Nuclear Inst. and Methods in Physics Research, A 877 (2018) 131–137

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

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

Matlab fractal techniques used to study the structural degradation caused by alpha radiation to laser mirrors

M.-R. Ioan

"Horia-Hulubei" National Institute for Physics and Nuclear Engineering (IFIN-HH), 30 Reactorului Street, RO-077125, Magurele-Bucharest, Romania

ARTICLE INFO

Keywords:
Laser mirror
Multilayer coatings
Alpha particles
MATLAB box-count
Fractal dimension
Reflectivity

ABSTRACT

Almost all optical diagnostic systems associated with classical particle accelerators or with new state-of-the-art particle accelerators, such as those developed within the European Collaboration ELI-NP (Extreme Light Infrastructure-Nuclear Physics) (involving extreme power laser beams), contain in their infrastructure high quality laser mirrors, used for their reflectivity and/or their partial transmittance. These high quality mirrors facilitate the extraction and handling of optical signals. When optical mirrors are exposed to high energy ionizing radiation fields, their optical and structural properties will change over time and their functionality will be affected, meaning that they will provide imprecise information. In some experiments, being exposed to mixed laser and accelerated particle beams, the deterioration of laser mirrors is even more acute, since the destruction mechanisms of both types of beams are cumulated. The main task of the work described in this paper was to find a novel specific method to analyse and highlight such degradation processes. By using complex fractal techniques integrated in a MATLAB code, the effects induced by alpha radiation to laser mirrors were studied. The fractal analysis technique represents an alternative approach to the classical Euclidean one. It can be applied for the characterization of the defects occurred in mirrors structure due to their exposure to high energy alpha particle beams. The proposed method may be further integrated into mirrors manufacturing process, as a testing instrument, to obtain better quality mirrors (enhanced resistance to high energy ionizing beams) by using different types of reflective coating materials and different deposition techniques. Moreover, the effect of high energy alpha ionizing particles on the optical properties of the exposed laser mirrors was studied by using spectrophotometric techniques.

1. Introduction

It is a known fact that different specific components of the optical diagnosis systems involved in heavy particles (alpha, protons, deuterons etc.) nuclear physics experiments [1–5], such as laser mirrors, are affected by the deposition of a high energy in their volumes. In these kinds of experiments, the thin layer coatings (dielectric/semiconductor types) of the laser mirrors are affected by their interaction with high energy particles, leading to an increased number of structural defects [6,7]. These structural micro-defects may show agglomeration processes, leading to macro-defects, craters or cracks. The accelerated heavy particles used for irradiation of the mirrors characterized in this paper were high energy alpha particles. The degradation of the optical materials exposed to alpha particles occurs mainly due to the physical modifications of their surface profiles. The most unwanted effect occurring when exposing optical analysing systems to strong ionizing particles is the degradation of their optical proprieties. In the case of laser mirrors, this optical degradation is transposed in a decreased reflectivity and an increased magnitude of the incident signal scattering phenomenon. These phenomena corrupt the transmitted optical signals leading to incorrect optical information.

In order to highlight the deterioration of the laser mirrors when exposed to accelerated alpha particles, the complex modifications produced in their structure (induced defects) were studied using the fractal dimension concept. This concept was introduced due to the variety of shapes and sizes of the induced defects. The fractal techniques were applied to high quality images taken from the exposed laser mirrors. The images were captured using a MCX100LCD type magnification enhanced transmission microscope. The fractal dimension allows to decide if a surface shows a fractal character, but also to determine the step from where the structure concept is transformed into texture concept. According to the literature [8–11], the fractal dimension is an instrument for studying the regularity (pattern) or its absence (chaos)

E-mail address: razvan.ioan@nipne.ro.

https://doi.org/10.1016/j.nima.2017.09.037
Received 22 November 2016; Received in revised form 20 July 2017; Accepted 15 September 2017
Available online 4 October 2017
0168-9002/

