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Research Paper

Numerical study on thermal deformation characteristic of water-cooled mirror with interdigitated channels

Xiao Chen, Ping Zhou *, Ren-ke Kang, Zhi-gang Dong

Key Laboratory for Precision and Non-traditional Machining Technology of Ministry of Education, Dalian University of Technology, Dalian 116024, China

HIGHLIGHTS

- A new configuration for water-cooled mirror with mini-channels is proposed.
- A simplified model is derived for designing of the new configuration.
- The new configuration is useful to improve the uniformity of flow field.
- It performs well in reducing the thermal distortion of the reflecting surface.

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ABSTRACT

A novel water-cooled mirror with interdigitated channels is proposed for solving the problems of high flow resistance and non-uniform heat dissipation in a conventional water-cooled mirror with straight channels. The temperature field and the thermal deformation of the reflecting surface of the mirror are analyzed by fluid-solid-heat coupling simulation. A comparative analysis of the new configuration and the conventional straight channel water-cooled mirror is carried out under equal flow rate and equal pressure drop, respectively. The numerical results demonstrate that the new configuration is better on the consistency of heat transfer coefficients than the conventional one. At the same time, under the condition of equal flow rate, the peak value of the deformation on the reflecting surface is decreased by around 1/3, and the global thermal distortion within the irradiated region is only about half that of the conventional one. Besides, the flow resistance of the new configuration is so small that the flow rate is about triple that of the conventional configuration under the condition of equal pressure drop, which raises its superiority over other designs. The new flow channel structure provides a feasible solution to reduce the thermal deformation of a large size laser mirror.

1. Introduction

High power lasers are widely applied in many fields such as national defense and industrial manufacture. As one of the key components in a high-power laser system, the design and fabrication of a large size laser mirror (usually over 100 mm dia.) remain a hot research area facing the requirement of increasing the irradiation power. However, the thermal deformation of the reflecting surface of the laser mirror is generated due to the temperature rise, as the mirror absorbs laser energy. This degrades the shape accuracy of the reflecting surface as well as the quality of the output laser beam. Therefore, it is crucial to keep the thermal distortion of the irradiated region at a low level in order to extend the continuous operating time of a laser mirror.

Increasing the reflectivity by coating high reflection film is a fundamental method of reducing the thermal deposition and the thermal deformation of the reflecting surface of laser mirrors. But it is restricted to the development of high-reflectance coatings, thereby prompting the active cooling to be the most common method.

Concerned with this issue, many cooling schemes have been presented, such as water cooling, phase change cooling, and thermoelectric cooling. Han et al. introduced the achievements in the research of water-cooled mirrors and demonstrated that the micro-channel water-cooled mirror is superior to the water-jet-cooled mirror [1]. Peng et al. filled the laser mirror substrate with phase-change materials and succeeded in reducing the thermal distortion to under 0.4 μm. But this practice may be useless in a long-time operation, because the amount of phase-change materials stored is limited and the phase transition only lasts for a short period [2]. Riffat displayed a large range of applications of thermoelectric devices and discussed their prospects [3]. Although these devices are compact and environmentally friendly, the thermoelectric cooling is not widely

* Corresponding author. Tel.: +86 13478754767; fax: +86 411 84707430.
E-mail address: pzhou@dlut.edu.cn (P. Zhou).

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used in laser mirrors due to its high manufacture costs and low efficiency. Overall, the water cooling has become the most frequently used method because of its advantages, such as high heat removal rate, low cost, non-pollution and so on. Cheng et al. presented several types of cooling channels, including straight channels, arc-shaped channels and Archimedes-spiral channels [4,5]. The straight channel is easy to design and machine for its simple geometry, thereby being widely used in the structural design of small size laser mirrors. Hu et al. introduced several types of water-cooled mirrors with straight channels but the mirror size is small [6,7]. For a large size mirror, the area of the cooling region and the lengths of cooling channels both increase with the area of the irradiated region, which brings about a range of problems. The thermal entrance effect, first of all, makes the local heat transfer coefficient decrease significantly with the increasing entrance distance, especially for a long straight channel at a high Reynolds number. When the mirror is circular, the channel lengths are unequal, thus the flow resistance and the heat transfer performance differ from each other. Consequently, both the temperature rise and the thermal deformation are not-uniform, aggravating the reflecting surface distortion. Another problem is that if the hydraulic diameter is on a small scale of sub-millimeters, a huge water pressure is needed to overcome the significant growth of the flow resistance of the cooling channel. The pressure distortion is detrimental to the ultra-thin mirror layer. But there are few publications about the design of large laser mirrors.

