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Surface texturing method and roughness effect on the substrate performance: A short review

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KEYWORDS

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ABSTRACT

Surface texture is one of interest to researchers as alterations surface roughness along with wettability are key factors towards properties enhancement of a material that would be beneficial for many industrial applications. This paper reviews published works on surfaces that had been roughened to various degrees, as well as techniques that had been utilised during the preparation of surface texture. The role of roughness in determining the static / dynamic wetting of the micro textural surface was discussed, how different shape and size parameters were used to fabricate the textural surface were examine, and how particular progress on some features on surface texture effect the wettability and roughness of the surface. Superhydrophobic surfaces have been considered for various industrial application due to the properties such as low adhesion and friction, as well as their extreme water-repellent properties. As interest in this field grow, there are a greater number of techniques and parameters used were reported for fabricating surface texture that result in surface roughness and wettability.

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1.0 INTRODUCTION

The development of new materials with properties such as excellent adhesion and wettability, low friction, and high surface to volume ratio are required to meet the requirements stipulated for the advancement of nanotechnology, such as micro/nanoelectro mechanicals systems (MEMS/NEMS). In interconnect applications, sandpapering or surface peening technology was used during soldering and brazing to produce the desired surface conditions, however, it was challenging to obtain uniform microstructures on the substrate's surface by using this method (Chen et al., 2000). Currently, researchers utilize a myriad of methods to produce surface texture, such as laser surface texturing (Wahab & Ghazali, 2009; Bathe et al., 2014; Chunha et al., 2016; Samanta et al., 2020), lithography (Imran et al., 2017; Balma et al., 2011), chemical etching, ion beam texturing and mechanical machining. Textured surface has always been interrelated with wettability properties (Bhaduri et al., 2011; Gao et al., 2020) the latter of which can be determined using the water contact angle measurement. The contact angle can be divided into two parts: static and dynamic contact angle. The static contact angle is the angle between the surface and a water droplet, which characterizes wetting (Mchale et al., 2004; Cheng et al., 2020; Shiomi et al., 2014). When the value of the contact angle (Bathe et al., 2014; Cunha et al., 2016) is less than 90° (Sung et al., 2015), then the surface is considered hydrophilic (Wen et al., 2015; Trdan et al., 2017; Dong-Geun et al., 2016) and if it is while greater than 90°, the surface is considered hydrophobic (Wan et al., 2015; De et al., 2016). Superhydrophobicity (Mohamed et al., 2015; Zhang et al., 2015; Bhushan et al., 2006) is when the contact angle is between 150° (Jung & Bhushan, 2006) and 180° (Imran et al., 2017). Surface texturing can be divided into two types; positive, where it protrudes out of the surface and is extensively used in MEMS, and negative which is prevalent in automotive components and machining tools. Both types of surface texture dictate the hydrophobicity and hydrophilicity of their respective surfaces. The contact angle measurement, done using the sessile drop, shows that hydrophobic surfaces are governed by the Cassie-Baxter equation while hydrophilic surfaces are governed by the Wenzel equations (Jung & Bhushan, 2006). In the Wenzel model, the surface roughness, r, is defined as the ratio of actual area to the projected area on surface, and written per equation (1) , while in the case of the Cassie-Baxter equation, f_1 and f_2 are the fraction of solid and air under a drop on the substrate, respectively, and is written as per equation (2) (Jung & Bhushan, 2006) .

$$\cos\theta^* = r \cdot \cos\theta_y \tag{1}$$

$$\cos\theta^* = f_1 \cdot \cos\theta_y - f_2 \tag{2}$$

From Young's equation on an ideal solid without roughness, θ^* is the apparent contact angle and θ_y is the equilibrium contact angle. In Young's equation the interactions of liquid and solid in the three-phase line and the wetting behaviour of droplets on surface is represented by [23]:

$$\gamma_{sv} - \gamma_{sl} = \gamma_{lv}\cos\theta \tag{3}$$

where γ_{sv} , γ_{sl} and γ_{lv} are the surface tensions of solid-vapor, solid-liquid and liquid-vapor contacts respectively. This Young's equation quantifies the equilibrium contact angle of the interfacial at three-phase contact line (Jung & Bhushan, 2006).

