On the wettability diversity of C/SiC surface: comparison of the ground C/SiC surface and ablated C/SiC surface from three aspects

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Abstract

Most of the coefficient of thermal conductivity was influenced by the wetting state of material. The wetting state usually depends on the surface wettability. C/SiC is a promising ceramic composites with multi-components. The wettability of C/SiC composites is hard to resort to the classic wetting theory directly. So far, few investigations focused on C/SiC surface wettability diversity after different material removal processes. In this investigation, comparative studies of surface wettability of ground C/SiC surface and laser-ablated C/SiC surface were carried out through apparent contact angle (APCA) measurements. The results showed that water droplets easily reached stable state on ground C/SiC surface; while the water droplets rapidly penetrated into the laser-ablated C/SiC surface. In order to find out the reason for wettability distinctions between the ground C/SiC surface and the laser-ablated C/SiC surface, comparative studies on the surface micro-structure, surface C-O-Si distribution, and surface C-O-Si weight percentage of were carried out. The results showed that (1) A large number of micro cracks in the fuzzy pattern layer over laser-ablated C/SiC surfaces easily destroyed the surface tension of water droplets, while only a few cracks existed over the ground C/SiC surfaces. (2) Chemical components (C, O, Si) were non-uniformly distributed on ground C/SiC surfaces, while the chemical components (C, O, Si) were uniformly distributed on laser-ablated C/SiC surfaces. (3) The carbon weight percentage on ground C/SiC surfaces were higher than that on laser-ablated C/SiC surfaces. All these made an essential contribution to the surface wettability diversity of C/SiC surface. Although more investigations about the quantitative influence of surface topography and surface chemical composition on composites wettability are still needed, the conclusion can be used in application: the wettability of C/SiC surface can be controlled by different material removal process without individual following up surface modification process.

Keywords: Surface wettability distinction; multi-component; composites; grinding; ablation;

1. Introduction

Most of the coefficient of thermal conductivity was influenced by the humidity of environment. The coefficient in wetting state is generally higher than the coefficient of the same material in dry state. Generally, moisture is absorbed into the composite matrix through the surfaces. Understanding the mechanism of surface wetting transitions is vital for material design. Different material removal mechanism[1,2,3,4,5,6,7,8,9,10,11,12] may form different micro-structure and affect surface chemical composition, it is especially this case for the composite material with multi-components. The carbon fiber reinforced silicon carbide ceramic matrix composites are composited by a variety of components (carbon fiber, SiC matrix and pyrocarbon), each component has its important function in application. These components were exposed directly on the composites surfaces after material removal process. The micro-topography changing and chemical composition changing of these components may lead to great different of the surface wettability, but it can not easily resort to the classical wetting theory of isotropic material. Therefore, it is important to study the surface wettability variation of each component.

So far, few investigations were concentrated on the surface wettability diversity of C/SiC composites, especially the reason for the surface wettability variaty. In this investigation, grinding and laser ablation were selected to work as the finishing material removal process for C/SiC composites. The apparent contact angle (APCA) measurements were performed on ground C/SiC surface and laser-ablated C/SiC surface in order to characterize the surface wettability of ground C/SiC surface and laser-ablated C/SiC surface. The distinctions of each component on these two kinds of surfaces were investigated from the following three aspects: 1. Surface micro structure; 2. C-O-Si distribution; 3. C-O-Si weight percentage. Finally, some exceptions on the C/SiC surface wettability were also discussed.

2. Experimental details

2.1 Fabrication of C/SiC substrate

The precast body was prepared by uni-directional carbon fibers. The porous C/SiC composites were made by chemical vapor infiltration(CVI) process. The C_3H_6 was used as carbon source, the methyltrichlorosilane(CH_3CL_3Si) was used as silicon source and the H_2 was used as carrier gas. Infiltration was carried out under vacuum for hours, silicon carbide matrix was formed during this process. The C/SiC consists of carbon fiber, pyrocarbon, and SiC matrix, more information about the composite structure could be found in this literature[13, 14]. In this investigation, the density of the finished C/SiC composites was about 1.45 g/cm^3 . The finished uni-directional C/SiC composites were divided into small pieces. They were ground or laser treated in the following processes. Fiber direction is also shown in **Fig. 1(a)**, which corresponds to the fiber direction in **Fig. 1(b)**. Only the composite surfaces with the pillar fiber ending in **Fig. 1(b)** were selected to work as the experimental surface.

