Available online at www.sciencedirect.com

ScienceDirect

International Journal of Heat and Mass Transfer 51 (2008) 757–767

International Journal of HEAT and MASS TRANSFER

www.elsevier.com/locate/ijhmt

Thermal fatigue on pistons induced by shaped high power laser. Part I: Experimental study of transient temperature field and temperature oscillation

Hong-Wei Song [a,b,*], Gang Yu [a], Jian-Song Tan [c], Liang Zhou [a], Xiao-Li Yu [c]

[a] *Laboratory for Laser Intelligent Manufacturing, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100080, PR China*
[b] *State Key Laboratory of Nonlinear Mechanics, LNM, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100080, PR China*
[c] *College of Mechanical and Energy Engineering, Zhejiang University, Hangzhou 310027, PR China*

Received 2 February 2006; received in revised form 14 April 2007
Available online 3 July 2007

Abstract

Thermal fatigue behavior is one of the foremost considerations in the design and operation of diesel engines. It is found that thermal fatigue is closely related to the temperature field and temperature fluctuation in the structure. In this paper, spatially shaped high power laser was introduced to simulate thermal loadings on the piston. The incident Gaussian beam was transformed into concentric multi-circular beam of specific intensity distribution with the help of diffractive optical element (DOE), and the transient temperature fields in the piston similar to those under working conditions could be achieved by setting up appropriate loading cycles. Simulation tests for typical thermal loading conditions, i.e., thermal high cycle fatigue (HCF) and thermal shock (or thermal low cycle fatigue, LCF) were carried out. Several important parameters that affect the transient temperature fields and/or temperature oscillations, including controlling mode, intensity distribution of shaped laser, laser power, temporal profile of laser pulse, heating time and cooling time in one thermal cycle, etc., were investigated and discussed. The results show that as a novel method, the shaped high power laser can simulate thermal loadings on pistons efficiently, and it is helpful in the study of thermal fatigue behavior in pistons.

Keywords: Thermal fatigue; Temperature field; Shaped high power laser; HCF; Thermal shock

1. Introduction

Thermal fatigue behavior of pistons is vital to the overall life-span of diesel engines. Pistons are subjected to severe thermal loads while in service, and the long-term transient internal stress may initiate cracks in the structure, a damage mechanism which is now known as "thermal fatigue". It is of great importance to evaluate the fatigue performance of piston component under simulated thermal loading condition in order to develop a robust design. Many experimental systems were developed to simulate the in-service thermal loadings on pistons during the past years. The heat sources in use are mainly localized intense flame, high frequency wire coil, thermal resistance heating, and quartz lamp heating, etc. [1–3]. However, the heat transfer process and thermal loading condition in a piston are very complex and elusive to simulate [4]. Combustion in the diesel engine is heterogeneous, and at any one time there are wide variations in gas temperatures through the charge. Despite the complexity, studies showed that the temperature field on the top surface of a piston is in an axisymmetric pattern basically [5]. This requires the heat source in an experimental simulation system can be

* Corresponding author. Address: Laboratory for Laser Intelligent Manufacturing, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100080, PR China. Tel.: +86 010 62651165; fax: +86 010 62561284.
E-mail addresses: songhw@imech.ac.cn, songhw@tsinghua.edu.cn (H.-W. Song).

0017-9310/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijheatmasstransfer.2007.04.035

Nomenclature

E	Young's modulus
P_h,P_q	heating power and cooling power
T_{max},T_{min}	maximum temperature and minimum temperature in one thermal cycle
ΔT	temperature change or temperature difference, $\Delta T = T_{max} - T_{min}$
$\alpha(T)$	thermal expansion coefficient
σ_T	elastic thermal stress
τ_h,τ_q	heating duration and cooling duration in one thermal cycle

Subscripts

h	heating
max	maximum
min	minimum
q	cooling

designed in both spatial and temporal domains in a controllable manner.

Lasers are able to deliver substantial amounts of power in the form of light. Meanwhile, laser beam can be conveniently modulated with the aid of diffractive optical elements (DOEs) to produce a desirable heating pattern. The temporal profile of laser pulse can be flexibly programmed in the level of millisecond. All these merits make laser an ideal candidate for heat source used in the thermal loading simulation test.

Some researchers have employed laser to study thermal fatigue behavior of material specimens from gas turbines, diesel engines and railroad steels. Schaus and Pohl [6] explained the principles of thermal fatigue which were simulated by laser, and performed thermal shock and high cycle thermal fatigue tests on railroad steel material. In order to accelerate the thermal damage of the materials in turbine housing and estimate the life time of casing in a relatively short time, Kutsuna et al. [7] used a pulse YAG laser to perform thermal fatigue tests. Zhu et al. [8–10] developed vast investigations on thermal fatigue behavior of ceramic thermal barrier coatings (TBCs) induced by laser. Later, they established a simulated engine test rig to evaluate thermal fatigue behavior of a candidate material for high-performance engines, and the material is tested under superimposed CO_2 laser surface impulsive thermal loads [11]. Long and Zhou [3] carried out experimental and numerical investigations on the thermal fatigue of particle reinforced metal–matrix composite induced by repetition-pulsed laser heating and mechanical load. However, the above studies were all focused on small material specimens. Up to now, no report has been found in the study of laser induced thermal fatigue for bulk structures like pistons. The difficulty for a large bulk structure test is that the intense incident laser beam been must be transformed into specific heating patterns to obtain desirable temperature fields, and the input energy must be sufficiently high.

In the present paper, we are trying to simulate the temperature field on the top surface of light alloy piston with a spatially shaped high power laser. The incident laser beam was transformed into three concentric circular bands and irradiated on the top surface of the piston. The piston is made of LD11 aluminum alloy, and its dimension is 150 mm in diameter and 138 mm in height. Typical thermal high cycle fatigue and thermal shock tests were carried out to simulate the normal working conditions and conditions with a sudden change of loads on pistons. Some important parameters that affect the results of simulation tests were examined and discussed.

2. Fundamentals for simulation test

When a structure is heated or cooled, its volume changes. Thermal compressive stresses or tensile stresses occur if thermal expansion or contraction is obstructed. The obstruction is produced either from external constraints or internal constraints due to the heterogeneous temperature distribution and fluctuation. In the thermoelastic condition, the stress can be written as

$$\sigma_T = E\alpha(T)\Delta T \tag{1}$$

where σ_T is thermal stress, $\alpha(T)$, ΔT and E are thermal expansion coefficient, temperature change, and Young's modulus, respectively. Therefore, material damage can be induced by temperature fluctuation, and the alternating compressive and tensile stresses may cause an incremental damage which is called thermal fatigue.

