International Journal of Thermal Sciences 111 (2017) 379–389

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Performance of shot peened surfaces subject to crystallization fouling

A. Al-Janabi [a, *], M.R. Malayeri [b, c], O.O. Badran [d]

[a] Department of Mechanical & Industrial Engineering, College of Engineering, Sultan Qaboos University, P.O. Box. 33, P.C. 123, AlKhoud, Muscat, Oman
[b] School of Chemical and Petroleum Eng., Shiraz University, Shiraz, Iran
[c] Institute for Process Technology and Environment (IVU), Technische Universität Dresden, 01062, Dresden, Germany
[d] Mechanical Engineering Department, Faculty of Engineering, Taibah University, P.O. Box. 344, Al Madina Al Munawara, 42353, Saudi Arabia

ARTICLE INFO

Article history:
Received 23 January 2016
Received in revised form
17 September 2016
Accepted 19 September 2016

Keywords:
Heat exchanger fouling
Shot peening
Wettability
Roughness
Nucleation site

ABSTRACT

Shot peening is frequently used in industry to primarily improve surface properties in term of material fatigue and corrosion. It is nevertheless questionable whether such shot peened surfaces would simultaneously withstand fouling conditions. The present study endeavours to put this question into perspective. Two different shot peened surfaces with intensities of 4N and 6N were investigated in which the stainless steel surfaces AISI 304 BA was used as baseline substrate. The surface characterizations showed that shot peening increased the surface roughness up to 7-fold compared with the untreated stainless steel surface. The degree of wettability in terms of water contact angle was also reduced up to 28.3% in comparison to the untreated surface. The shot peened surfaces were then subjected to the deposition of $CaSO_4$ during convective heat transfer. Compared to the untreated stainless steel surface, the induction period reduced by more than 30% along with increased initial fouling rate by more than 2-fold. The overall heat transfer coefficient also decreased up to 65%. In addition, visual observations confirmed that the deposit layer on the shot peened surfaces was thicker, more adhesive, rough and less porous than the one that was formed on untreated stainless steel surface.

1. Introduction

Water is extensively used as coolant in many industrial processes. This, though, may lead to crystallization fouling (scaling), if water is mineralized, and corrosion especially in heat exchangers when cooling and heating is required. Fouling or/and corrosion may, in turn, compromise the performance, and effectiveness of heat exchangers in desalination plants, water treatment processes, and power plants. Crystallization fouling occurs whenever the concentration of mineral salts, such as carbonates, sulfates, and silicates of calcium exceeds its equilibrium solubility product, resulting in scale formation on the surface. This would, in turn, lead to major operational problems for poorly treated waters [1]. There is a large body of research on the impact of scale formation on metal heat transfer surfaces [2,3]. In general, the deposit layer acts as barrier to heat transmission which would substantially deteriorate the thermal performance of heat exchangers as a result of the low thermal conductivity of the deposit layer [4]. Deposition would also compromise the performance of exchangers in terms of higher fuel consumption, lower production throughput due to increased pressure and reduced exchanger efficiency [5–7].

The occurrence of scaling may also accelerate under-deposit corrosion, e.g. even minor components of the deposits can sometimes cause severe corrosion of the surface substrate [8]. Corrosion may, in particularly, attack and ultimately damage the substrate of the cooling system and exacerbate the above-mentioned fouling drawbacks. In a typical desalination plant, about 40% of the additional heat transfer area is required to compensate the reduction in heat transfer arising from scale formation problems [9]. Uneven scale deposition on various parts of the surface may also result in pitting corrosion [10].

The resistance to corrosion can greatly be improved by a cold working process called shot peening. The process is an economical and effective technique of producing and making surface residual compressive stresses to improve stress-corrosion resistance [11] as well as to increase the product life of treated metal parts. The effect of shot peening on stress corrosion resistance is well documented for different processes [12]. One feature of shot peening is to increase surface roughness to some extent depending on the intensity of the process. This may not cause any problem at all if the working fluid is not prone to deposition. If so then the new small

---

[*] Corresponding author.
E-mail address: ab.aljanabi@squ.edu.om (A. Al-Janabi).

http://dx.doi.org/10.1016/j.ijthermalsci.2016.09.023
1290-0729/

generated cavities and pits would act as nucleation sites which may, in turn, accelerate the formation of scales on the shot peened surface. Taborek et al. [13] showed that surfaces with higher surface roughness would be prone to more crystallization fouling. In addition, Keysar et al. [14] also reported experimentally that a stronger adhesive bond would be anticipated as surface roughness increased.

There is not any known study in the open literature to quantify the relative importance of shot peening process on heat transfer surfaces under fouling conditions. The main objectives of this work were therefore i) to utilize the shot peening process as a surface treatment for the heat transfer surfaces; ii) to shed light on the influence of such surface treatment on the surface characterization and fouling propensity through experimental investigations, and finally iii) to understand the drawbacks associated to the use of shot peening technique when the shot peened surface is prone to crystallization fouling. The resultant finding would serve as a tool to make decision about the intensity of shot peening and whether or not to use this technology when such surfaces would be exposed to crystallization fouling.