Fig. 1 (a) the finished uni-directional C/SiC composites (b) the enlarged view of the selected C/SiC surface before experiment

2.2 Parameters of grinding process

The diameter of the grinding wheel is 70mm, the thickness of the grinding wheel is 16mm. The rotational speed of the grinding wheel varied from 1000RPM to 5000RPM respectively. The depth of cut is 0.5mm, as shown in **Table. 1**.

Table. 1 The parameters of the grinding operation

Grinding wheel	46#
Diameter of the grinding wheel	70mm
Thichness of the grinding wheel	16mm

Rotational speed of the grinding wheel	1000-5000RPM
Depth of cut	0.5mm

2.3 Parameters of laser ablation process

The spot diameter of the laser beam was approximate $10\mu\text{m}$, the laser ablation was carried out through scanning of the laser beam according to the predetermined trace on C/SiC surfaces, as shown in **Fig. 2**. The scanning path began from the top left hand corner, and it stopped at the top right hand corner. The number of scanning repetition was one time, two times, and three times respectively. The laser trace distance (d) were $5\mu\text{m}$, $10\mu\text{m}$, $15\mu\text{m}$, respectively. The detailed laser parameters could be found in **Table. 2**. Only the qualified surfaces of all of these workpieces were selected to work in the following experiments.

Fig. 2 Top view of the laser scanning trace and geometry relationship of laser trace direction and fiber direction

Table. 2 The parameters of the laser operation

Wavelength	1064 nm
Average power	20 W (80%)
Repetition rate	20 kHz
Scanning velocity	400 mm/s
Diameter of focus point	$10\mu\text{m}$
Focal length	220mm
Focus position	Top surface
Number of scanning repetition	1, 2, 3
Laser trace distance(d)	5, 10, $15\mu\text{m}$

2.4 Specimen selection characterization and contact angle measurement

The surface topography was measured by Talysurf i120. The workpiece with surface roughness between 10 μ m and 40 μ m were selected from all of the ground and laser-ablated C/SiC composites to work as the specimens in the following research (20 ground specimens, 20 laser-ablated specimens). The micro topography of the C/SiC surfaces was also observed by scanning electron microscope (SEM) with energy dispersive X-ray spectroscopy (EDX) and optical microscope. The contact angle was determined by apparent contact angle (APCA) measurement at the ambient temperature about 24 $^{\circ}$ C and air humidity about 50%. For each test, a droplet of 1 μ L water was carefully dropped on the specimen surface, then the contact angle was observed and recorded.

3. Results and discussion

3.1 Comparison of apparent contact angle on ground C/SiC surface and laser-ablated C/SiC surface

Almost all the water droplets disappeared within 1 second on laser-ablated C/SiC surfaces. They rapidly penetrated into the C/SiC surfaces, and disappeared in the observation range in **Fig. 3(a)**; while, the typical steady state of the water droplets can be observed on ground C/SiC surfaces in **Fig. 3(b)**. In this study, the “hydrophilic” and “superhydrophilic” is defined according to the time that water droplet disappeared from the C/SiC surface. The hydrophilic behavior refers to as the water droplets kept a stable shape more than 1 second on the surface. The superhydrophilic behavior refers to as the water droplets disappeared within 1 second on the surface. The experimental results showed that all the C/SiC sample surfaces exhibited superhydrophilic behavior after laser ablation process; while, all the C/SiC sample surfaces exhibited hydrophilic behavior after grinding process.

Fig. 3 comparison of surface wettability by apparent contact angle measurement. (a) the typical contact angle on laser-ablated C/SiC surface. (b) the typical contact angle on ground C/SiC surface.