Thermal stress status is therefore directly related to the temperature gradients and temperature fluctuation. To examine the thermal fatigue behavior of a piston, one must simulate the temperature field and temperature oscillation of the piston that is in service. A disagreement between experimental estimations of the temperature field given by different authors seems to due to the type of the engine being tested and the experimental method being employed [4]. For the Φ150 mm piston examined in the present study, it has been sampled that the temperature field on the top surface is roughly in a circular pattern. Referring to Fig. 1, the representative temperatures at $T1$, $T2$ and $T3$ are 310, 280 and 350 °C, respectively, in the cooling cycles, while they are 320, 290 and 360 °C, respectively, in the heating cycles in the normal working condition [12].

To simulate this character, a shaping lens has been designed to transform the incident Gaussian laser beam (Fig. 2a) into concentric multi-circular beam with certain intensity distribution (Fig. 2b). The shaping lens was manufactured according to the diffractive optical element

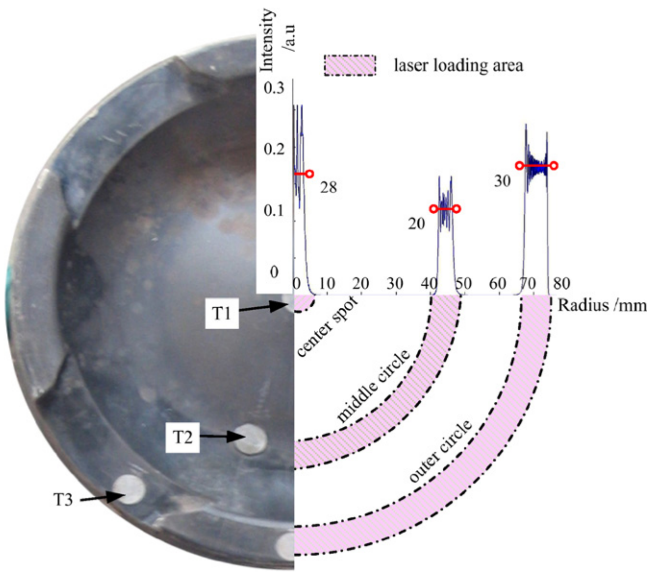

Fig. 1. Top surface of the piston and illustration of superimposed shaped laser irradiation.

(DOE) technique. The intensity distribution of the shaped beam was obtained through a reverse design method with the aid of finite element model (FEM), which is detailed in the accompanying paper [13]. In the simulation test, the shaped concentric multi-circular beam superimposed on the top surface of the piston, as illustrated in Fig. 1. Temperature gradients across the top surface were produced due to the inhomogeneous character of the shaped laser beam. Temperature oscillations occurred when it was incorporated with periodic heating and cooling, by alternating the output laser powers or assisted with cooling air or cooling water. Therefore, thermal loadings similar to those of normal working could be possibly simulated.

Thermal stresses in the piston could be roughly predicted when the piston is periodically loaded with the shaped laser beam. Transient working temperatures at the top surface would induce heterogeneous temperature distributions in the component. Such temperature gradients cause thermal stresses: compressive stresses, when the heated zones are obstructed in their thermal expansion by the cooler areas; and tensile stresses, when the contraction of a quenched surface is obstructed by the hot underlying region [6].

It is observed in the present study that the transient temperature response in the surface is much more sensitive than that of underlying region (or component temperature). Thermal stresses therefore could be analyzed according to Fig. 3. When a cold piston is heated, the surface temperature rises rapidly while the component temperature remains low. Obstruction to expansion causes compressive stresses in the surface, which is illustrated in Fig. 3a. When a hot piston is quenched, the surface temperature drops rapidly while the component temperature is still high. Obstruction to contraction causes tensile stresses in the surface, as illustrated in Fig. 3b. Another case that is normally found in the present study is shown in Fig. 3c. When a dynamic equilibrium is established between input energy and convective heat transfer, the component temperature maintains relative stable, and the surface temperature oscillates around the temperature of underlying component under the periodic laser loading. This produces both compressive stresses and tensile stresses in one cycle.

Under the action of long-term alternating thermal stresses or extreme high thermal stresses, the material failure criteria may be reached, producing a phenomenon of thermal fatigue.

3. Experimental set-up

The experimental set-up in the operating room is illustrated in Fig. 4. A high power laser, HAAS HL 3006 D industrial Nd:YAG laser has been employed in the experimental simulation. The maximum output power is 3 kW. A 5-axis (three translation axes, two rotation axes) framed robot system has been built up to give a precise positioning for the laser head. The laser head is positioned on top of the piston workpiece, and is 1000 mm away from the top surface, producing a loading case illustrated in Fig. 1 once working.

The experimental workbench, the composition of which is detailed in Fig. 5, is another important part of the

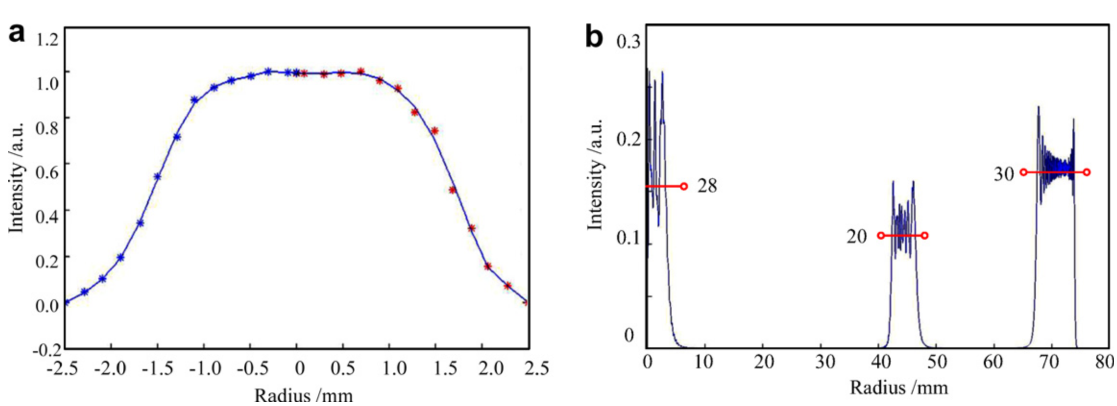

Fig. 2. Incident beam and shaped beam; (a) incident Gaussian beam and (b) shaped concentric multi-circular beam.

