensile strength of 180 MPa on 10 wt% SiC and 77VHN showed by the addition of 15 wt% SiC. While increased secondary phase content of SiC in AA6063 alloy matrix resulted in reduced tribomechanical behavior of composite reported by Chen [13]. However, the distribution and interfacial strength of the composite are to be decided by the selection of stir cast input process parameters [14]. Balaji et al. [15]studied the corrosion characteristics of an aluminium alloy composite developed by stir cast process. They recommended a vortex shape crucible with constant mechanical stirrer action was suitable for obtain increased wettability of composite. Chandradass et al. [16] experimentally studied the tribomechanical characteristics of silicon carbide (SiC) and silicon carbide/aluminum oxide (SiC/Al_2O_3) reinforced aluminum alloy (AA6061) hybrid composite by liquid state processing with a constant stir speed of 650 rpm. They found a superior tensile strength of 134.3 MPa and a minimum wear rate of 2.5312×10^{-5} mm^3/Nm of a composite containing (7 wt% SiC_p/3 wt% Al_2O_3). It was due to its constant presence of hard ceramic particles in the AA6061 matrix. Venkatesh et al. [17] studied the thermal, corrosion, and wear properties of copper-based MMC's by a stir casting process developed with alumina and graphite particles. They found increased thermal stability due to its good interfacial action between the matrix to reinforcement phase and the good adhesion characteristics of graphite. Raju et al. [18] studied the stir cast developed material behavior of hypoeutectic alloys (Al–Cu) and aluminum/copper composite. They reported that the stir cast, developed Al–Cu composite has enhanced corrosion resistance. Aluminum alloy-based engine piston materials play a vital role in automobile sectors related to enhancing thermal performance and resisting thermal stress during high frictional forces. The inclusion of hard ceramic particles into a matrix (aluminum alloy) results in increased thermal stability and low thermal expansion [19, 20]. Jacob et al. [21] studied the thermal characteristics of stir cast developed Al7075/Al_2O_3 composite. They found that the composite had good thermal conductivity and stability. However, the thermomechanical features of AA7075 alloy nanocomposite heat transfer rate, convective heat transfer coefficient, and tensile strength were enhanced by the addition of SiC nanoparticles and the stir cast process developed for it.

2. Experimental Details

2.1. Selection of Matrix Material. In the present investigation, aluminum alloy (AA7075) was selected as the matrix phase due to its enhanced solidification characteristics, superior thermal properties, and better tensile strength compared to traditional aluminum alloy [22]. The chemical constitution of AA7075 alloy and its thermomechanical properties were denoted in Tables 1 and 2.

2.2. Selection of Secondary Phase Reinforcement. Among the various ceramic reinforcements, the SiC nanoparticle has excellent thermal properties, is stable at higher temperatures, has high hardness, and good wettability [12, 13, 16].

Table 1: Chemical composition of AA7075.

Elements	Zn	Mg	Cu	Fe	Si	Ti	Mn	Cr	Al
%	5.6	2.5	1.5	0.5	0.4	0.2	0.3	0.25	BAL

Table 2: Characteristics of AA7075 alloy.

Properties	Units
Vickers hardness	68 VHN
Tensile strength	228 MPa
Elongation	10%
Coefficient of thermal expansion (CTE) linear	21.6 μm/m-°C
Specific heat capacity	0.960 J/g-°C
Melting point	477–635°C
Density	2.810 g/cc

2.3. Selection of Liquid State Processing (Stir Cast) Processing Parameters. The stir cast technique was preferred for AA7075/SiC nanocomposite fabrication because the AA7075 alloy matrix and SiC were mixed uniformly with the help of constant mechanical stir action and it was easy to solidify liquid to solid phase on the casting die to make the desired shape [23]. Table.3 illustrates the input stir cast process parameter for AA7075/SiC nanocomposite fabrication.

