Fabrication of anti-icing surface structures on aluminum alloy for aerospace applications

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Abstract. Icing, the phenomenon of the formation and accumulation of ice or frost on a surface due to the solidification of water droplets at low temperature can be undesirable in many applications. Surface icing can lead to increased energy consumption in aerospace and automotive applications due to increased aerodynamic drag. Ice formation can also present a mechanical and electrical safety hazard, and as such significant work has been done to produce surfaces with anti-icing properties through surface modification to decrease ice formation and adhesion to surfaces. One route toward the generation of anti-icing surfaces is through laser surface processing. Laser micro/nano structuring of surfaces has shown a commendable progress in recent years due to advancements in laser source technology and reduction in capital costs for ultrafast femtosecond pulsed machining lasers. Laser material processing offers a rapid, scalable, and non-contact method for fabricating large area anti-icing surfaces.

In this work, the production of anti-icing surfaces using femtosecond laser micro- and nano-structuring on aluminum alloy 7075 surfaces was examined. With an aim to optimize the anti-icing properties of the substrates, laser parameters such as pulse energy, repetition rate and beam scanning speed were varied to produce highly defined microstructures on the aluminum surface. Also examined was the use of scanning optics and spatial light modulation to allow upscaling of the laser process to large areas.

Introduction

The anti-icing surfaces are an area of great interest because of their significant economic, energy and safety implications in the prevention of accumulation of ice on the surfaces which interact with the fluid it is in contact [1]. Ice accumulation on the surfaces of the wings of an aircraft reduces the performance by 50% and may significantly changes the dynamic characteristics of aircraft and can be a cause of flight accidents [2,3].It also affects the components such as wind turbine in various ways, such as including measurement and control errors, increase in power losses, mechanical and electrical failures and safety hazard [4]. Hence it has been requirement to develop efficient techniques that can protect solid surfaces from being covered with ice or manufacture such types of surfaces on which ice cannot accumulate. This problem was first encountered and studied by Raraty et al. and had presented in research on adhesion and strength properties of ice on surfaces made of different materials such as metals and plastics. In this study the fundamentals of icing have been described and various experimental tests have been conducted [5]. The following Fig 1 shows the icing on wings of airplane and wind turbines.

Fig 1. Icing on aircraft wing and wind turbine [6,7]

Many chemical and physical based strategies are being used to make different types of surfaces anti icing [8,9]. However, the stability of these surfaces reduces after time. Also due to wear and tear the chemical coatings are worn out with time especially at changing pressure and temperature environments. Hence more robust technique is required which will not be affected due to these aspects.

Till now, many studies have successfully fabricated the superhydrophobic surfaces with anti-icing property by various methods. Laser machining or surface structuring is a one-step direct fabrication method that makes it possible to produce features on a micro and or nano scale on essentially any type of material surfaces. In the review by Volpe et al have described various laser-based techniques such as direct laser writing, laser-based interference patterning, laser induced periodic surface structuring. Various materials on which these patterns can be formed are also explained. The effect of different laser parameters on different material processing is also described. The laser parameters especially such as fluence, repetition rate, scanning speed affect the most for ice-phobicity. Moreover, key concept of surface wettability and its relationship with anti-icing is discussed which are icing delay, interaction between water and the solid surface and further ice adhesion. Out of these the most important characteristic is the interaction between the surface and water. This can be evaluated by the wetting behavior. It is normally evaluated by considering the contact angle (CA) which is the angle (θ) between a droplet deposited on the surface and the surface itself. According to the Wenzel theory stated, the water droplet adapts to the contours of the real solid surface, conforming to the peaks and valleys of its roughness [10].Hence, the surface properties especially depend on the roughness values such as and the type of microstructure of the surface which can be evaluated using different measuring instruments.

Aluminum alloy Al 7075 has excellent property such as high strength, good ductility, toughness, and good resistance to fatigue, high mechanical capacity and on other hand it is light weight hence it is used in aviation, mechanical equipment, hydraulic equipment and automotive industry [11]. As the surface of the aluminum 7075 is not reactive to chemicals as well as it is hard to machine using conventional methods. In order to achieve high accuracy and quality ultrafast lasers can be used to produce these [12].

In this work, an experimental study is conducted by using one-step femtosecond laser induced surface structuring or fabrication of Al 7075 substrate plates and the study is conducted on the surface morphology, roughness and wettability properties of the processed surfaces. The interaction behavior between water droplets on self-cleaning stainless steel (SS) was investigated and an attempt is made to bridge the gap between hydrophobic surface and anti-icing surface.

Material and Methods

Material

The material used in this project is made up of commercially available Aluminum alloy 7075 in form of flat plates with 110×36 mm and 3.5 mm thick. The chemical composition of Al 7075 alloy is as mentioned in the Table1 below.

