Laser Treatment Technique for Boiling Heat Transfer Application

ORMAN Łukasz J.[1, a *], RADEK Norbert[1, b], PIETRASZEK Jacek[2, c],
HONUS Stanislav[3] and DZIEDZIC Joanna[4, d]

[1]Kielce University of Technology, al. Tysiaclecia P.P.7, 25-314 Kielce, Poland

[2]Cracow University of Technology, Al. Jana Pawła II 37, 31-864 Cracow, Poland

[3]Technical University of Ostrava, 17. listopadu 2172/15, 708 00 Ostrava-Poruba, Czech Republic

[4]Jan Kochanowski University of Kielce, ul. Uniwersytecka 15, 25-406 Kielce, Poland

[a]orman@tu.kielce.pl, [b]norrad@tu.kielce.pl, [c]jacek.pietraszek@mech.pk.edu.pl,
[d]s145704@ujk.edu.pl

Keywords: Boiling, Laser Treatment, Surface Treatment

Abstract. The article discusses the use of laser treatment to produce surfaces that enhance boiling heat transfer. The laser beam has been applied on copper substrates to generate longitudal fins of regular geometry. The altered morphology pattern enables to dissipate higher heat flux values than the smooth, untreated surface – in the case of distilled water and ethyl alcohol as boiling agents. The issue of modeling nucleate pool boiling heat flux on laser processed surfaces is discussed in the paper considering two selected models of boiling.

Introduction

Boiling is a highly complex phenomenon. It allows to exchange considerable heat fluxes at small temperature differences and – as a result – has a significant practical application potential. It is commonly known that the application of additional layers or surface modifications can increase the heat flux values being exchanged. Piasecka et al. [1, 2] considered laser texturing as the method of enhancement for flow boiling conditions, while Kaniowski and Pastuszko [3, 4] focused on the pool boiling mode. In [3] water boiling on samples with microchannels containing long fins of 0.2 - 0.5 mm depth was analyzed. It turned out that the largest heat flux was almost 2.5 times bigger then the in the case of the smooth surface. A different medium (namely, FC-72) was used on the same type of microstructures in [4]. Similarly, enhancement of boiling was observed. The heat transfer coefficient was higher by over 500% - reaching values comparable to those obtained when nanotubes are applied. Pranoto et al. [5] tested sub-cooled boiling of HFE-7100 and the influence of the geometrical shape of pin fins on heat flux. The authors studied surfaces containing 196 and 144 microfins and reported that rectangular fins performed better than the circular ones. Moreover, the flow resistance of both types of pin fins was compared and the rectangular ones show ca. 1.06 times higher resistance, which leads to smaller bubble departure frequency. It was concluded that both kinds of microstructures enhanced boiling due to agitated movement caused by evaporation as well as the rewetting process at bubble detachment. Chinnov et al. [6] experimentally analyzed water boiling on heaters with different patterns of hydrophobic spots made on the copper surface as well as the surface covered with a matrix of micrococoons made of silicon oxide nanowires. It was reported that biphillic heaters showed better performance that non-biphillic ones. Moreover, the morphological texture of the surface, the shape of the hydrophobic areas or their production method did not have a considerable influence of the heat exchange process. However, the heat flux values depend on the hydrophobic spot size, the distance between the spots as well as the number of those spots. Belyaev et al. [7] tested the augmentation of flow boiling caused by modifying the inner surface of the vertical channel with the laser. The laser treatment developed formations of various heights and diameters. It was stated that the treatment of the surface with laser improved heat transfer conditions. The largest impact was recorded at the reduced pressure of 0.43 with the maximal increase in the critical heat flux of over twenty percent. Considerable rise in heat transfer coefficient was also reported.

Due to the fact that there exist large opportunities offered by the laser treatment the present paper aims to address the issue of surface modification with laser and provide data on the boiling performance of the laser treated heater with the focus on modeling boiling heat flux. The problem is especially important for the proper design of heat exchangers produced with the laser technology.

The technique presented here, which utilizes lasers to modify the surface morphology affecting heat transfer, can also find application in other laser processing cases where surface morphology is a crucial process or technological factor [8-10]. Changing the characteristics of the surface layer is a frequently employed solution [11-13], with image analysis serving as a vital diagnostic tool [14-16]. Such modifications are of interest not only in the energy sector [17] but also in hydraulic power systems [18,19] and the broader field of material engineering [20-22]. Modifying the surface layer morphology significantly contributes to reducing machine part wear [23-25], improving the quality of products in the automotive [26,27] and railway industries [28,29], which, in turn, serves as inspiration for new quality control methods [30-32] applied in the automotive [33,34] and metal industries [35,36]. Such quality enhancements substantially limit the range of potential failure scenarios and their consequences [37-39], enabling the effective implementation of lean manufacturing principles [40-42].

