LASER TREATED METAL HEAT EXCHANGERS FOR BOILING HEAT TRANSFER ENHANCEMENT

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Abstract

Laser treatment of metallic layers can significantly change the morphology of the surface. Due to the action of the laser beam, the surface roughness considerably increases. Moreover, laser can modify the shape of the samples to produce the extended surface of longitudinal fins. The paper discusses the development of such metal heat exchangers as well as the effects of laser beam treatment on the surface characteristics. The test results of surface morphology were presented and discussed. The samples produced in the course of the experiments were used to test their performance for boiling heat transfer of two working agents (distilled water and ethyl alcohol under ambient pressure). The test results indicated a significant improvement in heat flux in relation to the unmodified surface (without laser treatment). The laser treatment method proved to provide considerable advantage over the unmodified surface.

Keywords: Laser treatment, heat exchanger performance

1. INTRODUCTION

Laser treatment technology offers significant possibilities for shaping the surface geometry and morphology. The application of laser in modern engineering systems enables to produce various elements of improved properties including anti-wear coatings, coverings of increased resistance as well as enhanced heat transfer performance, which is considered in the present paper due to the significant possibilities for practical applications.

Kruse et al. [1] tested water boiling heat transfer on heaters that were modified with a femtosecond laser. The generated coatings were made of microstructures surrounded by dense layers of nanoparticles. The roughness of such samples amounted to 1.4 - 7.8 μm. It was reported that the maximal value of heat transfer coefficient was almost three times bigger in comparison to the polished sample. Ho et al. [2] analysed boiling of FC-72 on surfaces produced with laser from AlSi10Mg base powder with micro-cavities separated by grooves. The diameters of the cavity mouths were 500 and 700 μm. The applied method of selective laser melting also made it possible to generate micro-fin samples. The authors observed up to 70% increase in heat transfer coefficient for the treated samples. Zakšek et al. [3] focused their experiments on 25-μm-thick stainless steel foils treated with pulsed fiber laser, on which boiling took place. The laser beam generated textured lines of the width from 0.5 to 2.5 mm. The value of the heat transfer coefficient was even 2.8 times in relation to the the smooth. Zupančič et al. [4] tested boiling on stainless steel foils, which were modified by laser texturing method with the use of a nanosecond laser. The lines generated on the specimens were within the distance of 10 to 200 μm from each other. It was found out that the laser treatment provided considerable increase (up to 110%) of the heat transfer coefficients. The experimental analysis of heat transfer performance of polydimethylsiloxane-silica laser modified coatings has been provided in [5]. The laser beam produced square patterns of the spot size up to 2 mm^2. The biggest heat fluxes were dissipated from the specimen whose spot size was the smallest. Može et al. [6] used laser texturing with a nanosecond fiber laser (one made in air and the other in argon atmosphere) to produce the samples. The enhancement of the heat transfer coefficient reached over 115% in relation to the smooth (untreated) surface. Karthikeyan et al. [7] focused their experiments on a combined impact of laser treatment of surfaces and the use of nanofluids. A femtosecond laser micromachining was applied to generated periodic nanoscale and dual scale roughness of the surface. As a result of such dual enhancement it was possible to obtain almost 60% boiling heat transfer improvement. Nirgude and Sahu [8] presented a study of boiling on copper heaters modified with a nanosecond laser. The generated specimens used in the experiments had longitudal grooves and surface roughness of about 0.24 - 0.29 μm. The value of the heat transfer coefficient of the produced samples was maximally 1.8 times larger with reference to the unmodified surface.

Apart from laser treatment of heaters, other boiling heat transfer augmentation techniques and methods are used (as discussed for example in [9,10]). However, due to the significant ease of surface morphology modification and the considerable possibilities offered by the laser treatment in view of heat flux improvement, this technique will be considered in the present study.

The obtained results are directly in the area of interest of the energy industry [11], but may also be useful in the case of other issues, including corrosion protection [12,13], fracture toughness improvement [14,15], overall quality improvement of final products [16-18] and thus reduction of associated risks [19]. This may be of particular interest for military applications [20]. The results are also very useful for research practice, including in the field of modification of existing [21,22] and production of new materials [23,24], improvement of corrosion resistance [25], including biotechnological apparatus [26] and introducing favorable changes in mechanical properties [27,28], including acoustic [29,30] and fatigue [31].

2. LASER TREATMENT OF HEATERS – SURFACE CHARACTERISTICS

The study involves the modification of the copper surfaces with laser. This process was conducted with the SPI G3.1 SP20P pulsed fiber laser. The production of the samples required the use of impulse frequency of 60 kHz, pulse duration of 60 ns and scanning velocity of 200 $mm \cdot s^{-1}$. The power value was 20 W. As result of this production procedure, the longitudal grooves have been generated on the samples, as presented below in (**Figure 1**).

