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Effect of environmental dust particles on laser textured yttria-stabilized zirconia surface in humid air ambient

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ABSTRACT

Zirconium nitride is used as a selective surface for concentrated solar heating applications and one of the methods to form a zirconium nitride is texturing of zirconia surface by a high intensity laser beam under high pressure nitrogen gas environment. Laser texturing also provides hydrophobic surface characteristics via forming micro/nano pillars at the surface; however, environmental dust settlement on textured surface influences the surface characteristics significantly. In the present study, laser texturing of zirconia surface and effects of the dust particles on the textured surface in a humid air ambient are investigated. Analytical tools are used to assess the morphological changes on the laser textured surface prior and after the dust settlement in the humid air ambient. It is found that laser textured surface has hydrophobic characteristics. The mud formed during condensate of water on the dust particles alters the characteristics of the laser textured surface. The tangential force required to remove the dry mud from the textured surface remains high; in which case, the dried liquid solution at the mud-textured surface interface is responsible for the strong adhesion of the dry mud on the textured surface. The textured surface becomes hydrophilic after the dry mud was removed from the surface by a desalinated water jet.

1. Introduction

Solar energy harvesting has a crucial role for widening renewable energy applications around the Globe. Utilization of high temperature resistant ceramic components becomes unavoidable for solar thermal applications. Zirconium nitride can serve as a selective surface for solar energy harvesting in thermal systems, which is because of excellent optical properties in terms of absorption and emission [1]. On the other hand, climate change has imitated dust storms around the Middle East [2]. The dust settlement on solar energy harvesting surfaces lowers device performance in terms of output power and efficiency [3]. The environmental dust particles compose of various elements and compounds including alkaline and alkaline earth metals [4]. In humid air ambient, water condensates on the dust particles and some compounds of the dust particles dissolve into water condensate. This forms a chemically active liquid solution, which accumulates at the interface of the device surface and the dust particles under the gravity [4]. The chemically active liquid solution causes some asperities on the device surface, such as pin holes and pit sites, while causing permeant damages [5]. In addition, once the liquid solution dries at the device surface, adhesion between the dried liquid and the surface becomes significantly strong and the efforts required removing the dried solution and the mud from the surface increase significantly. One of the solutions to create self-cleaning characteristics at the surface is to improve surface hydrophobicity. In general, surface hydrophobicity is associated with the micro/nano scale surface texture and low surface free energy. However, plane yttria-stabilized zirconia surface has high surface free energy and demonstrates hydrophilic characteristics. Consequently, altering characteristics of zirconia surface through surface processing becomes essential to generate surface hydrophobicity. Several methods have been suggested and many techniques were reported for generating hydrophobic characteristics at the surfaces [6–11]. The techniques reported were involved with multi-steps processes and harsh conditions. Some of these processes include phase separation [6], electrochemical deposition [7], plasma treatment [8], sol-gel processing [9], electrospinning [10], and solution immersion [11]. Laser gas assisted texturing offers considerable advantages over the multi-step processes for hydrophobized surfaces, which is particularly true for ceramic surfaces [12]. Some of these advantages include high speed processing, the precision

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of operation, and low cost. In laser texturing process, a combination of melting and evaporation of ceramic surface takes place via ablation [12,13]. This in turn generates surface texture consisting of micro/nano poles and cavities. The use of high pressure assisting gas, such as nitrogen, generates nitride compounds on the laser textured surface [12]; in which case, nitride compounds have low surface energy than the oxides [12]. In addition, arrays of micro/nano size pole/pillar improve the water repelling capacity of the laser textured surface. However, dust settlement on the laser textured surface changes the surface characteristics such as surface hydrophobicity. Hence, investigation of environmental dust particle adhesion and influence of dried mud solution on the characteristics of laser textured zirconia surface becomes essential.

Considerable research studies were carried out to examine laser processing of zirconia tiles. Laser micromachining of yttria-tetragonal zirconia polycrystal ceramic was carried out by Li et al. [14]. They demonstrated that crack and asperity free machined surfaces were possible under the precise control of laser treatment parameters. Laser short-pulse processing of yttria-stabilized tetragonal zirconia surfaces was carried out by Oyane et al. [15]. They indicated that submicro-/micro-structures on the zirconia surface were obtained after laser ablation and laser treated surface showed increased water wettability. A parametric study of laser surface patterning of zirconia was carried out by Roitero et al. [16]. They showed that increasing both fluence and number of pulses resulted in deep texture patterns at the surface. However, increasing number of pulses had a detrimental effect on the quality of the textured surfaces; in which case, surface damage, such as intergranular cracking, open porosity and nano-droplets formation, could be generated after the laser treatment process. Laser surface treatment of zirconia and the corrosion resistance of the resulting surface were studied by Ahmadi-Pidani et al. [17]. The findings revealed that the corrosion resistance of zirconia was enhanced more than twofold by laser surface glazing due to reducing the specific reactive area of the dense glazed surface layer and, consequently, decreasing the reaction between molten salt and zirconia stabilizers. The selective laser melting of yttria-stabilized zirconia ceramic was investigated by Liu et al. [18]. They showed that high-temperature preheating in 10 mm diameter range was possible with the Nd-YAG laser, and that orderly cracks were transformed into disordered little cracks by the high-temperature preheating.