Samples and Experimental Method

The preparation of the samples begins with cutting copper discs – 3 cm in diameter and 3 mm in height. Afterwards, the laser treatment occurs with the use of SPI G3.1 SP20P pulsed fiber laser with the focal spot size of 35 μm and power of 20 W. The pattern of the longitudal fins is made on the specimen within ca. 2 hours according to the design drawn using the appropriate software. Fig. 1 presents the sample with microfins.

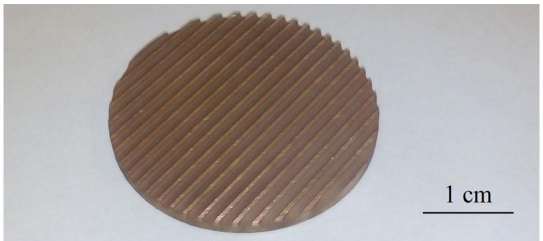

Fig. 1. *Laser treated sample with longitudal fins.*

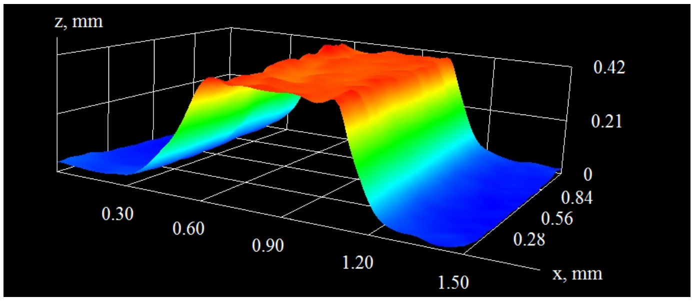

Fig. 2. *Optical microscope image of the laser made microfin.*

The laser treatment evaporated some of the material and, thus, the fins and grooves are created. However, the shape of the fins is not rectangular, but they are thinner at the top and broader at the base of the sample. Fig. 2 presents the optical microscope image of the fin, which confirms the statement regarding the shape of the produced element. It also needs to be added that the laser beam produces rough surface at the base of the sample (between the fins). It is the additional advantage for boiling heat transfer enhancement due to the fact that this type of surface morphology provides additional nucleation sites (locations where the vapor bubbles can develop). This leads to more heat being exchanged, especially at small temperature differences, due to large heat of vaporization and the motion of the bubbles that improve convective heat transfer.

The shape of the fin that becomes thinner at the tip is favorable because the vapor bubbles generated at the base of the sample can flow into the pool of liquid (and later to the surface) more easily. Consequently, heat transfer is further improved. This advantageous shape of the microfins can be naturally obtained due to the laser beam interaction with the material of the sample and would otherwise be difficult to obtain using mechanical methods. The drawback of the laser technique might be the time-consuming process of samples' preparation.

The tests are done on the experimental set-up, which consists of the electric heater. The sample is soldered to this heater and above it the pool of liquid is located. Two kinds of boiling liquids are considered by the authors: distilled water and ethyl alcohol. The rising electric power supplied to the heater leads to increasing the temperature of the sample and, consequently, boiling curves can be prepared as a dependence of the heat flux (q) vs. temperature difference (θ), calculated at the difference between the sample temperature and the saturation temperature of the boiling fluid.

Results and Discussion

The test result of the laser processed surface will be presented for the sample of microfin height of 0.25 mm, microfin width of 0.5 mm and groove width of 1.5 mm. The process of bubbles' formation on the sample as well as their movement in the pool of water has been shown in Fig. 3. The vapor bubbles form on the surface and typically merge together before a departure into the liquid. As can be seen the process is very intense and heat exchange occurs both due to a change of phase (involving large values of the heat of vaporization) and convection mode of heat transfer.

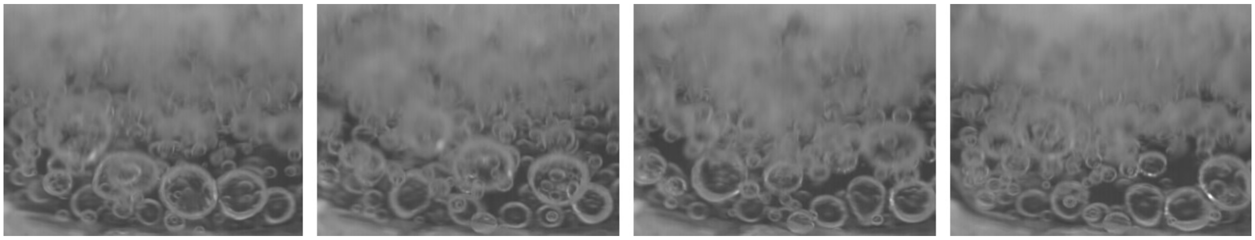

Fig. 3. *Boiling phenomenon on the laser treated sample – time interval between each picture 0.02 s.*