Fig. 4 depicts a typical droplet contact angle variation as a function of time (within 10 seconds) on a ground C/SiC surface. On the ground C/SiC surface, the increasing of spreading time leads to a global decrease of droplet contact angle. The droplet contact angle on the ground C/SiC surface was 71.9° at the beginning. It has decreased to 61.2° and 57.4° at 2 second and 3 second respectively. It decreased further at 4 second (56°). The contact angle remains stable about 54° from 6 second to 10 second.

Fig. 4 A typical contact angle variation on ground C/SiC within 10 seconds.

From the APCA experiment results, all the water droplets could not reach stable state on laser-ablated C/SiC surface.

They rapidly penetrated into the matrix. The wettability variety between ground C/SiC surfaces and laser-ablated C/SiC

surface in **Fig. 3** tended to attribute to surface topography variation and surface chemical composition variation. And it can be easily understood basically by Wenzal's model $\cos \theta = \gamma \cos \theta_y$ [15]. Besides, C/SiC is a typical composites material, different components have their special functions in applications, for example, carbon fiber can improve the fracture toughness of the composites, SiC matrix can improve the bearing capacity of the composites. However, different components react different to laser and grinding process in form of surface roughness changing and surface chemical composition changing. The surface wettability of C/SiC may vary a lot correspondingly, which can not resort to the classical surface wetting theory of isotropic material. Therefore, it is important to study the surface variation of each component separately after material removal process. In order to find out the specific reason for surface wettability diversity of C/SiC surfaces in **Fig. 3**. Comparative studies of each component on C/SiC surfaces were carried out from the following three aspects: (1) surface micro structure (2) surface C-O-Si distribution (3) surface C-O-Si weight percentage.

3.2 Comparison of micro topography on ground C/SiC surface and laser-ablated C/SiC surface

After laser ablation processing, the surfaces represented by **Fig. 1(b)** evolved into the surfaces represented by **Fig. 5(a)**. The C/SiC surface was seemingly covered by a fuzzy pattern layer, as shown in **Fig. 5 (a)**. The fuzzy pattern layer included multi-scale surface structures (micro-scale and nano-scale flocculent structures, as shown in **Fig. 5(b)-(f)**. (b) is the enlarged partial view of (a), (c) is the enlarged partial view of (b), (d) is the enlarged partial view of (c), (e) is the enlarged partial view of (d), (f) is the enlarged partial view of (e). The fuzzy pattern is uniformly distributed on the laser-ablated C/SiC surface despite a slight difference in shape. One explanation about the fuzzy pattern layer is that these surface structures were produced by the laser beam moving in the ablation regime on both of the carbon fiber and SiC matrix (and pyrocarbon). The C/SiC composites were easy to be oxidized. The SiO_2 was hard to be evaporated, thus they were accumulated on the surface in form of fuzzy pattern layer and spherical particles in **Fig. 5(b)(c)(d)**. SEM view also showed that some cracks on these flocculent structures and some scattered spherical particles on

laser-ablated surfaces in **Fig. 5(b)(c)(d)**. Another explanation about the fuzzy pattern layer formation is that although the ablation was alleviated in certain areas, it still went on in the adjacent areas. Therefore, some of the laser-ablated C/SiC surfaces were covered by high temperature sputtering residual particles from the adjacent ablated area. Almost the entire surface was covered with these fuzzy pattern layer, the water droplets were easily destroyed by these flocculent structure and quickly penetrated into the C/SiC surface. Therefore, the water droplets hardly reached steady state on laser-ablated C/SiC surface in **Fig. 3(a)**.

