Influence of surface structures on wettability

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Abstract. Wettability of solid surfaces is a key parameter for many industrial applications of solid materials. The wettability is influenced not only by the nature of the material but also by the existence of surface structures. Crucial influence of the oriented surface structures on the shape of liquid drop was observed in this study. Observed differences in value of contact angle measured on the metal surface at two perpendicular directions were 19° for water and 23° for diiodomethane. These surface structures can significantly influence liquid and heat transfer on structured surfaces.

1 Introduction

The surface structuring of metallic materials significantly affects their application properties. Research aimed at formation of these structures is thus at the forefront of interest not only in the field of materials technology, but also in the field of basic materials research. Recently, methods using intense laser radiation [1] have been investigated, which are useful for structuring of the surface of metallic materials preparing wide scale structures from micrometric to nanometric. Since the first research bringing the method of laser surface texturing (LST), number of specific methods have been developed, differing mainly in the type of laser used, where the basic parameters are the wavelength of radiation as well as a pulse time. The last parameter significantly affects the dimensions of the resulting surface structures. Probably the most commonly used for surface structuring are femto-second lasers, with which surface structures with dimensions from tenths up to tens of micrometers can be achieved by a combination of power and the number of laser’s pulses repetitions - laser induced periodic surface structuring (LIPSS) [2]. With picosecond lasers, up to submicrometric surface structure dimensions were achieved by the method commonly named as picosecond direct laser interference patterning (ps-DLIP) [3]. On the other hand, with nanosecond lasers, structures up to hundreds of micrometers in size can be created [4].

The effect of surface texturing is manifested mainly in the change of wettability of surfaces [5] and associated effects such as self-cleaning [6], adhesion of microorganisms [7], corrosion resistance [8], improving of adhesive bonding [9] and wear resistance [10], reduction of friction [11] etc. Another interesting effect relates to specific geometry of surface structures in the case of their linear arrangement to a line-pattern. This is manifested in the case of wetting with biaxial drop shaping [12], or in the so-
called wetting anisotropy [13]. This phenomenon causes interesting effects especially in the transport of heat [14] and liquids [16] over such a structured surface. 

Presented study is focused on the evaluation of the influence of laser-generated microstructures on the process of wetting metal surfaces. The wetting process is monitored using goniometric measurements of static contact angles using standard liquids with polar (water) and non-polar (diiodomethane) character. The aim of this study is to evaluate the influence of linearly arranged surface structures on the wetting process in terms of the wetting anisotropy.

2 Materials and methods

The metal surfaces used for this study, designated as VUTS and C1, were prepared at company HOFMEISTER s.r.o. They are plates with dimensions of 9 x 9 x 3 mm, which surfaces are modified by laser method forming linear surface structures. The basic substrate (steel) is covered by layer of sintered carbide based on WC + Co (approx. 8%), and by the subsequent layer of 4th generation called nAlCrO4 with a thickness of about 3 µm composed from nanocrystalline AlCrN grains, which are embedded in an amorphous Si3N4 matrix. The final layer consists of a nc-AlCrN / a-Si3N4 nanocomposite coating, forming a quaternary (four-component) nanocomposite. Silicon is involved in the formation of the nanocomposite structure, the addition of which to CrAlN can significantly affect grain size, phase composition, and mechanical properties of the coating, and generally also serves to improve nitride coatings. In general, quaternary nanocomposite coatings have better properties than ternary coatings, of the TiAlN or CrAlN type, due to higher hardness, toughness, corrosion resistance as well as higher temperature resistance up to 1100 °C.

To measure the contact angle, a KRÜSS GmbH device marked KRÜSS DSA30 was used in conjunction with the ADVANCE software (version 1.4.1.2) of the company of the same name, which was used to evaluate the shape of the drop and thus the contact angle. The non-polar liquid chosen for determining the contact angle was diiodomethane (Sigma-Aldrich s.r.o.; 99%), due to its zero value of the polar contribution to the surface tension, and the polar liquid was ultrapure water (conductivity 18.2 MΩ ∙ cm at 25 ºC). The geometry of the surface treatment was evaluated using optical microscopy (Olympus BX-50p polarizing microscope). The Olympus Lext OLS 5000 confocal laser scanning microscope and the Taylor Talson Form Talysurf Series 2 contact profilometer were used to obtain the exact geometry of the surface structures of the VUTS sample.

Measurements on a droplet shape analyser were preceded by cleaning of the plate surface. The plates were washed with ethanol and then dried in an oven at 60 °C for fifteen minutes, and then stored in a desiccator until were taken for measurement. Drops with a volume of 4-5 µl were placed manually on the plate surface using a Hamilton microsyringe. The measurement of the droplet shape was repeated 6 times, the results show the average values from these six measurements.

