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An Investigation of Surface Texturing by Ultrasonic Impingement of Micro-Particles

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Abstract—Surface topography plays a significant role in the functional performance of engineered parts. It is important to have a control on the surface geometry and understanding on the surface details to get the desired performance. Hence, in the current research contribution, a non-contact micro-texturing technique has been explored and developed. The technique involves ultrasonic excitation of a tool as a prime source of surface texturing for aluminum alloy workpieces. The specimen surface is polished first and is then immersed in a liquid bath containing 10% weight concentration of Ti6Al4V grade 5 spherical powders. A submerged slurry jet is used to recirculate the spherical powders under the ultrasonic horn which is excited at an ultrasonic frequency and amplitude of 40 kHz and 70 µm respectively. The distance between the horn and workpiece surface was remained fixed at 200 µm using a precision control stage. Texturing effects were investigated for different process timings of 1, 3 and 5 s. Thereafter, the specimens were cleaned in an ultrasonic bath for 5 mins to remove loose debris on the surface. The developed surfaces are characterized by optical and contact surface profiler. The optical microscopic images show a texture of circular spots on the workpiece surface indented by titanium spherical balls. Waviness patterns obtained from contact surface profiler supports the texturing effect produced from the proposed technique. Furthermore, water droplet tests were performed to show the efficacy of the proposed technique to develop hydrophilic surfaces and to quantify the texturing effect produced.

Keywords**—**Surface texturing, surface modification, topography, ultrasonic.

I. INTRODUCTION

THE art of surface texturing for modifying the surface properties of metals and non-metals has become an area of interest in the recent years. Surface texturing is the process of modifying the surface to alter its surface properties such as wettability, surface tension, friction, wear and tribological properties [1]. The textured surfaces as a whole are referred to as functional surfaces. Many different techniques are available to produce surface textures in the range of nanometer to millimeter scale. As a result of texturing, many new surface properties can be exploited and used for a variety of applications.

The most common techniques used for surface texturing can be categorized into the following divisions (a) Addition methods, (b) Removal methods, (c) Forming methods and (d) Non-contact methods.

Some of the common methods adopted to alter the tribological properties of metals are by surface coating processes. Addition methods mainly employ chemicals to be coated on the specimen surface. The target surface is coated with a hydrophilic or hydrophobic coating to alter the wettability properties. An investigation on friction and wetting effects by coating DLC (Diamond like carbon) on various patterns and textured resulted in spalling off of coating upon lubricating the surface unless the texture had perpendicular grooves [2]. Electrodeposition of silver halide-based photographic films was done to create microstructures suitable for microfluidic applications [3]. Other texturing methods by adding materials include catalytic plating [3], precipitation coating [4], precursor deposition [5], patterned curing [6], chemical printing [7] and coating of Nano and micro particles [8]. The major drawback of these methods is that the produced textures are not permanent and may get deteriorated upon usage.

To overcome the drawbacks, permanent textures were created by material removal techniques such as laser texturing [9], laser honing [10], electric discharge texturing [11], masking methods [12] and patterned erosion by sand blasting [13] etc. However, the uniformity and regularity in the geometry of the texture created by material removal techniques is difficult to control. Due to the irregularities in the texture, during lubrication and load bearing scenarios, the textures tend to get eroded and lose their performance on a longer run. Investigations on texturing effects using forming methods such as sand blasting [14], embossing techniques using patterned tools [2], vibro rollers [15] and molecular migration [16] showed promising results and were reliable on a longer run. This is due to the reason that there is no addition or removal of any material from the surface but purely due to plastic deformation and atomic dislocations.

Ultrasonic manufacturing methods such as ultrasonic turning [17], ultrasonic drilling of materials which have high hardness [18], ultrasonic grinding [19] and ultrasonic surface modification [20] are recently gaining more attention due to their high precision and accuracy in achieving desired results. Existing ultrasonic surface modification methods for improving the tribological behavior of materials involves excitation of a micro tipped ball by ultrasonic frequency. The tool embosses the pattern on the target surface upon touching and created a texturing effect. This technique leads to tool wear and is limited to the design of an ultrasonic tool for creating a dimple on the surface [21]. Non-contact ultrasonic surface finishing techniques employ the use of cavitation phenomenon to reduce the surface irregularities. Cavitation bubbles upon collapse exert high pressure and temperature on

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the solid surface, resulting in micro pitting on the surface. Cavitation on a solid surface with high initial roughness characteristics has the capability to reduce the irregularities and produce a smooth surface [22]. Therefore, in this investigation, an attempt is made to develop a texturing method using ultrasonic impingement of micro particles on the target surface. Aluminium 6061-T4 is selected as the target material for the texturing experiments. The target surface was textured using spherical titanium micro particles by ultrasonic excitation. Results are discussed based on the profile of the texture created and variation achieved in surface wettability properties.