On the other hand, zirconia is used in dentistry because of its durability and biocompatibility. Bacterial adhesion and growth are critically important in dental implants, which are associated with the surface characteristics such as texture and surface energy. Low surface free energy reduces the interfacial bonding between the surface and adhering particles. Considerable research studies were carried out to examine surface characteristics of zirconia for the improvement of surface resistance towards the bacterial adhesion. The correlation between the surface roughness and bacterial adhesion of zirconia-porcelain veneer were examined by Kang et al. [19]. They demonstrated that a positive correlation between surface roughness and bacterial adhesion was found in glazed porcelain surface while a negative correlation was observed in zirconia surface of Cerapol group. In addition, surface roughness and bacteria adhesion were significantly influenced by the polishing method and surface material. A study on the direct silanization of zirconia for increased bio-integration was carried out by Caravaca et al. [20]. They introduced 3-aminopropyldimethylethoxy silane (APDMES) directly on the surface of zirconia (3Y-TZP) and used a plasma of oxygen to clean the surface promoting hydroxylation of the surface and increasing silane density. Treated surface displayed a qualitatively higher spreading rate in opposition to the untreated zirconia surface. Surface treatment of zirconia towards achieving improved biocompatibility was studied by Hsu et al. [21]. They indicated that the hydrothermal treatment of the surface resulted in phase transition from tetragonal phase to monoclinic phase and proliferation and cellular activities on the treated surface were enhanced considerably. The wetting analysis and surface characterization of flax fibers modified zirconia by sol-gel method were carried out by Boulos et al. [22]. They engineered the surface chemically while forming a modified zirconia film, which improved the surface hydrophobicity.

Although laser surface texturing of ceramic surface was investigated earlier [13], the study was focused on the surface characteristics of zirconia, and dust and dry mud effects on the surfaces of zirconia were left for the future study. In addition, when the ceramic surface, such as zirconia, exposed to the outdoor environment, surface characteristics are modified by dust settlement and mud formed in the humid air ambient. Consequently, in the present study, laser processing of zirconia surface and influence of environmental dust and mud on the properties of surface is investigated. In laser surface texturing, high pressure nitrogen gas is used. Morphological and metallurgical changes in the laser textured layer are analyzed incorporating the analytical tools, which include scanning electron microscope, energy dispersive spectroscopy, and X-ray diffraction. The micro-tribometer is used to assess the surface scratch resistance and friction coefficient. Surface hydrophobic characteristics are evaluated through water contact angle measurements. Environmental dust settlement and mud formation on the laser treated surface is realized while mimicking the outdoor environment. Dry mud adhesion on the laser textured surface is measured and after effects of dry mud removal from the surface is analyzed.

2. Experimental

A CO_2 laser (LC-ALPHAIII) with a nominal output power of 2 kW was incorporated for laser texturing of workpiece surfaces. A focusing lens of 127 mm focal length was used during laser processing, which provided the irradiated spot diameter of about 0.2 mm at the workpiece surface. High pressure nitrogen gas is used as the assisting gas during laser texturing. The laser melting parameters are given in Table 1.

Zirconia wafers of 25 mm × 1 mm × 3 mm were used as workpieces. JEOL JDX- 3530 scanning electron microscope (SEM) was used for the morphological examination of the laser textured zirconia surface. Bruker D8 Advance XRD, having Cu Kα radiation, was utilized to assess the compounds formed on the laser textured surface. 3-dimensional image and line scan of the surface was obtained through atomic-force microscope (AFM/SPM), by Agilent, in a contact mode. The atomic force microscope (AFM) was used to examine the surface texture of the zirconia samples. The AFM probe tip had a manufacturer specified force constant $k = 0.12$ N/m and it was made of silicon nitride with the tip radius of $r = 20–60$ nm.

Kyowa (model - DM 501) goniometer was used for the contact angle measurements of workpiece surfaces. The dispensing system was utilized to control the droplet volume with 0.1 μL steps. The water droplet contact angle measurements were repeated three times at different locations of the workpiece surfaces. It is estimated that the measurement errors are in the order of 5%. The free surface energy of the laser textured surface is determined from liquid droplet method [23–27] and water, Glycerol, and Diiodomethane are used in this regard. The surface free energy determined is in the order of 49.33 mJ/m^2, which is slightly less than that presented in the early study (52.6 mJ/m^2) for ZrN [28].

Since water condenses onto the dust particles in humid air ambient, experiments were conducted to investigate the formation of mud from the dust particles on the laser textured zirconia sur-