Microtexturing D2 steel surface to induce superhydrophobicity on it using EDM process

Bibeka Nanda Padhi*, Sounak Kumar Choudhury, J. Ramkumar

Indian Institute of Technology Kanpur, Kanpur, India

Presented in International Conference on Precision, Micro, Meso and Nano Engineering (COPEN - 12: 2022)
December 8 - 10, 2022 IIT Kanpur, India

KEYWORDS

Surface Texturing, Texture Dimension, Hydrophilicity, Hydrophobicity, Contact Angle.

ABSTRACT

This work attempts to induce superhydrophobicity on a hydrophilic D2 steel surface by microtexturing, using the Electro-discharge machining process, as hydrophobic surfaces offer enhanced self-cleaning and corrosion resistance. The laser machining process is praiseworthy for surface texturing on nonmetals but not widely recommended for conductive metals. Electro-discharge machining is very effective for micro fabrications on metals and its potential in surface texturing should be explored. Texturing of the D2 steel surface is done by fabricating microchannels in mutually perpendicular directions using a thin Cu foil as a tool in the EDM process. Texture dimensions in relation to the microchannel width are calculated from Cassie-Baxter equations. It has been observed that surface texturing improves the contact angle of water droplets on a metallic surface. The static contact angle of a water droplet on a hydrophilic D2 steel surface was increased from 78.6° to 158.7°, resulting in superhydrophobicity.

1. Introduction

Researchers are replicating the available surfaces in the nature to attain their superior properties on the surfaces of materials since the characterisation capabilities have been evolved to the point where microscopic features can be examined. Target material surfaces are textured in order to imitate natural surfaces and attain expected surface traits (Kim et al., 2018). Surface texturing is the technique of generating patterned protrusions, dimples or pillars of different sizes ranging from nano levels to micro and meso levels on a material surface to obtain targeted surface attributes (Patel et al., 2016). Since increasing a surface’s hydrophobicity improves its ability to self-clean, the surface texturing can be employed to make hydrophilic surfaces hydrophobic and hydrophobic surfaces even more hydrophobic. A water droplet has a contact angle higher than 90˚ on a hydrophobic surface and less than 90˚ on a hydrophilic surface. A superhydrophobic surface has a contact angle more than 150° (Patel et al, 2019).

*Corresponding author E-mail: bibeka@iitk.ac.in

https://doi.org/10.58368/MTT.22.6.2023.68-74

Few studies on EDM have been reported mentioning the capability of the process to generate texture on the metal surfaces. A thin foil tool was employed instead of the micro cyllendrical tool previously employed in normal micro EDM to manufacture micro slots (Yeo & Murali, 2003). A larger machining area was accomplished by employing a thin foil tool; thus, MRR was enhanced by 50 times more than in standard micro EDM using a micro cylendrical tool. This procedure has been improved by effectively incorporating a gravity aid to remove generated debris during machining from the inter-electrode gap. During the gravity-aided micro EDM process, the thin foil tool was positioned at the bottom, and the workpiece was positioned on top (Murali & Yeo, 2004). As a result of gravity, the eroded debris flushed down from the inter-electrode gap. The debris accumulation on the micro slot has reduced considerably as flushing has become more effective. As a result, phenomena such as arcing short circuits, and secondary discharges have been significantly reduced enhancing the aspect ratio of the micro-slot and removal rate of material. In micro EDM, a pulsed power supply based on a transistor circuit was employed instead of an power supply based on RC circuit while using a rotary disc tool of 25 µm thick