II. EXPERIMENT METHODOLOGY

Ultrasonic texturing is performed on polycrystalline aluminium alloy 6061-T4 specimens. Specimens were initially cut using Excetek 850 wire cutting EDM machine. The wire cut EDM surface is then polished until a mirror surface is achieved. Mirror polishing was done to analyze the texture created on the surface. To determine the geometrical profile of the texture created, an optical microscope and contact profilometer were used. Surface wettability analysis using water droplet contact angle test was done before and after texturing to support the results obtained.

A. Experimental Set-Up

The set-up used for ultrasonic texturing is shown in Fig. 1. The setup consists of an ultrasonic generator (Dukane 4100 benchtop controller) of 40 kHz frequency with a horn at a vibrating amplitude of 70 µm. The ultrasonic horn with a tip diameter of 5 mm is made to vibrate using piezoelectric transducer. The specimen (aluminium alloy 6061-T4 with a diameter of 25 mm and thickness of 3 mm) is placed just beneath the horn. The working distance between the horn tip and the specimen surface was fixed at 200 µm for all test conditions using a precision control stage.

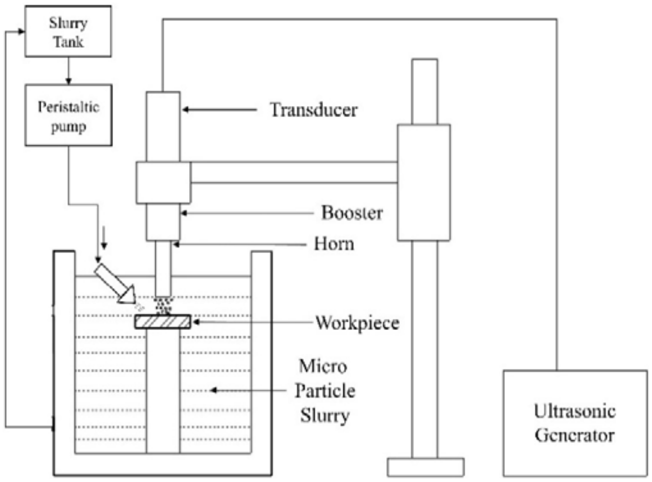

Fig. 1 Schematic drawing of experimental setup

Spherical powders were suspended inside the fluid medium. To maintain homogeneity in the mixture, a magnetic stirrer is used to stir the micro slurry. The insertion depth of horn from the slurry surface is fixed at 10 mm. A small nozzle injects the slurry from the stirrer bath under the horn surface. The fluid is continuously recirculated between the texturing bath and stirrer bath using a peristaltic pump.

B. Experiment Procedure

The polished specimens were ultrasonically cleaned for 5 minutes to remove surface debris. Surface topography of the specimens was then extracted using optical and confocal microscopes. Water droplet contact angle analysis was also performed to analyze the surface wettability. The specimens were then carefully placed under the horn surface. Texturing experiments were carried out as per experimental plan in Table I. The ultrasonic horn excitation was varied for 1, 3 and 5 seconds to create a texture on the specimen surface. Three repetitions were performed in each experimental run to check the consistency of texture created. After texturing, the surface topography of the textured area was analyzed under an optical microscope and water droplet contact angle measurements were performed using contact angle testing machine. The results are then compared, analyzed and discussed.

TABLE I
EXPERIMENTAL CONDITIONS

Experiment Parameters	Values
Frequency	40 kHz
Amplitude	70 µm
Working fluid	Spherical Ti-6Al-4V slurry
Temperature	25 °C
Working distance	200 µm
Workpiece	Aluminium alloy 6061-T4 (diameter=25 mm, thickness=3 mm)
Process time	1 s; 3 s; 5 s

III. RESULTS AND DISCUSSION

After experimentation, the specimens were then removed and cleaned with ethanol solution to remove any dust remnant present on the surface. The texturing results were analyzed using an optical microscopy and contact profiler. The effect of texturing on wettability properties was analyzed using water droplet contact angle measurements. Finally, the texturing profile was analyzed under a contact profilometer. Ultrasonic texturing mechanism, profile of the texture created and changes in tribological properties of the specimen are discussed below.

A. Ultrasonic Texturing Mechanism

Ultrasonic texturing is performed by exciting the micro titanium spheres using an ultrasonic horn. The time step of ultrasonic texturing is shown in Fig. 2. As ultrasonic frequency is applied, the horn vibrates at a certain amplitude and excites the micro titanium spheres. Due to this excitation, the spherical balls indent the elastic half-space below them (Fig. 2 (a)). The titanium spheres indent the surface (Fig. 2 (b)) at a very high force, leaving a texture (Fig. 2 (c) and Fig. 2 (d)) almost close to a hemispherical curvature in the range of

20-30 μm.