Therefore, a new configuration should be proposed to satisfy the requirement of large size and high power water-cooled mirrors. Bejan gave the essential concept of constructal theory that stated 'for a finite-size system to persist in time, it must evolve in such a way that provides easier access to the imposed currents flowing through it.' [8]. In recent years, Hajmohammadi et al. have carried out many investigations on the design of heat exchangers based on the constructal theory, and presented some unconventional configuration, such as fork-shaped pathways, Phi and Psi shaped conductive routes, and bend tubes [9–11].

This paper introduces a multistage structure with interdigitated flow channels for water-cooled mirrors. Monocrystal silicon is selected as the construction material for its good optical machinability and thermal physical properties. The uniformity of the flow distribution and heat dissipation is set as the design objective based on the constructal theory, and the manufacturability is also taken into consideration. A type of interdigitated flow channel is designed to improve the uniformity of the flow distribution. Special attention is also given to the comparative analysis between the new configuration and the conventional configuration, under the equal condition of flow rate and pressure drop, respectively.

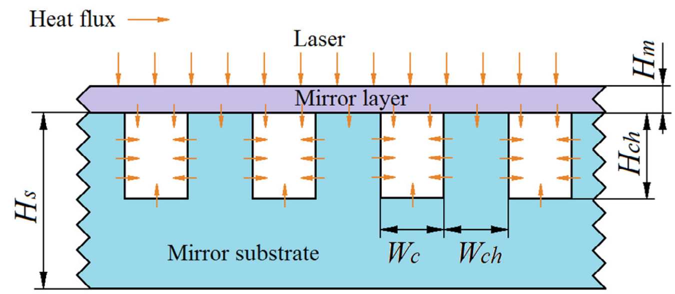

Fig. 1. Sketch of physical system for a water-cooled mirror.

2. Analysis

2.1. Physical problem

As exhibited in Fig. 1, a water-cooled mirror is simplified as an assembly of mirror layer and mirror substrate. They are used to reflect the laser beam and transfer the absorbed heat, respectively. Under the irradiation of laser, the absorbed heat goes into the mirror layer at first. Most of them dissipate by convective heat transfer in cooling channels, while the remaining heat results in the temperature rise of the mirror, causing the thermal expansion of the reflecting surface. The thermal distortion refers to the difference between the maximum deformation and minimum deformation in the normal direction. It directly exerts an impact on the surface shape accuracy of the reflecting surface and then the quality of the output laser beam. The temperature rise and the thermal distortion of the reflecting surface are continuously increasing with the laser irradiating time until the balance is reached between the heat gain and heat dissipation. Hence, to realize infinite operating time of mirror, the system should be at thermal equilibrium before the thermal distortion of the irradiated region reaches the threshold value (1/10 laser wavelength).

2.2. Modeling description

Considering the machining technology for monocrystal silicon, the conventional configuration for a water-cooled mirror (shown in Fig. 2a) is divided into the mirror layer, channel layer and flow distribution layer as shown in Fig. 3 (a1)(a2)(a3). Fig. 2b and Fig. 3 (b1)(b2)(b3) illustrate that the new configuration is also a three-layer structure. In the new configuration, a couple of straight

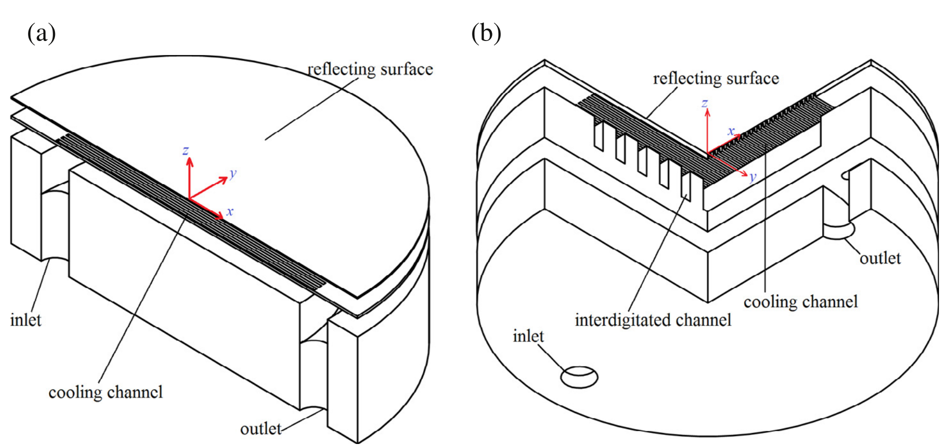

Fig. 2. Sectioned view of water-cooled mirror: (a) conventional configuration, (b) new configuration.