Table 1. Chemical composition of Al 7075

Chemical composition	Weight%
Si	0.4
Fe	0.5
Cu	1.6
Mn	0.3
Mg	2.5
Cr	0.15
Zn	5.6
Ti	0.2
Al	Balance

Al 7075 alloy material has excellent mechanical properties and corrosion resistance, and it can be used at high range of temperature. Below table shows the mechanical properties of Al 7075 alloy.

Laser Processing

In this study we used ultrafast femtosecond laser (NKT One Five Origami 10XP) that generates 400fs pulses with 1030nm central wavelength at a maximum pulse repetition rate of 1 MHz the beam diameter of laser at the focused position was 45 µm.

The substrate was mounted on 4-axis translation stage (Aerotech) and the translation stage was moved in X-Y direction at variable speed. The laser beam was scanned in form of parallel line pattern. 51 samples of parallel lines with variable hatch distance of 80µm, 100µm and 120µm were manufactured with laser processed area of 8 mm x 8 mm. The laser pulse energy (12-40 µJ) and repetition rate (100-300 kHz) were variable with each sample.

Design of Experiments

An experimental design was made using Response surface methodology with four factors or variables laser pulse energy (12-40 µJ), repetition rate (100-300 kHz), hatch distance (0.08-0.12mm) and scan speed (1-2 mm/s). This was conducted to find out the explores the relationships between factors which were the laser parameters and response variables such as contact angle and the Sa roughness values. This was conducted in order to obtain an optimal laser process parameters to make antifouling surface based on the roughness and contact angle.

Surface Analysis and Characterization

An optical profilometer (Bruker Contour GT 3D) was used to measure the roughness of the laser irradiated surface. The area surface texture parameters such as arithmetical mean height (Sa) roughness values were measured using this technique.

The wetting properties were measured by Contact angle analysis. FTA200 Dynamic Contact Angle Analyser was used for this. Contact angles describe the shape of a fluid drop in contact with a solid. contact angles are used to derive adhesion and wettability parameters of the surface.

Results and Discussions

Microstructure

The microstructure analysis was conducted using Keyence 3D digital Microscope which has magnification range (0.1x - 5000x). This was conducted using high speed image stitching feature. The figures below show the microstructure which shows laser processed samples with different hatch distances.

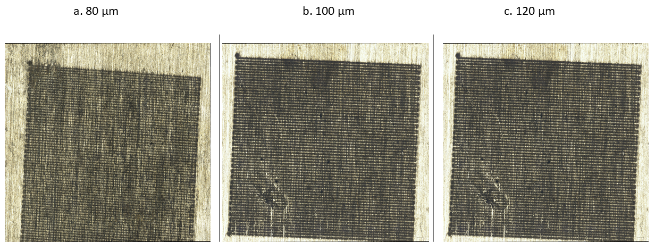

Fig 2. Digital microscope images showing the laser processed surface of different hatch distance

Surface Roughness

3D optical profilometer is an instrument which is rapid, nondestructive, and non-contact type of instrument which is capable of measuring the surface roughness and texture features on the surface.

The laser micro-machined textures on the surface are in the micro meter range and were analyzed with different roughness attributes such as arithmetical mean height (Sa), maximum height roughness (Sz) and root mean square (Sq). In the Fig 3 graphs shows the result plots of the surface roughness attributes such as root mean square roughness values, arithmatic mean heights and maximum peak heights.

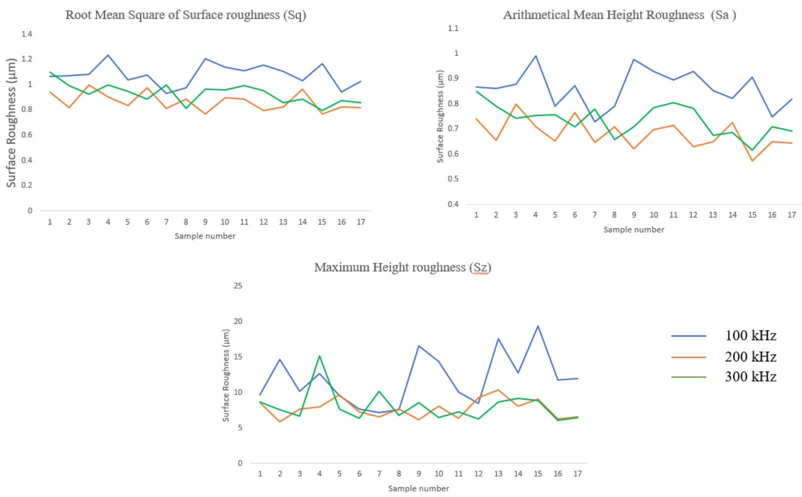

Fig 3: Results of Surface roughness attributes of ultrafast laser processed Al7075 samples (0.63 - 0.991 µm) measured by optical profilometer

To find the most affecting laser process parameter for the different attributes of the surface roughness mentioned above the response surface method was used. The below Fig 4 shows that the laser pulse energy and rep rate were the most important paprametes for roughness attributes such as Sa, Sz and Sq roughness values. It was found that the significant process parameters affecting the roughness values were Laser pulse energy and the repetation rate.