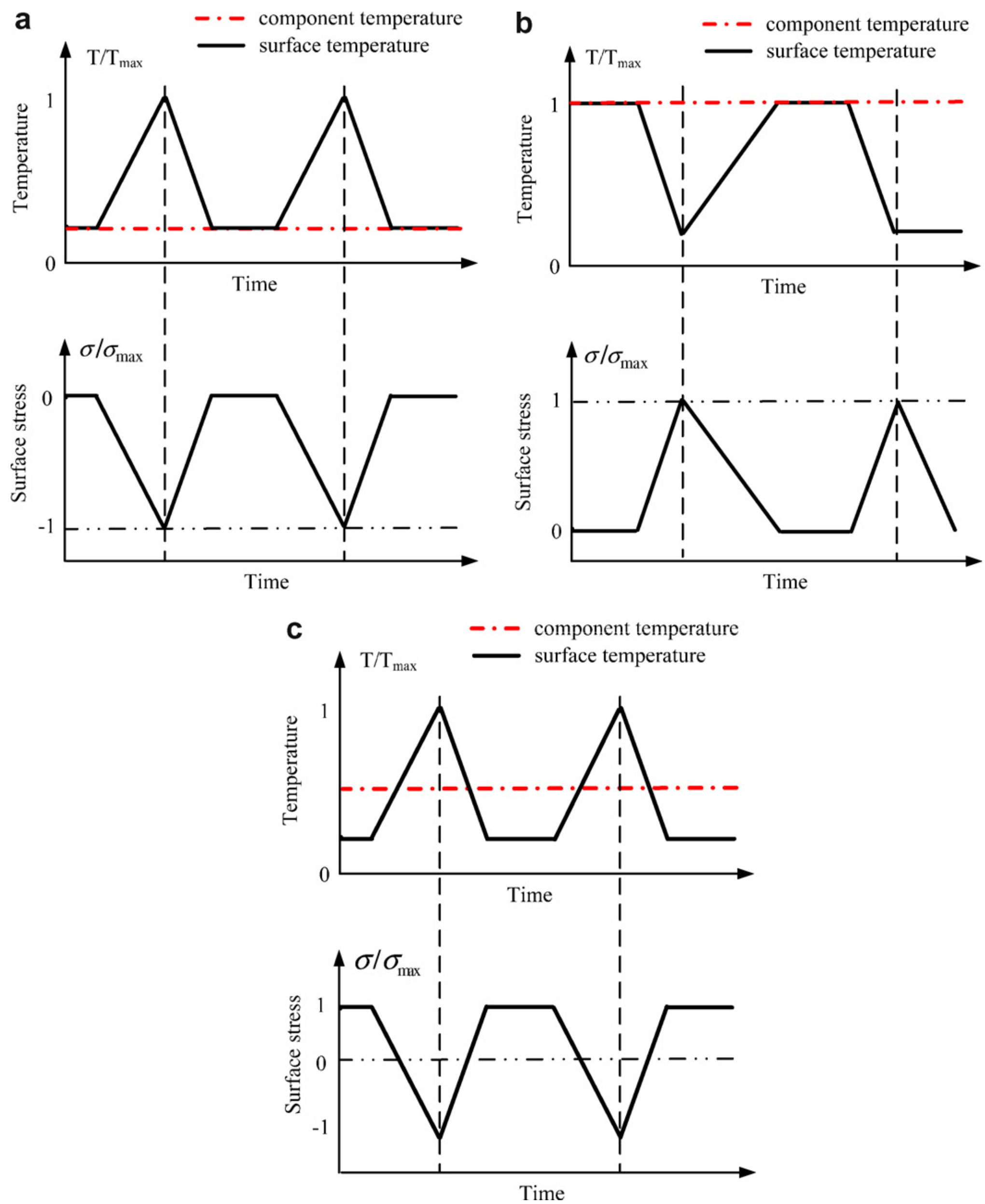

Fig. 3. Schematic of thermal stresses during heating, quenching, and stable oscillation: (a) Heating period, compressive stresses occur in the surface due to expansion obstruction. (b) Quenching period, tensile stresses occur in the surface due to contraction obstruction. (c) Stable oscillation period, produces both compressive stresses and tensile stresses in one cycle.

system. Infrared pyrometers were mounted on the top of the workbench to sample the transient surface temperatures at spots $T1$, $T2$ and $T3$, which are illustrated in Fig. 1. The infrared pyrometers work at 2.4 μm, a wavelength that is not interfered by the working laser. Three NiCr-NiSi thermocouples were buried about 2 mm beneath these sampling spots, serving as auxiliary sampling methods. Three high resolution CCD cameras were employed to sample transient images of the piston specimen. Air valve and water valve would be released when auxiliary cooling methods are necessary.

Two computers were installed in the controlling room. One gives experimental instructions and samples transient temperature data, the other programs loading cases and detects piston surface images. The computers and the laser system communicate each other through Ethernet. System integration and information feedback were accomplished based on PROFIBUS-DP (Process FieldBus–Decentralized Periphery) protocol. The protocol guaranteed a closed-loop feedback for the entire system during simulation tests.

4. Thermal high cycle fatigue and thermal shock

Usually thermal fatigue transients in a diesel engine can be classified into two types [6,11]. One is called thermal high cycle fatigue (HCF), which is associated with the in-cylinder combustion process, typically with

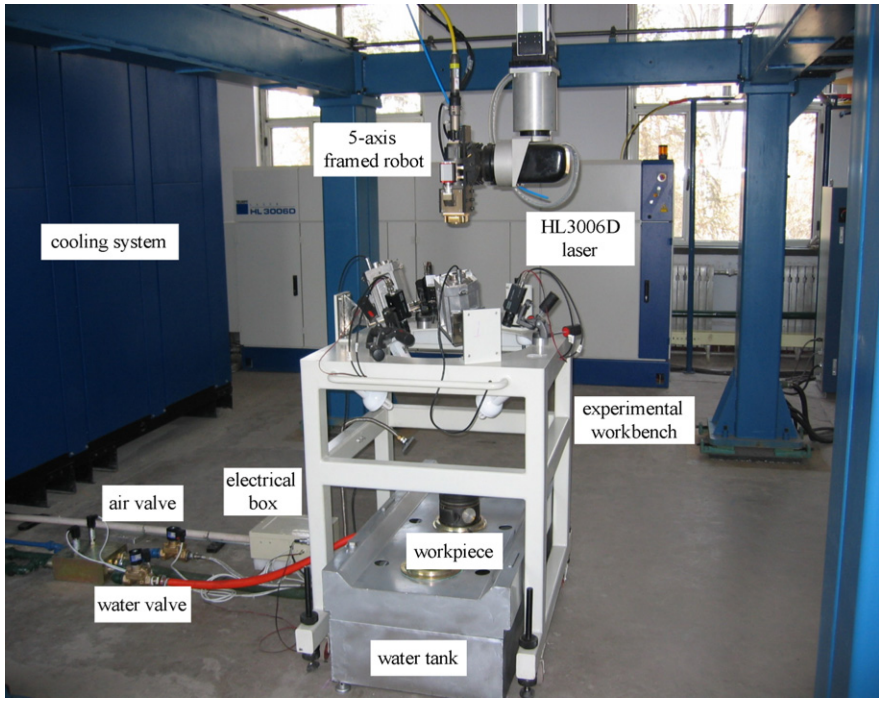

Fig. 4. Experimental system for laser simulated thermal fatigue on pistons.