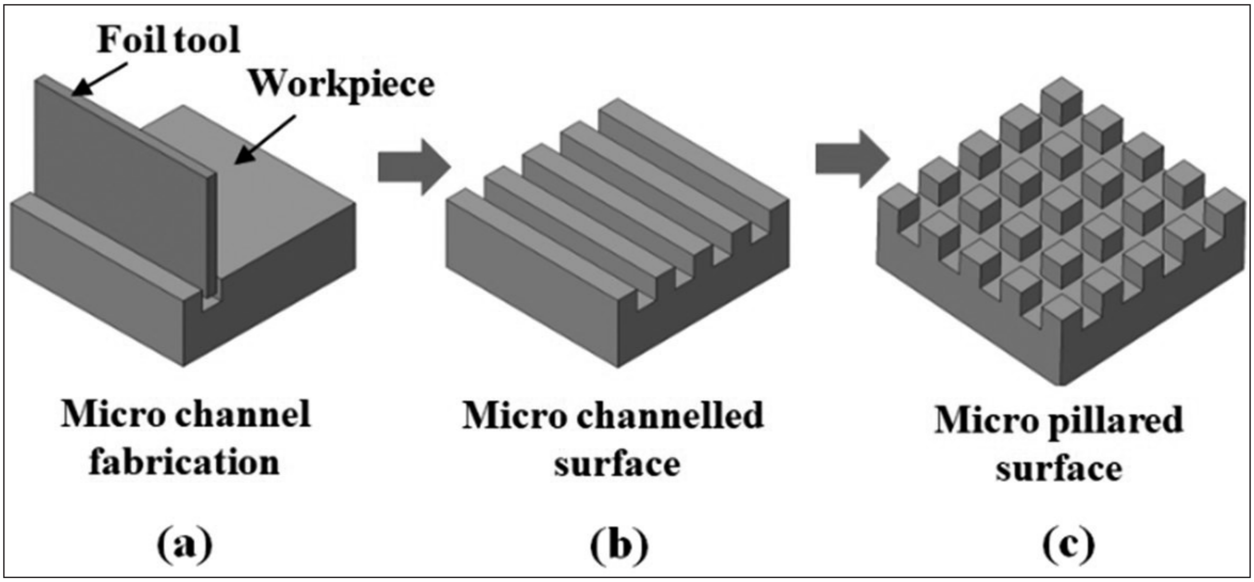

Fig. 1. Diagrammatic representation of the procedure used to generate microtextured surface showing (a) microchannel fabrication, (b) micro-channeled surface, and (c) micro-pillared surface.

for the fabrication of micro channels (Chow et al., 1999). A power supply based on an RC circuit had a charging duration that was considerably longer than the discharging time, which led to a relatively low duty cycle throughout the machining process. The advantage of the pulsed power supply, on the other hand, was that it operated at a very high duty cycle, which enhanced the rate of material removal. In addition, the pulsed power supply allowed the user to freely choose the duty cycle value by adjusting the duration of pulse on and pulse off period. Furthermore, the tool wear was spread out along the periphery since this process used a disc-shaped rotary foil tool. Due to the significantly reduced local volumetric tool wear compared to a static tool, the shape of the tool was effectively conserved. In addition to the previously mentioned advantages, this approach has a number of drawbacks. Due to the disc tool's flatness defect, rotation of the electrode increased the overcut. The flatness inaccuracy made the disc tool to fluctuate as the the tool rotates, resulted in machining wider grooves compared to the grooves machined with the static tool.

Some of the reported findings of use of the thin foil tool in EDM have been thoroughly investigated. The advantages of those methodologies have been included, and the limits of the existing work have been overcome. To obtain a better material removal rate, a pulsed power supply was used. In addition, a thin foil tool was employed to obtain a faster machining process than traditional micro-EDM. To achieve successful flushing by gravity aid, the foil tool was positioned at the bottom, and the workpiece was positioned at the top. Furthermore, a static foil electrode was employed instead of a rotational electrode to obtain a lesser overcut.

2. Materials and Method

The schematic representation of the method followed to fabricate a textured surface consisting of micropillars is shown in Fig. 1. Fig. 1(a) shows the fabrication of a microchannel using a foil tool on a workpiece surface. In the same way, parallel microchannels were fabricated to generate a micro-channeled surface, as shown in Fig. 1(b). Then microchannels in the perpendicular direction were fabricated to generate a micro-pillared surface, as depicted in the Fig. 1(c).