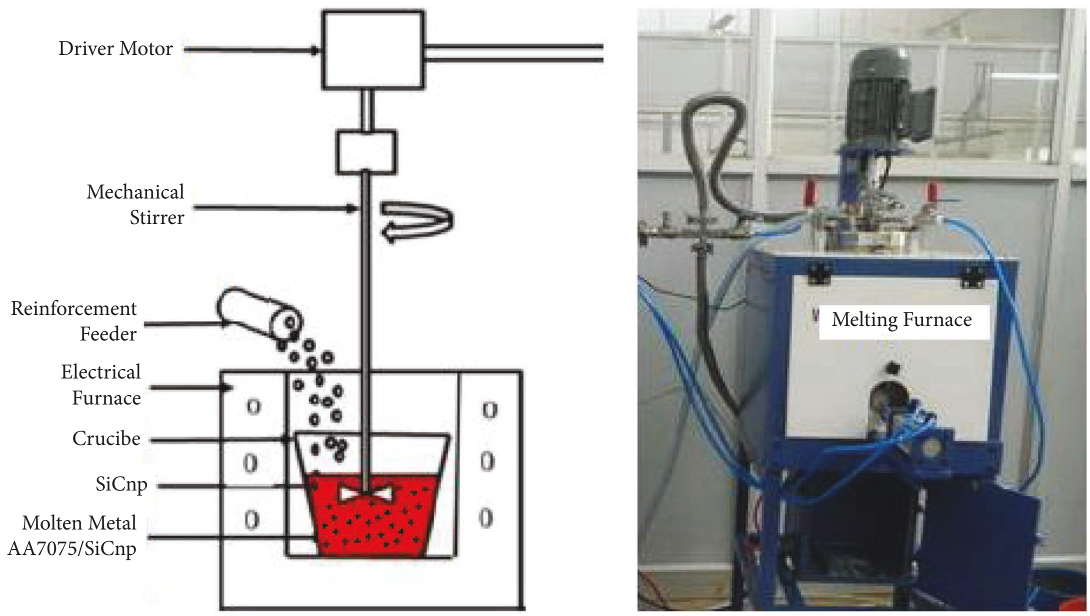
2.4. Methods and Processing of AA7075/SiC Nanocomposite

2.4.1. Preparation of AA7075/SiC Nanocomposites. Figure 1 illustrates the aluminum melting stir casting apparatus consisting of an electrical furnace (3ϕ-5 KW/1000°C), mechanical stirrer (graphite), a reinforcement feeder, and a crucible. Both the matrix and reinforcements are weighted as per composition as mentioned in Table 4. Initially, the AA7075 blocks were placed in a furnace crucible at 300°C to preheat them. The furnace temperature was gradually increased to 700°C with the help of a control panel [24]. The AA7075 was melted at 700°C and the temperature of the molten metal was reduced to 650°C correspondingly, the preheated (300°C) SiC nanoparticles were feed into the molten metal pool via a reinforcement feeder [25]. Both the SiC and molten AA7075 are uniformly stirred at 400 rpm for 15 mins. It leads to increase wettability and limits the porosity of MMC [11, 16, 22]. The prepared liquid state metal has streamed in casting die is shown in Figure 2. The cast samples ($100 \times 50 \times 20$ mm) were cleaned and sized as per test standards.

The developed AA7075 nanocomposites were tested as per ASTM standards. A universal tensile test machine tested the nanocomposite's tensile strength with a capacity of 40 ton (FIE-UTN 40) under theASTM E-8 standard [26]. The VEGAJ model TESCAN type scanning electron microscope was used for microstructure studies. The heat flow rate and its convective heat transfer coefficient of nanocomposites were measured using pin fin setup and thermocouple arrangements on ASTM E 457 standards [27].

Table 3: Liquid state processing parameter (Input).

Process parameters	Stir						Impeller	
	Type	Temperature	Speed	Feed	Time	Stage	Blade angle	Material
Units	—	°C	rpm	g/sec	mins	Qty	degree	—
Dimensions	Vortex flow	650	400	1	15	1	30	Graphite



(a) (b)

Figure 1: Aluminum melting stir casting apparatus (a) Block diagram (b) Actual setup.

Table 4: Weight percentages of AA7075/SiC nanocomposites.

Elements/Sample		1	2	3	4
AA7075	Wt%	100	97	94	91
SiC		0	3	6	9

Rectangular aluminum alloy (AA7075) and its composites (treated as fin plate) were fitted individually into the pin fin apparatus duct. The fin was placed on the heater side and the thermocouple fixed between the fin surface and the pin. The suction fan has internally fixed to the duct to provide the appropriate air flow. Temperature sensors and anemometers measure the temperature and velocity of air flow. The digital type watts meter was used to measure the power between the inputs and the heater.

