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Letter

Investigation of nanomechanical properties and thermal fatigue resistance of gray cast iron processed by laser alloying

Xiao Yang [a], Zhihui Zhang [a,*], Jintian Wang [b], Luquan Ren [a]

[a] *Key Laboratory of Bionic Engineering (Ministry of Education, China), 5988 Renmin Street, Changchun 130022, People's Republic of China*
[b] *Technology Center, Changchun Railway Vehicles Co., Ltd., China Northern Locomotive and Rolling Stock Industry Corporation, Changchun 130062, People's Republic of China*

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ABSTRACT

The effect of laser alloying on thermal fatigue resistance of gray cast iron was investigated and explicated by nanoindentation test. It was founded that nanohardness of alloying zone was improved pronouncedly by generating a homogeneous microstructure which has upgraded chemical composition and refined grains. The load–displacement curves showed that the resistance to plastic flow of alloying zone was better than that of matrix. The alloying zone rich in Cr and Ni has a promoted capability of inhibiting the initiation and blocking the propagation of thermal cracks. It was demonstrated that the resistances of plastic deformation and oxidation reaction in alloying zones were main reasons for their effect of inhibiting cracking. The alloying zone can also be accepted as enlarged hard "phase" because of their high nanohardness, which contributed to the effect of blocking cracks.

1. Introduction

Gray cast iron (GCI) is one of the most popular cast metals which have been long used in engineering components such as brake discs, cylinders, and exhaust manifolds, because of its low cost (20–40% less than steel) and wide range of desirable/achievable mechanical properties such as good castability, convenient machining property and better wear resistance [1–3]. However, due to their extreme servicing conditions in terms of thermal loading or thermal–mechanical loading, these components are generally damaged through the processes of thermal fatigue cracking which has become one of the main issues that limits their servicing life. Therefore, there is great need to improve the thermal fatigue resistance (TFR) of GCI without sacrificing its other performances. As well known, GCI is characterized by graphite lamellas which disperse into the ferrous matrix. The quantity, distribution, and morphology of the free graphite all affect the degree to which the steel matrix is weakened [4,5]. As a result of the heterogeneous microstructure, micro-cracks are easily produced at the lamellas tips even at low cyclic thermal stress. For this reason, considerable interests were paid to improve its TFR by modifying graphite. It had been reported that thermal shock resistance and fatigue performance could be improved by adding a certain amount of alloy additions into the whole matrix [1,6,7]. However, it was noted that with regarding to the modification of chemical compositions of the whole matrix, it was difficult to improve TFR without changing other properties of the bulk materials, and also such method is often with high cost. Although some techniques in the field of surface treatment of cast iron had been developed such as chemical plating, electric plating, and laser melting, most of them were focused on improving wear and corrosion resistance, only a few was related with TFR [8]. In this paper, laser alloying (LA) was introduced to change not only the composition but also the microstructure of some local areas on the surface in order to improve the TFR. Compared with other methods, alloying additions can reach into the surface layer of GCI with greater depth and without changing the bulk properties using LA technique. To investigate the nanomechanical property and the thermal fatigue behavior in laser alloying zone (AZ), nanoindentation test was applied to characterize the changes during thermal crack initiation and propagation of GCI.

2. Experimental procedures

Annulus samples of external diameter 30 mm, internal diameter 6 mm, and thickness 5 mm were cut from a commercial brake disc of which material was GCI. The chemical compositions were (in wt.%): C 3.250, Si 1.570, Mn 0.920, P 0.060, S 0.059, balanced Fe. A self-fluxing alloy powder with particle size of 100 μm was applied to carry out the surface alloying, and its chemical compositions were (in wt.%): Cr 17, Si 3.5, Ni 3, balanced Fe. In order to have a better result of melting, circular grooves of depth 0.5 mm and width 2 mm were machined on both sides of samples for placing powder. A solid state Nd-YAG laser with the maximum power of 800 W was employed for LA. The chosen LA parameters after optimization were: electric current 165 A, pulse duration 4.5 ms, frequency 20 Hz, beam diameter 2 mm, speed 5 mm/s, and the single pulse energy 23 J .

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* Corresponding author. Tel./fax: +86 431 85095575.
E-mail address: zhzh@jlu.edu.cn (Z. Zhang).

