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Dropwise condensation of steam on ion implanted titanium surfaces

M.H. Rausch, A. Leipertz, A.P. Fröba *

Lehrstuhl für Technische Thermodynamik (LTT), Universität Erlangen-Nürnberg, Am Weichselgarten 8, D-91058 Erlangen, Germany

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ABSTRACT

Stable dropwise condensation of steam was achieved by ion beam implantation of N^+ on titanium surfaces stabilized by a preoxidation procedure. It is pointed out that dropwise condensation can be adjusted by ion implantation in spite of increased wettability indicated by contact angle and surface free energy measurements. Our results suggest a nucleation mechanism possibly caused by interactions of nanoscale surface roughness and surface chemistry effects connected with precipitation of nitrides. Measured heat transfer coefficients for dropwise condensation were up to 5.5 times larger than values calculated by Nußelt film theory. No significant influence of the applied ion implantation parameters was found.

1. Introduction

Titanium is an important material for heat transfer equipment when high corrosion resistance is required. For example, it is used in combined water evaporation/condensation units for mechanical vapor compression desalination plants [1]. In such units, which in most applications are tube bundle or plate heat exchangers, the enhancement of the overall heat transfer coefficient implicates advantages for the desalination process. An increased mass flow of product water, a reduced heat transfer area, or a decreased temperature difference between condensation and evaporation side can be obtained. In the last case, the pressure rise from evaporation to condensation chamber accomplished by a compressor can be reduced. In practice, the choice of one of the mentioned advantages or adequate combinations is an optimization problem regarding investment and operating costs [2].

If there are no other dominating heat transfer resistances, the overall heat transfer coefficient can be augmented by enhancing the condensation heat transfer coefficient (CHTC). One possible approach for this purpose is the adjustment of dropwise condensation (DWC). For this condensation phenomenon, the CHTC is up to one order of magnitude larger compared with filmwise condensation (FWC) [3]. The reason for this effect is the frequent exposure of free wall surface to the steam caused by the DWC dynamics. Metallic surfaces normally show FWC due to their relatively high surface free energies. Therefore, appropriate surface modifications have to be applied for the adjustment of DWC on metals like titanium. The use of coatings with low wettability may cause an additional heat transfer resistance and often fails due to mechanical instabilities. Thus, a direct modification of the metallic surfaces is preferable. Previous work at LTT-Erlangen showed that implantation of nitrogen ions can induce stable DWC of steam on metals, e.g., stainless steel and the aluminum alloy Al 6951 [4,5]. With titanium, DWC periods of not more than a few weeks have been observed so far, probably limited by advancing oxidation effects [6].

For inducing stable DWC by ion implantation, fundamental knowledge on the changes of the metal surface characteristics and their influence on the condensation form is necessary. Until now, it is more or less speculative which effects are the real origins of DWC on ion implanted metals. Contributing to a fundamental understanding, results for the adjustment of stable DWC of steam on nitrogen ion implanted titanium surfaces with different pretreatments are discussed in this paper. In addition, the heat transfer performance of such surfaces is demonstrated by CHTC measurements with saturated steam.

2. DWC by ion implantation

Various experiments have shown that DWC of steam on metals can be induced by ion implantation. Nevertheless, no consistent theoretical explanation for this effect could be found so far. The approaches available in literature were summarized by Zhao and Burnside [7] and are all based on a reduction of the surface free energy γ_s. Referring to the fundamental equation

$$\gamma_s = U_s - TS_s, \tag{1}$$

* Corresponding author. Tel.: +49 9131 85 29789; fax: +49 9131 85 29901.
E-mail address: apf@ltt.uni-erlangen.de (A.P. Fröba).

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Nomenclature

A	area (m^2)
$\bar{c}_p$	mean specific heat capacity at constant pressure (J kg^{-1} K^{-1})
h	heat transfer coefficient (W m^{-2} K^{-1})
Δh	heat of vaporization (J kg^{-1})
$\dot{m}$	mass flow (kg s^{-1})
R_a	mean surface roughness (m)
S	entropy (J m^{-2} K^{-1})
T	temperature (K)
U	internal energy (J m^{-2})
W	work (J m^{-2})

Greek symbols

γ	free energy, interfacial tension (N m^{-1})
Θ	contact angle (rad)

Subscripts

a	adhesion
c	condensation
cond	condensate
exit	at the exit of the apparatus
LV	liquid/vapor interface
s	surface
st	steam
SV	solid/vapor interface