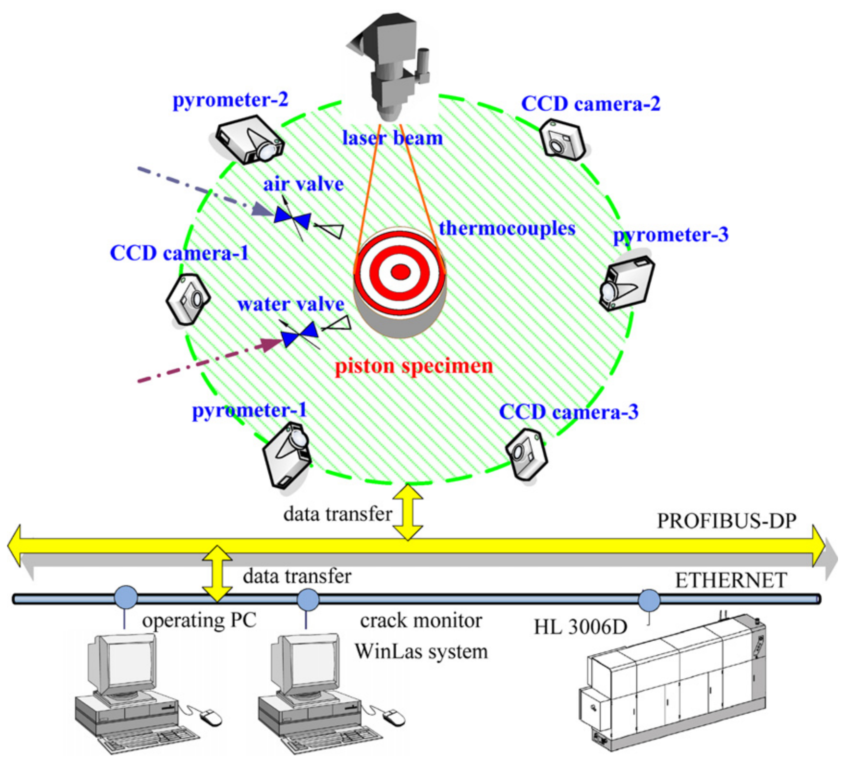

Fig. 5. Schematics of experimental workbench and system control.

frequency in the order of 10 Hz. The transient temperatures on the top surface are among 300–350 °C, with a fluctuation of 10–20 °C during one thermal cycle. The other is called thermal shock or thermal low cycle fatigue (LCF), which is associated with engine cycles characterized by the start/stop, no-load/full-load and a sudden change of speed. The temperature fluctuation may reach 300 °C. The shaped high power laser system can simulate loading conditions of both thermal HCF and LCF on pistons.

4.1. Thermal HCF

Typical thermal HCFs are shown in Figs. 6 and 7. The figures illustrate the transient temperature responses at spots $T1$, $T2$ and $T3$ (refer to Fig. 1), representatives of center, middle and outer circular bands, respectively. The temperatures were sampled by infrared pyrometers. Simulation tests can be accomplished either in a "temperature-controlled mode", or in a "time-controlled mode".

The temperature-controlled mode is achieved by setting up maximum temperature $T_{\max}$ and minimum temperature $T_{\min}$ in one thermal cycle for a given inspection spot. The laser operates in a high power mode till $T_{\max}$ is reached, then shifts to low power mode or no power mode till $T_{\min}$ is reached, forming one thermal cycle. Temperature change ΔT, or temperature difference in one thermal cycle, can be calculated from $\Delta T = T_{\max} - T_{\min}$. Fig. 6 illustrates a thermal HCF simulation test up to 400 cycles in the temperature-controlled mode, where $T2$ (representative of middle circular band) is the monitoring spot. In general, the temperatures maintain the oscillation of 300–313 °C, 286–292 °C and 248–264 °C in one cycle for the center, middle and outer circular bands, respectively, in the overall process. This temperature field and temperature fluctuations are similar to those of a piston in normal operating condition.

The time-controlled mode, however, is achieved by setting up period of thermal cycles, typically in parameters of the heating duration τ_h and cooling duration τ_q in one loading cycle. Fig. 7 gives a thermal HCF simulation test up to 600 cycles in the time-controlled mode. The loading cycles are $\tau_h = 2$ s, with the output power of

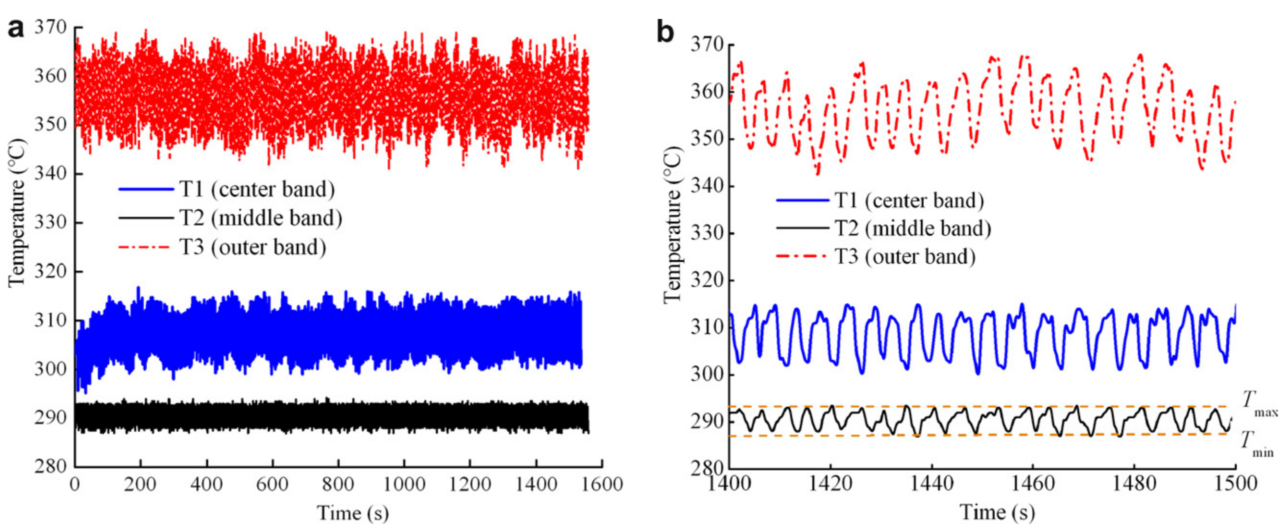

Fig. 6. Shaped high power laser induced thermal HCF in temperature-controlled mode (a) 400 cycles; (b) cycles from 1400 s to 1500 s, with the illustration of temperature control.