2. Shot peening procedure and surface characterization

The selected specimens for this study were made of high-grade stainless steel sheet metal AISI 304 BA with a thickness of 0.3 mm and 50 mm × 59 mm dimensions. The chemical composition, mechanical and physical properties for the substrate are also given in Table 1.

Shot peening was performed with the standard condition of low intensity (N) type Almen strip which basically refers to the utilization of glass and ceramic beads for hitting the target surface. Two Almen intensities of N4 and N6 were attempted. To shot peen the surfaces, an air blast Pang born Es-1580 machine was used in which the compressed air was introduced at the rear of the nozzle producing a low pressure, high velocity air flow in the nozzle body. The peening shots were then stored in an overhead hopper before directing them to the nozzle by means of gravity assist, where they were accelerated by the air of high velocity before hitting the target surface.

Prior to fouling runs, the influence of shot peening process on surface characteristics of the specimens was investigated in terms of two essential parameters of i) surface roughness profile (R_a), and ii) surface wettability. The roughness profile is a general evaluation parameter which describes the roughness of machined surfaces as the arithmetic mean deviation of the assessed profile. A stylus instrument (Perthometer M4Pi, Mahr, Germany) was used to determine the roughness profile of the specimens over a length (l) 15 mm in three horizontal and vertical lines, respectively. To obtain the required accuracy in measurement, the roughness profile value was determined by averaging the mean values of the 9 points at the intersection between the horizontal and vertical lines, as described in Eqs. (1)–(3) and shown in Fig. 1.

$$(R_a)_{specimen} = \frac{\sum_{i=1}^{3}\sum_{j=1}^{3}(R_a)_{ij}}{9} \tag{1}$$

$$(R_a)_{ij} = \frac{(R_a)_i + (R_a)_j}{2} \tag{2}$$

$$R_a = \frac{1}{l}\int_0^l |Z(x)|\,\mathrm{d}x \tag{3}$$

The attraction between liquid molecules and the molecules of another surface (i.e. solid surface) is referred as wettability. The wetting interaction between a liquid and a solid can be evaluated through the measurement of the contact angle (θ) which may vary from 0° to 180°. Wetting occurs once the molecules of a liquid have a stronger attraction to the molecules of a solid surface than to each other. In this study, the drop shape analysis device (DSA) was used to measure the effect of shot peening process on wettability through the observation of a sessile drop of water on the specimen The instrument consists of a micro-syringe with a needle of 0.5 mm inner diameter and a video camera type charge-coupled device (CCD) with a resolution of 768 × 512 pixels.

The presence of any contaminations on the specimen would influence the wetting characterization of the surface [15]. To avoid this to occur, the specimens were ultrasonically cleaned firstly by acetone (96%) and deionized water in sequence before drying them with a dried air stream to ensure that no acetone remains on the surface. Afterwards, water droplets were placed upon the specimens at room temperature. The drop image was then recorded by the video camera and displayed on a monitor. Once stabilized, a frozen picture of the droplet was taken in order to measure the contact angle by the use of the DSA program with an accuracy of ±0.1°.

The characterization results of the shot peened and untreated stainless steel surfaces are listed in Table 2. A closer look at the data in the table reveals that:

i) A significant increase in the surface roughness profile is noticeable. It increased more than 7-fold compared to the untreated stainless steel surface. The plastic deformation in the surface that is occurred due to shot peening process creates a roughness profile that is linearly proportional to the velocity/intensity of the shot [16]. This is because during the shot peening process with the hit of high energy particles, many pits and extruded ridges around the edge of the pit will be formed on the surface [17]. For industrial applications, surface roughness sometimes may be considered undesirable since it would cause friction and drag, while a beneficial influence can be achieved through the increased convective heat and mass transfer due to the agitation of the viscous sub-layer [18]. Generally, larger shot sizes result in greater roughness [16]. This is in fact clearly shown in Table 2, where the roughness profile of the large intensity shot-peened 6N surface is greater by 22% to that of the 4N surface.

ii) The degree of surface wettability was also affected by the shot peening process. The indicated parameter for such influence was the profound reduction in the measured water contact angle. Up to 28.3% reduction in water contact angle in comparison to the untreated stainless steel surface was measured as illustrated in Fig. 2. Such reduction can be attributed to the influence of the sharp edge of the roughness profile. In other words, the sharp edge may pin the triple line position far from a

Table 1
Chemical composition, physical and mechanical properties of 304 BA stainless steel substrate.

Chemical composition							
Element	C	Mn	Si	P	S	Cr	Ni
Weight (%)	0.08	2	0.75	0.045	0.03	18–20	8–10.5

Physical properties		Mechanical properties	
Thermal conductivity @100 °C, (W/m·K)	16.3	Tensile strength (N/mm^2)	520
Specific heat @ 0–100 °C, (kJ/kg·K)	0.5	Yield strength (N/mm^2)	205
Melting point, (°C)	1400–1455	Elastic modules, (GPa)	193