2.0 TECHNIQUES FOR SURFACE TEXTURE FABRICATION

Surface texture is formed using machining and chemical processes. It greatly influences the subsequent components' mechanical properties, including friction coefficient, lubrication, and wear condition (Sun et al., 2017). Tribology and wear are major challenges faced by the manufacturing industry. These problems can be addressed using surface modification, where it controls the frictional performance of the materials via manipulation of the surface texture. Demand for surface texturing fabrication increasing, especially at the micro and nano scales. Surface texture plays a fundamental role in the development of many engineering applications, such as energy, biomedical, optic, mechanical processing, and microelectronic industry (Qu et al., 2015). Surface texturing is a material manufacturing process that is used to fabricate specific micro-grooves, micro-dimples and micro-convex arrays on a substrate's surface (Kuroiwa et al., 2013). It is regarded as an effective and widely used method that can modify the interactions between surfaces to better lubricate, control friction and enhance the wear resistance of materials (Mao et al., 2020).

Various surface texturing techniques have been developed such as diamond cutting, laser surface machining, lithography, electro-chemical machining, ion beam etching, hot embossing, and micro-milling (Zhang et al., 2019). However, laser surface processing has received extensive attention due to its unique advantages, such as fast, efficient, controllability, and the ability to manufacture highly complex surface textures. However, the high temperature generated by the laser scanning process could oxidize the metal's causing the molten metal to deposit around the irradiated dimple texture (Zhang et al., 2019). This would also transform the metal phase steel from austenite to martensite, which increases the hardness of the metal oxides to levels exceeding their base counterparts.

Etsion, (2015) stated that micro-dimples on the surface of mechanical seals can be used to reduce friction and improve wear resistance (Mao et al., 2020). Thus, the laser surface texturing (LST) method has been used to fabricate the dimple texture because the LST method have advantages such as fast processing, high efficiency, control ability, and able to produce highly precise and accurate surface textures (Singh & Harimkar, 2012). When the laser surface texturing process create the laser ablation mechanism which is irradiating laser beam to removing the materials from the solid surface. The interaction between the laser beam and the substrates resulted in the absorption of laser energy that evaporates the surface materials, dispelling the localized materials and allowing for specific texture patterns and designs to be obtained.

Photolithography also called optical lithography is a conventional lithography technique relative to other high functionality lithography instruments such as immersion lithography, electron-beam lithography, laser beam machining, focused ion beam lithography, X-ray lithography, and near-field scanning optical microscope lithography (Won & Kim, 2019). The photolithography texturing method transfers the texture pattern onto the substrate's surface with the aid of UV light. This renders the photolithography texturing process simpler, efficient, reliabile, and least expensive compare with other lithography method which provide a high precision, high resolution, high dimension stability and but there is high processing cost, so these all method are not suitable for in large volume production.

Photolithography technique has been introduced among various lithography texturing method. The major application of the photolithography texturing technique is used to manufacture integrated circuit (IC) in semiconductor industries (Zhang et al., 2016). This technique has one more advantage over LST; is does not require high temperature environment and is only reliant on chemical liquid such as photoresist, developer, etchant, and UV light. A typical photolithography texturing process involves of several steps for device manufacturing, from layers grown on a substrate, which involves pre-cleaning the substrate surface layer, heating to dried off the moisture from the surface, applying the photoresist via spin coating, expose the photoresist by texture pattern of intense light to induce a the chemical reaction that allows some of the photoresist to be removed using photographic developer, followed by etching, and finally, stripping (Zhu et al., 2020).

3.0 ENHANCEMENT OF SURFACE PERFORMANCE BY SURFACE TEXTURING

Surface texturing, via improvement in technology, can now be used to enhance materials performance. In certain applications such as practical engineering applications, surface roughness and excellent wettability are needed to mitigate potential problems. Chen et al., (2016) investigated the enhancement of solder wetting behaviour via laser-textured surface microcosmic topography. Copper (Cu) plate with purity of 99.9 wt% was used as the substrate material and a 0.6 mm 96.5Sn-3.0Ag-0.5Cu (wt.%) was used as the solder alloy. A femtosecond laser machining was used to fabricate the surface microtexture on the Cu substrate. The results showed that surface texturing using laser technology helps improve surface wettability (Zhou et al., 2016). The result for the wetting angle of the textured Cu substrate decreased from 58.2˚ to 26.3˚ relative to its smooth surface counterpart (Chen et al., 2016).

