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Laser surface modified ductile iron by pulsed Nd: YAG laser beam with two-dimensional array distribution

Y. Chen[a], C.H. Gan[a], L.X. Wang[a], G. Yu[a,*], A. Kaplan[b]

[a]Laboratory for Laser Intelligent Manufacturing, Institute of Mechanics, Chinese Academy of Sciences, 15, Beisihuanxi Road, Beijing 100080, PR China
[b]Division of Manufacturing System Engineering, Luleå University of Technology, SE 97181, Luleå, Sweden

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Abstract

A novel modification layer on the surface of pearlite-ferrite matrix ductile iron was fabricated under irradiation of Nd:YAG laser beam equipped with self-designed diffractive optical element (DOE) which produces a 5×5 two-dimensional array distribution at the focal plane. The microstructure of the layer along the surface and the direction of the layer depth had obvious gradient distribution, and therefore the two-dimensional microhardness map of the layer alternated higher hardness with lower hardness. The results showed that the novel modification layer is expected to have excellent combination of strength and toughness.

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Keywords: Ductile iron; Nd:YAG laser; Laser surface modification; Diffraction optical element (DOE)

1. Introduction

Ductile iron has been an attractive kind of materials for stamping and drawing dies of automobiles because of the combination of low cost of the material, good castability and good mechanical properties. To improve further the wear resistance of the ductile iron, laser surface modification has been used in industrial applications, as it prevents failure by initiation of the cracks at the surface. Laser surface modification techniques, involving laser transformation hardening, laser remelting, laser cladding and laser surface alloying, is an important solution for fabrication of wear- and corrosion-resistant surface coatings/layers. With laser surface modification techniques, the surface of a matrix material can be coated with a layer of another designed material using laser cladding [1], the composition of the matrix material may be modified by laser surface alloying [2] and high solidification cooling rate can be obtained by

* Corresponding author. Tel.: +86 10 62651166; fax: +86 10 62521859.
E-mail address: gyu@imech.ac.cn (G. Yu).

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laser melting [3]. As to the laser surface modification of ductile iron, laser transformation hardening and laser remelting are the main laser processing methods in practical applications. In transformation hardening in the solid state by laser processing, ductile iron is hardened to obtain a martensitic structure [4], and laser remelting of ductile iron often produces an ultra-fine ledeburitic hard surface layer [5–7]. It is noting that the significant improvement in wear resistance by laser surface remelting is at the expense of the excellent self-lubricant, damping properties of graphite, which are equally as important as the abrasive wear properties in some service conditions [8]. Thus, it would be attractive if the surface of the modification layer on the ductile iron contains periodic gradient zones, i.e., the laser remelted zone and the laser transformation hardened zone are formed alternately on the surface of laser processed ductile iron, originated from laser remelting or laser transformation hardening, respectively. However, due to the simple space characteristics of conventional laser beam with a transverse power density distribution, the microstructure of the surface of above-mentioned laser modification layers is relatively uniform. In order to realize this aim, the space distribution (intensity distribution) of applied laser beam should be modified. Fortunately, it is well-known that space-time characteristics of beam can be modified by means of beam transformation technique [9]. To the knowledge of the authors, little literature has been reported with regard to the application of beam transformation technique into the laser surface modification. In this paper, the surface of ductile iron was treated by a Nd:YAG pulsed laser equipped with the self-designed diffractive optical element (DOE), which can result in 5×5 two-dimensional array distribution at the focal plane [10]. Furthermore, the microstructure of the modification layer was characterized and the two-dimensional hardness distribution of the layer was tested.

2. Experimental procedures

The as-cast pearlitic-ferrite matrix ductile irons, with the nominal chemical composition (at.%) of 3.4C, 2.19Si, 0.60Mn, 0.018S, 0.040P and banlance Fe, were selected as the tested material. The ductile iron specimens, 9 mm $\times$ 9 mm $\times$ 15 mm in size, were

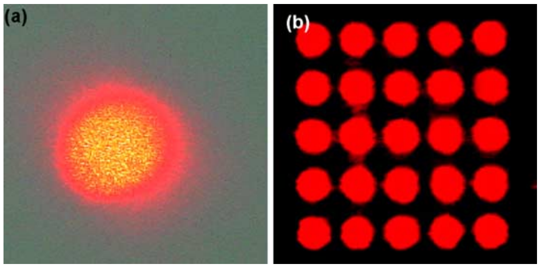

Fig. 1. Microphotos showing the distribution of original single-spot pulsed laser beam (a) and transformed single-spot pulsed laser beam by DOE (b) in the focus domain.

laser modified by a IQL-10YAG 500W pulsed Nd:YAG laser equipped with a self-designed diffractive optical element. The distribution of original single-spot pulsed laser beam and transformed single-spot pulsed laser beam by diffractive optical element (DOE) are shown in Fig. 1a and b, respectively. The pulsed laser processing parameters were as follows: laser output power 12 J, pulse frequency 4 Hz, pulse duration 24 ms, beam spot diameter 1.2 mm and the beam scanning speed 5.5 mm/s.