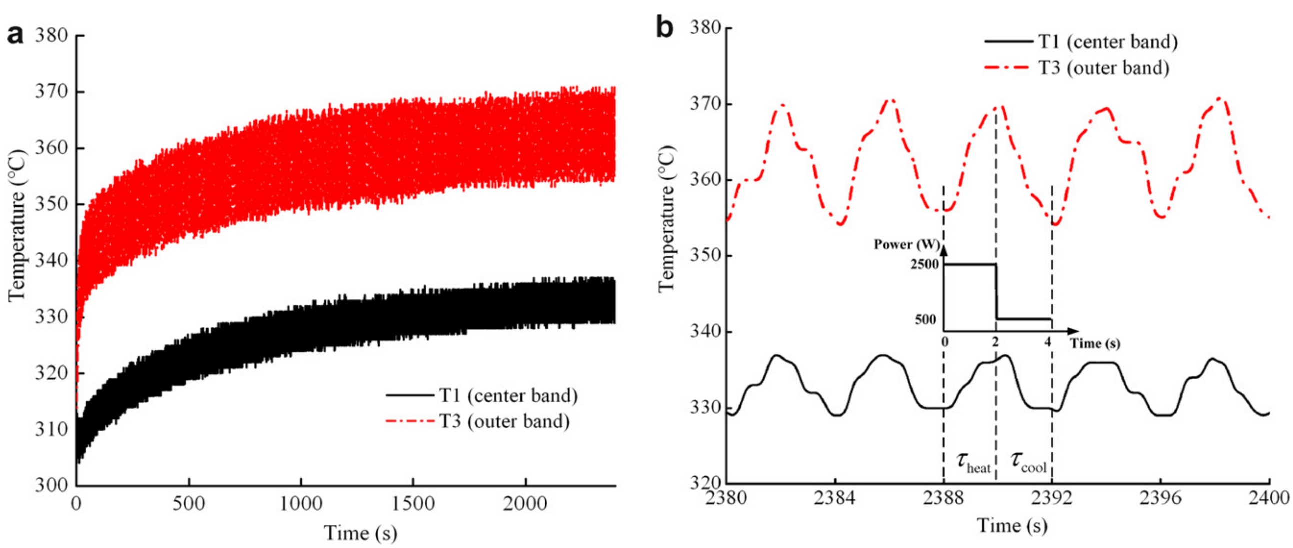

Fig. 7. Shaped high power laser induced thermal HCF in time-controlled mode (a) 600 cycles; (b) cycles from 2380 s to 2400 s, with the illustration of time control.

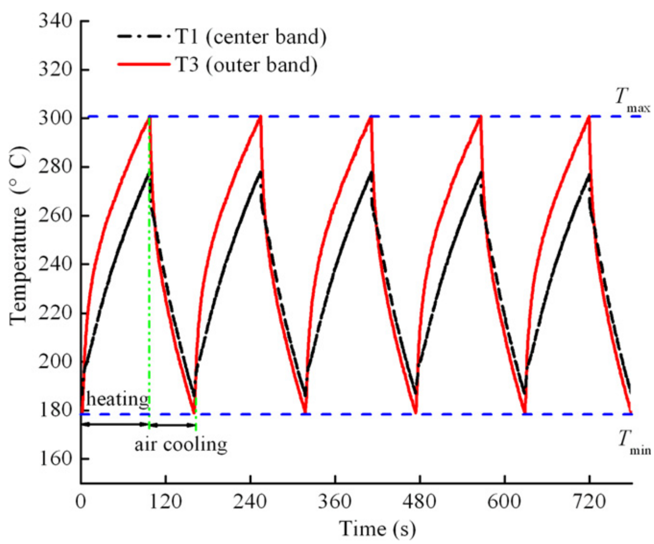

Fig. 8. Shaped high power laser induced thermal shock.

$P_h = 2500$ W, and $\tau_q = 2$ s, with the output power of $P_q = 500$ W. Although the magnitude of temperature oscillation in each cycle is relatively constant, the temperature level of the workpiece increases gradually in the overall process, as shown in Fig. 7a. In contrast, both temperature field and temperature oscillations maintain relative constant in a short time span, as shown in Fig. 7b.

The advantage of time-controlled HCF is that it can simulate thermal cycles with fixed or any changed period that is associated with in-cylinder normal working or speed changing. In a long-term HCF test, temperature field and temperature oscillations in a temperature-controlled mode are more stable and more predictable than those in a time-controlled mode, when compared Fig. 6a with Fig. 7a. In a relative short period, however, temperatures besides the inspection spot may fluctuate randomly in a temperature-controlled mode test (Fig. 6b), when compared with those in a time-controlled mode test (Fig. 7b).

4.2. Thermal shock

Thermal shock is characterized by a steep rise and drop of transient temperature in a relatively short period, which induces high level thermal stresses. Fig. 8 illustrates a typical thermal shock accomplished in the temperature-controlled mode. The temperature of the monitoring spot $T3$ oscillates between $T_{max} = 300$ °C and $T_{min} = 180$ °C. In the heating cycles, the piston is loaded with the shaped laser in the output power of $P_h = 3000$ W, and temperature rises from 180 to 300 °C. In the cooling cycles, laser stops (or $P_q = 0$ W), and cooling air was applied to the piston surface to implement forced convection. The cooling cycles can also be incorporated with the cooling water. Thermal shock could accelerate thermal fatigue process and reduce experimental period.

5. Influences of laser parameters on thermal fatigue test

As mentioned in Section 2, thermal stress and thermal fatigue are functions of temperature field and temperature fluctuation. Many parameters in the laser system can influence the temperature field and temperature fluctuation in the piston. Desirable thermal performances could be designed by modifying these parameters once knowing their influence. Systematic experiments were

