Investigation the influence of surface topography on scattering ability of aluminium reflectors from infrared quartz heater

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Abstract. Infrared (IR) heaters are used in many industries where heat treatment is required as well as in household appliances. One of the main problems with this type of equipment is non-uniform temperature field in the heating area, which results in a different degree of heating of the heated objects. In order to achieve greater uniformity of the temperature, some approaches are explored in practice, such as using embossed reflectors, mounting two or more heaters side-by-side, using emitter lamps with power controller devices, formation of gold or silver coatings, etc. The drawbacks of these approaches are complicating the design of the IR heaters, reducing the dimensions of heating area, increasing energy consumption, etc. Among the above-mentioned methods, the creation of a specific reflector surface topography is easily attainable and inexpensive technological approach. The main task of the present study is to investigate experimentally the influence of the specific patterns, obtained by ball burnishing process on scattering ability of the aluminium reflectors from infrared quartz heater.

1. Introduction

Infrared heaters can be classified by the wavelength they emit. The wavelength depends mainly on the temperature of the emitting object (or body) [1, 2]. The higher the temperature, the shorter the wavelength and the higher the intensity of the infrared radiation. When the temperature is lower, longer wavelengths and a lower intensity are observed. There are many different constructions of IR-heaters, but they mainly consist of three parts: an infrared emitter, a suitable reflector(s) that redirect the radiation into the heating area, and a housing in which the emitter and the reflector are mounted. Reflectors are designed in many different shapes and sizes, and can produce different heat patterns, depending on their macro shape (see figure 1). The production methods used by the manufacturers of heat equipment include processes like: deep drawing, roll bending, spinning and blanking, supported by 2D or 3D laser cutting to obtain the macro shape of the reflectors. The appropriate design of the macro shape of a reflector is the first important factor on which depends how much of the energy from the emitter will be delivered to the heating area. The second one is the scattering ability of the reflector.

It is known that the smoother the surface of the reflector, the greater the amount of reflected radiation. This is an important condition if it is needed to achieve a high efficiency of the heater.
However, when the reflector is smooth, a near to specular reflection is obtained. In this case the incident electromagnetic waves are reflected into a narrowly focused outgoing direction or they spread closely to it. In result, the different reflector sections focus the radiation unevenly on the heated area (see figure 1), which in some cases may have undesired effects on the heated objects [3]. For example, if a reflector heater is used to heat a greenhouse in winter, plants that fall into the areas with high radiation concentration can be overheated, and those in low-concentration areas may freeze. Moreover, the distribution of radiation is essential in describing the various operational phases of the heater’s electronic part and the electronic equipment in its vicinity because the ambient temperature is one of the main factors influencing their reliability [4, 5]. Therefore, in such cases the distribution of radiation from the emitter, and that reflected by the reflector, should be as uniform as possible, in order to achieve a more uniform temperature field. Some of the existing solutions include mounting two or more heaters side-by-side to create more even heated areas, using emitter lamps with power controller devices to adjust precisely needed levels of IR radiation, etc. The main drawback of these approaches, however, is that they complicate the construction of the heating devices, therefore increase their cost, and often lead to an increase in the energy consumption.

To achieve greater diffuse reflection and smaller deformations, some IR heater manufacturers use embossed (or hammered) aluminium coil roll sheet with pea texture and thickness ranging from 0.1 to 1.5 mm (see figure 2, a). The rolled embossed aluminium coil for reflectors is produced by rolling with pre-machined relief rollers (formed on CNC lathe machines) which stamp this pea texture on it. Regardless of the fact that this process is of high performance, the use of profile rollers with unchanging patterns is the main disadvantage of this approach. This is so, because if the shape or dimensions of the texture need to be changed for some reasons, a new pair of rollers for the new type of reflector has to be made, which can be an expensive and time-consuming activity. In addition, it is necessary a reflector with highly repeatable periodic structure to be used in order to split and diffract IR radiation into several beams, travelling in different directions, which is obviously not fulfilled for the embossed aluminium sheets shown in figure 2, a).