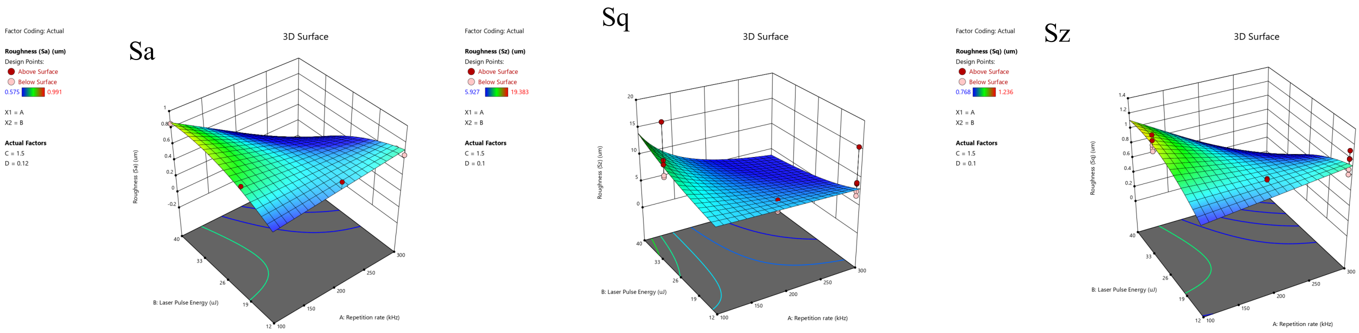

Fig 4: Response surface analysis of surface roughness attribute values of 51 samples

Contact angle

Surface contact angle is normally influenced by surface morphology and chemical compositions. The contact angle of the water droplet was analyzed using a video-based optical contact angle-measuring device FTA200 Dynamic Contact Angle Analyser which can calculate many quantities of interest from the drop shape, including static, equilibrium, capillary, advancing & receding Contact Angle.

The contact angle was calculated at the point when the drop landed on the surface. The contact angle test was conducted on the 51 samples which were manufactured using different laser parameters. The volume of the water droplet was at an average of 13µl at a controlled flow rate of 1.4 µl/s. The flow rate was kept constant, and the droplet was captured as soon as it landed on the processed surface.

Initially the contact angle on the non-processed stainless-steel sample was observed to be 66.3 º. The minimum contact angle was noted to be 26.56º showing hydrophilicity. The maximum contact angle observed was 139.34º showing hydrophobicity.Below Fig 5 shows the results from the contact angle test.

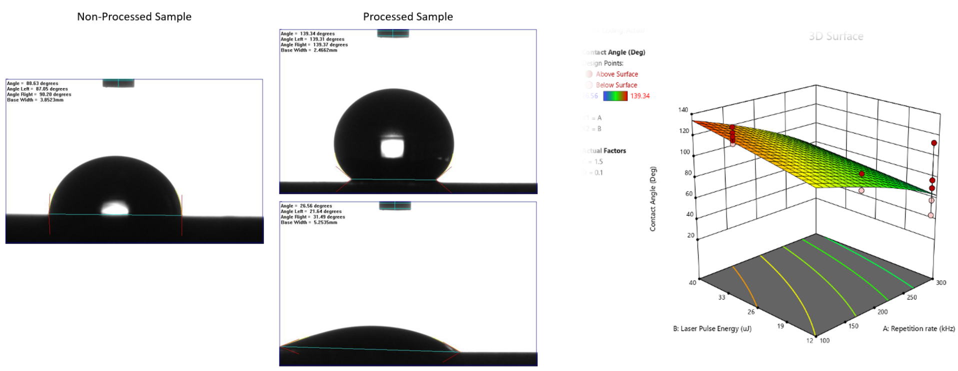

Fig 5: Results of contact angles on unprocessed samples and laser processed samples and response surface analysis of all 51 samples

Response surface method was used to find the most influencing laser process parameter for the contact angle. The results show that two parameters which are repetition rate, and the hatch distance were the most influencing parameters. shows the relationship between the contact angle numeric factors such as repetition rate and hatch distance.

Conclusions

Ultrafast pulse laser surface machining of aerospace grade aluminum alloy (Al7075) is demonstrated. The maximum contact angle observed was 139.3° on the sample 1 which was manufactured with laser parameters 100kHz ,30µJ pulse energy, scan speed of 1.5 mm/s and hatch distance of 100µm. The average roughness of this sample was measured to be 0.88µm.

The laser process parameters to develop anti icing surfaces were optimized by conducting response surface analysis of the measured parameters such as surface roughness, contact angle and ice adhesion which are important in measuring degree of icing.

In the future different type of structures can be investigated using different scan strategies.

Ice adhesion tensile test can be conducted in the future to measure degree of icing on the surface.

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