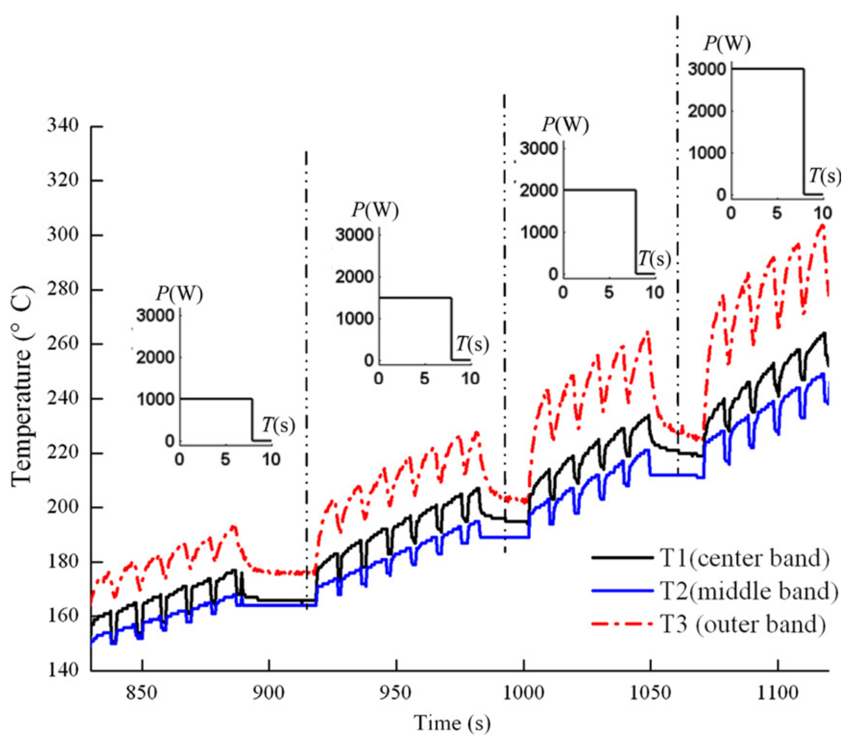

Fig. 9. Influence of laser power on temperature response.

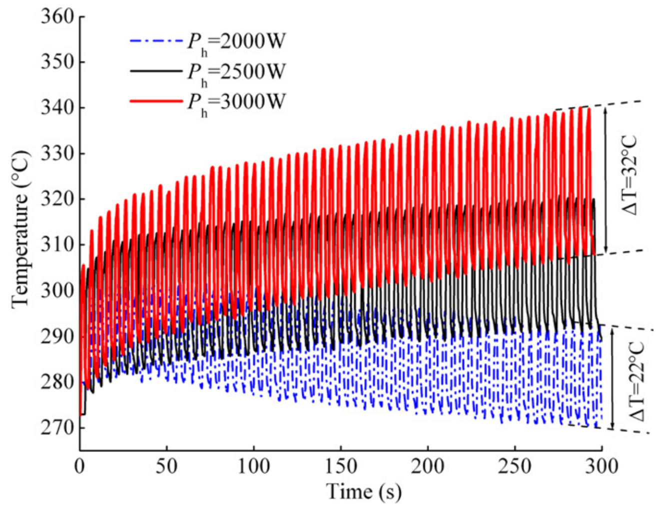

Fig. 10. Influence of laser power on dynamic equilibrium temperature and ΔT.

carried out to investigate the influence of intensity distribution of shaped beam, laser output power, period of loading cycle, temporal profile of laser pulse, and forced convection.

5.1. Effects of intensity distribution of shaped beam

Fig. 2b illustrates a typical intensity distribution of shaped laser beam. During a simulation test, the shaped beam is superimposed on the top surface of the piston, as shown in Fig. 1. Apparently, the transient temperature field and temperature gradient are directly related to the spatial profile of the shaped beam. The influence of intensity distribution of shaped beam has been discussed in details in the accompanying paper [13]. Since the spatial transformation is fixed in the DOE, one must design the intensity distribution of the shaped beam that could induce the target transient temperature field before a DOE can be manufactured. The accompanying paper has compared the

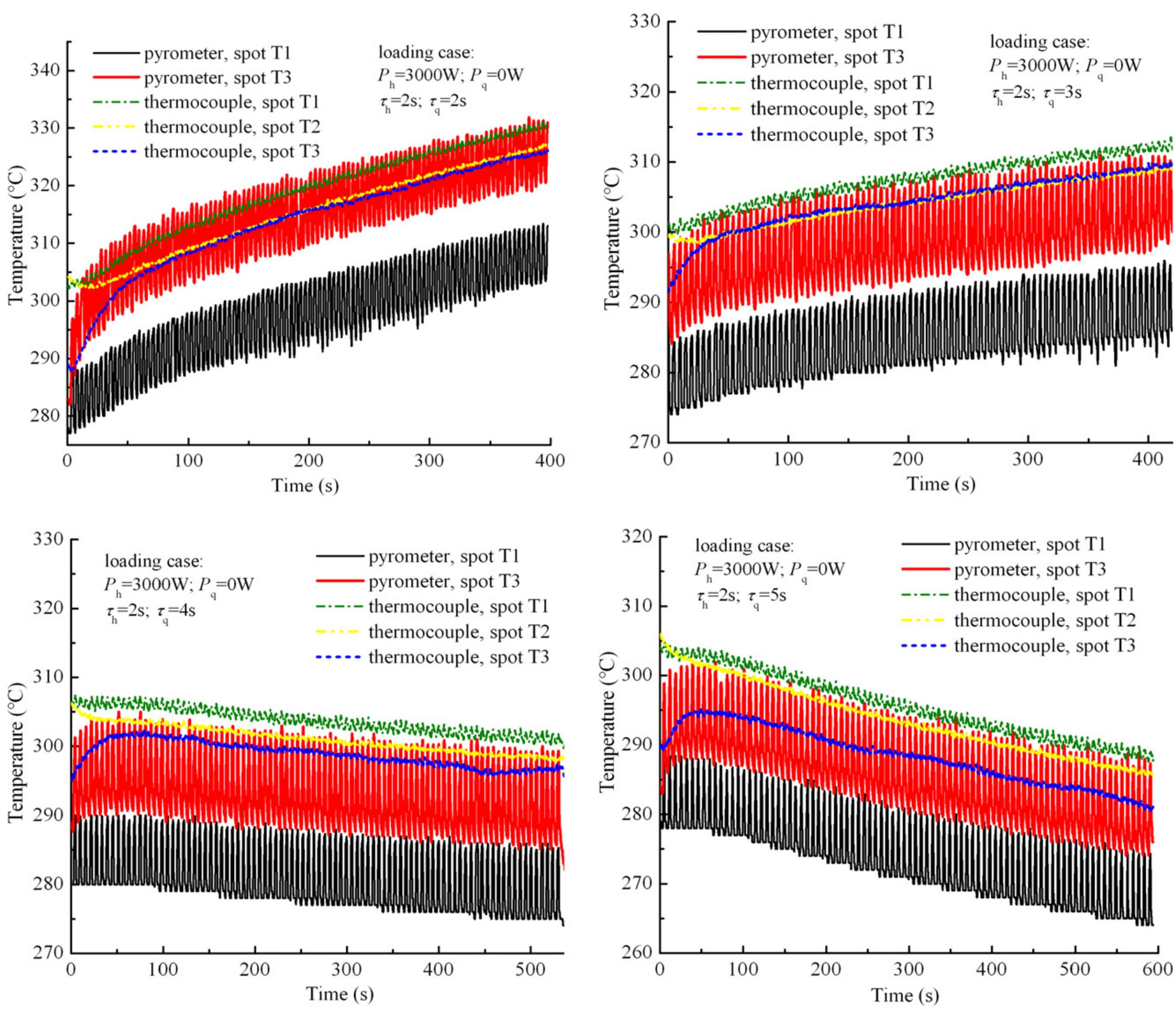

Fig. 11. Temperature responses under different loading periods.

three-dimensional transient temperature fields induced by the original design and optimal design for DOEs through numerical simulation.