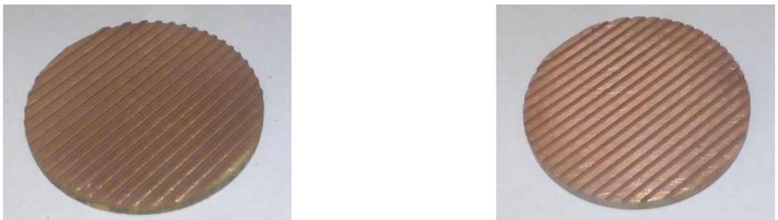

Figure 1 Copper samples produced with laser and used in the experiments: A (on the left), B (on the right)

Sample A had the groove depth of 0.55 mm and groove width of 1.15, while sample B: groove depth 0.25 mm and its width 0.60 mm. The diameter of the specimens was the same and amounted to 3 cm, while their height 3 mm. The laser beam applied on pure copper substrates produced changes both in macroscale (grooves) and in microscale (surface roughness). The generated grooves are highly regular as seen in (**Figure 2**) due to the fact that the metal material evaporated in the area of the laser spot movement. A characteristic feature is the edge at the entrance to the groove (clearly visible on the left side).

The microstructure made with the laser is characterized by increased roughness, which – in the case of boiling (and condensation) heat transfer enhancement – is considered as a highly favorable feature. The analysis of the surface at the bottom of the groove of sample A indicates that its surface roughness is 7.81 μm (with the standard deviation 1.75 μm, minimal and maximal values: 3.04 μm and 13.37 μm, respectively). That is over ten times the value the untreated sample. A selected spot of the laser modified surface has been presented in (**Figure 3**).

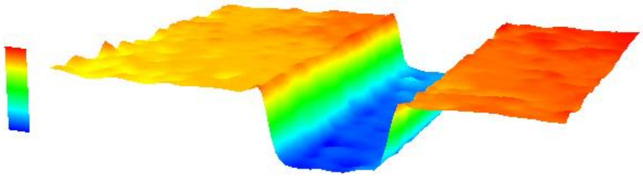

Figure 2 3D image in pseudo color of sample B from an optical microscope, magnification 140x

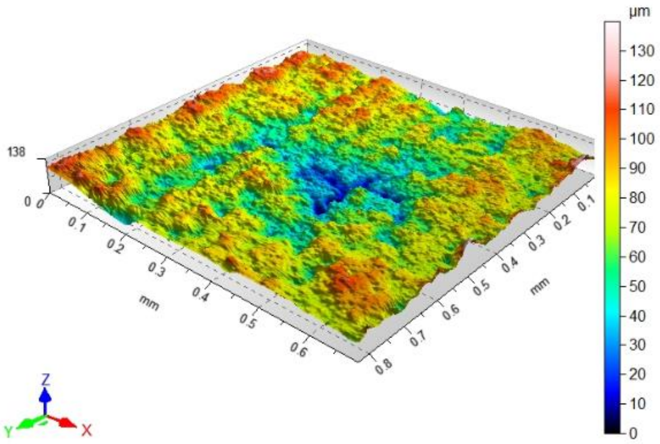

Figure 3 Surface morphology of the bottom of the groove (selected spot)

The irregularity of the surface in the microscale is further visualized in the profile of the selected line (**Figure 4**), where the changes of the peaks and valleys can be easily noticed. Their character seems to be random with significant changes in the up and down direction.

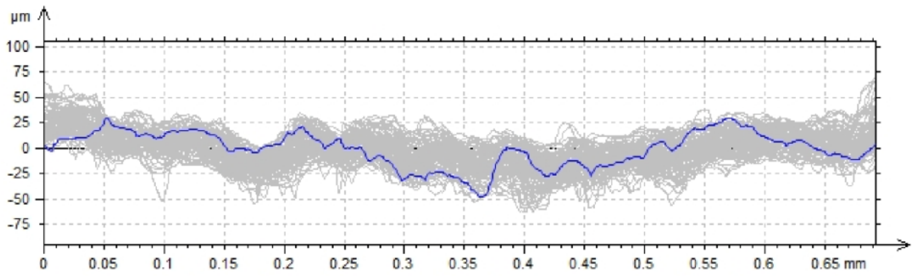

Figure 4 Profile of the selected line

3. BOILING HEAT TRANSFER TESTS

The experiments have been performed under ambient pressure for boiling of distilled water and high purity ethanol. The samples were located horizontally and attached to the heater by soldering. They were heated from below with an electric heater with the power changed at given steps to generate up to 5 experimental points for each specimen. The obtained dependence of heat transfer coefficient for the two boiling agents have been presented below in (**Figure 5**). The values of the heat transfer coefficient (and, consequently, heat fluxes) for both water and ethanol rise quickly with rising surface temperature over the saturation temperature (this difference is defined as superheat and denoted θ), however when a certain value is achieved (this value is lower in the case of ethanol) that increase becomes smaller and might diminish. This phenomenon is more clearly visible for boiling of ethyl alcohol, but it might also be anticipated for higher superheats in the case of distilled water (above 7 K). The values obtained for water and typically higher than for ethyl alcohol. It might be explained by the thermal properties of water (especially the value of heat of vaporization and thermal conductivity), but also a higher bubble departure diameters than in the case of pure ethanol. It might also be noticed from the figure that boiling was initiated at smaller superheats (below 2.7 K) in the case of ethanol, which can also be linked with the bubble diameters and the geometric dimensions of the cavities generated with the laser beam, where these bubbles can grow.