After grinding processing, the surfaces represented by **Fig. 1(b)** evolved into the surfaces represented by **Fig. 6(a)**. The fuzzy pattern layer mentioned above was not observed on ground C/SiC surfaces. It was easy to distinguish the carbon fiber from the SiC matrix (including pyrocarbon) on the ground C/SiC surfaces in **Fig. 6 (a)(b)(c)(d)**. There were not so many cracks on ground C/SiC surfaces like those on laser-ablated C/SiC surfaces. Correspondingly, residual debris was also observed on the ground surface in **Fig. 6 (a)(b)(c)(d)**, which is the residual fragments of carbon fiber, pyrocarbon, and SiC matrix after brittle fracture. Both laser-ablated C/SiC surface and ground C/SiC surface produced a large number of residual particles in various forms. **Fig. 6 (e)** is the enlarged partial view of the pyrocarbon & SiC matrix in **Fig. 6 (d)**. **Fig. 6 (f)** is the enlarged partial view of the carbon fiber in **Fig. 6 (c)**. Unlike the laser-ablated C/SiC surface, the ground C/SiC surface was mainly composited by the sectional surface of carbon and SiC matrix (including pyrocarbon) without fuzzy pattern layer. Therefore, the water droplets easily reached the steady state (equilibrium contact angle) on the ground C/SiC surface in **Fig. 3(b)** and **Fig. 4**.

Fig. 5 Details of SEM views on the laser-ablated C/SiC surface. (b) is the enlarged partial view of (a), (c) is the enlarged partial view of (b), (d) is the enlarged partial view of (c), (e) is the enlarged partial view of (d), (f) is the enlarged partial view of (e).

Fig. 6 Details of SEM view on the ground C/SiC surface. (b) is the enlarged partial view of (a), (c) is the enlarged partial view of (b), (d) is the enlarged partial view of (c), (e) is the enlarged partial view of (d), (f) is the enlarged partial view of (e).

In summary, the laser-ablated C/SiC surface topography is different from the ground C/SiC surface topography because of the different material removal mechanisms in laser ablation and grinding. The C/SiC surfaces are dense after grinding process, which makes the water droplets easily keep a stable state on the C/SiC surface; while, a fuzzy pattern layer with many micro cracks exists on the laser-ablated surface, which makes the water droplets quickly penetrate into the C/SiC surface. The different C/SiC topography produced by laser ablation and grinding may exert certain influence on C/SiC surface wettability diversity to some degree.

3.3 Comparison of C-O-Si distribution on ground C/SiC surface and laser-ablated C/SiC surface

It is well known that the surface wettability was not only affected by surface topography but also affected by surface chemical composition. The energy dispersive X-ray spectroscopy (EDX) maps of the C-O-Si distribution can help us get a

better understanding of the surface chemical distribution distinction between laser-ablated C/SiC surfaces and ground C/SiC surfaces. Almost all of C, O, Si were evenly distributed over the laser-ablated C/SiC surface in **Fig. 7**; while the C, O, Si were distributed unevenly on the ground C/SiC surface in **Fig. 8**. Besides, the boundaries among carbon fiber, pyrocarbon, and SiC matrix were not clear enough to be identified in **Fig. 7(a)**. And the C distribution map, O distribution map, and Si distribution map in **Fig. 7(b)(c)(d)** were also hard to give a good indication about the exactly position of the boundary among carbon fiber, pyrocarbon and SiC matrix. It is hard to associate the C distribution in **Fig. 7 (b)**, O distribution in **Fig. 7 (c)** and Si distribution in **Fig. 7 (d)** with the corresponding parts of the C/SiC surface in **Fig. 7(a)**. It can be attribute to the fuzzy pattern layer covered on the laser-ablated C/SiC surface.

Fig. 7 SEM view of the laser-ablated C/SiC surface (a) micro topography of the laser-ablated C/SiC surface (b) EDX Map of C distribution (c) EDX Map of Si distribution (d) EDX Map of O distribution

We can also get some helpful information from EDX maps of C-O-Si distribution on the ground C/SiC surfaces. Almost all of C, O, Si are non-uniformly distributed over ground C/SiC surfaces in **Fig. 8**. It is easy to distinguish the boundary among carbon fiber, pyrocarbon, and SiC matrix in **Fig. 8(a)**. For example, C was mainly distributed in Region 1 in **Fig. 8(b)** because C is mainly distributed on the same area as the carbon fiber exposed area in **Fig. 8(a)**. O was mainly distributed in region 2 in **Fig. 8(c)** because the pyrocarbon and SiC matrix were exposed on the surface in region 2 in **Fig. 8(a)**

correspondingly, they were easy to be oxidized. Si was mainly distributed in region 3 in **Fig. 8(d)** because the residual particles were accumulated on the surface in region 3 in **Fig. 8(a)**. The carbon fiber, SiC matrix, and pyrocarbon are directly exposed on the sectional surface, thus the concentrated areas of C, O, Si in **Fig. 8 (b)(c)(d)** are clear.

