Progress in Organic Coatings 119 (2018) 183–193

Contents lists available at ScienceDirect

Progress in Organic Coatings

journal homepage: www.elsevier.com/locate/porgcoat

Fuzzy based models for estimating static contact angle and sliding angle of liquid drops

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ARTICLE INFO

Keywords:
Amphiphobic surface
Silica multilayer
Fluoropolymer
Fuzzy model
Contact angle
Sliding angle

ABSTRACT

Prediction of the contact angles and sliding angles of liquid drops is so difficult, because the interaction among the variables, which have impact on the angles, is so complex. Therefore, in this paper fuzzy logic was used to develop prediction models. Experimental sliding angle and contact angles of liquid drops on the metal samples with several surface treatments were divided into training data and testing data. By using the knowledge, which was extracted from the training data and experience of authors, the effective if-then rules were developed. Then, the weight of the rules was optimized by particle swarm optimization. The obtained results for testing data by using proposed Fuzzy_CA and Fuzzy_SA models showed that the regression index for the contact angles and sliding angles were 0.9970 and 0.9980, respectively. It means that the predicted angles are so close to measured angles and the proposed fuzzy based models are so reliable.

1. Introduction

Up to now, a large number of different liquid repellent surfaces have been reported (mentioned) in the literature. These surfaces exhibit (manifest) self-cleaning property and have many practical applications such as drag reduction, anti-fogging, anti-fouling, anti-icing, corrosion resistance and stain-resistant surfaces among many other potential applications [1–12]. A super-liquid-repellent surface is the solid surface which the static contact angle (CA) of water and oil on it, is greater than 150° and dynamic contact angle of water and oil on it, is less than 10° [13]. The CA is the angle formed between the tangent plane to the surface of the liquid droplet and the tangent plane to the surface of the solid at the point of intersection (Fig. 1a). One type of dynamic contact angles is the sliding angle (SA) of liquid drops on the surface, which is the angle between the sample surface and the horizontal plane where the probe liquid droplet starts to slide off the surface (Fig. 1b).

It has been observed that the amphiphobicity is governed by both the chemical composition and the geometrical structure of the solid surface. Several methods and materials have been used for fabrication of suitable surface structure and lowering the surface free energy. Hierarchical structure fabricated by using multilayer coating is a kind of suitable surface structure for superamphiphobicity. Also, fluoropolymers are the most popular materials for lowering the surface free energy due to their low surface energy end groups. Many studies have reported the fabrication of liquid-repellent surfaces with hierarchical multilayered structure and fluoropolymer coating on it for various applications [14–17]. The results have shown that the concentration of fluoropolymer in the coating sol, pre-roughening the surface by using the abrasive papers or sandblasting, the number of inorganic layers on the surface and the surface tension of probe liquids have simultaneous effect on the obtained CA and SA of liquid droplets on the prepared surfaces. Therefore, the prediction of the CA and SA of liquid drops is so difficult, because the simultaneous effect of variables on them is so complex. So, a method for predicting the final CA and SA of liquid droplets on this kind of amphiphobic surfaces can be very useful to determine their wettability and the quantity of mentioned variables, providing required wettability.

The fuzzy based models have been used for the prediction of the several phenomena. For the first time fuzzy logic was introduced by Professor Lotfi Aliasker Zadeh in 1973. In contrast with Boolean logic, fuzzy logic uses truth-values of variables to explain the events. These values can be a real number between zero and one. Fuzzy logic is usually used whenever introducing exact mathematical formulation is difficult or complex for solving a problem. For example, the fuzzy based models have been used to predict surface roughness in machining operation in two previous studies [18,19]. Extracting the best and optimum rules for predicting problems is so difficult. Therefore, in some cases neural network is used to extract fuzzy rules. Adaptive neuro-fuzzy inference system (ANFIS) is the fuzzy system which is trained by neural network [20]. For example, ANFIS was used to predict thermal

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https://doi.org/10.1016/j.porgcoat.2018.02.029
Received 9 October 2017; Received in revised form 3 January 2018; Accepted 26 February 2018

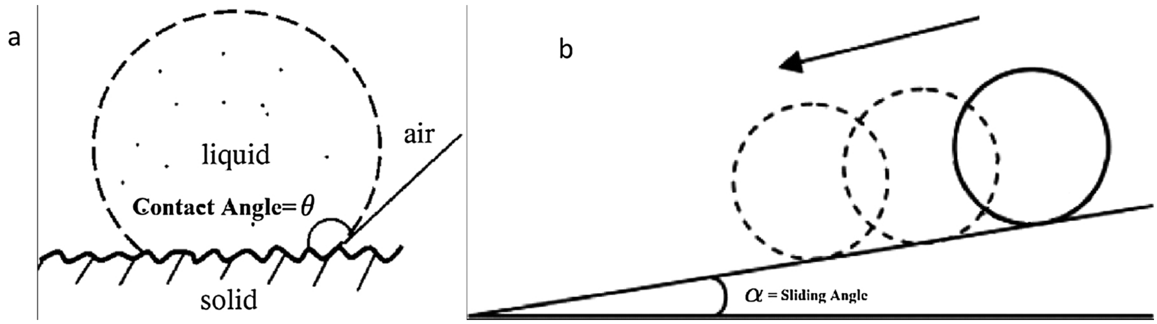

Fig. 1. Schematic of static contact angle (a) and sliding angle (b).