3. Results and Discussion

3.1. Thermal Performance of AA7075/SiC Nanocomposites

3.1.1. Heat Transfer Rate. Figure 3 illustrates the heat transfer rate of cast AA7075 alloy and its nanocomposites (Q_{fin}) with varied weight percentages of nano SiC. The heat transfer rate for the unreinforced model AA7075 alloy is 11.81 watts. At the same time, the addition of nano SiC in the AA7075 alloy matrix shows a gradual improvement in heat transfer rate. It varies from 12.65 watts to 13.35 watts, respectively. It was because the aluminum alloy matrix may lead to the transfer of heat and the presence of hard silicon carbide particles can withstand the high temperature (more than 600°C) [2, 13]. The maximum heat transfer rate of 13.35 watts was founded on 9 wt% SiC. It increased 11.5% compared to the AA7075 alloy. It was due to SiCnp's good thermal stability there [12, 15]. The heat transfer between AA7075 nanocomposite plate and pin surfaces is divided equally, and its energy was increased by 0%, 6.6%, 9%, and 11.5% with increasing the weight percentages of (0, 3, 6, and 9 wt %) nano SiC.

3.1.2. Convective Heat Transfer Coefficient. The convective heat transfer coefficient of the unreinforced cast AA7075 alloy and the AA7075/SiC nanocomposite is shown in Figure 4. It indicates the variations of the convective heat transfer coefficient from 25.5 W/m^{2}K to 30.81 W/m^{2}K with increasing the content of SiC from 0 wt% to 9 wt%. The nanocomposite containing 9 wt% of SiC shows an optimum convective heat transfer rate of 30.81 W/m^{2}K. The presence

Figure 2: Poured molten metals into die.

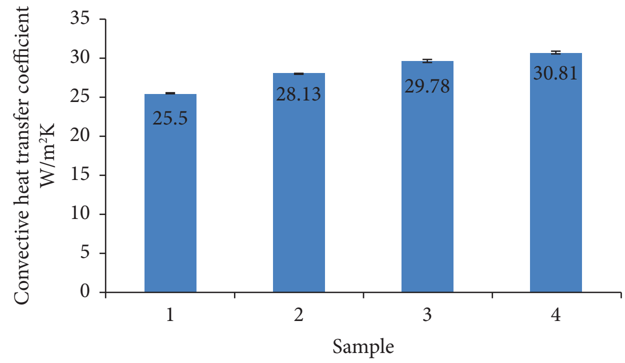


Figure 4: Convective heat transfer coefficient of AA7075/SiC nanocomposite.

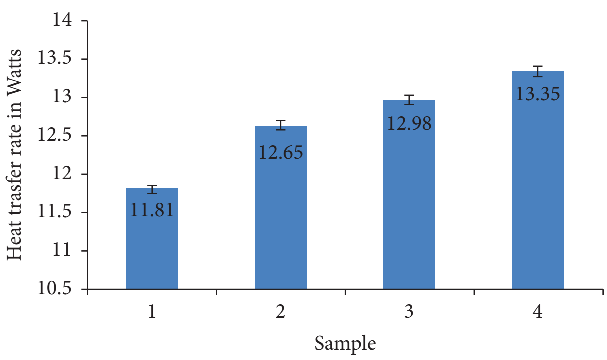


Figure 3: Heat transfer rate of AA7075/SiC nanocomposite.

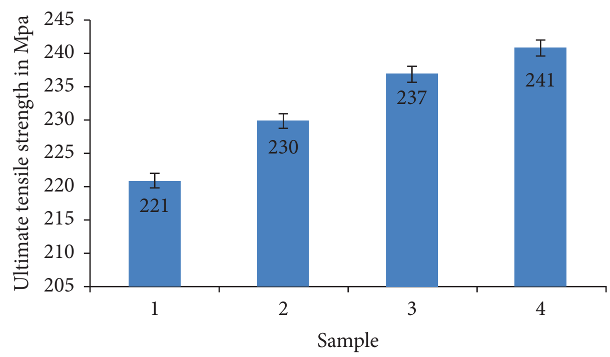


Figure 5: Ultimate tensile strength of AA7075/SiC nanocomposite.

of hard SiC nanoparticles in soft aluminum matrix alloy leads to an increase the thermal response. The thermal response, such as heat transfer rate and convective heat transfer coefficient, is directly proportional to the additions of complex ceramic particle. So the variations in thermal performance of nanocomposite are decided by incorporating (weight percentage) SiC_{np} into AA7075 matrix. The convective heat transfer coefficient of AA7075/9 wt% is increased by 17.2% compared to the unreinforced cast AA7075 alloy. It is recommended for high-temperature automotive alloy wheel and brake applications.