An Electra R-50-ZNC Electro-discharge die sinker has been used in this study for the micro-texture fabrication using a Cu foil tool of 110 µm thickness on a D2 steel surface. Debris build-up in the inter-electrode gap is a serious issue since it reduces the efficiency of the medhod due to arcing and short-circuiting. The thin foil tool may deflect while being machined due to debris flushing techniques like the high and low-frequency tool vibration, injection of high-pressure dielectric into the machining zone and a magnetic field. Since cleaning debris from the machining zone will improve process performance, gravity-aideded EDM is chosen for this work.

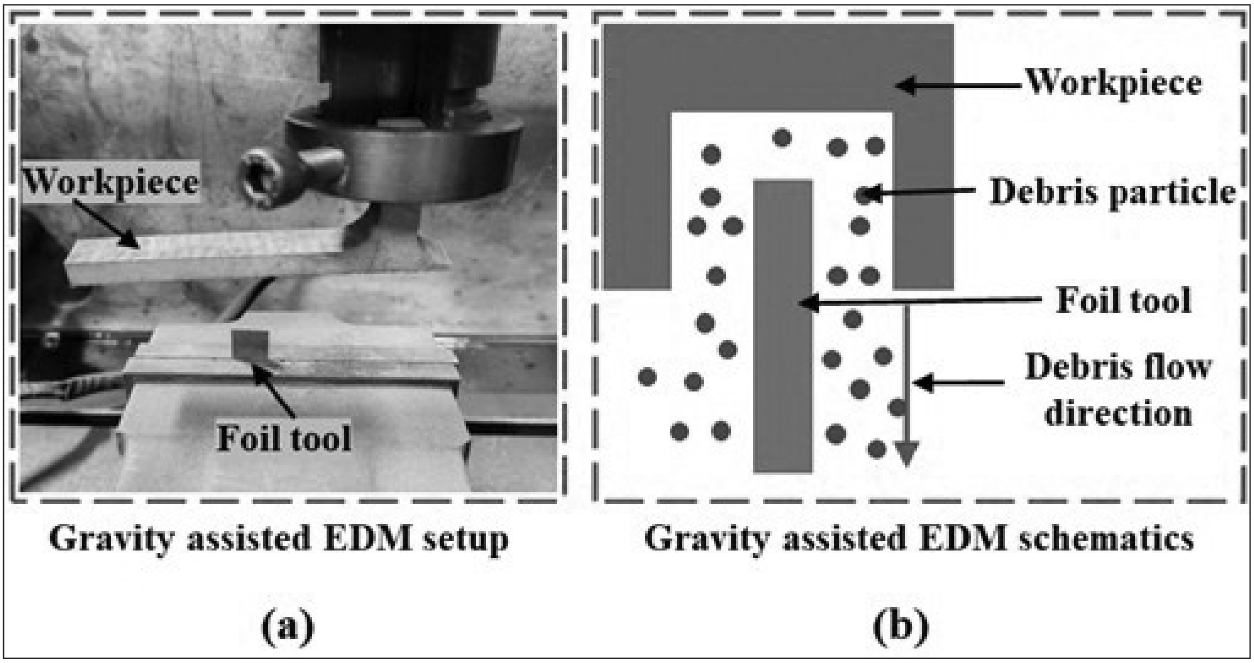

Fig. 2. (a) Experimental setup showing Cu foil tool at the bottom and D2 steel workpiece at the top and (b) schematics of a gravity assisted setup showing the debris flow direction.

Table 1
Process parameters.

V_g	I_d	T_{on}	*d*
30 V	3 A	5 µs	56 %

The tool was at the bottom and workpiece was at the top in a gravity-assisted EDM. Due to gravity, the debris particles avoid building up in the inter-electrode gap by flowing downward from the inter-electrode gap. Arcing short circuiting circumstances were consequently minimized. Fig. 2(a) shows the experimental setup used in this study to achieve gravity-assisted flushing of debris from the inter-electrode gap by positioning the tool at the bottom and the workpiece at the top. The diagrammatic representation of a gravity-assisted EDM process showing debris flow in a downward direction is depicted in Fig. 2(b). The process parameters' pulse on time (T_{on}), discharge current (I_d), gap voltage (V_g), and duty cycle (d) used are listed in Table 1. In this study, an initial set of experiments are conducted to study the overcut and tool wear to decide feed in the machining depth direction and pitch of the microchannels.