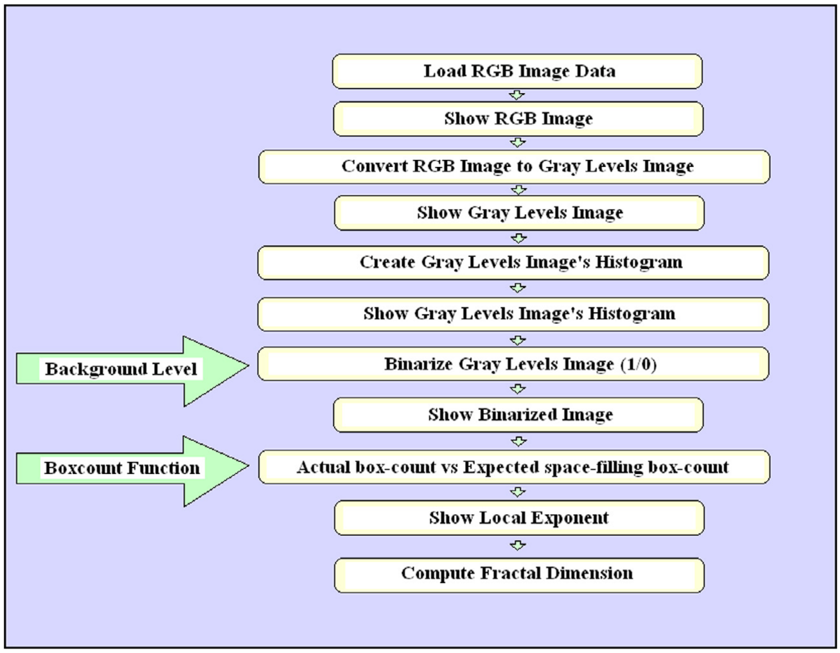

Fig. 1. Logical scheme of the developed Matlab code.

in a structure of shapes, meaning the degree in which a certain chosen shape fills a space. In the case of 2D space, when the value of the fractal dimension is 1 or 2, the analysed surface is of Euclidean type. When the value is situated between these two, the analysed surface shows a fractal character. Generally, the fractal dimension of a surface highlights the differences between two or more different surfaces which seem to be visually identical. In order to determine the fractal dimension, a Matlab code involving the box-count function was developed. The box-counting technique is especially indicated to be applied to images of surfaces lacking the true auto-similarity property, since for those having it, less complex algorithms can be used.

The logical scheme of the developed Matlab code can be seen in Fig. 1. A studied image is processed, binarized and covered with a square surface (box), having the r dimension. Then, a network made by a decreasing string r_n (2^n, $n = 0, 1, 2$, etc.) of box dimensions covering the entire surface is computed. The value of the fractal dimension is obtained by determining the number of boxes, n_r, which intersect at least one point of the tested surface. According to Mandelbrot, the fractal dimension can be expressed as (1):

$$D_f = -\lim_{r\to 0} \frac{\ln\left(n_r\right)}{\ln\left(r\right)}. \tag{1}$$

Considering that n_r follows a power type function, as (2):

$$n_r \cong \left(\frac{1}{r}\right)^{D_f}, \tag{2}$$

the best linear approximation of the fractal dimension, D_f, in $\left(\ln\left(\frac{1}{r}\right); \ln\left(n_r\right)\right)$ coordinates, called Richardson diagram, is plotted. If the obtained set of values is distributed in a linear function, the analysed structure is considered to have fractal characteristics, its slope providing an estimation of the fractal dimension value, D_f [12].

The fractal dimension is a measure of complexity and needs to be studied with respect to the Euclidean and topological dimensions. From the point of view of the Euclidean geometry, the dimension of a geometrical element represents the number of spatial coordinates needed to describe it. The Euclidean and topological dimensions represent limits for fractal dimension, the $D_e \geq D_f \geq D_t$ inequality being valid (D_f—fractal dimension, D_t—topological dimension, D_e—Euclidean dimension). For the analysis, the $D_t - D_f$ difference is considered to be a measure of the system chaos. If $D_t = D_f$, the system has an ordered or a low disordered structure. If $D_f > D_t$, the system structure is highly disordered. In the case of a 2D space study, the $D_t = D_e = 2$ equality is valid.

In the case of thin layers, the structural defects occurrence mechanisms are not substantially different from those involved in the same bulk material, but their magnitude shows some specific particularities. These particularities exist mainly due to the fact that thin layers absorb a smaller quantity of energy than the bulk materials. This leads to a lower magnitude of the defects inducing phenomenon.

By exposing semiconductors, amorphous or crystalline materials to ionizing radiation, the atoms placed in the network nodes migrate in interstitial regions (vacancies creation) leading to Frenkel type reticular defects. Ionizing radiation induced defects are threshold type processes, starting to appear only after a high enough energy is transferred to the atoms of the exposed material. These energy thresholds need to be reached for atoms to be removed from network nodes and be transferred to interstitial positions [13–16].

In this study the exposure of the two multilayer coating laser mirrors to charged alpha particles was performed, by using a 50 nA beam of alpha particles with energy 3 MeV. After the exposure, the target samples are instable systems, meaning that some types of radiation induced defects (those not involving broken chemical structures) tend to regain their initial equilibrium states in a natural manner. This process can be accelerated by subjecting the samples to controlled heating treatments [17,18].

2. The experiment

In this study the reflecting surfaces of two laser mirrors having a diameter of 10 mm, 9 layers coatings and a total thickness of 5 mm were exposed to high energy alpha particles. Mirrors substrate was made of BK-7 glass and the coatings were made of thin SiO_2 layers (Fig. 2).

The irradiation process was performed using the U120 cyclotron type particle accelerator from "Horia Hulubei" National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH), Romania. The following parameters were involved: 3 MeV energy alpha particles, a beam current of 50 nA, an exposure time of 800 s and a total absorbed dose in the sample of 3.4 MGy (4.8 kGy/s dose debit).

To characterize the two irradiated laser mirrors as a function of their optical proprieties (reflectivity), a SM242 Spectral Product type