In this work, the ball burnishing (BB) method [6, 7] is proposed as finishing process of IR-heater’s reflectors, in order to increase their scattering ability. BB process provides high repeatability in shape and dimension of the obtained cells pattern (see figure 2, b) and possibilities for broadly varying the steps between asperities, and this way it is possible to achieve better scattering of the reflector’s surface.

![Figure 1. Cross sections of four different reflectors with smooth surfaces, which form four different types of IR radiation distribution in the heating zone [3].](image1)

![Figure 2. a) Examples of luminaire and IR heater with embossed pea pattern reflectors; b) Vibratory ball burnishing process diagram and two different cell patterns, obtained after its implementation on flat surfaces.](image2)
2. Optical properties of cell patterns, obtained by ball burnishing process

2.1. Short description of the ball burnishing process

The BB is a process, based on cold plastic deformation of the surface layer of a workpiece by pressing (with certain external force $F$) a hard steel ball with a certain diameter $d_{ball}$ that moves along the feedrate direction $f$ [6] (see figure 2, b). BB usually is used for minimizing the roughness, an increasing hardness in the surface layer and to achieve compressive residual stresses, which further enhances the operating characteristics, such as increased strength, higher fatigue life, higher corrosion resistance, etc. When an oscillation move of the ball is added, specific overlays of traces after its passing are obtained and specific cell patterns are formed on the machined surface (see figure 2, b). The dimensions and shape of the cells depends on the regime parameters [6] in classical BB. The BB process can also be performed on CNC milling machines [7], where the necessary oscillation of the ball tool is replaced by a complex trajectory, based on a pre-programmed toolpath. In this way, the resulting cells patterns have a very high degree of repeatability of shape and dimensions on the burnished surface. After the implementation of the BB process, the maximum roughness asperities height can vary from 8 to 80 $\mu$m, and steps between the adjacent cells borders between 30 to 3300, $\mu$m [6, 7].

2.2. Diffraction grating properties of cells patterns after BB process

A diffraction grating is an optical component with a periodic structure that splits and diffracts light into several beams, travelling in different directions [1]. The directions of these beams depend on the spacing of the grating and the wavelength of the light, so that the grating acts as the dispersive element. In sources [6, 8] a theoretical model is presented, which describes an incident light beam at three different angles $\varphi_0$ in diffractive maxima, for three different wavelengths $\lambda$ and for two types of reflection surface roughness. The model lies on the assumption that the field at each point of the resulting beams depends on the falling beams, and for two types of reflection surface roughness. The model describes the assumption that the field at each point of the surface, is assumed to be the same, as if the reflection in it occurred from the infinite plane that is tangent to the rough surface at that point. The beam diffracts as set of diffraction maxima (see figure 3) which are produced from the surface irregularities. Their angular positions are determined by the expression:

$$\varphi_m = \arccos\left(\cos(\varphi_0) + \frac{j_m}{S\lambda}\right),$$

where: $\varphi_m$ is the angle of the spectrum of the m-th order; $\varphi_0$ is the angle of incidence of the falling beam; $\lambda$ is the wavelength of the falling beam; $S$ is wavelength of irregularities of the scattering surface (i.e. the step between asperities along the rough surface).

The angular dependence of the diffraction maxima amplitude in the plane of incidence of light beam for a sinusoidal shaped scattering surface can be calculated by using equation [6]:

$$A_m = \frac{1 - \cos(\varphi_m + \varphi_0)}{\sin(\varphi_m) + \sin(\varphi_0)} \cdot I_m(t),$$

where: $t = k \cdot R_{max} \cdot (\sin(\varphi_m) + \sin(\varphi_0))$; $k$ is the wave number ($k = (2 \cdot \pi) / \lambda$); $R_{max}$ is maximum height of the irregularities of the scattering surface; $I_m(t)$ is the Bessel function of order $m$.