5.2. Effects of output power

The working power of laser, which governs the magnitude of input energy, is one of the most important parameters that affect the simulation test. Fig. 9 shows temperature responses when P_h was raised from 1 kW to 3 kW. The loading cycle is heating duration $\tau_h = 8$s and cooling duration $\tau_q = 2$ s. Both temperature raising rate and temperature change ΔT increase as the heating power P_h is elevated. Higher working power means higher dynamic equilibrium temperature, since the component temperature of the piston seeks a value that could balance the input energy of laser and the energy lose due to the convection at surfaces. Fig. 10 illustrates temperature responses in the outer band (spot T3) when P_h is changed from 2 kW to 3 kW, where the initial component temperature of the piston and loading cycles are the same. The balance temperature would be lower than the initial component temperature for $P_h = 2000$ W, whereas it would be higher than initial component temperature for $P_h = 3000$ W, as can be seen by comparing temperatures at the beginning of tests with those at the end of tests. Fig. 10 also shows that for the loading cycles of $\tau_h = 2$ s and $\tau_q = 3$ s, ΔT is about 22, 27 and 32 °C for heating power of 2000, 2500 and 3000 W, respectively.

5.3. Effects of loading cycle

Period of thermal cycle, or the ratio of heating duration to cooling duration in one thermal cycle, determines the energy release rate when the working power is fixed. Fig. 11 shows temperature response when the heating duration and cooling duration ($\tau_h - \tau_q$) varies in the sequence of 2 s–2 s, 2 s–3 s, 2 s–4 s, 2 s–5 s. The working power is $P_h = 3000$ W and $P_q = 0$ W. The increase in the cooling duration τ_q means the input energy per unit time is reduced, therefore, the dynamic equilibrium temperature would decrease.

Fig. 11 also indicates, the transient temperature sampled by infrared pyrometers responses more sensitively to the power shift than that sampled by thermocouples. Thermocouples were buried about 2 mm away beneath the surface, and what they sampled are component temperature rather than surface temperature. Thermocouples can serve only as a referential method, since the rough-measured burying position may cause the sampled temperature deviate from the real.

5.4. Effects of temporal profile of laser pulse

Figs. 9–11 are loaded with square pulses, which are defined by P_h, P_q, τ_h, and τ_q. The temporal profile of output laser pulse can be designed into any forms. Fig. 12 gives the examples of output laser pulses in the square wave, sine wave and triangular wave, and the corresponding temperature responses. The peak power is 3 kW, and the pulse duration is 4 s. It can be calculated that the total energy in one thermal cycle is 12 kJ, in each of the three loading case. The temperature response mimics the temporal profile of laser pulse, while the overall temperature and ΔT in one thermal cycle show little variation between different loading cases.

One can perform simulation tests characterized by random temperature fluctuation, a phenomenon associated

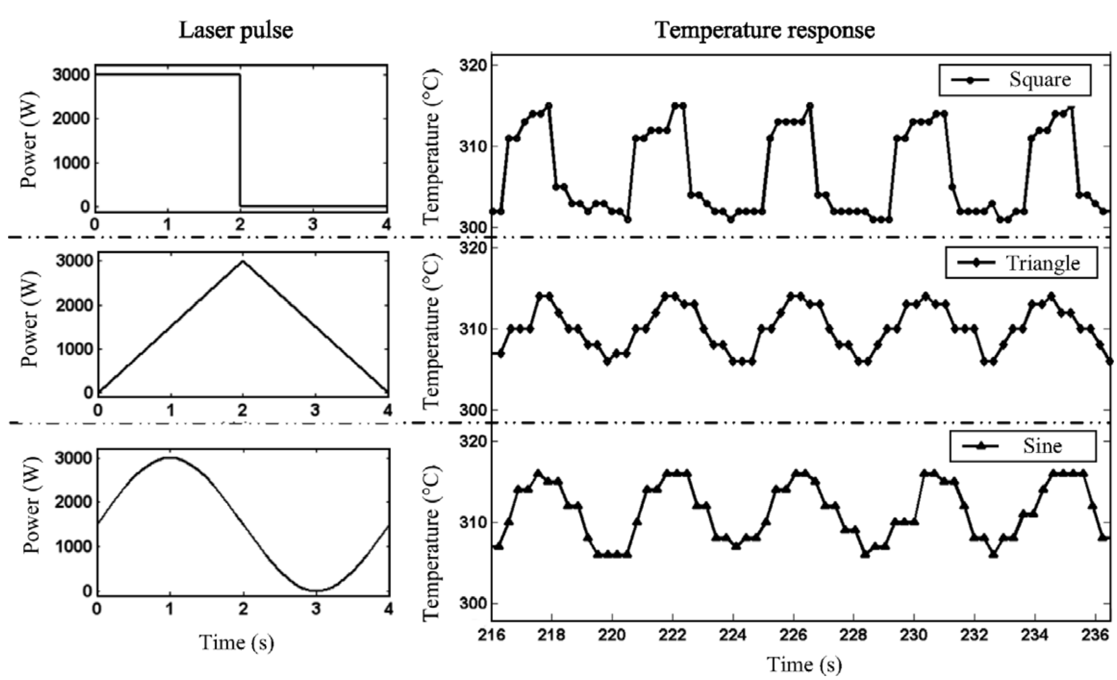

Fig. 12. Temperature responses under different laser pulse profiles.

with the speed or load changing in the engine. By altering output power, period of thermal cycle and temporal profile of laser pulse, random thermal fatigue simulation can be obtained. Fig. 13 is a typical test of this kind. The piston were loaded with 30 sine waves, 10 trapezoid waves, 10 triangular waves, 5 square waves, 5 sine waves and 5 trapezoid waves.

5.5. Effects of external cooling method

Air cooling at the top surface and water cooling at the bottom of the piston are optional in the simulation tests. Fig. 14 shows the temperature responses before and after surface air cooling. Surface air can be applied solely in the cooling duration τ_q to accelerate the cooling rate, as illustrated in Fig. 8 (also refer to Section 4.2). In the simulation test, air cooling can also be applied through an oil tunnel beneath the middle circular band to alter the temperature field. The example is Fig. 6, in which the temperature in the middle band is brought down due to the tunnel air cooling.