3. Theory

The contact angle, which is the angle between the solid-liquid interface and the liquid-air interface for a liquid droplet on a solid surface, determines a surface's wettability. In this study, an untextured hydrophilic surface is modified into a superhydrophobic surface by texturing the surface, as shown in fig. 3(a). The texture dimensions can be used to estimate the contact angle of a textured surface in reference to the contact angle of a smooth surface, as illustrated in Fig. 3(b).

Given the width of the micropillar (α) and the distance between micropillars (*b*), total unit area (*A*), solid-liquid interface area (A_{SL}), and liquid-air interface area for a unit area (A_{LA}) of the textured surface.

$$A = (a + b)^2 \quad \text{..................(1)}$$

$$A_{SL} = a^2 \quad \text{..................(2)}$$

$$A_{LA} = A - A_{SL} \quad \text{..................(3)}$$

The following formulae can then be used to get the solid-liquid interface area fraction fraction (f_{SL}) and the liquid-air interface area fraction (f_{LA}).

$$f_{SL} = \frac{A_{SL}}{A} \quad \text{..................(4)}$$

$$f_{LA} = 1 - f_{SL} \quad \text{..................(5)}$$

The Cassie-Baxter equation that follows can then be used to calculate the contact angle of the textured surface (θ_T) in reference to the contact angle of the untextured surface (θ_U) (Patankar, 2003).