Superscripts

d	disperse
p	polar

Abbreviations

AFM	atomic force microscopy
CHTC	condensation heat transfer coefficient
DWC	dropwise condensation
FWC	filmwise condensation

where T is the absolute temperature, the decrease of γ_s is explained with an increase of the surface entropy S_s. This is ascribed to an increased disorder in the surface caused by the implanted foreign elements. In addition, the surface internal energy U_s is decreased in case the ion energy is high enough to reduce the interatomic bond energy in the surface. In some cases, ion implantation may even cause a transition of the surface state from crystalline to amorphous. This effect is accompanied by a measurable reduction of the modulus of elasticity, which is directly proportional to γ_s. According to double electric layers theory, implanting elements with weak metal properties like nitrogen can significantly reduce the number of free electrons on the metal surface and hence γ_s. The relation between γ_s and the composition of two component systems, expressed by Gibbs' equation, suggests that surface alloys with low γ_s can be produced by implanting elements like F, C, or O. Finally, similar to Beilby layers evoked by polishing processes, the impact of the implanted ions may induce compressive stress in the surface layer. Thus, the repellent forces between the atoms are increased and γ_s is decreased.

For a plane solid surface, γ_s is approximately equal to the interfacial tension between the solid and the vapor γ_{SV}. It also contains information on the wettability of the solid surface as given by the Young-Dupré equation [8],

$$W_a = \gamma_{LV}(1 + \cos\Theta). \tag{2}$$

Eq. (2) describes the work of adhesion W_a between a liquid and a solid surface. It implies the interfacial tension between liquid and vapor γ_{LV}, which is also known as the surface tension of the fluid. The contact angle Θ for idealized conditions is given by Young's equation [9]. According to Owens and Wendt [10], the interfacial tensions can be described by disperse and polar contributions,

$$\gamma = \gamma^d + \gamma^p. \tag{3}$$

Combining Eq. (3) with Girifalco and Good's [11] geometric averaging approach, W_a can be expressed by

$$W_a = 2\left(\sqrt{\gamma_{LV}^d\gamma_{SV}^d} + \sqrt{\gamma_{LV}^p\gamma_{SV}^p}\right). \tag{4}$$

The combination of Eqs. (2) and (4) yields

$$2\left(\sqrt{\gamma_{LV}^d\gamma_{SV}^d} + \sqrt{\gamma_{LV}^p\gamma_{SV}^p}\right) = \gamma_{LV}(1 + \cos\Theta), \tag{5}$$

where Θ increases for a given fluid when the disperse and polar contributions of γ_{SV} decrease. The same conclusion results from the approach by Wu [12],

$$4\left(\frac{\gamma_{LV}^d\gamma_{SV}^d}{\gamma_{LV}^d + \gamma_{SV}^d} + \frac{\gamma_{LV}^p\gamma_{SV}^p}{\gamma_{LV}^p + \gamma_{SV}^p}\right) = \gamma_{LV}(1 + \cos\Theta), \tag{6}$$

which is considered to be more exact for solids with $\gamma_{SV} < 35$ mN m^{-1}. Here, W_a is determined with the harmonic mean values of the contributions of the interfacial tensions. Thus, according to the approaches summarized by Zhao and Burnside [7], implantation of nitrogen ions should always produce surfaces with decreased surface free energies and increased contact angles.

In contrast to this straight forward conclusion, our previous studies with aluminum alloys [5] already showed that many side effects have to be taken into account. Further influences on the condensation form were found, e.g., the macroscopic surface roughness, alloy composition, oxidation effects, ion implantation parameters, and even applied implantation techniques. Hence, the current approaches must be checked by further experiments, which may reveal new insight into the origin of DWC by ion implantation.

3. Experimental

3.1. Surface preparation

Discs with a diameter of 60 mm and a thickness of 12 mm for visual observations as well as plates with a condensation area of 240 mm × 50 mm and a thickness of 10 mm for heat transfer measurements were prepared from commercially available titanium grade 1. Most of the samples were polished, resulting in a mean surface roughness R_a of approximately 0.15 µm. For the unpolished samples, R_a was about 0.5 µm. Before ion implantation, some of the samples were preoxidized by permanent condensation of steam at 100 °C for at least one day. These samples were cleaned with deionized water and a soft cloth afterwards. The preoxidation and cleaning process was repeated until no more oxidation products could be found on the cloth. Thus, the titanium surface could be considered to be completely passivated. After further cleaning