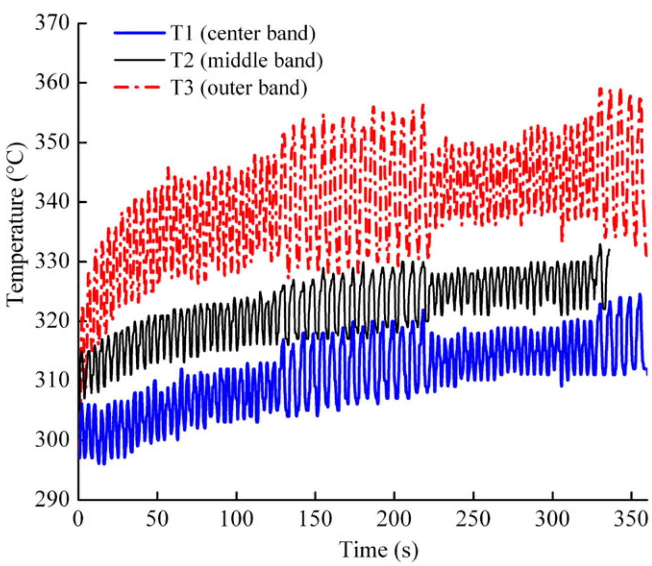

Fig. 13. Thermal fatigue test characterized by random temperature fluctuation, obtained from altering temporal profile and period of thermal cycle.

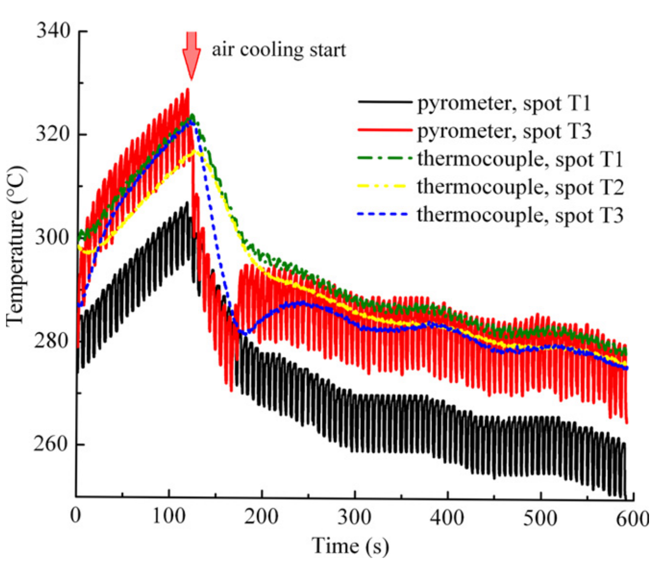

Fig. 14. Temperature response with and without surface air cooling.

6. Conclusions

The experimental study manifests that the shaped high power laser system can perform thermal fatigue simulation tests on pistons. The advantages of shaped laser method over conventional methods lie in the flexibility in the design and control, efficiency in thermal fatigue simulation. Many parameters, including intensity distribution of shaped beam, laser output power, period of loading cycle, temporal profile of laser pulse, and external cooling method, governs and influences the simulation test. A desirable thermal fatigue test therefore can be designed by altering these parameters. The system has been utilized to perform high cycle thermal fatigue, thermal shock and random thermal fatigue simulation test. Efficiency is another notable feature of present system. Typically it takes about 4 s to complete one thermal cycle. Comparably, the conventional flame heating method would take about 60–80 s to complete one thermal cycle, and the whole thermal fatigue test may last as long as 10–12 weeks.

Acknowledgements

Supports for this work from National Nature Science Foundation of China (No. 10502049) and Foundation of State Key Laboratory of Nonlinear Mechanics from Institute of Mechanics, Chinese Academy of Sciences, are gratefully acknowledged.

References

[1] H.G. Baron, Thermal shock and thermal fatigue, in: P.P. Benham, R. Hoyle (Eds.), Thermal Stress, Sir Isaac Pitman & Sons Ltd., London, 1964, pp. 182–206.
[2] X.L. Yu, R.B. Jin, Y.M. Shen, Z.Q. Hu, Z.D. Yan, Thermal fatigue simulating test bench for the engine piston, Trans. of CSICE 18 (1997) 43–47 (in Chinese).
[3] S.G. Long, Y.C. Zhou, Thermal fatigue of particle reinforced metal-matrix composite induced by laser heating and mechanical load, Compos. Sci. Technol. 65 (2005) 1391–1400.
[4] A. Weronski, T. Hejwowski, Thermal Fatigue of Metals, Marcel Dekker Inc., New York, 1991.
[5] B. Challen, R. Baranescu, Diesel Engine Reference Book, Elsevier, Oxford, 1999.
[6] M. Schaus, M. Pohl, Nd-YAG-Laser simulated thermal shock and thermal fatigue behaviour of railroad steel, Metallurgy 52 (1998) 464–470.
[7] M. Kutsuna, S. Fujita, Y. Sugita, K. Yamada, Thermal fatigue test for turbine housing by a pulse YAG laser, in: Proceedings of SPIE, High-Power Lasers in Manufacturing, vol. 3888, 2000, pp. 438–445.
[8] D.M. Zhu, R.A. Miller, Investigation of thermal high cycle and low cycle fatigue mechanisms of thick thermal barrier coatings, Mater. Sci. Eng. A – Struct. 245 (1998) 212–223.

[9] D.M. Zhu, R.A. Miller, Determination of creep behavior of thermal barrier coatings under laser imposed high thermal and stress gradient conditions, J. Mater. Res. 14 (1999) 146–161.

[10] D.M. Zhu, S.R. Choi, R.A. Miller, Development and thermal fatigue testing of ceramic thermal barrier coatings, Surf. Coat. Technol. 188–189 (2004) 146–152.

[11] D.M. Zhu, D.S. Fox, R.A. Miller, L.J. Ghosn, S. Kalluri, Effect of surface impulsive thermal loads on fatigue behavior of constant volume propulsion engine combustor materials, Surf. Coat. Technol. 188–189 (2004) 13–19.

[12] J.S. Tan, J.B. Di, Transient Temperature Field of Pistons, Experimental Report, China North Engine Research Institute, Datong, 2002, (in Chinese).

[13] H.W. Song, G. Yu, A.F.H. Kaplan, J.S. Tan, X.L. Yu, Thermal fatigue on pistons induced by shaped high power laser. Part II: design of spatial intensity distribution via numerical simulation, Int. J. Heat Mass Transfer, in press, doi:10.1016/j.ijheatmasstransfer.2007.04.034.