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Thermal fatigue resistance of H13 steel treated by selective laser surface melting and CrNi alloying

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ABSTRACT

In this study, the selective laser surface melting and laser surface alloying technologies were adopted to improve the thermal fatigue resistance of medium carbon hot-work die steel (H13) by a CO_2 laser. Two kinds of mixed chromium (Cr) and nickel (Ni) powders were used as the laser alloying materials, and the effects of the mixing ratio on the thermal fatigue resistance were investigated thoroughly. Some important results such as cross-sectional morphology, phases, hardness and thermal fatigue behavior were analyzed and evaluated. It indicates that the laser surface alloying technique using mixed powder with ratio of 75%Cr–25%Ni can considerably enhance the thermal fatigue resistance of the H13 steel. The laser alloyed zone has excellent properties such as preventing crack initiation and oxidation corrosion compared with original H13. Thermal cracking and oxidation corrosion that occurred at substrate surface can be surrounded and intercepted by a gridded laser strengthened structure. Therefore, the naturally developed cracks could be effectively prevented. Theses results and analysis show that laser surface technique can be positively used to improve surface mechanical properties of H13 dies.

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1. Introduction

Die casting processes are increasingly used to produce metal casting because of their high quality, low cost and short lead-time. However, premature failures caused by thermal fatigue on die surface degrade the quality and increase the cost of castings significantly. It is well known that thermal fatigue is resulted by internal stress initiating from cyclic temperature gradient, and it is an important life-limiting factor for many engineering metallic parts, especially for those serving in alternatively heating and cooling conditions such as hot-work dies [1,2]. Accordingly, improving the resistance to thermal fatigue of hot-work die steel is always a subject of major concern to engineering researchers [3]. In previous studies, enhancing the thermal fatigue life of metallic materials was mainly studied by choosing either a right heat treatment conditions or an appropriate chemical composition. Nevertheless, due to the complexity of thermal fatigue processes and the variety of the factors that influence them, it is difficult to enhance the thermal fatigue properties without sacrificing the mechanic properties of materials [4].

Once a sample is subjected to the thermal shock conditions, large thermal stress is induced by an abrupt temperature gradient between the outer surface and the interior [5]. Among the thermal fatigue situations, the surface region suffers the highest temperature and the largest thermal stresses, which is a state of alternating plasticity [6]. Thermal cracks mainly initiate at the working surface of a die and thereby crack propagation leads to mechanical failure. Thus, the surface treatment technology has become an effective method to improve the service performance of a metal die. Recently, major interests have been developed in the field of the surface treatment for steel, including electric plating, nitriding, chemical plating, thermal spray, vapor deposition, etc. [7–9]. Though many methods have been used, they are mainly aimed at improving wear and corrosion resistance, only a few have been reported on improving thermal fatigue performance. For example, Persson et al. [10] evaluated the effect of several surface treatments to prevent thermal fatigue cracking of hot-work tool steels, and moreover Shivpuri et al. [11] carried out the computer modeling of thermal fatigue cracking in die casting tooling; however, due to the harshness of service condition of such hot-work components and the complexity of thermal fatigue processes, there is still much space to improve thermal fatigue in many engineering fields.

It should be noted that, laser surface modification can form a surface layer with strong metallurgical bonding to the substrate. It is one of the most important surface modification methods which can offer a versatile approach to the production of surface layers of a wide range of structures and compositions on a variety of substrates

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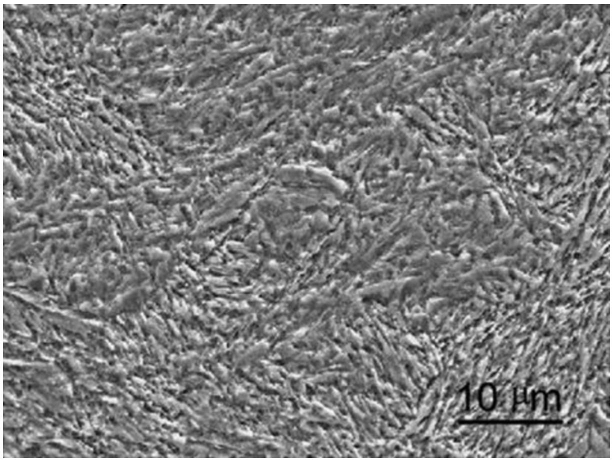

Fig. 1. Microstructure of the H13 steel as substrate.

