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A microfocus X-ray tube based on a microstructured X-ray target

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ABSTRACT

We present a novel concept to develop a microfocus X-ray tube based on a microstructured X-ray target that is irradiated with a nonfocused electron beam. X-ray emissions from the microstructured targets with various morphologies were studied using Monte-Carlo simulation code MCNP5. The calculations revealed that the microstructured targets are quite capable of minimizing the effective X-ray spot size compared with those of conventional transmission-type X-ray targets. Based on the simulation results of X-ray brightness, optimum geometric parameters were derived for the microstructured targets with different morphologies. Moreover, the stability of the microstructured target against heat loads delivered by an electron beam was also investigated under both the continuous and pulsed operation modes. From the analysis, the limitations of the maximum allowable electron beam currents for the stable operation of the X-ray targets are presented. The combination of the microstructured targets and nonfocused electron beam allows the miniaturization of a microfocus X-ray tube by eliminating the needs for massive and complex focusing devices.

1. Introduction

Microfocus X-ray tubes have now become a robust and powerful tool for high quality X-ray imaging because they provide minute image details at the micron level [1,2]. The high image resolution rendered by microfocus X-ray sources is due to their small effective X-ray focal spot size [3,4]. The term, *effective X-ray focal spot size*, stems from the fact that the interactions between the impinging electrons and the atoms of an X-ray target result in significant electron beam broadening [5]. The phenomenon of the electron beam broadening happens even if a well focused and collimated electron beam strikes an X-ray target. Minimization of the effective X-ray spot size is desirable in order to enhance the spatial resolution of an X-ray image. In this sense, a reflection-type X-ray target composed of a bulk metal is not feasible to obtain smaller X-ray focal spot size because of serious electron beam broadening inside the target. Recently, a transmission-type X-ray target made of a thin metal layer on an X-ray window has been widely used to obtain a small X-ray focal spot size, especially for microfocus X-ray tubes [6]. Since the thickness of a metal layer in a transmission-type X-ray target is of the order of a few micrometers, electron beam broadening inside the target can be limited [7]. Thus, most of the present microfocus X-ray tubes are operated with a transmission-type X-ray target and a micrometer-sized electron beam that impinges on the target [8]. However, in order to get such a micrometer-sized electron beam, focusing devices such as a magnetic lens, beam apertures and focusing electrodes are required [9,10]. These devices make the system massive and complex, preventing the miniaturization of a microfocus X-ray tube. Moreover, even if a thin metal layer is used for a transmission-type X-ray target, the thickness of the layer cannot be reduced below a certain limit because the intensity of the produced X-ray decreases according to the decreased target thickness [11].

For this reason, we propose a new concept to develop a microfocus X-ray tube. Instead of using a transmission-type X-ray target combined with a fine focused electron beam, we suggest the use of a microstructured X-ray target combined with a nonfocused electron beam. Although the size of the electron beam impinging on a target is larger than the micron scales, the focal spot size of an X-ray generated from the target is inherently limited to the micron scales due to the finite size of the microstructured target. The focal spot size of X-rays can be readily changed by changing the lateral size of the microstructures. In addition, since no focusing devices or elements are required in this concept, the size of an X-ray tube can be dramatically decreased and thus a very tiny X-ray tube can be developed.

In this paper, we report detailed research on the microstructured targets. The X-ray intensity, the angular distribution, the effective focal spot size and brightness of X-rays produced from the microstructured targets have been calculated via Monte-Carlo (MC) simulation. Based on a series of simulation results for

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microstructured X-ray targets of different morphologies, we propose the optimum dimensions of the targets to achieve the brightest possible X-rays. In addition, we discuss the thermal stability of the microstructured X-ray targets and the limitations of electron beam power loading for the stable operation of the target.

2. Materials and methods

2.1. The concept of a microfocus X-ray tube with a microstructured target

In X-ray radiography, microfocus X-ray tubes are considered state of the art for rendering high spatial resolution of an image because of their small focal spot sizes. Generally, a very fine-focused and small-sized electron beam is considered an essential element of a microfocus X-ray system. However, once the electrons strike an X-ray target, the effective focal spot size becomes larger than the actual size of the electron beam due to beam broadening. A transmission-type X-ray target, which is composed of a thin metallic layer supported by a thicker X-ray window layer, is very helpful in minimizing the effective focal spot size by restricting the electron beam broadening. A conventional microfocus X-ray tube is generally composed of a well-focused electron beam and a thin transmission-type X-ray target, as illustrated in Fig. 1a.