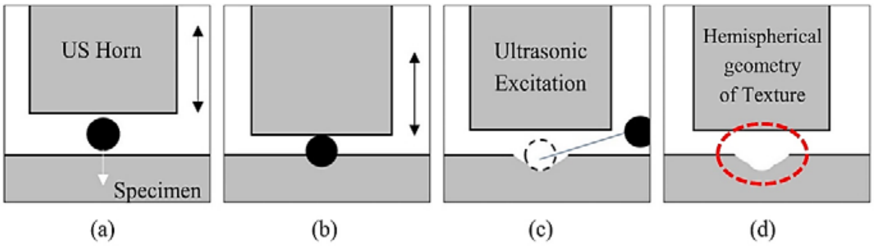

Fig. 2 (a) Excitation of ultrasonic horn, (b) Ultrasonic hammering on the specimen, (c) Micro particle escape from the surface and (d) Hemispherical texture left over by the micro particle

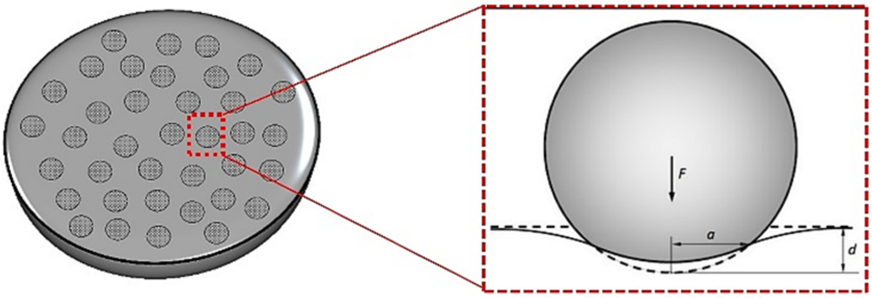

Fig. 3 Free body diagram of a single hemispherical texture

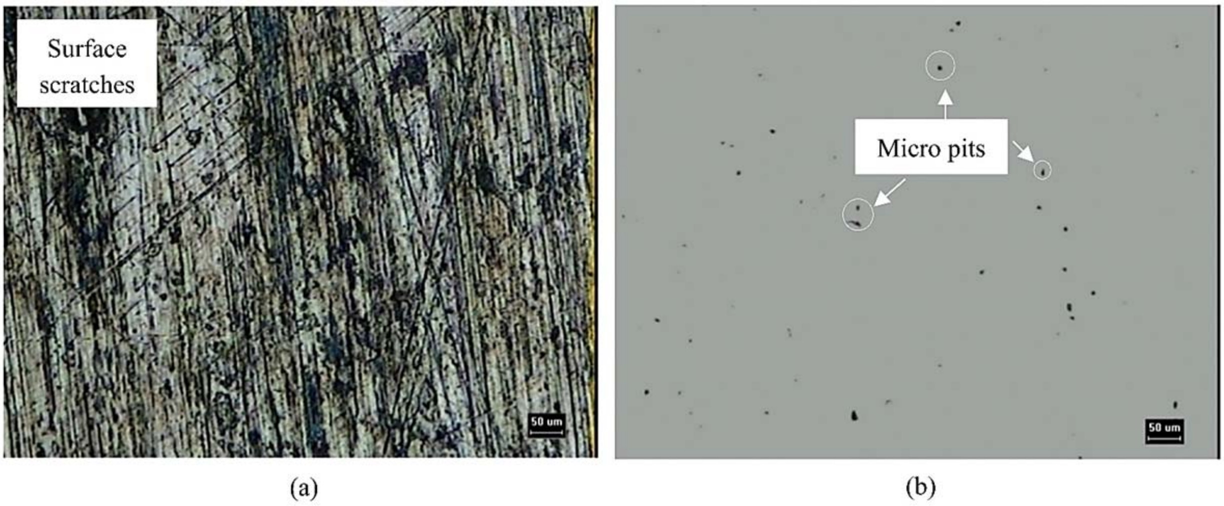

Fig. 4 (a) Optical microscope image of EDM cut surface and (b) Polished surface

The indentation created by micro titanium spheres is in relation to Hertz indentation theory as shown in Fig. 3. The relation between the radius of spherical titanium powders (*R*), the contact area of radius (*a*) and depth (*d*) of indentation produced on the surface is given by (1) [23]:

$$a = \sqrt{Rd} \tag{1}$$

Apart from ultrasonic excitation, the titanium spheres also get accelerated towards the surface due to microbubble generation. These micro bubbles are known as cavities generated in a fluid due to ultrasonic horn vibration. These bubbles, upon collapse, emit high pressure to its surroundings. This collapse pressure, in turn, accelerates the titanium spheres to indent the surface and produce a texturing effect. The relation between the force applied (*F*), Young's modulus (*E*), Poisson's ratio (*υ*) the radius of spherical titanium powders (*R*) and depth of indentation (*d*) is given by (2) [23]:

$$F = \frac{4ER^{1/2}d^{3/2}}{3(1-\upsilon^2)} \tag{2}$$

Thus, the force (*F*) represents the summation of forces acting on the titanium spheres due to ultrasonic excitation and bubble collapse. This force can be controlled by varying the amplitude of vibration depending on Young's modulus of the specimen.

B. Qualitative Analysis of Ultrasonic Texture

Optical microscope microscopic images of the specimens before texturing are shown in Fig. 4. After electric discharge machining, the specimen surface had many irregularities with scratches in random orientation as shown in Fig. 4 (a). The specimens were polished to make the surface homogenous as shown in Fig. 4 (b). Texturing experiments were carried out as per experimental plan in Table I. After texturing for 1 s, it is evident from the image shown in Fig. 5 that there is significant change in the surface topography. Impingement of micro particles created random hemispherical indentations on the surface. Increasing the process time to 3 and 5 s shows that the number of indentation created on the surface increases as in Figs. 6 and 7 respectively.

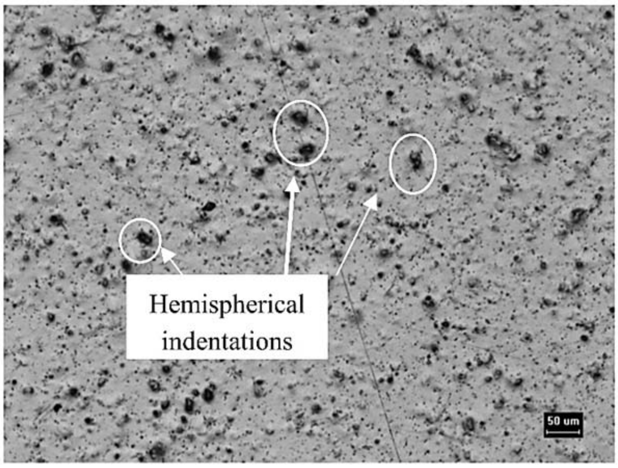

Fig. 5 Specimen surface after texturing for 1 s

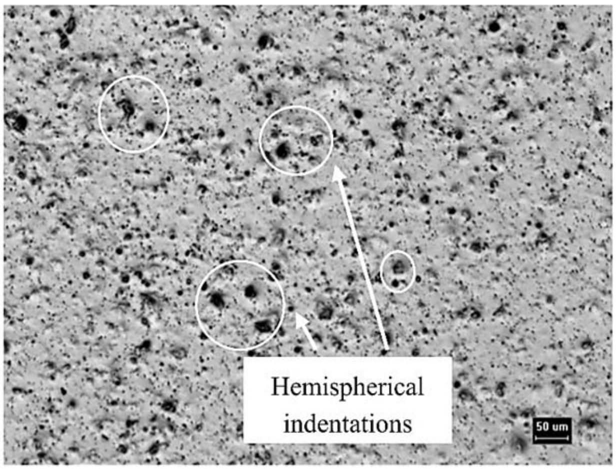

Fig. 6 Specimen surface after texturing for 3 s

A contact profilometer with a stylus of arm length 60 mm with a 2 µm diamond tip with 70° cone angle is used to scan the textured surface. The measurement data were filtered using a cut-off value of 0.025 mm to remove the high frequency roughness data. The resulting waviness patterns are shown in Figs. 8, 9 and 10, respectively.