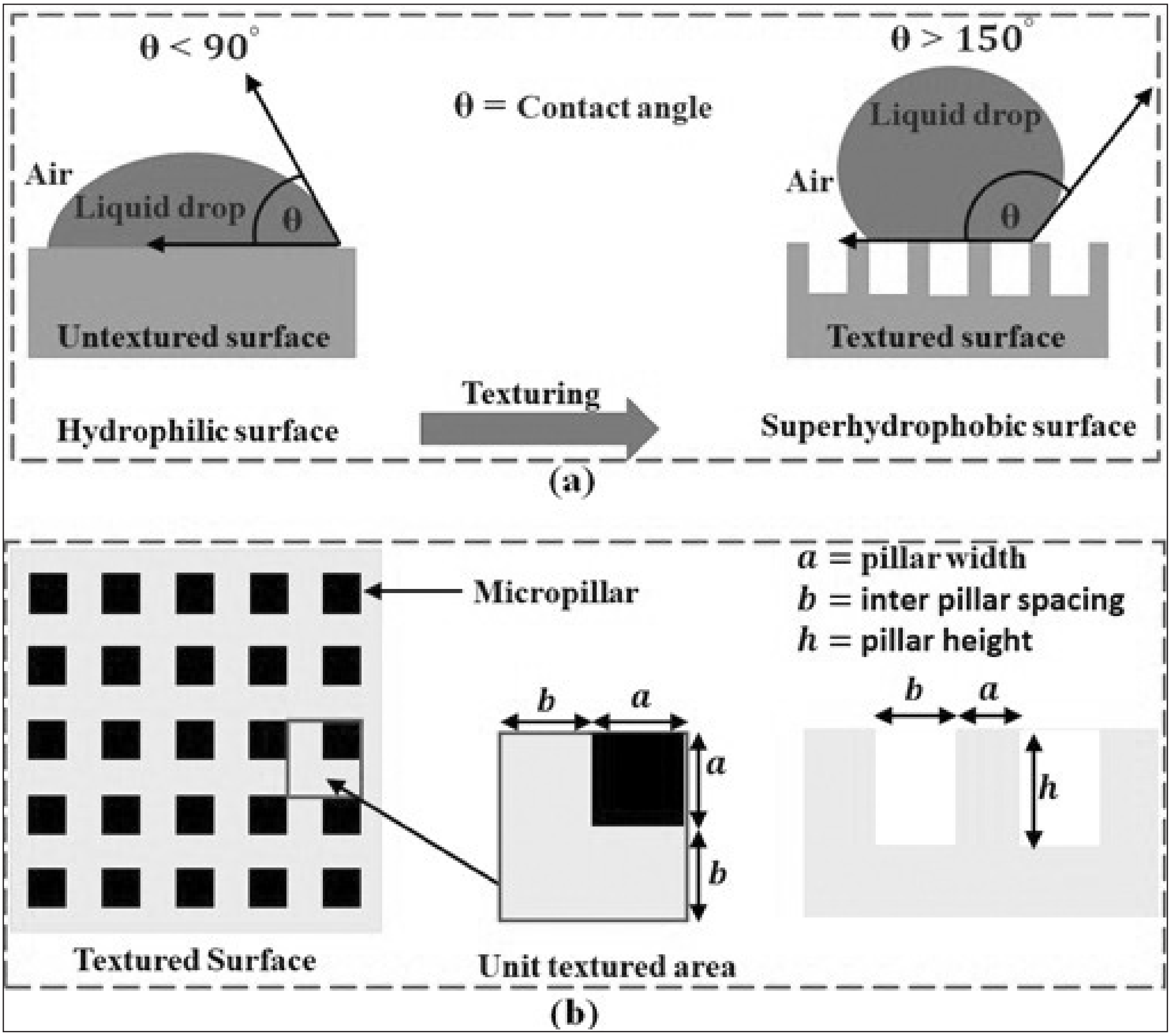

Fig. 3. Schematic diagrams of (a) transformation of a hydrophilic surface to superhydrophobic surface by surface texturing and (b) a textured surface showing the texture dimensions.

$$cos\theta_T = f_{SL}cos\theta_U - (1 - f_{SL}) \quad \text{..................(6)}$$

4. Results and Discussion

The initial set of experiments is conducted to determine the overcut and the tool wear obtained during the microchannel fabrication. Based on that, the feed in the machining depth direction and the pitch of microchannels are calculated to obtain desired width and depth of micropillars.

4.1. Tool wear and overcut

Fig. 4 shows the interrelationship between the dimensions of the foil tool and the machined feature. It shows that the depth of the machined channel (*h*) is less than the tool feed (F_T) due to tool length wear (L_{TI} - L_{TF}). Also, it shows that the channel width (*b*) is wider than the thickness of the foil tool (t_f) due to the overcut (t_o).

Using Cu foil tool of 110 µm thickness and the parameters mentioned in Table. 1, 10 numbers of microchannels were machined, giving a feed of 300 µm in the direction of machining depth, as shown in Fig 5(a). For which the average depth and width of the machined channels obtained are 171.86 µm and 164.45 µm, respectively. The average overcut per side obtained is 27.22 µm and the foil tool length consumed per 1 µm depth of microchannel depth is calculated to be 0.746 µm. So, the feed given to the tool per µm of machining depth will be 1.746 µm to compensate for the tool wear. The depth and width measurement for a machined channel is shown in Fig. 5(b).