3.2. Mechanical Performance of AA7075/SiC Nanocomposite

3.2.1. Ultimate Tensile Strength. The ultimate tensile strength of cast aluminum alloy and its nanocomposite containing 3 wt%, 6 wt%, and 9 wt% of SiC is illustrated in Figure 5. It is proof that the ultimate tensile strength of AA7075 nanocomposite gradually increased with the increased content of nano SiC. It was observed from Figure 5, that the tensile strength of the AA7075 alloy was found to be 221 MPa. While adding 3 wt%, 6 wt%, and 9 wt% nano SiC particles to AA7075 shows 230 MPa, 237 MPa, and 241 MPa respectively. The maximum tensile strength of 241 MPa is observed in the AA7075/9 wt% SiC alloy nanocomposite tested at room temperature (27°C). It was caused by good bonding strength between the matrix to the reinforcement phase [16, 22]. While the axial load is applied to the nanocomposite, the AA7075 alloy transfers the load into the SiC reinforcement phase and limits the rupture of the composite. The AA7075/9 wt% SiC nanocomposite has an identified 8.1% improvement in tensile strength.

3.2.2. Scanning Electron Microscope Image of AA7075 Alloy and Its Nanocomposites. The $10 \times 10 \times 10$ mm cubic shaped test samples were polished by a different emery grade sheet and then polished fine by a rotating silky disc. The polished cubic test sample of AA7075 alloy and its nanocomposite surfaces were examined by a scanning electron microscope in different positions to identify the SiC particles and its bonding regions. Figures 6(a)–6(d) illustrates the scanning electron micrograph of liquid stir cast developed AA7075 alloy and its nanocomposites. Figure 6(a) illustrates the micrograph of AA7075 alloy contains coarse grain structure. It was observed from Figure 6(b) that the SiC particles were distributed evenly in AA7075 matrix. It was due to constant mechanical stirring action. A similar trend was reported by Balasubramaniam and Maheswaran [12] during the evaluation of AA6063/SiC composite. Figures 6(c) and 6(d) clearly show that the SiC grains in AA7075 matrix attached with good interfacial bonding leads to increased composite quality. Figure 7 illustrates the EDS SEM image of the AA7075/9 wt% SiC composite with their element contribution percentage.