Fig. 8 SEM micrography of the ground C/SiC surface (a) micro topography of the laser-ablated C/SiC surface (b) EDX Map of C distribution (c) EDX Map of Si distribution (d) EDX Map of O distribution

As a matter of fact, the C-O-Si are uniformly distributed on laser-ablated C/SiC surface, while the C-O-Si are non-uniformly distributed on ground C/SiC surface. The partial view and XRD analyzation of the laser-ablated C/SiC surface and ground C/SiC surface can help us get a better understanding of C-O-Si distribution distinction of C-O-Si on two typical surfaces. The weight percentage of C-O-Si on carbon fiber dominate region(61.49:29.05:9.46) was similar as SiC (including pyrocarbon) dominate region(58.37:27.76:13.87) of the laser-ablated surface. However, the weight percentage of C-O-Si showed a great different on carbon fiber dominate region(100:0:0) and SiC dominate region (68.63:26.26:5.11) of the ground surface. This is one of the main reason for the uniform distribution of C-O-Si on laser-ablated surface in **Fig. 7** and the non-uniform distribution of C-O-Si on ground surface in **Fig. 8**. All of these distinction on laser-ablated C/SiC surface and ground C/SiC surface may exert certain influence on C/SiC surface wettability diversity.

Fig. 9 The weight percentage of C, O, Si on carbon fiber dominate area and SiC & pyrocarbon dominate area. (a)the weight percentage of C, O, Si on carbon fiber dominate area on laser-ablated C/SiC surface (b)the SEM view of the laser-ablated C/SiC surface, (c)the weight percentage of C, O, Si on SiC & pyrocarbon dominate area on laser-ablated C/SiC surface, (d)the weight percentage of C, O, Si on carbon fiber dominate area on ground C/SiC surface, (e)the SEM view of the ground C/SiC surface, (f)the weight percentage of C, O, Si on SiC & pyrocarbon dominate area on ground C/SiC surface.

3.4 Comparison of weight percentage of C-O-Si on ground C/SiC surface and laser-ablated C/SiC surface

On the ground C/SiC surface and laser-ablated C/SiC surface, the C-O-Si distribution variety may lead to the C-O-Si weight percentage variety. Therefore, the influence of C-O-Si weight percentage on C/SiC surfaces wettability diversity should not be neglected. The EDX area scanning map can provide the overall C-O-Si weight percentage in the whole area. The overall weight percentage of C-O-Si on laser-ablated C/SiC surfaces is basically different from that on ground C/SiC surface, as shown in **Fig. 10** (a) and (b). The weight percentage of C-O-Si is 58.88: 30.74: 10.38 on laser-ablated C/SiC surface. On the other hand, the weight percentage of C-O-Si is 87.19: 10.59: 2.22 on ground C/SiC surface. The C percentage (87.19%) on ground C/SiC surface is higher than the C percentage (58.88%) on laser-ablated C/SiC surface; while, the O percentage (30.74%) and Si percentage (10.38%) on laser-ablated C/SiC surface are higher than the O percentage (10.59%) and Si percentage (2.22%) on ground C/SiC surface. Most of carbon fibers were completely exposed on ground C/SiC surface, only a small part of the carbon fibers were randomly covered by residual particle

mentioned above. Therefore, the weight percentage of C on ground C/SiC surface in **Fig. 10** (b) is generally higher than the weight percentage of C on the laser-ablated C/SiC surface in **Fig. 10** (a). Most of laser-ablated C/SiC surface was covered by a fuzzy pattern layer which was mainly comprised of SO_2 . Therefore, the weight percentage of O and Si on the laser-ablated C/SiC surface in **Fig. 10**(a) is generally higher than the weight percentage of O and Si on the ground C/SiC surface in **Fig. 10**(b). Actually, laser ablation process and grinding process are not only material removal process, but also surface modification process including surface topography modification and surface chemical modification; although the exact influence of C-O-Si weight percentage on C/SiC surface wettability is still not clear, the distinction of C-O-Si weight percentage on laser-ablated C/SiC surface and ground C/SiC surface could exert certain influence on surface wettability diversity.