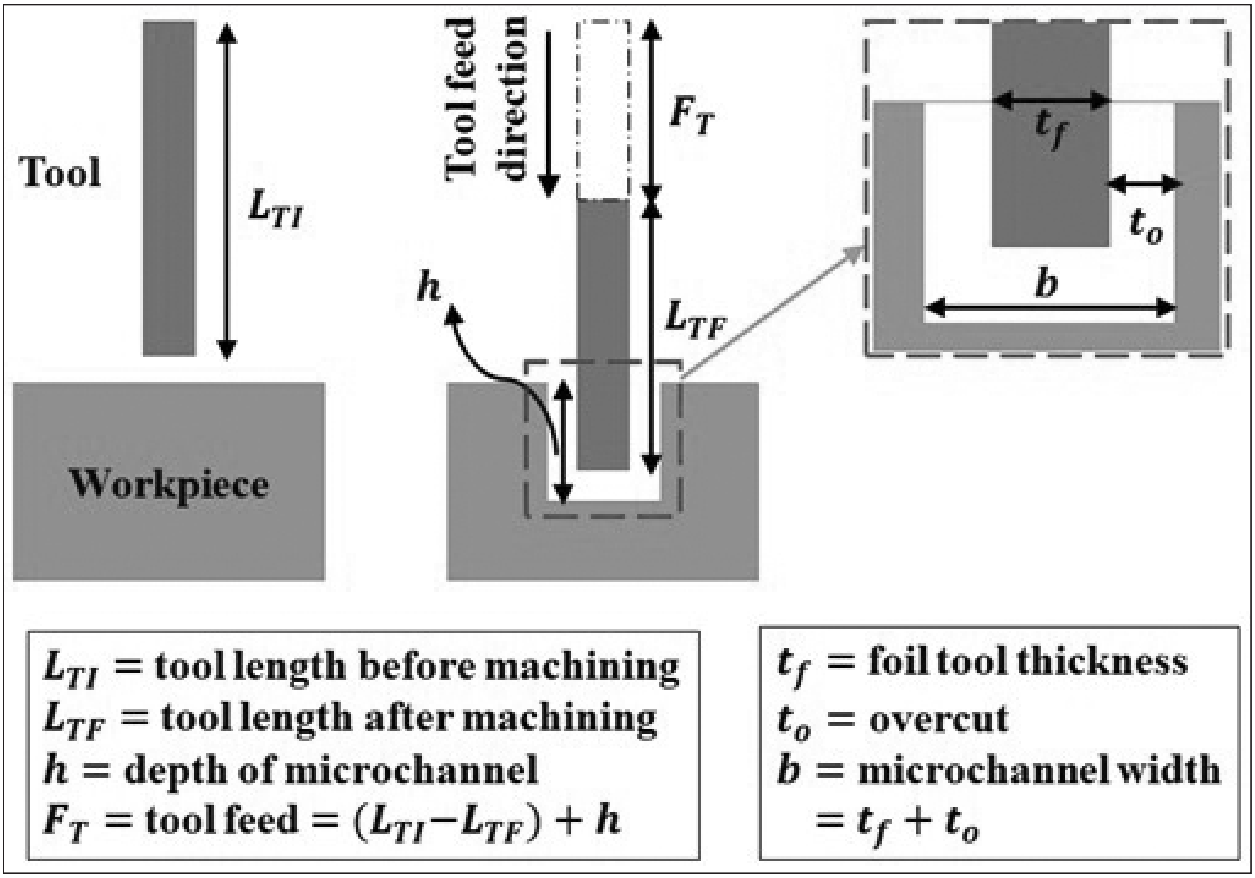

Fig. 4. Schematic diagram showing the inter-relationship between dimensions of foil tool and dimensions of machined channel.

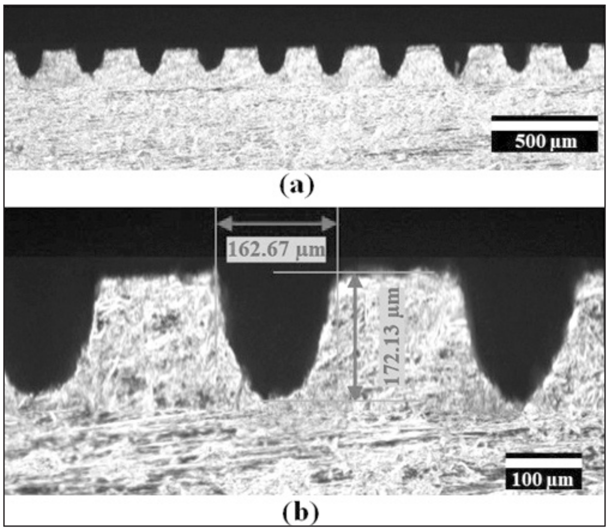

Fig. 5. (a) Micro channels machined to find out average width and depth and (b) sample measurement of width and depth machined channel.

4.2. Texture dimension and contact angle

In this study, using a goniometer, a sessile drop of distilled water with a volume of 2.5 µl was employed for all contact angle measurements. On the polished D2 steel surface, the average static contact angle was found to be 78.6°. Thus, it was discovered that the polished D2 steel surface was hydrophilic. Surface texturing with the creation of microchannels in mutually perpendicular directions employing the procedure depicted in Fig. 1 can turn this surface into a superhydrophobic surface.