By modelling the surface profile with a regularly distributed cells pattern after BB process as sinusoid with amplitude 0.5 $\cdot R_{max}$ and period $s$, using the formulas (1) and (2), it is possible to calculate the diffraction maxima $A_{max}$, resulting from an incident beam to the scattering surface as shown on figure 3, a-f. As can be seen from this figure, when the scattering surface has a roughness with a small amplitude $R_{max}$=1.55, $\mu$m and a wavelength period $S$ =110, $\mu$m, no large diffraction of the incident beam is observed (see figure 3, a, b, c) for three wavelengths $\lambda$=1.40, 3.00 and 14.00, $\mu$m and for incident angles $\varphi_0$=45°. When the amplitude and the steps of the roughness become larger $R_{max}$=61.3, $\mu$m and $S$=2450, $\mu$m (see figure 3, d, e, f) at the three wavelengths, much more diffraction maxima are observed. This gives us a reason to assume that by forming regular reliefs by BB process...
on the concave surface of aluminium reflectors, a more even distribution of the temperature field in the heating zone will be obtained. This assumption will be verified by conducting a comparatively experimental study.

![Diffraction maximums obtained for smooth surface a), b), c) and for rough surface d), e), f) for three different wavelengths λ.](image)

**Figure 3.** Diffraction maximums obtained for smooth surface a), b), c) and for rough surface d), e), f) for three different wavelengths $\lambda$.

3. **Comparative experimental study of the degree of uniformity of the temperature field in the area of heating of a reflecting infrared heater**

3.1. **Methodology of experiments**

To carry out the comparative experimental study, four cylindrical reflectors and an infrared quartz heater were used (see figure 4, a - d). One of them is the original reflector, which is polished and has a radius of 60, mm. The other three reflectors are made of aluminium alloy 1100 sheets (ASTM B 209) with dimensions $485.0 \times 134.4$, mm, and thickness $\delta=1.0$, mm. On the upper side three patterns with three different cells sizes (see table 1) were machined by BB process according to the regime parameters combinations shown in figure 5, using a specially designed algorithm and a tool [7], as well as a CNC milling machine TM-1, Haas (see pos. 2 on figure 4, a). After the cells patterns are processed, the reflectors are bended to the radius of 60, mm, using a Baykal APH 21040 hydraulic press brake.

![Processing of the aluminium reflectors by BB on CNC milling machine; Diagram of the experimental setup for measuring temperatures distribution frontal and sides of the heater; Photographs of the experimental setup.](image)

**Figure 4.** a) Processing of the aluminium reflectors by BB on CNC milling machine; b) Diagram of the experimental setup for measuring temperatures distribution frontal and sides of the heater; c) and d) Photographs of the experimental setup.

The experimental setup, shown on figure 4, b-d was used for measuring the temperature distribution in front of the IR heater. It consists of three plywood square panels (pos. 1), each of them
with dimensions 1000×1000×8, mm, perpendicularly fixed to each other and painted in matte black colour. The main purposes of these panels are to reduce the effect of convection from the air in the laboratory room and serve as screens for thermographic imaging. At the rear of this structure, a transverse board is placed, on which the infrared quartz heater is mounted so as the IR quartz tube (pos. 3) to be horizontal and centred in the middle of the front plywood panel. A thermographic camera FLIR i7, FLIR Systems, Inc. (pos. 4) is used to capture the thermographic images (in JPEG standard format), which is placed on a tripod (pos. 5) and 3, m away from the central plywood panel. FLIR i7 is equipped with a focal plane array detector with uncooled microbolometer. The experimental setup and test environment conditions correspond to the guidance of international standard IEC 62798 [2]. All thermographic images are captured 30 minutes after the start-up time of the heater.

3.2. Methodology for evaluating the thermographic images captured
The thermographic images, captured by FLIR i7 (see figure 5) are processed with ImageJ software [9], in order to comparatively evaluate the distribution of the temperature field in the area frontal to the heater (see pos. 1 from figure 4, b). Every colour thermographic image is initially converted to 8-bit grayscale (i.e. linearly scaling image from min - max to 0-255). After that, the “Threshold” method is used, in order to segment the grayscale image into feature of interest and background. In this operation, the threshold values are set to be minimum (175) and maximum (255), or ~70% above the

![Figure 5](image)

Figure 5. Surface topography, thermographic and segmented images of polished and ball burnished reflectors.
zero minimum. The method “IsoData” of converting and the “Dark background” options are checked, because the temperature feature is lighter than the background in the present case. The described sequence is successively executed for the four captured thermographic images.