Fig. 10 The weight percentage of C, O, Si on laser-ablated C/SiC surface and ground C/SiC surface. (a) the weight percentage of C, O, Si on laser-ablated C/SiC surface is 58.88:30.74:10.38. (b) the weight percentage of C, O, Si on ground C/SiC surface is 87.19:10.59:2.22

3.5 Other potential influence on the C/SiC surface wettability (contact angle)

Please note that, in a few case, the water droplet may also rapidly penetrate into all the C/SiC surface(including ground

C/SiC surfaces and ablated C/SiC surfaces), no matter what kind of material removal process, the possible explanations are as following: (1) The selected C/SiC composite surface presented fiber misalignment, as shown in **Fig. 11(a)-(f)**. Fiber misalignment occurs when there is misorientation of the precast body. It is a kind of fabrication control error. If the surface quality did not satisfy with the experimental requirement, no matter what kind of material removal process (such as grinding or laser ablation), the porous surfaces will make the water droplet rapidly penetrate into the surfaces. (2) Typical pores induced by matrix starved area generally occurred during the production and preparation of material such as improper quality control, as shown in **Fig. 12(a)(b)**. All the matrix starved area may affect the surface wettability in form of pores to some degree. Pores may be presented in isolation form or random accumulated interaction with other pores. The pores induced by matrix starved area is also the main reason for the rapid penetration of water droplet into the surface. In summary the density of the composite materials will be destroyed during manufacturing, storage, and even transportation. The water droplet will also rapidly penetrate into the destroyed surfaces, which will exert certain influence on the surface wettability to some extent;

Fig. 11 Fiber misalignment on the C/SiC surface. Fiber misalignment can cause the water droplet rapidly penetration into the C/SiC surface, no matter what kind of material removal process.

Fig. 12 Typical pores on C/SiC surface (a) typical pores induced by matrix starved area, from pore 1 to pore 9. (b) typical pores induced by matrix starved area, from pore 1 to pore 3.

4. Conclusions

Machining process (laser ablation or grinding) makes actual difference in C/SiC surface wettability. The water droplets are hard to form stable state on laser-ablated C/SiC surfaces; while, the water droplets are easy to reach stable state on ground C/SiC surfaces. In this study, the distinctions of each component on ablated C/SiC surfaces and ground C/SiC surfaces were investigated from three aspects and the conclusions are as follow:

(1) The topography distinction: a fuzzy pattern layer with dense micro cracks was formed on laser-ablated C/SiC surfaces including carbon fiber dominate area, pyrocarbon and SiC matrix dominate area. They are likely to destroy the surface tension of water droplets in APCA measurement, which makes water droplets quickly penetrate into the C/SiC surface. This is one of the main reasons accounted for the difference of ground C/SiC surface wettability and laser-ablated C/SiC surface wettability.

(2) The C-O-Si distribution distinction: the C-O-Si is distributed unevenly on the ground C/SiC surfaces. C mainly concentrated on the carbon fiber dominate area; O and Si mainly concentrated in the vicinity of C/SiC matrix,

pyrocarbon, and residual particles; while the C-O-Si is distributed evenly on the laser-ablated C/SiC surfaces because a fuzzy pattern layer covered on the laser-ablated C/SiC surfaces.