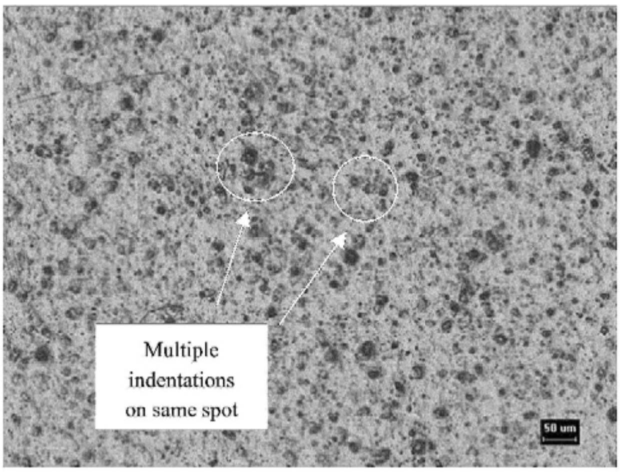

Fig. 7 Specimen surface after texturing for 5 s

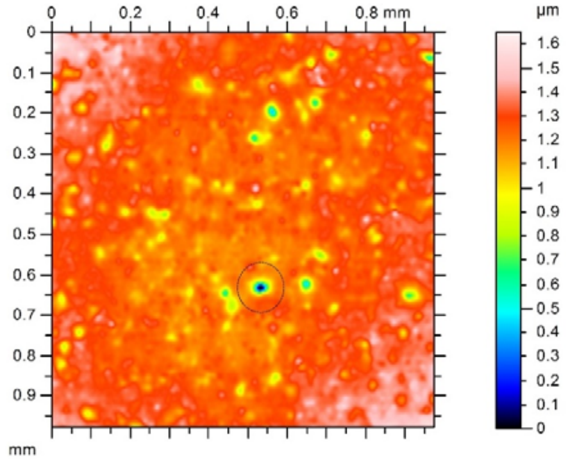

Fig. 8 Waviness pattern after texturing – 1 s

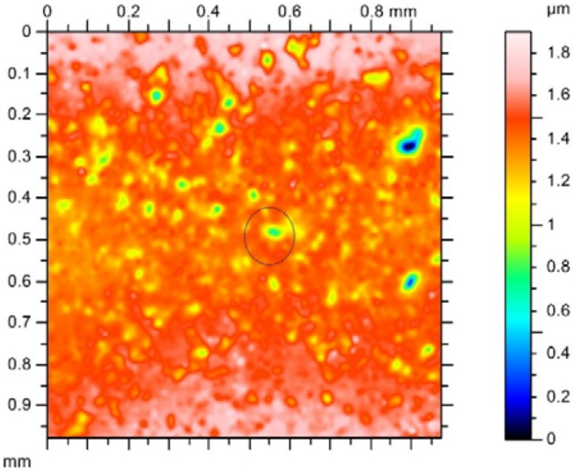

Fig. 9 Waviness pattern after texturing – 3 s

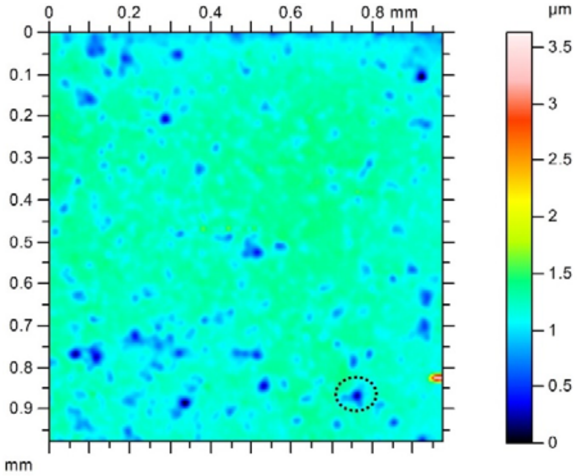

Fig. 10 Waviness pattern after texturing – 5 s

Profile data of a single indentation created are extracted from the waviness patterns. Therefore, this profile corresponds to the geometric outline of a single indentation and not the waviness in the indentation produced. Therefore, the geometric profiles developed after texturing for 1, 3 and 5 s are shown in Figs. 11, 12 and 13 respectively are found to correlate with the theory of Hertz contact indentation. Regular indentation profiles were created on the specimen surface. These profiles resulting from ultrasonic texturing alter the surface properties of the material. It can be noticed from Figs. 8-10 that the number of indentations has increased as the process time increases. Further increasing the process time resulted in multiple indentations at the same location (i.e., more than one indentation at a location). These multiple indentations on the same location created an irregularity in the hemispherical waviness profile of the texture generated. In addition, static contact angle (θ) measurements using Sessile drop technique was performed using an optical goniometer to determine the variation in surface wettability properties due to texturing. Contact angle is one of the common ways to measure the wettability of a surface or material. Wetting refers to the property of a fluid to spread out on a solid surface or the ability of liquids to form boundary surfaces with solid states.