Metallographic cross- and surface-sections of the modification layer were prepared using standard mechanical polishing procedures and were chemically etched in a solution of HNO_3 and H_2O. Microstructure was characterized using Neophot optical microscopy (OM) and SIRION400NC field emission microscopy (FEI, Netherlands). Conventional method of microhardness measurement of coating/layer is to measure the microhardness distribution along its depth. In order to describe the microhardness distribution within the cross-section of laser modified layer, a newly measurement method is adopted in this investigation, i.e., microhardness is measured every 51 μm within two-dimensional coordinates consisted of the depth direction and the laser beam scanning direction. Hardness of the laser-surface-treated layer was measured by an automatic microhardness tester (HXD-1000B, Shanghai Optics Apparatus Ltd., China) with a tested load of 100 g and a loading time of 15 s.

3. Results and discussion

As shown in Fig. 2a, OM micrograph of the cross-section of the laser modification layer, it is clearly seen

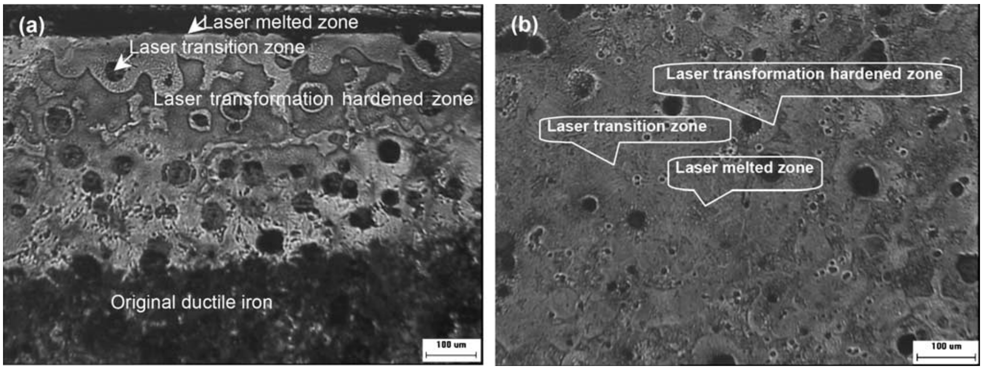

Fig. 2. OM micrographs showing the cross-section microstructure (a) and the surface-section microstructure (b) of the laser modified layer.

that the layer consists of laser remelted thin surface layer, laser transition zone and laser transformation hardened zone. Also, it is interesting that the microstructure of the surface-section of the layer is non-uniform because of the effect of a single-spot laser beam with 5×5 two-dimensional array distribution, and the microstructure distribution is approximately equal with that of along the depth of laser modified layer (Fig. 2b). This unique microstructural distribution of the laser surface modified layer is attributed to the special intensity distribution of transformed laser beam.

