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Laser-induced cracks in ice due to temperature gradient and thermal stress

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ABSTRACT

This work presents the experimental and theoretical investigations on the mechanism of laser-induce cracks in ice. The laser-induced thermal gradient would generate significant thermal stress and lead to the cracking without thermal melting in the ice. The crack density induced by a pulsed laser in the ice critically depends on the laser scanning speed and the size of the laser spot on the surface, which determines the laser power density on the surface. A maximum of 16 cracks within an area of 17 cm × 10 cm can be generated when the laser scanning speed is at 10 mm/s and the focal point of the laser is right on the surface of the ice with a laser intensity of $\sim 4.6 \times 10^7$ W/cm^2. By comparing the infrared images of the ice generated at various experimental conditions, it was found that a larger temperature gradient would result in more laser-induced cracks, while there is no visible melting of the ice by the laser beam. The data confirm that the laser-induced thermal stress is the main cause of the cracks created in the ice.

1. Introduction

Due to the cold weather, water vapors are usually condensed, liquefied and frozen on the surface of the equipment, which is exposed to air, such as the power transmission lines, the vehicles and outdoor facilities in the cold high latitude northern China and in the high humility southern China, where the temperature could be below the freezing point in winter and the freezing induced accident is a commonplace. The freezing may jeopardize the performance of the equipment and pose danger to the safe operation. In 2011, because of a rare snow-disaster and freezing weather, the bogies of many high-speed trains were covered by thick ice cups and this posed a huge threat to the safety of the trains. Fig. 1 shows some photograph of the ice-covered bogies, which not only caused serious threat to the operation safety [1], but also increased the daily maintenance time. Therefore, it has become an important issue to solve the problem. However, there are very few report focused on de-icing in the literature. The traditional methods of deicing included blowing the ice with hot air, shooting the ice with hot water to melt the ice [2]. For example, the Chinese Railway Administration has been using hot water to melt down the ice during the maintenance and then spray the deicing fluid over the surface of the equipment to prevent it from refreezing for a short period of time. But many delicate components, such as the Pitot tube and the inlet of the engine, are not allowed to contact with the deicing fluid. The technique is also very messy and time consuming. Recently, the deicing technique using a laser has attracted some research attentions and laser-dicing can be a novel and promising method for de-icing.

Two main de-icing methods using lasers are currently been explored: One is to use continuous wave (CW) laser to radiate the ice. The ice then absorbs the laser energy, heats up and melts down. In 2007, Zhu et al. introduced a de-icing scheme using laser-induced thermal melting and ice weight desquamation method. However, the de-icing efficiency of direct melting is very low due to the high specific heat of the ice. The experimental results show that it took 90 kJ of laser energy and 26 min to de-ice 1 kg of ice [3]. In 2010, Qi et al. presented a model of deicing with Nd:YAG and CO_2 lasers using ANSYS software. The calculation showed that the laser with high output power and low ice absorption coefficient is more suitable for the laser deicing of the ice-covered power-lines [4]. In 2011, Zhao developed a high-power semiconductor laser for deicing and figured out the corresponding parameters for effective de-icing. The results showed that the device can operate reliably and efficiently under severe weather conditions [5]. In 2011, Chen et al. simulated the temperature

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Fig. 1. The image of ice-covered bogies of the trains.

and stress distributions in the ice during the laser de-icing process. The temperature and stress distributions and the penetration rates were also given for different initial temperatures, laser powers and spot sizes [6]. The other technique is to use high power-density pulsed laser to irradiate the ice that were frozen on the surfaces of some out-door equipment, such as the bogies in the high-speed trains operated in the cold zones. In 1976, Jean W. Lane and Stephen J. Marshall found that it is feasible to fracture accumulations of ice on a surface by irradiating with a single laser pulse of energy ranging from 1 to 5 joules at a wavelength of 1.064 μm if the laser pulse is focused to a point with a diameter less than 0.2 cm at the interface between the ice and the substrate. Under the pulsed laser radiation, part of the thin ice layer on the equipment can be crushed and vaporized [7]. The main idea of these two methods is that the ice would be melt when it absorbs enough laser's energy, but it also faces some problems: on one hand, because of the high specific heat capacity of the ice, the efficiency of melting the ice based on the conversion of laser energy to the heat needed for heating and melting appears to be less efficient so that one need high laser energy; On the other hand, a high laser energy may do harm to the surface of the equipment under the ice and it is difficult to control the laser energy, which is just enough to melt down the ice completely without hurting the equipment.