Alternatively, we propose another approach to form a microfocus X-ray tube, as shown in Fig. 1b. In our concept, a metallic microstructure is attached to a substrate that acts as an X-ray window. The microstructured X-ray target is irradiated with a nonfocused electron beam with a much larger size than the micrometer-sized X-ray target. Although the beam size is sufficiently large, X-rays are produced only at the microstructured target and electrons passing beyond the lateral dimensions of the micro-particle cannot contribute to X-ray production. In addition, even if beam broadening occurs inside the microstructured target, the electrons crossing over the lateral extent of the target do not produce X-rays. Consequently, the focal spot size of the generated X-ray is determined only by the lateral size of the microstructures and independent of the incident electron beam size. A micrometer-sized X-ray focal spot size is inherently generated by a microstructured target and the X-ray spot size can be further decreased, for example, down to the submicron level by decreasing the lateral dimension of the target. Moreover, due to the usage of a nonfocused electron beam, a massive and complex device for focusing an electron beam is not required for a microfocus X-ray tube, which is very favorable for the miniaturization of a microfocus X-ray tube.

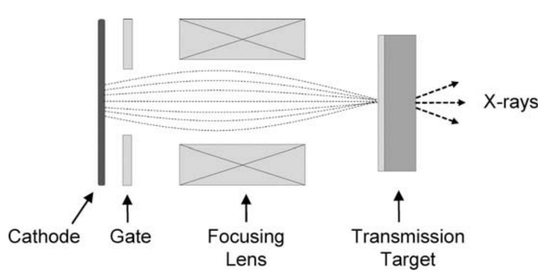

Fig. 1a. Schematic layout of a transmission-type microfocus X-ray system with a foil target.

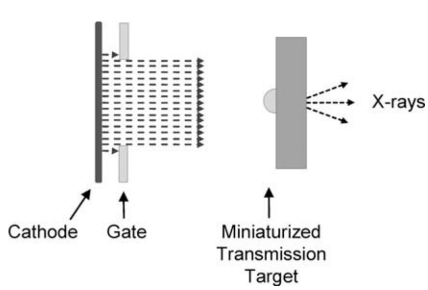

Fig. 1b. Schematic layout of a microfocus X-ray system with a microstructured target.

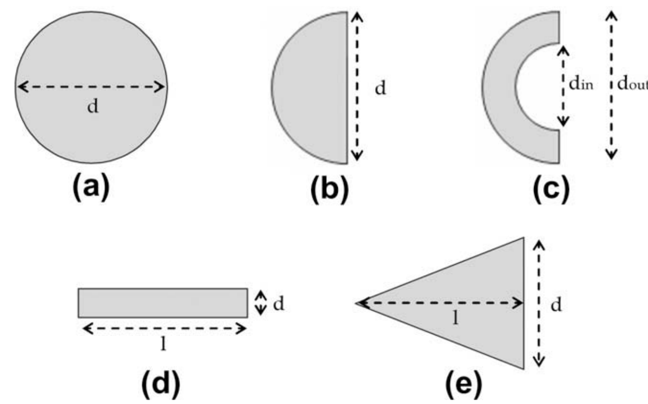

Fig. 2. The morphologies of microstructured targets used in the simulation. (a) Spherical micro-particle, (b) hemispherical micro-particle, (c) micro-shell, (d) micro-rod and (e) micro-cone.

In this study, we considered the microstructures of several morphologies including spherical and hemispherical micro-particles, micro-shells, micro-rods and micro-cones. Fig. 2 depicts the morphologies of the microstructures used in this study. Molybdenum, which is one of the commonly used X-ray target materials, was considered as the material of the microstructured target.

By virtue of recent advancements in micro- and nano-technology, microstructures with various morphologies can be controllably synthesized. Because of the sputtering capability, focused ion beam (FIB) technique has emerged as a good tool for the fabrication of diverse metallic micro- and nano-structures [12–17]. Based on these reports about the capability of FIB process, we believe that the microstructures shown in Fig. 2 can be fabricated by FIB technique.

2.2. Simulation tools

Calculations for X-ray target design involve several mutually contending and interrelated parameters: X-ray intensity, effective focal spot size, electron beam current density, accelerating voltage and temperature elevation. There is always a mutual trade-off among these parameters. Monte-Carlo simulation is a well-established and highly effective approach to resolve these interdependent and competing factors during the X-ray emission process. It incorporates realistic interaction cross-sections and can be applied to targets having complex geometries. In this research, we implemented MC simulations using MCNP code version 5 [18] for the estimation of effective focal spot size, and the calculation of the intensity distribution of X-rays generated from the microstructured targets. Furthermore, the stability against thermal loading was also investigated for the microstructured X-ray targets using COMSOL Multiphysics [19], which is commercialized software based on the finite element method.

2.3. Estimation of effective focal spot size

Contrary to thick and bulky targets, the microstructured targets do not suffer from electron beam broadening because electron