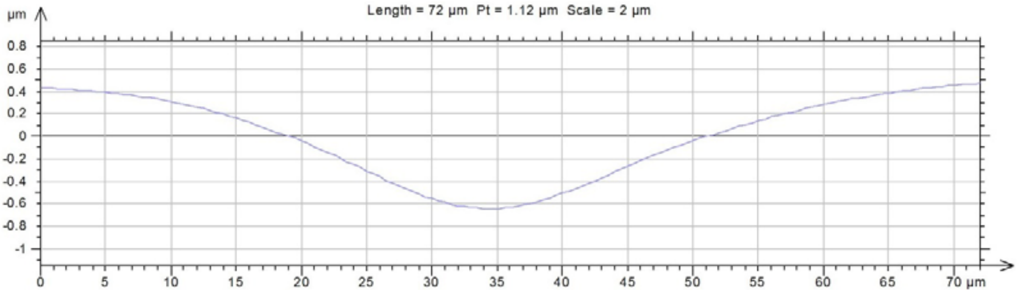

Fig. 11 Profile of single indentation – Texturing 1 s

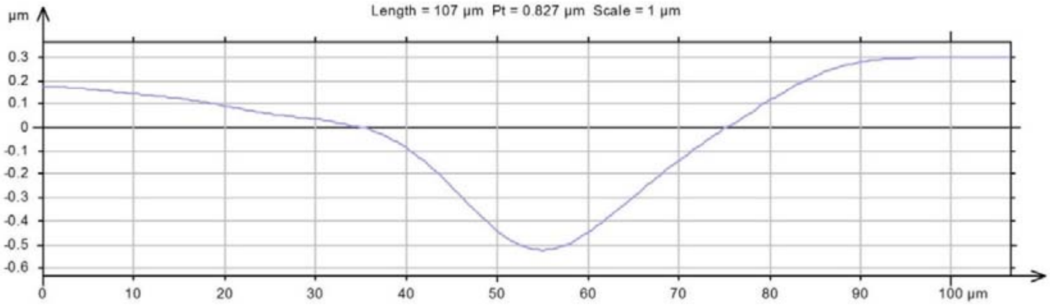

Fig. 12 Profile of single indentation – Texturing 3 s

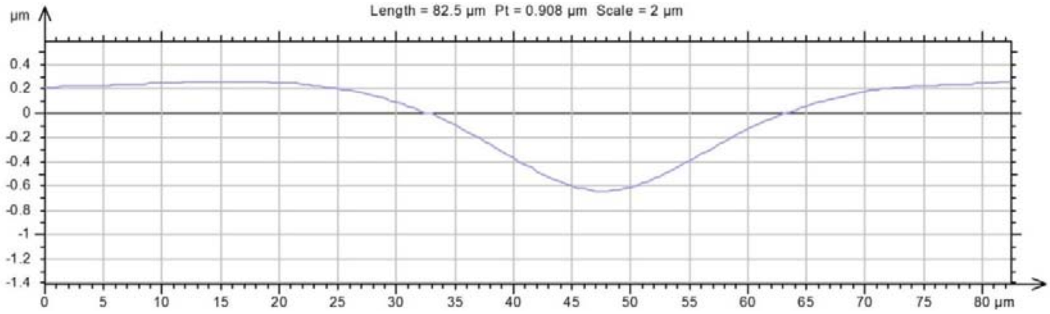

Fig. 13 Profile of single indentation – Texturing 5 s

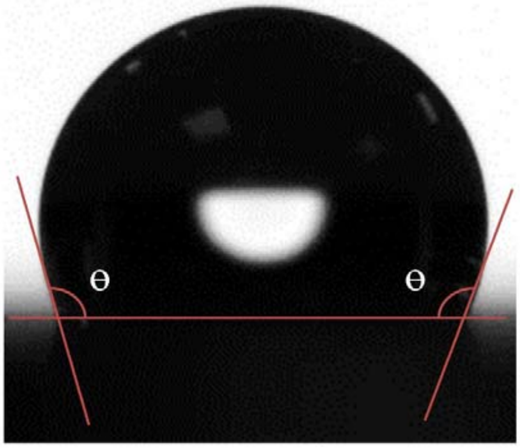

Fig. 14 Contact angle of EDM cut Aluminium 6061 T4 surface; ɵ left = 113.0°, ɵ right = 113.0°