In this article, we proposed a method of de-icing based on laser induced temperature gradient and the corresponding thermal stress, which leads to the creation of the cracks in the ice, and the cracked ice-bulk can be removed without significant melting so that it, on one hand, saves a lot laser energy, and, on the other hand, the surface of the equipment would not be damaged by the laser. It is understood that when the ice absorbs pulsed laser energy, it creates a temperature distribution surrounding the laser beam. When the temperature gradient is high enough, the cracks could be induced due to a large temperature gradient and the corresponding thermal stress without melting of the ice. And this can be achieved by a pulsed laser. A maximum number of the cracks can be created when the power density, the focal position, and the scanning speed are optimized. Experimentally, it was found that there is basically no melting of the ice before the cracks are created. In addition, by controlling the scanning speed and the laser intensity, one can avoid damaging of the ice-covered surface. Once the crakes are created in the ice, it is very easy to remove the ice mechanically, such as by knocking it with a rubber hammer, and yet there is no damage to the instrument underneath the ice after the laser irradiation.

2. Theoretical simulation

The idea of de-icing using laser-induced thermal stress is based on the fact that when the ice absorbs the energy of the laser, the ice is heated up locally following the shape of the laser beam and the temperature of the ice depends on the power density of the laser beam and the amount of the laser energy absorbed. The heat in the laser-heated zone is then transferred mainly through heat-conduction to the surrounding low-temperature ice and thus created a temperature distribution. Based on the simple physics of thermal expansion, the difference in temperature would result in different value of thermal expansion in the bulk of the ice and thus created a thermal stress. The thermal stress will be strong enough to create cracks in the ice if the temperature gradient is large enough. A larger temperature gradient would result in a large thermal stress and thus a higher number of crack-density in the ice. The thermal-gradient-induced stress in the materials has been investigated in a laser slab both theoretically [8,9]. Similar calculation can be applied to investigate the laser-induced thermal gradient and the corresponding thermal stress in the ice.

To effectively create cracks in the ice, a laser with proper wavelength is essential to the experiment. For a laser in the far infrared, such as CO_2 laser at 10.6 μm, the absorption coefficient of ice is 1.58×10^5/m, which is 6810 times higher than a laser in the near-IR, such as a Nd:YAG solid-state laser at 1.064 μm or a fiber laser, whose absorption coefficient in the ice is only 23.2/m [10]. Fig. 2 is an illustration of the laser-irradiated ice. As shown in Fig. 2, the laser at 1.064 μm has a relatively low absorption in ice and thus can penetrate certain thickness (several centimeter) of ice and change the temperature within certain depth like demonstrated in Fig. 2(a), while for the 10.6 μm laser only a very thin top layer (at μm level) of ice is affected as shown in Fig. 2(b). The ice exposed with a Nd:YAG is body-heated, while the ice with a CO_2 laser is plane-heated. The two different heating mechanisms show significant differences in deicing. When a CO_2 laser of high absorption coefficient is used to irradiate the ice, the ice will melt layer by layer. While in the case of Nd:YAG laser, besides the surface absorption, the bulk of the ice also absorbs the laser energy and thus creates a heated cylindrical zone and results in a 3D-temperature distribution and 3D-thermal stress.

The absorption coefficient of ice at 1.064 μm is 23.2/m. According to the Beer-Lambert Equation:

$$P_{out} = P_{in} \exp(-\eta H) \quad (1)$$

where P_{in} and P_{out} present input power and transmitted power, H is the thickness of ice and η is absorption coefficient [5]. If a 600 W laser at 1.064 μm irradiates a bulk of ice whose thickness is 5 cm, the residual power is about 188 W, while the residual laser power of a 600 W laser of 10.6 μm would be zero, which indicates that the 1.064 μm laser has a higher transmission distance in the ice and it can cause a great temperature gradient and a high thermal stress distribution in the whole bulk. The ice irradiated by the laser at 1.064 μm will become opaque due to laser-created micro-bubbles and its solid structure became loose and can be cracked easily [4].