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Application of millisecond pulsed laser for thermal fatigue property evaluation

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ABSTRACT

An approach based on millisecond pulsed laser is proposed for thermal fatigue property evaluation in this paper. Cyclic thermal stresses and strains within millisecond interval are induced by complex and transient temperature gradients with pulsed laser heating. The influence of laser parameters on surface temperature is studied. The combination of low pulse repetition rate and high pulse energy produces small temperature oscillation, while high pulse repetition rate and low pulse energy introduces large temperature shock. The possibility of application is confirmed by two thermal fatigue tests of compacted graphite iron with different laser controlled modes. The developed approach is able to fulfill the preset temperature cycles and simulate thermal fatigue failure of engine components.

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1. Introduction

Thermal fatigue due to varying working temperature is one of the damage mechanisms that occur on the surface of engine combustion chamber components in the automotive industry [1,2], and is becoming serious with the development of higher power density engine. Therefore, it is of great importance to evaluate the thermal fatigue property under simulated thermal loading condition in the early conception stages. Two different kinds of temperature fluctuation range both exist in an internal combustion engine [3,4], which is 100–300 °C with uncertain frequency and 20–50 °C with typical frequency of 1–10 Hz. Several experimental methods with different heat sources have been developed to simulate and accelerate thermal damage, such as high frequency wire coil, localized flame, quartz lamp, and so on [5,6]. However, these heating methods show energy dispersity and difficulty in precise control.

Nowadays, laser is considered as a kind of ideal heat source due to its high spatial and temporal controllability [7]. Laser thermal fatigue experiments have been researched for the past few decades, and applied to rail steel, gas turbine, nuclear power plant, thermal barrier coating system and so on [8–11]. The current studies mainly focus on the fast heating features of continuous wave laser. Nevertheless, due to its intrinsic nature, it is difficult for the continuous wave laser to accomplish cyclic energy output in millisecond interval, especially for the engine conditions.

On the contrary, pulsed laser can realize energy output in pulse form, which has been widely used owe to its easy regulation of pulse duration, precise control of pulse repetition rate and high pulse energy [12]. Recently, the ultra-short pulsed lasers, which are with a few to dozens of nanosecond (ns), picosecond (ps) or femtosecond (fs) time durations, are attractive in evaluation of thermal and mechanical properties [13–15]. However, the extremely high peak power of ultra-short pulsed lasers would break down the surrounding material easily and cause undesired local surface damage. In addition, the characteristic time for heat conduction can be deduced from Fourier's heat conduction equation which is used to analyze the temperature evolution during thermal fatigue. It is expressed as a function of material properties, such as density, specific heat, characteristic body length and thermal conductivity approximately [16]. Taking the thermo-physical properties of general metals and the characteristic length of millimeter scale into account, the estimated characteristic time is of milliseconds order, which is consistent with the common working period of engine components. Therefore, a millisecond (ms) pulsed laser is more adaptable as heat sources for thermal fatigue experiments. As for the ms pulsed laser, the energy cumulative effect is noticeable when the pulse repetition rate is high enough, which reflects the thermal and mechanical effect of laser-material interaction. Consequently, the ms pulsed laser has aroused general concern and has been used in thermal fatigue test [17–19]. M. Schaus et al. [17] have performed the analyses on thermal shock and

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thermal fatigue properties of railroad steel sample by pulsed YAG laser with pulse duration of 15 ms. Muneharu Kutsuna et al. [18] have analyzed the life time of Cr-Mo ferritic steel used for turbine housing after thermal fatigue test induced by ms pulsed laser. However, thermal fatigue tests with complex cycles using ms pulsed laser, especially designed for engine working conditions, have not been available in the scientific literature. Additionally, researches about the effects of laser parameters on the surface temperature response during thermal cycles are rarely reported.

Creatively, a novel approach of thermal fatigue experiment based on millisecond YAG pulsed laser is developed here, which can produce complex and transient temperature cycles. Particular emphasis is placed on the temperature change of compacted graphite iron with laser parameters, such as pulse energy, pulse duration and repetition rate, and the relationship is established for experimental parameter design. In addition, two experiments with different control modes are conducted, and the evolution process of thermal fatigue crack initiation and propagation is discussed.