Table 2
Texture dimensions.

Targeted texture dimensions			Pitch	Tool feed
a (µm)	*b(µm)*	*h(µm)*	*(a + b) (µm)*	*h × 1.746*
70.55	164.45	71.59	235	225

The contact angle of a liquid droplet on a micro-squared textured surface depends upon the texture dimensions and the contact angle of the liquid droplet on an untextured surface. For a micro-squared textured surface, the microchannel width becomes the interpillar spacing (*b*). For a textured surface to be superhydrophobic, the required micropillar width (*a*) can be calculated using Eq. (1-6) with respect to the contact angle

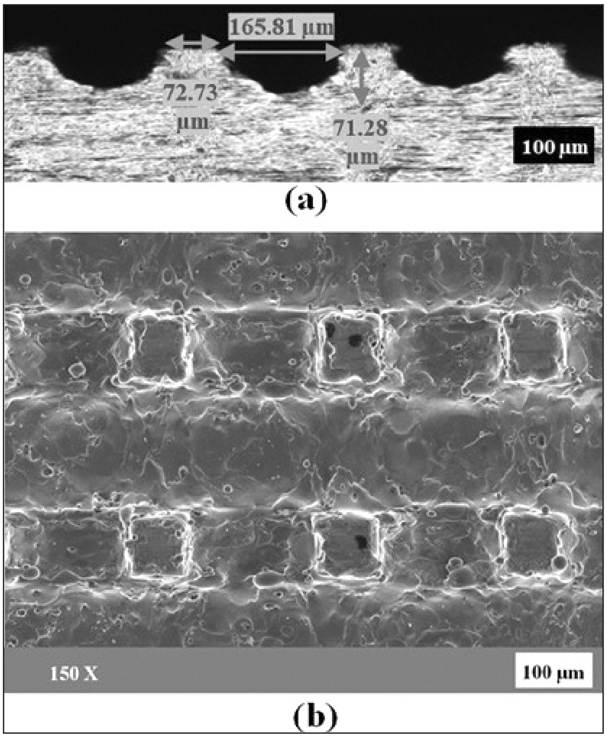

Fig. 6. (a) Optical microscopic image showing the texture dimensions and (b) SEM image of the textured surface.

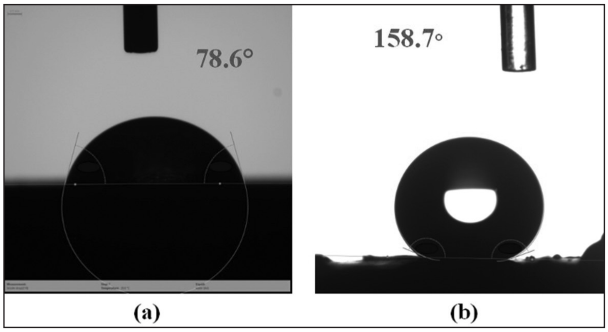

Fig. 7. Contact angle of (a) untextured surface and (b) Textured surface measured using goniometer.

of the untextured surface (θ_u) and the interpillar spacing. Putting the values of interpillar spacing of 164.45 µm (a = 164.45 µm) and contact angle of the untextured surface 78.6° ($\theta_u = 78.6^o$) in Eq. (1-6), the micropillar width should be less than 82.66 µm.

The aimed texture dimensions of the superhydrophobic surface, along with the given pitch and tool feed, are listed in Table 2. The optical microscopic image of the textured surface is depicted in Fig. 6(a), showing the measured values of micropillar width, interpillar spacing, and pillar height, which are close to the targeted values mentioned in table 1. Also, the SEM image of the textured surface is shown in fig. 6(b). Surface texturing has transformed a hydrophilic surface, the contact angle of which is shown in Fig. 7(a), to a superhydrophobic surface, as shown the contact angle in Fig.7(b).

5. Conclusion

The gravity-assisted EDM method's potential for creating metal surfaces with fine textures was examined in this study. Cu foil with a thickness of 110 µm was used as the electrode, and 164.45 µm wide micro slots were created on the D2 steel surface to create textured surfaces.