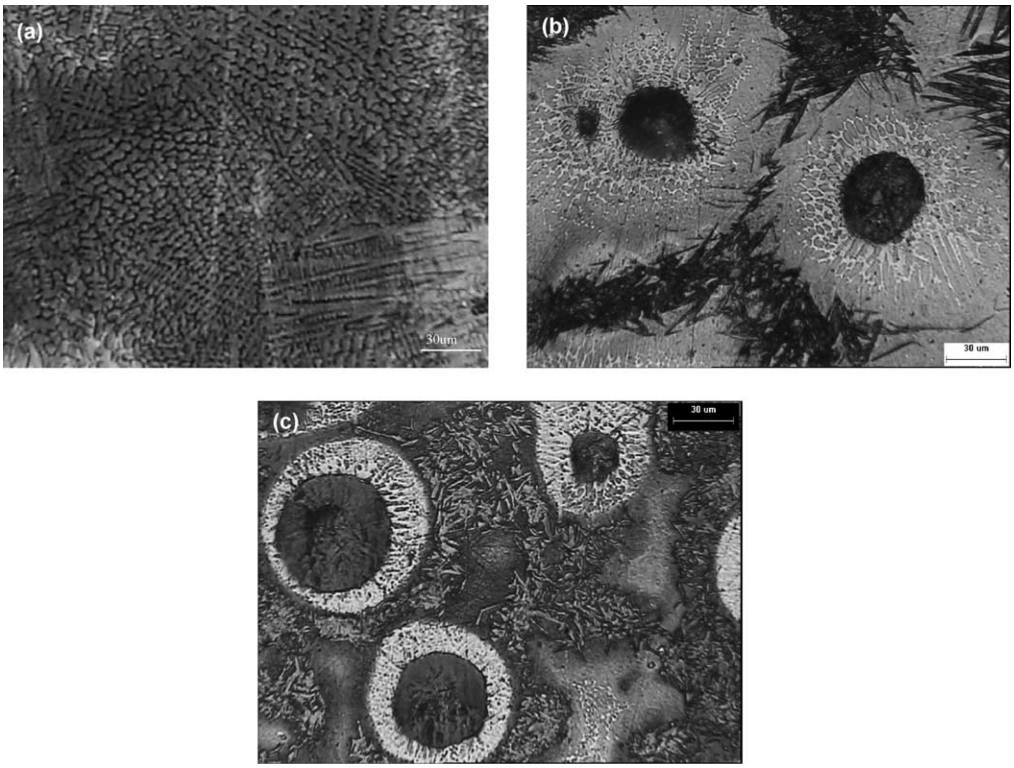

Fig. 3. OM micrographs showing the typical microstructure of laser remelted zone (a), laser transition zone (b) and laser transformation hardened zone (c).

The microstructure in the laser remelted zones, which might be produced on the surface ductile iron beneath lattice points in the array within a single spot region, consists of very fine dendritic austenite (Fig. 3a). Moreover, little graphite nodules can be found in the laser remelted zone. It can be explained by that both hydrodynamic forces and the buoyancy move towards the free surface, only large nodules can reach the free surface where they may be blown away by the inert gas or evaporated by the laser beam [11]. Therefore, it leads to a smaller proportion of graphite in the formation of cementite or martensite, favoring the formation of fine austenitic dendrite. As described above, no matter what the cross- and the surface-section of the layer, laser remelted zone is followed by the transition zone and transformed hardened zone. In the transition zone, the diameter of graphite nodules is decreased in comparison to those in transformed zone, and the dendritic austenite grows radially along the periphery of graphite, as clearly shown in Fig. 3b. This phenomenon illustrates that the periphery of the graphite nodules in this region are slightly melted. It is well-known that the specific heat capacity of graphite is more than greater that of austenite and subsequently a large amount of heat is accumulated in the graphite in the process of laser heating, resulting in slow cooling rate around the graphite. Therefore, the kinetic conditions for the formation of ledeburite cannot be satisfied. For this reason austenite is remained and it grows freely to dendrite along the peripheral of graphite. With distance from the graphite nodule increasing, austenite changes into martensite with some amounts of residual austenite due to higher cooling rate, as indicated in Fig. 3b. In the hardened zone, the austenitic temperature can be obtained during the laser irradiation, and therefore the transformation in the solid condition occurs in the following process of self-quenching cooling by substrate. The pearlite-ferrite structure surrounding the graphite nodules transforms firstly into austenite, into which carbon from graphite nodules is increased by diffusivity, resulting in the iron's melting point