(3) The C-O-Si weight percentage distinction: the weight percentage of C on ground C/SiC surface is higher than the weight percentage of C on laser-ablated C/SiC surface, while, the O and Si weight percentage on laser-ablated C/SiC surface is higher than the O and Si weight percentage on ground C/SiC surface. The distinction can also be attribute to the fuzzy pattern layer covered on each component of the laser-ablated C/SiC surfaces

All of these variation on laser-ablated C/SiC surface and ground C/SiC surface may exert certain influence on C/SiC surface wettability diversity. Please note that if the surface density did not satisfy with the experimental requirement, the waterdroplet will also rapidly penetrate into the surface, no matter what kind of material removal process(such as grinding and laser ablation). A suitable machining process can easily satisfy with the C/SiC surface wettability requirement during material removal process without individual following up surface modification process, which can reduce resource consumption and time consumption for a sustainable development of environment.

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References

[1] Ming Du,Hua wei Zhang,Yan xiang Li, Inner surface alloying on pores of lotus-type porous copper through electroless

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- plating with supersonic vibration and annealing treatment, *Surface and Coatings Technology*. 261 (2015) 1–6.
- [2] Lijun Liu, Jiashou Zhao, Yi Zhang, Fan Zhao, Yanbo Zhang, Fabrication of superhydrophobic surface by hierarchical growth of lotus-leaf-like boehmite on aluminum foil, *Journal of Colloid and Interface Science*. 358 (2011) 277–283.
- [3] Daniel Ebert, Bharat Bhushan, Durable Lotus-effect surfaces with hierarchical structure using micro- and nanosized hydrophobic silica particles, *Journal of Colloid and Interface Science*. 368 (2012) 584–591.
- [4] Tianchi Wang, Lijing Chang, Sen Yang, Yang Jia, Chingping Wong, Hydrophobic properties of biomorphic carbon surfaces prepared by sintering lotus leaves, *Ceramics International*. 39 (2013) 8165–8172.
- [5] Ming Du, Hua wei Zhang, Yan xiang Li, Inner surface alloying on pores of lotus-type porous copper through electroless plating with supersonic vibration and annealing treatment, *Surface and Coatings Technology*. 261 (2015) 1–6.
- [6] Lijun Liu, Jiashou Zhao, Yi Zhang, Fan Zhao, Yanbo Zhang, Fabrication of superhydrophobic surface by hierarchical growth of lotus-leaf-like boehmite on aluminum foil, *Journal of Colloid and Interface Science*. 358 (2011) 277–283
- [7] Daniel Ebert, Bharat Bhushan, Durable Lotus-effect surfaces with hierarchical structure using micro- and nanosized hydrophobic silica particles, *Journal of Colloid and Interface Science*. 368 (2012) 584–591.
- [8] K. Takahashi, M. Tsukamoto et al, Influence of laser scanning conditions on CFRP processing with a pulsed fiber laser, *Journal of Materials Processing Technology*. 222 (2015) 110–121.
- [9] C. Leone, S. Genna, V. Tagliaferri, Fibre laser cutting of CFRP thin sheets by multi-passes scan technique, *Optics and Lasers in Engineering*. 53 (2014) 43–50.
- [10] A. Riveiro, F. Quintero et al, Experimental study on the CO₂ laser cutting of carbon fiber reinforced plastic composite, *Composites: Part A*. 43 (2012) 1400–1409.
- [11] A. N. Fuchs, M. Schoeberl, J. Tremmer, M.F. Zaeh, Laser cutting of carbon fiber fabrics, *Physics Procedia*. 41 (2013) 372–380.
- [12] C.-H. Tsai, H.-W. Chen, Laser milling of cavity in ceramic substrate by fracture machining element technique, *Journal of Materials Processing Technology*. 136 (2003) 158–165.
- [13] M.L. Wu, C.Z. Ren, Active control of the anisotropic wettability of the carbon fiber reinforced carbon and silicon carbide dual matrix composites (C/C-SiC), *Applied Surface Science*. 327 (2015) 424–431.
- [14] M.L. Wu, C.Z. Ren, H.Z. Xu, Comparative study of micro topography on laser ablated C/SiC surfaces with typical uni-directional fiber ending orientations. *Ceramics International*, 42 (2016) 7929–7942.
- [15] R.N. Wenzel, Resistance of solid surfaces to wetting by water, *Industrial Engineering Chemistry*. 28 (1936) 988–994.