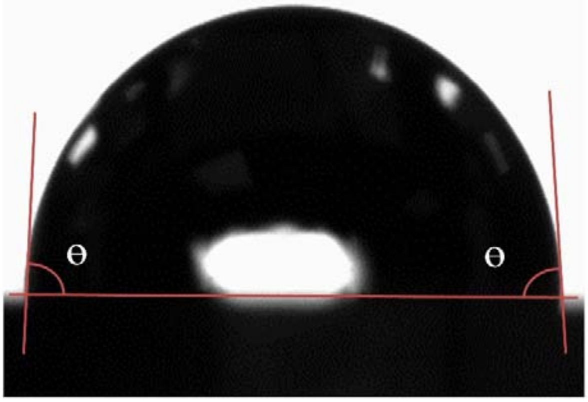

Fig. 15 Contact angle of polished surface

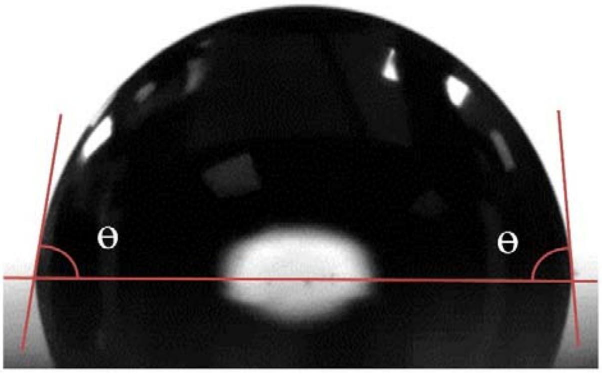

Fig. 16 Contact angle of textured surface: ɵ left = 90.8°, ɵ right = 91.1°

More specifically, a contact angle less than 90° indicates that wetting of the surface is favorable, and the fluid will spread over a large area on the surface; while contact angles greater than 90° generally mean that wetting of the surface is unfavorable so the fluid will minimize its contact with the surface. It was found that the contact angle of water on EDM surface was 113.0° as shown in Fig. 14 and has hydrophobic characteristics. EDM surfaces are usually heterogeneous and the hydrophobic domains in the surface will restrict the motion of water droplet from spreading further resulting in an increase in contact angle. This effect arises due to the roughness present in the surface. Hence after polishing the surface becomes homogenous and a contact angle of 90.8° as shown in Fig. 15 was observed. Thus, after texturing, the barrier for water droplet to spread on the surface decreases due to insufficient boundaries. Finally, after texturing a contact angle of 78.7° as shown in Fig. 16 was observed denoting that the surface exhibits hydrophilic characteristics rather than hydrophobic characteristics. The hydrophilic property is due to the texture produced on the surface. The micro hemispherical indentation in the texture further reduces the irregularities in the surface. This reduction in irregularity, in turn, reduces the micro-barriers that restrict the motion of water droplet leading to large variation in macroscopic contact angle. Therefore, it is evident that a permanent hydrophilic surface property can be achieved by ultrasonic texturing for nanofluidic transportation and surface that require self-cleaning.

IV. CONCLUSION

The paper presents an investigation on a novel surface texturing technique using ultrasonic impingement of microparticles. Through ultrsonic horn excitation and cavitation mechanism, smooth and regular hemispherical profiles were achieved on the surface. The hemispherical profile generated was purely due to plastic deformation. Therefore, there is no removal of material from the specimen surface. The diameter of the hemispherical indentations produced on the surface is directly related to the size of the micro particles used for impingement. The profile of the texture created alters the surface wettability properties. Surface wettability results show that the wettability property increases by about 30.4% from the initial values. It is also found that the surface texturing achieved makes the surface permanently hydrophilic. This permanent property change is due to the micro hemispherical indentation pattern produced. This technique can be employed in applications that require hydrophilic surfaces such as cooling fins, nanofluidic that require a micro hydrophilic path for smooth liquid transportation and components that require self-cleaning surfaces to prevent contamination. Future work on ultrasonic texturing to produce uniform textures on the surface and texturing in micro scale will even enhance the surface wettability properties that can be used for a wider range of applications.

REFERENCES

[1] A. A. G. Bruzzone, H. L. Costa, P. M. Lonardo, and D. A. Lucca, "Advances in engineered surfaces for functional performance," *CIRP Annals - Manufacturing Technology,* vol. 57, pp. 750-769, 2008.

[2] U. Pettersson and S. Jacobson, "Friction and Wear Properties of Micro Textured DLC Coated Surfaces in Boundary Lubricated Sliding," *Tribology Letters,* vol. 17, pp. 553-559, 2004.

[3] T. Deng, F. Arias, R. F. Ismagilov, P. J. A. Kenis, and G. M. Whitesides, "Fabrication of Metallic Microstructures Using Exposed, Developed Silver Halide-Based Photographic Film," *Analytical Chemistry,* vol. 72, pp. 645-651, 2000.

[4] G. Popa, F. Boulmedais, P. Zhao, J. Hemmerlé, L. Vidal, E. Mathieu*, et*

Open Science Index, Mechanical and Mechatronics Engineering Vol:11, No:7, 2017 publications.waset.org/10007583.pdf

al., "Nanoscale Precipitation Coating: The Deposition of Inorganic Films through Step-by-Step Spray-Assembly," *ACS Nano,* vol. 4, pp. 4792-4798, 2010.