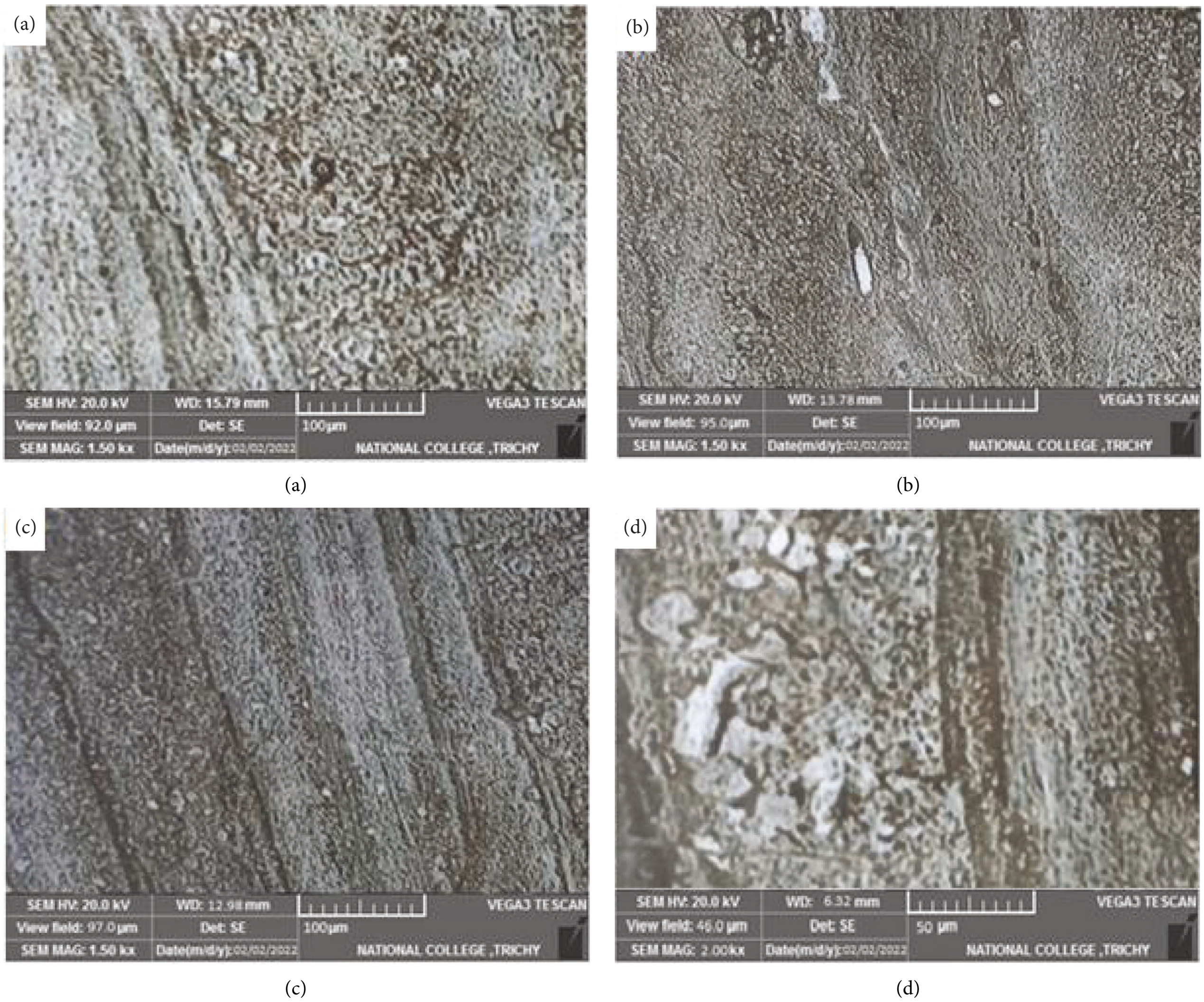
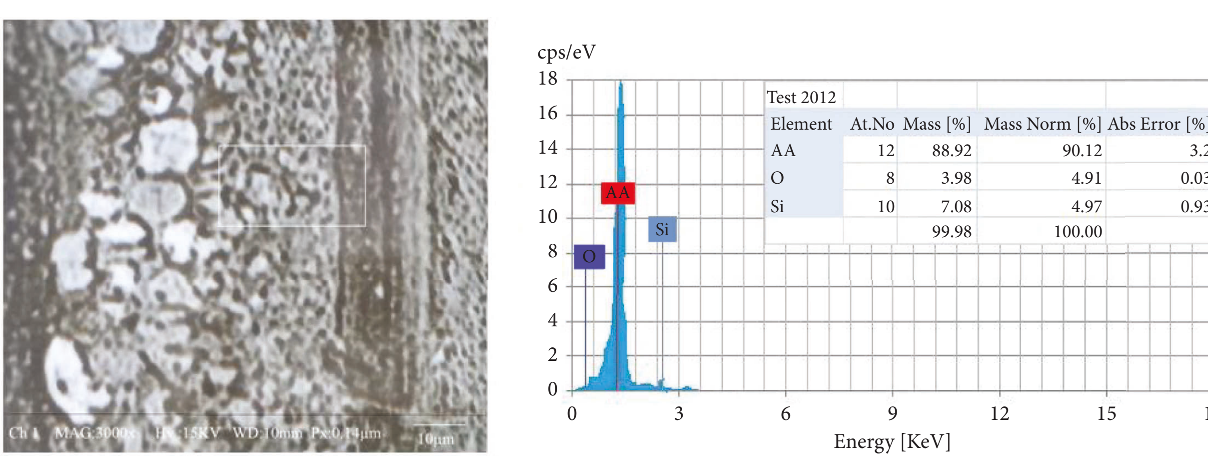


Figure 6: SEM Image of AA7075 alloy nanocomposites (a) AA7075, (b) AA7075/3 wt% SiC, (c) AA7075/6 wt% SiC, and (d) AA7075/9 wt% SiC.



Test 2012				
Element	At.No	Mass [%]	Mass Norm [%]	Abs Error [%]
AA	12	88.92	90.12	3.2
O	8	3.98	4.91	0.03
Si	10	7.08	4.97	0.93
		99.98	100.00	

Figure 7: EDS SEM images of AA7075/9 wt% SiC composite.

4. Conclusions

The nano-sized SiC particle reinforced aluminum alloy (AA7075) nanocomposites were developed successfully by liquid state processing (stir cast). The SiC nanoparticle increases the thermomechanical properties of the AA7075 nanocomposite compared to the unreinforced aluminum (AA7075) alloy. About 11.5% improvement in heat transfer rate and an increased 17.2% in convective heat transfer coefficient as compared to cast AA7075 alloy. The liquid state processing (stir cast) helps to increase the particle distribution. Good interfacial bonding between AA7075 and nano SiC leads to an increase in the mechanical properties of the nanocomposite. The tensile strength of the composite is increased by 8.1% compared to unreinforced aluminum alloy (AA7075). The nanocomposite containing 9 wt% SiC was found to have good thermomechanical performance and was recommended for automotive alloy wheel applications.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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