The heat transfer analysis of the sample has been presented and discussed by the authors in [43]. It was observed that the laser treatment provided significant augmentation of heat flux in relation to the untreated (smooth) reference surface. However, an important element for the design of heat exchangers is the proper calculation of heat flux based on the geometrical parameters of the surface morphology and its material properties. The models and correlations can be based on a number of concepts [44] and can show a different level of determination precision. In order to assess and compare the correctness and applicability of selected models of boiling, two correlations have been selected from the literature – one proposed by Smirnov and Afanasiev [45] and the other by Nishikawa et al. [46]. Fig. 4 and 5 present the comparison of the calculation results according to the above-mentioned models with the experimental data from [43] for water and ethanol, respectively.

Analysis of the above graphs indicates that the model proposed by Nishikawa et al. [46] provides calculation results which are much higher than the actual experimental data. On the other hand, the model by Smirnov and Afanasiev [45] is accurate, but only in the range of low temperature differences. Consequently, in order to obtain more precise calculation results a new model for the laser processed samples should be considered.

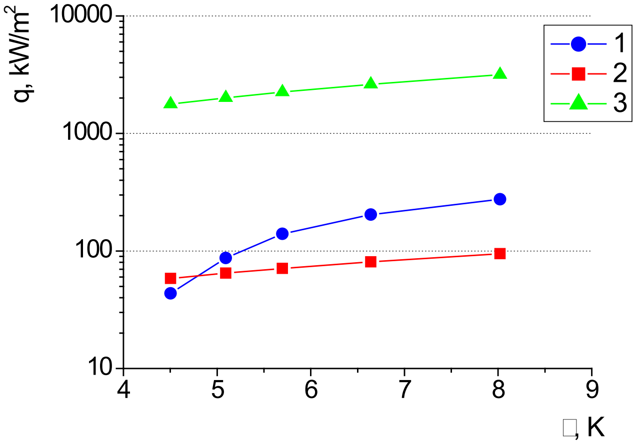

Fig. 4. *Comparison of the experimental data and model calculations for water: 1 – experimental data, 2 – calculation results according to the equation by Smirnov and Afanasiev [45], 3 – calculation results according to the equation by Nishivawa et al. [46].*

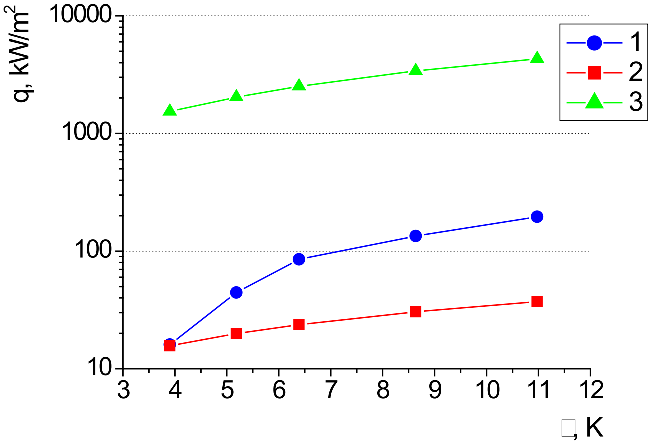

Fig. 5. *Comparison of the experimental data and model calculations for ethanol: 1 – experimental data, 2 – calculation results according to the equation by Smirnov and Afanasiev [45], 3 – calculation results according to the equation by Nishivawa et al. [46].*

It needs to be emphasized that all laser processed specimens tested by the authors in [43] largely outperformed the reference surface (the one without any modifications). Furthermore, the most efficient were the samples of the highest height of the longitudal fins as well as of the roughest surface at the base (two surface roughness values were considered). The authors reported that the biggest augmentation could have been observed for small temperature differences – both for the influence regarding the height of the fin elements and for the surface roughness.

Another vital problem that needs to be addressed in the future studies of the authors is the issue of bubble dynamics during boiling on laser modified heaters. As mentioned in [5] based on visual studies of dielectric liquid boiling, in the case of pin fins there is a bigger probability of occurrence at a cavity site, which increases nucleation site density.

Summary and Conclusions

The laser technology enables to alter the morphology of the heat exchanging surfaces. As a result, improved conditions for boiling might occur, which leads to higher heat fluxes being exchanged. It is an advantageous phenomenon due to the increase in the overall efficiency of heat exchangers. The problem might only be with the proper calculation of the heat flux values based on the geometrical and material properties of the heater surface. The selected models adopted from literature proved not particularly accurate and a new one needs to be developed to address this issue.

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