[5] K. M. Vaeth, R. J. Jackman, A. J. Black, G. M. Whitesides, and K. F. Jensen, "Use of Microcontact Printing for Generating Selectively Grown Films of Poly(p-phenylene vinylene) and Parylenes Prepared by Chemical Vapor Deposition," *Langmuir,* vol. 16, pp. 8495-8500, 2000.

[6] H. Wang, Y. Wang, R. Xue, L. Kang, and X. Li, "Fabrication and electron field-emission of carbon nanofibers grown on silicon nanoporous pillar array," *Applied Surface Science,* vol. 261, pp. 219-222, 2012.

[7] J. B. Nelson and D. T. Schwartz, "Electrochemical printing: in situ characterization using an electrochemical quartz crystal microbalance," *Journal of Micromechanics and Microengineering,* vol. 15, p. 2479, 2005.

[8] M. Zou, L. Cai, and H. Wang, "Adhesion and friction studies of a nano-textured surface produced by spin coating of colloidal silica nanoparticle solution," *Tribology Letters,* vol. 21, p. 25, 2006.

[9] S. Mailis, I. Zergioti, G. Koundourakis, A. Ikiades, A. Patentalaki, P. Papakonstantinou, *et al.*, "Etching and printing of diffractive optical microstructures by a femtosecond excimer laser," *Applied optics,* vol. 38, pp. 2301-2308, 1999.

[10] Y. Fu, Y. X. Ye, Y. K. Zhang, and L. Cai, "The technology of laser honing applied in distinctively improving the lubrication of frictional units," in *Key Engineering Materials*, 2001, pp. 265-270.

[11] D. Aspinwall, M. Wise, K. Stout, T. Goh, F. Zhao, and M. El-Menshawy, "Electrical discharge texturing," *International Journal of Machine Tools and Manufacture,* vol. 32, pp. 183-193, 1992.

[12] J. Zhang and Y. Meng, "A study of surface texturing of carbon steel by photochemical machining," *Journal of Materials Processing Technology,* vol. 212, pp. 2133-2140, 2012.

[13] P. Slikkerveer, "Model for patterned erosion," *Wear,* vol. 233, pp. 377-386, 1999.

[14] J. De Mello, J. Goncalves, and H. Costa, "Influence of surface texturing and hard chromium coating on the wear of steels used in cold rolling mill rolls," *Wear,* vol. 302, pp. 1295-1309, 2013.

[15] V. Bulatov, V. Krasny, and Y. Schneider, "Basics of machining methods to yield wear-and fretting-resistive surfaces, having regular roughness patterns," *Wear,* vol. 208, pp. 132-137, 1997.

[16] D. S. dos Santos, M. R. Cardoso, F. L. Leite, R. F. Aroca, L. H. Mattoso, O. N. Oliveira, *et al.*, "The role of azopolymer/dendrimer layer-by-layer film architecture in photoinduced birefringence and the formation of surface-relief gratings," *Langmuir,* vol. 22, pp. 6177-6180, 2006.

[17] T. Moriwaki and E. Shamoto, "Ultraprecision diamond turning of stainless steel by applying ultrasonic vibration," *CIRP Annals-Manufacturing Technology,* vol. 40, pp. 559-562, 1991.

[18] B. Azarhoushang and J. Akbari, "Ultrasonic-assisted drilling of Inconel 738-LC," *International Journal of Machine Tools and Manufacture,* vol. 47, pp. 1027-1033, 2007.

[19] H. Chen, J. Tang, and W. Zhou, "An experimental study of the effects of ultrasonic vibration on grinding surface roughness of C45 carbon steel," *The International Journal of Advanced Manufacturing Technology,* vol. 68, pp. 2095-2098, 2013.

[20] A. Amanov, I. Cho, Y. Pyoun, C. Lee, and I. Park, "Micro-dimpled surface by ultrasonic nanocrystal surface modification and its tribological effects," *Wear,* vol. 286, pp. 136-144, 2012.

[21] A. Amanov, O. V. Penkov, Y.-S. Pyun, and D.-E. Kim, "Effects of ultrasonic nanocrystalline surface modification on the tribological properties of AZ91D magnesium alloy," *Tribology International,* vol. 54, pp. 106-113, 2012.

[22] K. L. Tan and S. H. Yeo, "Surface modification of additive manufactured components by ultrasonic cavitation abrasive finishing," *Wear,* vol. 378–379, pp. 90-95, 2017.

[23] D. C. Lin, D. I. Shreiber, E. K. Dimitriadis, and F. Horkay, "Spherical indentation of soft matter beyond the Hertzian regime: numerical and experimental validation of hyperelastic models," *Biomechanics and modeling in mechanobiology,* vol. 8, pp. 345-358, 2009.