2. Experimental method and material

2.1. Basic principle of experimental method

In order to simulate the cyclic response of thermal stress and strain, and analyze the initiation and propagation mechanism of thermal crack, appropriate and transient temperature gradients are expected to induce in the specimen according to actual conditions. Depending on the pulse waveform and combination of laser parameters, two different kinds of pulsed laser tests can be realized: laser irradiation with a high pulse repetition rate (Fig. 1(a-1)) utilizing surface temperature accumulation effect for large thermal shock (Fig. 1(a-2)); heating to the maximum temperature

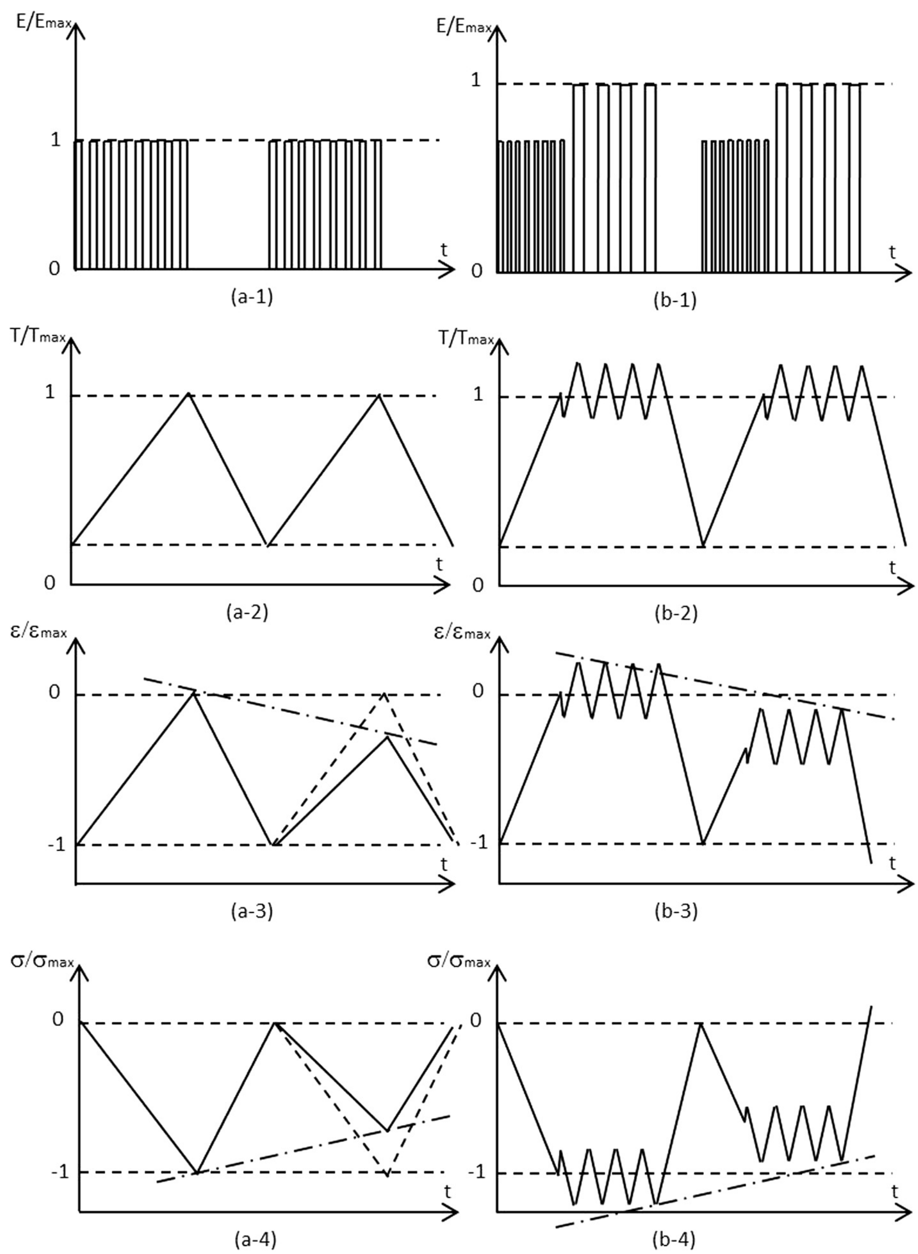

Fig. 1. Schematic variation diagrams of input energy, temperature, thermal strain and thermal stress during pulsed laser thermal fatigue tests. (a) Laser parameters of single group; (b) combination form of laser parameters.

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