- A low overcut in the order of 27.22 µm has been achieved by choosing an appropriate set of process parameters, which is desirable for microfabrication.
- Additionally, this method has demonstrated its ability to manufacture textured surfaces with various micropillar sizes.
- The superhydrophobic surfaces created by surface texturing successfully converted to a hydrophilic smooth D2 steel surface, increasing the static contact angle from 78.6° to 158.7°.
- This process can be used to fabricate hydrophobic and superhydrophobic surfaces on various conductive metals.

References

Chow, H. M., Yan, B. H., & Huang, F. Y. (1999). Micro slit machining using electro-discharge machining with a modified rotary disk electrode (RDE). *Journal of Materials Processing Technology, 91*, 161-166.

Kim, W., Kim, D., & Park, S. (2018). Engineering lotus leaf-inspired micro- and nanostructures for the manipulation of functional engineering platforms. *Journal of Industrial and Engineering Chemistry, 61*, 39-52.

Murali, M., & Yeo, S. H. (2004). A novel spark erosion technique for the fabrication of high aspect ratio micro-grooves. *Microsystem Technologies, 10*, 628-632.

Patankar, N. A. (2003). On the modeling of hydrophobic contact angles on rough surfaces. *Langmuir, 19*(4), 1249-1253. https://doi.org/10.1021/la026612+

Patel, D., Jain, V., & Rajkumar, J. (2016). Micro texturing on metallic surfaces: State of the art. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 232,* 941-964.

Patel, D. S., Jain, V. K., Shrivastav, A., & Ramkumar, J. (2019). Electrochemical micro texturing of flat and curved surfaces: simulation and experiments. *The International Journal of Advanced Manufacturing Technology, 100*, 1269-1286.

Yeo, S. H., & Murali, M. (2002). A new technique using foil electrodes for the electro-discharge machining of micro grooves. *Journal of Micromechanics and Microengineering, 13*(1), N1-N5. https://doi.org/10.1088/0960-1317/13/1/401

Bibeka Nanda Padhi is a Doctoral Student in the Department of Mechanical Engineering at Indian Institute of Technology Kanpur. His research focuses on the fields of Electric discharge machining, micro machining, surface texturing and thermal modeling of electrical discharge. He has published 8 articles in peer reviewed international journals and conferences.

Dr. Sounak Kumar Choudhury, Professor (Retired) in the Department of Mechanical Engineering from Indian Institute of Technology Kanpur, has more than 35 years of experience in research and academia. His research interests lie on the fields of Manufacturing Science - Condition Monitoring of Machine Tools; On-line Monitoring and Control of Tool Wear; Adaptive Control Systems, Manufacturing Automation, Hydraulic Control, Non traditional Machining Processes. He has obtained his Ph.D followed by his Post doctoral fellowship in Manufacturing Science from Lumumba University, Moscow. He joined as an Assistant Professor in the Department of Mechanical Engineering, IIT Kanpur in 1986 and retired as a Professor in 2021. He has published over 100 articles in peer reviewed international journal and conferences. He has completed several projects from Hindustan Aeronautics Limited (HAL) and Council of Scientific and Industrial Research (CSIR) and several patents. (E-mail: choudhry@iitk.ac.in).

Dr. J. Ramkumar, Professor in the Department of Mechanical Engineering and Design Program at Indian Institute of Technology Kanpur, has over 20 years of experience in industry, research and academia having specialization in the areas of Micro/Nano Manufacturing and New product/process development, Tribology, composite, Manufacturing Process modeling. He obtained his Ph.D in Mechanical Engineering from Indian Institute of Technology Madras. He joined as an Assistant Professor in the Department of Mechanical Engineering in Dec 2003. He has published over 330 articles in the peer-reviewed international journals and has delivered over 100 lectures in the international conferences. He has 4000+ citations for his publications & his h-index of 33, which endorses his high research productivity. Five of his patents are commercialized, total number of patents in his name being 88. Currently, he is the Project Investigator of MedTech facility, Imagineering Laboratory and RuTAG facility at IIT Kanpur.
(E-mail: jrkumar@iitk.ac.in).