[12,13]. In addition, laser technology can acquire very rapid rates during surface melting; similar with rapid solidification at cooling rate of 10^7 K/s. As a result, the microstructures can be significantly refined. Thus, the improvement in thermal fatigue resistance may be achieved by laser via homogenization and refinement of the microstructure and/or formation of a new alloy on the surface. Referring to Aqida et al., surface modification on H13 steel using laser glazing was investigated. They claimed the effective working limit (approx. 600 °C) for laser glazed die surface through observation and measurement of surface structure and hardness. The customized thermal fatigue test in their work also shows that high surface roughness of laser treated surface entrapped oxides and carbides which possibly led to the thermal fatigue failure [14,15]. In recent years, the authors have studied the thermal fatigue resistance of cast iron and hot work tool steel with non-smooth surface processed by a solid-state Nd-YAG laser [16–22]. The results indicate that thermal fatigue and wear resistance of these materials could be improved by it. Furthermore, many factors including laser parameters, surface shapes, units' spacing, scanning tracks, carbon content, graphite shapes and etc. were investigated and then optimized. However, more work should be carried out to investigate the availability of a continuous wave transverse flow CO_2 gas laser. In this paper, the selective laser surface melting and the laser surface alloying both were adopted to improve the thermal fatigue resistance of medium carbon hot-work die steel H13. In addition, two kinds of alloying powders of mixed Chromium and Nickel (Cr–Ni) were used as the laser alloying additions. The effects of the Cr–Ni ratio on the thermal fatigue resistance were also studied.

2. Experiment procedure

2.1. Materials

Medium carbon hot-work die steel H13 was applied as the substrate in this study, of which chemical composition (wt.%) is: 0.4 C, 1.1 Si, 0.4 Mn, 5.0 Cr, 1.1 V, 1.0 Mo and balanced Fe. The substrate material was quenched at 1024 °C, and then was tempered at 537 °C. The microstructure is composed of tempered martensite and granular carbide, which is shown in Fig. 1. The laser alloying materials were Cr and Ni powders with purity of 99.9%, and the average size of powder was less than 8 μm in diameter.

2.2. Sample preparation

The substrate plate was cut into rectangular sample of 60 mm × 40 mm × 10 mm and 10 mm × 10 mm × 10 mm in size for thermal fatigue tests and microstructural examinations, respectively. Meanwhile, the plates were polished using progressively finer grades of silicon carbide impregnated emery paper to remove all the surface irregularities and machining marks. A 3 mm diameter round hole was then mechanically drilled at one side of thermal testing sample so that they could be fixed onto the thermal fatigue experimental machine.

The laser surface melting and laser surface alloying treatments were carried out by a laser processing system consisting of a 10 kW continuous wave transverse flow CO_2 laser and a computerized numerical control working table. The laser parameters were: laser powder of 4 kW, scanning speed of 1000 mm/min and a beam diameter of 1.5 mm. During laser treating a protective gas of argon was used to protect the molten pool. In the following part of this work, LM sample represents the sample treated by laser surface melting, while LSA1 sample and LSA2 sample represent the sample treated by laser surface alloying technology with mixed powders of 75%Cr–25%Ni (wt.%) and 25%Cr–75%Ni (wt.%), respectively. All samples were selectively treated to form a gridded surface with a spacing of 2 mm between every two adjacent laser tracks. Before laser alloying, the samples were cleaned with alcohol and then pre-coated with CrNi mixed powder using cascophen (A kind of commercial colophony glue) diluted by alcohol. The thickness of pre-placed coatings was 150 ± 10 μm. An untreated sample (Substrate sample) was also prepared for comparing the thermal fatigue resistance with the treated ones.

2.3. Experimental methods

After laser treatment, samples for the plain-view microstructural observation were cut parallel to the laser direction, following standard metallographic methods. The samples for cross-sectional microstructral observation were evaluated by an optical microscope (LEICA-DMIRM; Leica Microsystems, Ltd.). Phase formations were identified by *D*/max-RC X-ray diffraction (XRD) with Cu Kα radiation operated at a voltage of 40 kV, a current of 40 mA, and a scanning rate of 4°/min. The microstructure was characterized by a JSM-5500LV scanning electronic microscope (SEM) (JSM-5500LV; JEOL, Ltd.). The elemental content and distribution were analyzed by an EDAX-Falcon energy diffraction spectrometer (EDS) equipped on the SEM. Vickers microhardness measurement was made on the cross section of alloyed layer at an applied load of 300 gram using a Leica microhardness tester (MH-5D; Leica Microsystems, Ltd.).

Thermal fatigue tests were carried out by a self-restrain testing machine which could record times of thermal cycles automatically. Its working detail is shown in Fig. 2. The machine was engineered to test multiple samples simultaneously, in order to give a good compare with different samples under identical testing conditions. The samples were heated by a high temperature electric resistance furnace and cooled by running water. The furnace temperature was controlled by a thyristor control (KSY-12-16), while the sample temperature was monitored by a thermocouple attached to the sample at the center of its length. A complete thermal cycle included heating to 680 ± 5 °C in 180 s and then cooling to 25 ± 5 °C in 5 s. The samples were free from any externally applied load. They were taken out to observe the thermal cracks until 10,000 cycles, and then the thermal fatigue resistance of samples was evaluated.

3. Results and discussion

3.1. Cross-sectional morphology

Fig. 3 shows the cross-sectional morphologies of samples, in which a–c are corresponding to LM sample, LSA1 sample and LSA2 sample, respectively. All the cross sections can be divided into three

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