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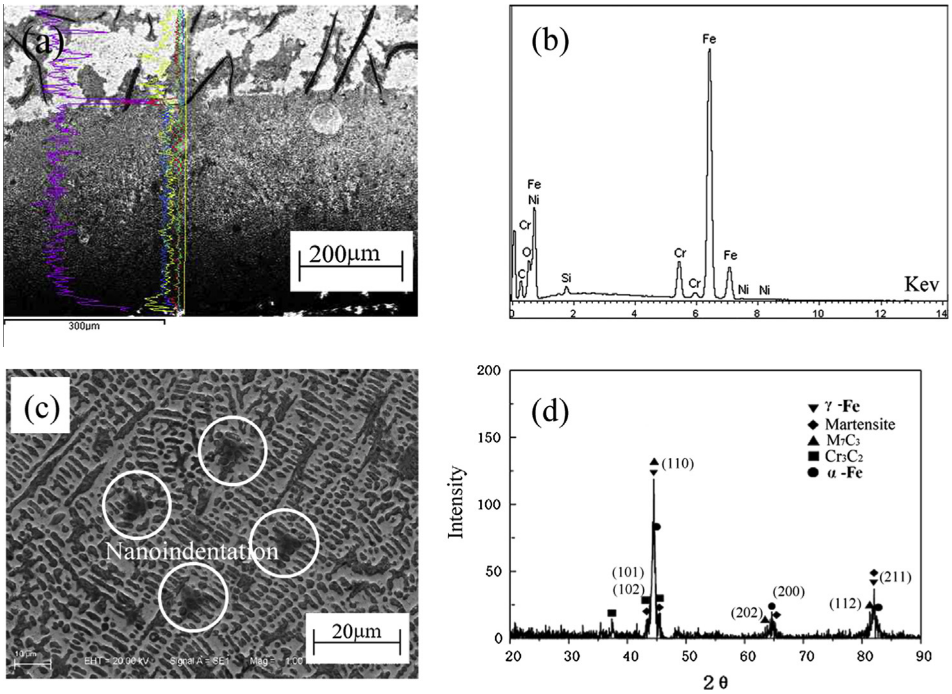

Fig. 1. Results of EDS and XRD: (a) testing area of EDS; (b) chemical compositions; (c) microstructures of AZ; (d) XRD pattern.

Thermal fatigue tests were carried out on self-restrain equipment. Samples were heated to 700 °C ± 10 °C in heating furnace, and were cooled to 25 °C ± 5 °C by immersing samples in running water. The duration of each cycle was determined after ensuring steady state had been reached. 2000 thermal cycles were executed totally in thermal fatigue test. At certain intervals, microstructures of samples were recorded by an optical microscope (Axio Scope A1, ZEISS) and a scan electrical microscope (EVO 18, ZEISS) which was equipped with energy dispersive spectrometers (EDS). The phase structure of AZ were analyzed by X-ray diffraction (XRD) with Cu Kα radiation operated at a voltage of 40 kV, a current of 40 mA, and a scanning speed of 40°/min. Nanohardness and load–displacement curves were obtained by Nanoindenter (Agilent Technologies G200) with the applied loading conditions: Displacement at maximum load was ~2020 nm; Drift correction was ~0.40 nm/s; Peak holding time was 2.0 s.

3. Results and discussions

Fig. 1 shows the results of EDS and XRD. It was apparent from Fig. 1(a) that there was fluctuation in the distributions of Fe and C. That was because the scanning line intersected with one graphite lamella in testing path. Apart from this, a homogeneous elemental distribution was acquired by LA. This was an essential characteristic for improving the mechanical properties [9]. The average contents of alloying elements in testing area were (in wt.%): Fe 73.47, C 12.27, O 6.84, Si 0.77, Cr 6.33, Ni 0.33. It was noted that the content of Cr was increased, which meant TFR was enhanced. Because Cr can improve heat durability of cast iron, for it formed an oxide film rich in Cr with oxygen which can restrain oxidation reaction with the result of improving TFR [10]. Moonesan had also demonstrated that an increase in the content of Cr and Ni can improve the ultimate tensile strength of GCI [1]. As exhibited in Fig. 1(c,d), the grain structure of alloying zone (AZ) became finer with generating new phases that mainly consisted of martensite, M–C carbide (M = Cr, Fe) and residual austenite, owing to the high heating/cooling rate of LA. Meanwhile, the graphite, which was considered as the 'Natural defects' that can lead to crack sources in GCI as indicated in Fig. 2(a), was also eliminated completely. According to Refs. [11,12], a certain amount of residual austenite can enhance the toughness and stop micro-cracks. Moreover, a finer grain structure had a better function of rejecting dislocation movement and balancing plastic deformation, so as to enhance the yield strength of materials. Therefore, the mechanical properties of AZ were improved, and it demonstrated that AZ was in the nature of resisting the initiation of cracks, because micro-cracks were harder to be generated in AZ as shown in Fig. 2(b).

Nanoindentation was applied in the characterization of mechanical behavior of AZ and matrix at nano-scales. Fig. 3(a) shows the load–displacement (penetration depth) curves of

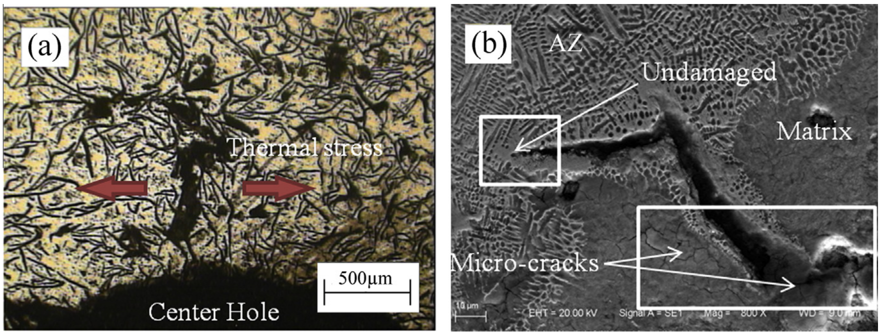

Fig. 2. Micro-cracks observed in microstructure: (a) thermal cracking in matrix; (b) micro-cracks in matrix.