Jung and Bhushan, (2006) analysed the contact angle, adhesion, and the friction properties of micro and nano patterned polymethyl methacrylate (PMMA) and polystyrene (PS) for for superhydrophobicity applications. They implemented the biomimetic of a lotus plant nature to create the micro and nanostructure patterns (Chen et al., 2013). Soft lithography was used to fabricate the biomimetic pattern. The findings revealed that the microstructure on a surface can produce a higher roughness factor relative to the nanostructured patterns on PMMA and PS, and a combination of microstructures and nanostructures were needed to produce superhydrophobic effect (Burton & Bhushan, 2006 ; Wen et al., 2014). The results also led them to conclude that increasing surface roughness on a hydrophilic surface reduces the contact angle while increasing roughness on a hydrophobic surface increases the contact angle.

Another study on fabrication of superhydrophobic surface with nano-in-microstructures using UV-nanoimprint lithography and thermal shrinkage was conducted by Sung et al., (2015). The bare thermal shrinkage films (TSF) were used as the substrate material, while UV nano imprint lithography (NIL) was used to fabricate surface pattern. The LPMA64, which is an organic-inorganic hybrid material and highly heat resistant was used to prevent thermal shrinkages process of polymers during UV-curing process. From the results, the static contact angles of bare TSF were within the range of 93.6˚ - 96˚, while in the case of the nano-patterned pillar structure, the contact angle increased by 40˚, resulting in a contact angle of 135.6˚. This increase can be contributed to the formation of Cassie-Baxter state on the surface of substrate (Sung et al., 2015).

Mishra et al., (2020) studied the friction and wear behaviour of laser textured surface of WC/Co using the open tribology test. Nanosecond laser was utilised to produce microhole texture on WC/Co pin surface and the textured surface was then coated with monolayers AlCrN and AlTiN using the PVD coating technique. The sample was then subjected to open pin tribo tester with two conditions of loading, speed and sliding duration. The results showed that under severe tribological conditions, the coefficient of friction was reduced for textured coated surface at low and high load conditions, where a maximum reduction of 27% has been achieved under the high load of AlCrN textured coated surfaces. It can be concluded that the textured surfaces are capable to reduce the friction coefficient under both conditions of low and high loadings. In the case of wear mechanism and wear analyses, the wear morphologies of the textured and untextured surfaces were imaged using an SEM. It can be seen from the SEM micrographs that the transverse crack and unstable growth of transfer layers were present on the untextured surfaces, while this phenomenon was absent in both the coated and uncoated textured surfaces. The textured coated surfaces also do not suffer from the severe adhesion or periodic ridge formation on its surface. It was surmised that the textured coated surfaces are effective in decreasing the adhesion and the subsequent growth of the adhered layers (Yang et al., 2019).

Common patterns were fabricated using laser surface texturing by Lu et al., (2018) to determine the effect of these patterns on friction and wear properties of chromium (Cr) alloy. Three patterns were fabricated on the sample's surface which are micro dimples, micro-grooves and micro-grids to analyse and compare the influence of texturing on tribological behaviours. The analysis and characterisation of friction and wear were conducted on the topography and the wear track of the sample. This study confirmed that the wear rate of the textured specimen was reduced relative to its untextured counterpart. The wear rate of the micro-dimples, micro-grooves, and micro-grids specimen ware reduced by 18%, 37%, and 57%, respectively. In the case of the friction coefficient, the laser textured surfaces had a lower friction coefficient compared to the untextured specimen, and it can be concluded that the friction coefficient of laser textured surface initially decreased than increased with decreasing texture density. Thus, the wear resistance was enhanced by the reduction of friction coefficient (Niketh & Samuel, 2007).

Bhushan and Jung, (2006) characterised the micro and nanoscale hydrophobic and hydrophilic leaf surfaces. They used two were using two different types of hydrophobic leaves, which were lotus and colocasia, and two hydrophilic leaves, which are fagus and magnolia. Acetone were applied on the surface of the leaves to remove the wax layer present on the surface and they also pointed out that wax is not present on the hydrophilic leaves surface while hydrophobic leaves do have a thin layer of wax. When the hydrophobic leaves are combined with roughness (microtextures), they create a superhydrophobic surface. On a hydrophobic surface, the increment of its contact angle contributed by the roughness factor of the nanobumps, which are higher than microbumps and formation of air pockets increase with decreasing the spaces between bumps on the nanobumps. The increment of the contact angle hysteresis can be represented using the Cassie-Baxter equation (Bhushan and Jung, 2006)

Chen et al., (2014) used four different groove widths starting from 10 μm, 20 μm, 30 μm and 40 μm on copper plate of 99.9 wt.% of purity and a dimension of 10 mm x 10 mm x 2mm. After considering the reaction layer thickness of the laser interaction and the precision of laser processing, they concluded that the optimal size of a surface microstructure was a = 40 μm, b = 20 μm, and h = 20 μm on copper plate reffered to the morphologies of surface microstructure.