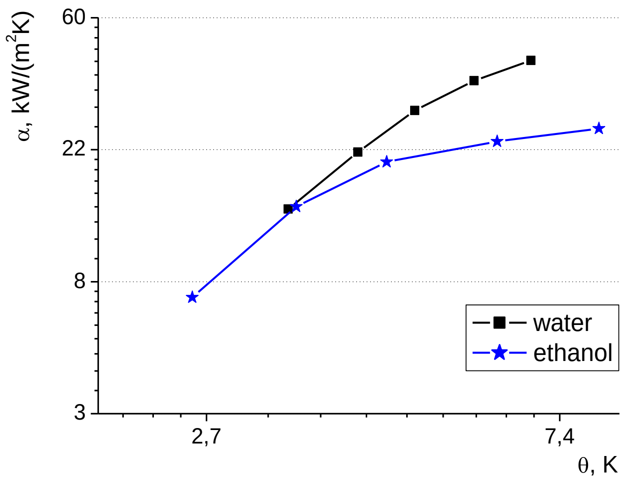

Figure 5 Heat transfer coefficient for the laser treated surface (sample A)

The study of heat transfer of laser modified surfaces have also indicated a significant improvement over the case, when such modification has not been applied. The heat flux (and heat transfer coefficient) transferred from the modified sample has been almost eight times larger than for the smooth surface – as shown in (**Figure 6**) (where the ratio of heat flux from the laser modified specimen to the heat flux from the smooth surface has been presented as the enhancement ratio in the range of superheat values between 7 K and 10 K).

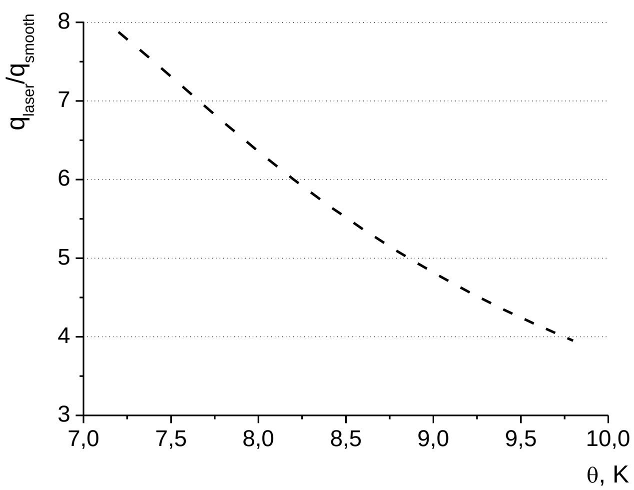

Figure 6 Enhancement ratio for water (sample B)

As can be seen in the figure above, the enhancement ratio decreases with rising superheat values, however it is still much bigger in relation to the untreated smooth surface (about four times larger for the temperature difference of ca. 10 K). The enhancement has been undoubtedly caused by increased roughness of the surface and the presence of cavities – favorable locations where vapor bubbles can be grown. This phenomenon is commonly considered as one of the reasons for elevated heat fluxes in phase change processes. It should also be noted that the rate at which the enhancement ratio falls is considerable. It might be linked with the activation of new nucleation sites (places on the surface where vapor bubbles are created) on the smooth surface, which – in the case of the current experiment – was characterized by some roughness (though much smaller than for the laser treated specimens).

From the practical point of view, the application of laser modified heat exchangers for phase – change heat transfer processes can result in more heat being exchanged at the same temperature differences or the heat flux can be maintained at the same level as for the smooth heat exchanging elements, but the laser treated heat exchangers can be produced smaller and lighter. Thus, the machines in which they are installed might be more compact and consume less fuel due to reduced weight (if they are located on transport means).

3. CONCLUSION

The laser treatment of surfaces used as heat exchangers considerably changes the surface morphology – both in the macro- and microscale. It is a highly effective way of producing increased roughness. This provides additional locations where bubbles can be created during boiling. As a consequence, heat transfer coefficients and heat fluxes exchanged during this phenomenon increase and the whole process is enhanced. The advantages of using laser treatment for this types of metal heat exchangers are quite straightforward and should ensure that more and more devices used for example in refrigeration or heat pump systems might be developed with the use of laser for their improved efficiency and high reliability.

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