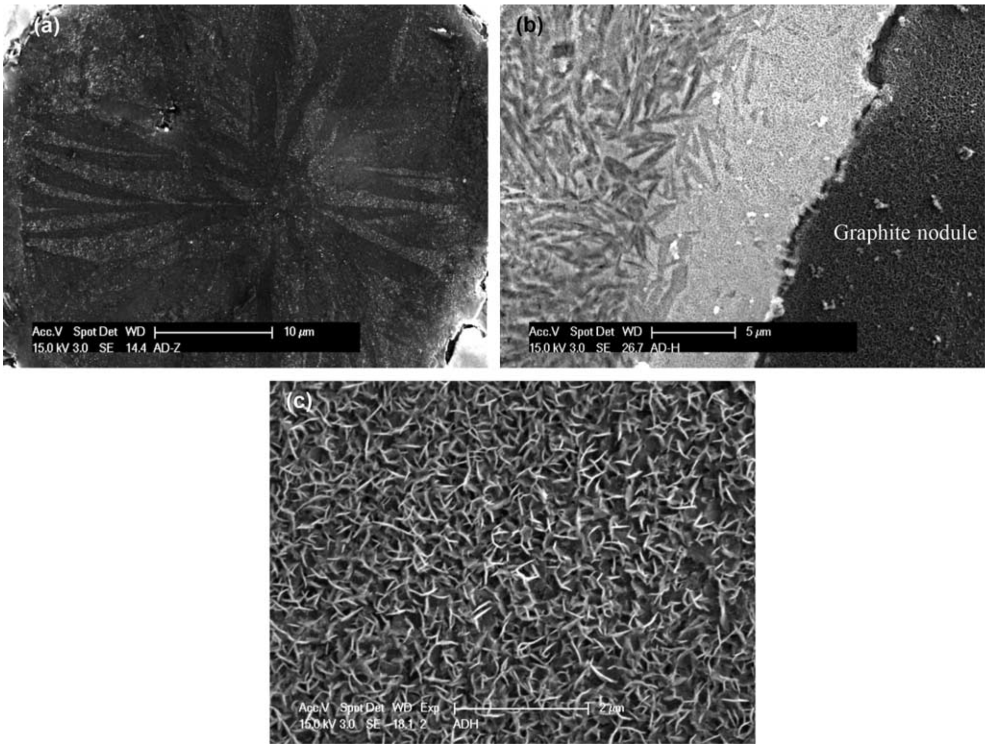

Fig. 4. Field emission micrographs showing that the radial spoke-like morphology of inner graphite nodule in original ductile iron (a), the interface morphology of graphite nodule (b) and the fine needle-like morphology of inner graphite nodule (c) in laser modification layer.

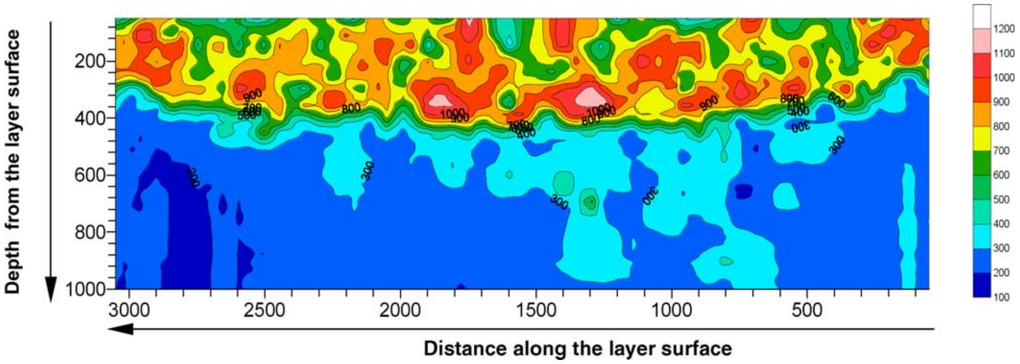

Fig. 5. Two-dimensional microhardness map of pulsed laser surface modified layer (laser beam with 5 × 5 two-dimensional array distribution).

falling sharply and subsequently remelted of the austenite closer to the graphite nodules. Therefore, the as-rapidly solidified ledeburite shell around graphite nodule is formed due to the graphite having a strong ability of absorbing heat, and austenite besides the ledebruite shell transforms into martensite with residual austenite, as shown in Fig. 3c.

It is interesting to note that the morphology of inner graphite nodules in the surface layer changs violently compared to that in the original as-cast pearlitic-ferrite matrix ductile iron.

As shown in Fig. 4, it is clearly seen that the morphology of inner graphite nodule in as-cast pearlitic-ferrite matrix ductile iron is radial spoke-like, and that in the laser modification layer changes to be fine needle-like. To the knowledge of authors, this phenomenon has, so far, been not reported in the open literature. More detailed works on this phenomenon, including the its evolution mechanism and its influence on the mechanical properties, are now under further investigation.

Fig. 5 shows the two-dimensional microhardness map of the cross-section of the laser surface modified layer. It clearly shows that hardness distribution along both the surface and the layer depth direction has a periodic gradient distribution, which results from the gradient distribution of microstructure, i.e., the microstructure of laser surface modified layer along in both the surface direction and the depth direction is alternately consisted the fine dendritic austenite, martensite with residual austenite and dendritic austenite growing radially along the periphery of the graphite, martensite with residual austenite and the high-hardness ledeburite shell around the graphite nodule. The novel pulsed laser surface treated layer having hardening phase (eutectic cementite/austenite and martensite), excellent-toughness austenite and self-lubricant graphite is expected to have excellent wear resistance.

4. Conclusions

A novel surface layer having both rapidly solidified eutectic cementite, martensite and the graphite particles is fabricated on the surface of pearlite-ferrite matrix ductile iron using laser surface treatment by Nd:YAG laser equipped with self-designed diffractive optical element. Due to the interaction area of 5 × 5 two-dimensional array in a single-spot laser beam, the microstructure along the layer surface and the layer depth has obvious gradient distribution consisting of fine austenite, martensite with residual austenite and dendritic austenite growing radially along the periphery of graphite, martensite with residual austenite and ledeburite shell around graphite nodule. As a result, the two-dimensional microhardness distribution of the modification layer has a periodic gradient distribution, endowing laser modified layer excellent combination of strength and toughness.

Acknowledgements

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