Ahuir et al., (2017) studies the surface texturing of aluminium alloy AA24-T3 using a picosecond laser. The effect of surface texture on the wettability and corrosion properties were determined using three different types of texture patterns which were dimples with two area densities of 5% and 50, 64% area density of cross groove pattern and 70% area density of concentric ring pattern (Ahuir et al., 2017). They concluded that in the case of the un-textured surface, surfaces with dimple densities of 5% and 50% are hydrophilic nature based on their contact angles measurement (Wang & Bai, 2015) of 65° and 75° respectively, while the crossed grooves with 64% and concentric rings 70% reported contact angles value close to 100° which changes the behaviour from hydrophilic to hydrophobic. From this study, the parameters outlines can be used as a reference for obtaining specific surface properties, such as hydrophobic or hydrophilic behaviours.

Zhan and Yang, (2014) analysed the effects of the dimple distribution angle on the tribology performance of a LST cylinder piston ring system. In this study, the material of the cylinder liner piston ring was not changed and the parameters of laser processing were kept constant, therefore, the dimples' diameter value of 100 μm was fixed and its depth of the dimple also fixed at 10 μm. The cylinder piston ring reciprocating test were set up with an ultimate load of 13.72 MPa, a maximum speed of 960 rpm, an effective sliding distance of 160 mm per revolution, an adding oil speed of 1 drop/s, and the cylindrical wall temperature of 140 ˚C. The test was conducted to determine the friction and wear characteristics of the friction system after laser texturing of the cylinder wall (Zhan and Yang, 2014). Five dimple distribution angles were used in this study starting from 0˚, 15˚, 30˚, 45˚ and 60˚. It was determined that 45˚ distribution angle of laser-textured dimple is the best wear characteristics for cylinder piston ring. They also confirmed that the wear characteristics of the textured cylinder liner-piston ring are invincibly related to the distribution angle of the laser-textured dimple and cylinder linear wear can be reduced by 78.6% using laser texture compared to non-laser processing (Zhan and Yang, 2014).

Liew et al., (2016) used aluminium alloy 7075 with a dimension of 11 x 11 x 20 mm 3 as a specimen to investigate the effect of EDM dimple geometry on friction reduction under boundary and mixed lubrication conditions. Three geometries with 10.4% uniform area density were designed. Round, diamond, and ellipse geometries were fabricated in this study and set out in a square array of four rows and four columns on the surface of each pin. The depth of each dimple is about 10 μm. All of the specimens with different geometries were tested against a rotating high-speed steel counter-disc using a pin on disc apparatus under mixed lubrication conditions. This study concluded that despite of the geometry types, the EDM dimpled surface reported reduced coefficient of friction, but the lowest friction coefficient results by the round dimples geometries, followed by diamond geometries and finally ellipse geometries. The round dimple geometry resulted in minimum wear relative to other geometries and un-textured surfaces. The hydrodynamic lift also took place over the agglomerations of the wear debris during wear, which giving arise to hydrodynamic lift force on the dimpled surfaces (Liew et al., 2016).

Milles et al., (2020) studied the fabricated aluminium surfaces using direct laser writing and direct laser interference patterning in the contact of the textured surface's self-cleaning properties. In this study, aluminum clad (Al 2024), which have the properties of high strength, stiffness, and fatigue performance was selected as the substrate materials. Al 2024 with the dimensions of 50 mm × 50 mm × 2 mm has a surface roughness of 43.5 nm ± 10 nm (Milles et al., 2020). Two laser structuring technologies were implemented to structure the micrometre-size pattern geometry on the surface of Al sample. The DLW laser technology was used to produce a mesh-like structure, DLIP was used to fabricate a pillar-like structure and combination of both laser technologies was used to form a hierarchical pattern on the surface of the Al. Manganese oxide with a particle size of 1 μm and polyamide particle sizes of 100 μm were used to contaminate the surface of samples. Dynamic self-cleaning characterisation and quantitative evaluation of self-cleaning properties were tested on the Al samples using different types of micrometre-size pattern geometry. Dynamic self-cleaning characterisation were conducted after 42 days of laser treatment, where the sample were tilted at two inclined angles of 15° and 30°, and 10 μl droplets were rolled over the surface of the textured area to drag the contamination particles away. Quantitative evaluation of self-cleaning properties was conducted by taking the measurements of the amount of particles left after each of the droplet has rolled off the surface inclined at a 30° angle, and the sample were tilted by 15° or 30° and 9 droplets were dropped over the textured Al substrate. This study concluded that DLIP and a combination of both DLW and DLIP structure resulted in the highest efficiencies of self-cleaning when used on the 100 µm particle size of MnO and polyamide as the contaminant, while in the case of particle size of 1 µm MnO, the DLIP structure resulted in the best performance, where the small particles size would not get stuck within the pattern of the DLIP. Self-cleaning behaviour seemed uninfluenced by the tilting angle of the Al substrate in this study (Milles et al., 2020).