As a result, four black and white (B&W) segmented images are obtained (see figure 5), that corresponds to the four tested reflectors. On them, the “white” features are enclosed in a rectangular window of the same size. The "Measure" command is used to calculate the ratio between the areas of temperature field and the background for all four B&W images. The ratios, calculated this way, are used as the basis for comparison of the diffusion capability of the tested reflectors. As a rule, it is assumed that the greater the ratio between “white” and “black” areas in the segmented image (see figure 5), the greater the scattering capability of the tested reflector, and vice versa.

3.3. Results and discussion
The results obtained about the ratios between the segmented areas on the B&W images, the maximum measured temperatures and the roughness parameters of the four tested reflectors are shown in table 1.

| №  | Reflector type        | $R_{\text{max}}$, μm | $\text{Step}$, μm | $T_{\text{max}}$, °C | $\Sigma \text{Area}$, px | Area, % | Increase |
|----|-----------------------|-----------------------|-------------------|------------------------|---------------------------|---------|----------|
| 1  | Original (polished)   | 1.55                  | 110.0             | 33.0                   | 26729                     | 37.89   | -        |
| 2  | BB processed, small cells | 71.40               | 1834.0           | 29.0                   | 34222                     | 48.51   | 28.03%   |
| 3  | BB processed, medium cells | 75.70               | 2450.4           | 30.0                   | 32813                     | 46.50   | 22.76%   |
| 4  | BB processed, large cells | 50.40               | 3201.9           | 26.0                   | 32574                     | 46.17   | 21.87%   |

Comparing the ratios (Area, %) it can be seen that in all the reflectors, having cells patterns machined by BB process, there are "white" sections with a larger area than the original polished reflector with about 25% averaged. A reverse proportional trend is observed with the measured maximum temperatures ($T_{\text{max}}$, °C), captured on the thermographic images. Maximum reached temperature for the polished reflector (33, °C) is about 16% greater than the maximum average temperature (28.3, °C) measured for the rest three reflectors, which have cells patterns. This can be explained with the higher scattering ability of the reflectors with cells patterns, compared to the smooth original reflector.

Comparing ratios “Area” from table 1 only for three reflectors with BB processed cells patterns, it is seen that the cells dimensions (i.e. parameters “$R_{\text{max}}$” and “Step”) have a minor influence on the scattering abilities of the tested reflectors (within no more than 5%). The largest scattering (Area 48.51 %) occurs with the smallest cell patterned reflector (№ 2 from table 1), and the lowest value (Area 46.17 %) is obtained with the largest sized cell reflector (№ 4 from table 1). This is due to the fact that the heights of the roughness asperities of the BB reflectors are quite close and are about 25 times greater than the wavelength ($\lambda=1.4 - 3$, μm) of the infrared radiation from the source.

4. Conclusions
Based on the BB finishing process, and the results obtained from the comparative experimental investigation carried out, the following conclusions can be made:

- The assumption, proposed in section 2.2, that reflectors with a cells patterned reflecting surface have a greater scattering ability than those with a mirror surface, is generally confirmed;
- The ball BB process to form appropriate cell patterns on the reflecting surfaces of reflectors from IR-heaters can be successfully used in practice. Moreover, in contrast to the use of the rolled embossing aluminium sheets for reflectors in which the patterns are constant, in a BB process, carried out on CNC milling machines, the size, shape, and roughness of the patterns cells can be adjusted in a very wide range;
- Under certain optimum values of the roughness and the dimensions of the cells, the proposed BB finishing process can also be used to fabricate embossed rollers with a mirror image of the
needed reflector patterns. Thus, significantly increased productivity of the production process for embossed reflectors for IR reflector heaters can be obtained.

The future development of the problems discussed in this work is to carry out further experimental studies in order to determine the optimal condition of the cell sizes and roughness, where maximum scattering effect of the reflectors is obtained, taking into account the wavelength of the infrared source.

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