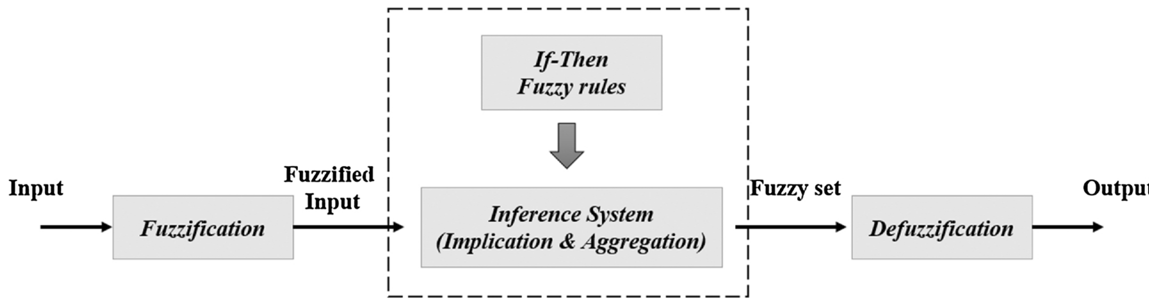

Fig. 2. Structure of a fuzzy inference system.

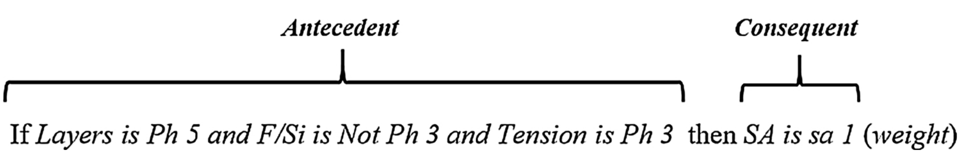

Fig. 3. If-Then rule of the fuzzy inference systems.

Table 1
Some samples of under studied dataset.

variables				Angles (degree)	
layers	F/Si	Roughened with the abrasive paper	Surface tension of liquid	Static contact Angle (CA)	Sliding angle (SA)
Sb-Micro-Submicro-Nano	2	0	72.8	170	1
Micro-Submicro-Nano	3	S80	72.8	146	15
Without coating	1	S80	72.8	125	41
Sb-Nano	2	0	23.8	72.5	70
Without coating	1	0	48	88	90

Table 2
Defined quantitative codes for qualitative variables.

Layers			**Roughened with the abrasive paper**	
Qualitative variable	**Surface treatment**	**Quantitative value**	**Qualitative variable**	**Quantitative value**
Wc	Without coating and sandblasting	10	Without abrasive paper	10
Sb	Sandblasting	20	S80 abrasive paper	20
Nano (N)	Coating with silica nano-particles	30		
SB-Nano (SbN)	Sandblasting and then coating with silica nano-particles	40	**F/Si**	
Micro-Nano (MN)	Coating with silica micro and nano-particles	50	**Qualitative variable**	**Qualitative variable**
SB-Micro-Nano (SbMN)	Sandblasting and then coating with silica micro and nano-particles	60	1	10
Micro-Submicro-Nano (MSN)	Coating with silica micro, submicro and nano-particles	70	2	20
SB-Micro-Submicro-Nano (SbMSN)	Sandblasting and then coating with silica micro, submicro and nano-particles	80	3	30

contact conductance between exhaust valve and its seat in another previous study [21]. The prediction of surface wettability by using artificial neural network (ANN) based models has rarely been reported in the literature [22–24]. Hadavi Moghadam et al. [22] predicted the CA of water droplets on the electrospun fiber mat by ANN based model. In another study, the surface hydrophobic behavior of plasma-treated cotton fabric was predicted by using ANN model [24]. Malik et al. used an ANN model for prediction of the hydrophobicity of silica coated dyed cotton fabric [23]. In all mentioned studies, the prediction of SA has not been considered. Also, the fabrication method of amphiphobic surfaces and the kind (type) of substrate which has been used in the present study is very different from previous studies. Most importantly, the predicting model we used in this study is different from other rare works.