Referring to the studies that have been conducted and reported by previous researchers, surface modification via the introduction of the surface texture on the surface of a materials can enhance the properties of a surface according to the final application of the sample as shown in Figure 1. In terms of friction and wear, when comparing of textured and non-textured surfaces, textured surface samples usually have lower coefficient of friction compared to the un-textured sample. This is due to the present of textures on the surface of materials trapping wear debris and reducing the friction due to the present of texture on the sample. Hydrophobic and hydrophilic properties of the sample can also be improved by introducing surface texture on the surface of the sample. Depending on final application of the sample, both Cassie-Baxter and Wenzel equations have their own benefits; applications that requires hydrophobicity properties can be achieved via the application of Cassie-Baxter equation, while hydrophilicity surface may govern by Wenzel equations. In terms of corrosion protection, introducing surface texture on a substrate can result in a superhydrophobic surface, which improves the corrosion resistance of the substrate. Texture also help reduce the contact between surfaces, resulting in the substrate with better corrosion resistance.

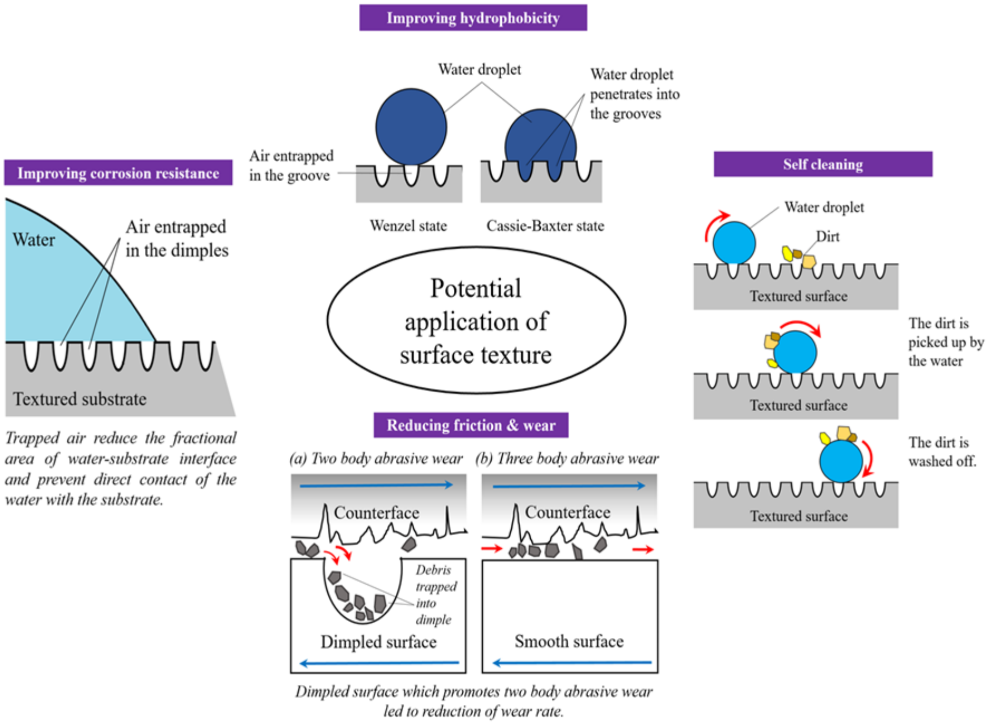

Figure 1: Info graphic of potential application of surface texture.

4.0 CONCLUSION

There are various methods that can be used for surface texturing to affect the desired properties for the substrate materials depending on its various application. Different parameters used for the surface modifications will also result in substrate with different properties. Thus, the parameters used during the modification need to be adjusted to a certain degree to fit the requirement of the application for the substrate. From the abovementioned studies, it can be concluded that there are various methods that can be used to fabricate micro or nano surface textures for multiple substrate materials. Textured surface has also been shows to enhance the surface properties of the materials in the context of applications the requiring hydrophobic surfaces and roughness.

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