3 Results and discussion

3.1 Geometry of surface structures

The geometry of the studied surface structures is documented by optical microscopy images (figure 1) and geometric models derived from these images (figure 2). The surface of the VUTS type plates is arranged in mutually parallel grooves with a fine transition, resembling the shape of waves, which are 118 µm apart. The grooves are also parallel to the diagonal of the plate. The surface structure of C1 type plates has a similar treatment as VUTS, but in this case some difference can be observed. The sample again resembles the shape of waves spaced 107.5 µm apart, which are parallel to each other. However, lines are parallel to the edge of the plate and the lower part of the pattern is intermittent and resembles the shape of welds that are on average 58 µm apart.

Accurate evaluation of the surface treatment of the VUTS type plate was performed using confocal laser scanning microscopy. The profile recorded from the center of the surface structures is shown in figure 3, from which can be seen that the exact distance of the wave peaks is 81.5 µm and the profile depth is 18.06 µm. This geometry was verified by measurements on a Form Talysurf Series 2 contact
profilometer, which showed very similar dimensions obtained by confocal laser scanning microscopy (figure 4).

Figure 1. Microscopic images of the surface of a) VUTS type and b) C1 type plates. Magnification 200x.

Figure 2. Models of geometry of surface structures of plates of a) VUTS type and b) C1 type.

Figure 3. Image of the surface of VUTS type plate from a confocal laser scanning microscope.

Figure 4. Surface geometry of VUTS type plate from Form Talysurf Series 2 profilometer. Legend: Aktuální bod=Actual point; Referenční bod=Reference point; Rozdíl=Difference
3.2 Wetting of surface structures
The wettability of the surface-structured plates was measured by the goniometric method on a KRÜSS DSA30 instrument. Water and diiodomethane were chosen as test liquids. Diiodomethane is a standard liquid used in the evaluation of the surface energy of solids as a non-polar solvent with a high value of surface tension. Therefore, it is possible to study non-polar interactions on a number of surfaces, where common organic liquids provide perfect wetting. The two studied surface structures did not differ significantly in their geometry, but it was essential for the study itself that in one case the linear surface structure was oriented parallel to the edge of the test plate, while the other was oriented diagonally. Due to the parallel orientation of linear surface structures it is possible to study the shape of the drop in two directions perpendicular to each other with respect to the optical axis of the measuring system. The measured values of contact angles on studied samples and for different orientations are given in table 1 as averages from measurements on 6 separate drops. Typical test liquid drop profiles are shown for water in figure 5 and for the diiodomethane in figure 6.

| Liquid          | Contact angle (°) |
|-----------------|-------------------|
|                 | VUTS      | C1 ⊥   | C1 ||   |
| Water           | 86±1.5    | 85±3.2 | 104±0.5 |
| Diiodomethane   | 41±1.0    | 48±2.7 | 71±1.6  |

Legend: ⊥ the optical axis is perpendicular to the surface structure
       || the optical axis is parallel to the surface structure

Figure 5. Typical profiles of water droplets on surfaces a) VUTS, b) C1⊥ and c) C1||.

Figure 6. Typical profiles of diiodomethane droplets on surfaces a) VUTS, b) C1⊥ and c) C1||.
The obtained results are in accordance with previously published studies describing the so-called wetting anisotropy [13]. In the case of different orientation of the optical axis of the measuring system with respect to the line of surface structures, the values of the contact angle differed for water by 19°, for diiodomethane even by 23°. These values are very similar to previously published results of studies with similarly structured metal surfaces [16]. However, it is interesting that in the case of the diagonal orientation of the linear surface structures (angle 45° to the optical measurement axis), the contact angles are closer to the situation for the perpendicular direction of the surface structure lines to the optical measurement axis. The differences in the magnitude of the contact angles observed in mutually perpendicular directions are explained by the existence of capillary forces which cause a drop of test liquid to flow in a direction parallel to the lines of the surface structures [17]. This is also a very probable reason for the transport of liquids over the surface in this direction in dynamic systems, which are closer to the situation of real practice in the interaction of such a modified surface of the machining tool with the cutting fluid. In the same direction, heat transfer is facilitated, which, with a suitable orientation of the surface structures, can help to more efficiently cool a part of the tool in contact with the material to be machined. The study of similarly structured surfaces can thus bring important knowledge for improving the service life of machine tools in mechanical engineering.

4 Conclusions

The performed study proved the fundamental influence of linear surface structures on the wetting of such treated surfaces from the point of view of asymmetry of the wetting angle observed on the droplet in two mutually perpendicular directions. Linear surface structures can thus directionally affect the interaction of liquids with metal surfaces, which to a large extent affects the important properties of cutting tools used in mechanical engineering, in particular the wear resistance of the tool surface.

Acknowledgments

The authors acknowledge financial support by Internal Grants of Palacky University in Olomouc (IGA_PrF_2020_034 and IGA_PrF_2020_007).

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