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Microstructure evolution and lubricant wear performance of laser alloyed layers on automobile engine chains

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ABSTRACT

Wear resistant layers on nodular cast iron chains with C–B–W–Cr powders were fabricated by laser surface alloying (LSA). Microstructure, phases and lattice parameters, were investigated by means of optical microscopy, scanning electron microscopy, transmission electron microscopy and X-ray diffractometry. Micro-, nano-hardness and elastic modulus were measured with a Vickers microhardness tester and a nano-indendation tester. Lubricant sliding wear performance was performed on a ball-on-disk apparatus in ambient air using the straight line reciprocating wear form. Results indicate that microstructure of the alloyed layers changes from hyper-eutectic to hypo-eutectic, varing with laser specific energy. Nano-grain size and micro-hardness decrease while martensite lattice parameters increase with laser specific energy. Existence of graphite in the substrate increases the carbon content in the retained austenite to 1.59 wt%. Nano-hardness and elastic modulus of the alloyed layers are close. Friction and wear properties of the layers are improved by LSA compared with the substrate. Wear mechanism of them is illustrated.

1. Introduction

Laser surface alloying (LSA) is a technique that involves melting of a pre/co-deposited layer of alloying materials along with a part of the underlying substrate to form an alloyed zone confined to a shallow depth from the surface by rapid solidification. With the addition of alloying element(s), LSA can produce tailor-made surface compositions which are not attainable by other methods. It can locally fabricate alloyed layers or coatings with desired properties, and is a kind of green manufacturing process which reduces energy consumption and resources [1]. Consequently, the improvement in corrosion and wear resistance may be achieved by LSA via homogenization and refinement of the microstructure, and/or formation of new alloys on the surface [2–4]. Nodular cast iron (NCI) are widely used in mechanical fields because of their low price, good castability and good machinability, all desirable features in the production of machine parts. The unique combination of carbide, nodular graphite and matrix structure offers an advantageous working capacity, such as surface roughening resistance and seizing resistance, to resist severe circumstace [5–7]. However, a lot of NCI components suffer from the cyclic heating and cooling, very high loads, thermal fatigue and severe environmental attack. As a result, they often fail due to one or another reason. For example, crack, spalling and wear for metallurgical rolls [5,8,9], thermal fatigue for diesel motors in automotive field [10], and large thermal stresses, friction and fatigue for railway brake discs [11]. The service lives of them can be prolonged by improving their wear resistance since the wear characteristic of them is the key factor to determine their performance. The authors have investigated the microstructural evolution and wear properties of NCI rolls with home-made C–B–W–Cr powders [9]. The authors have investigated effects of processing parameters (pre-layer thickness, laser specific energy) on the thickness, crack ratio, microstructure and phases of laser alloyed layers with NiCr–Cr3C2 and C–B–W–Cr powders on NCI rolls [12]. However, no hardness or wear behavior has been evaluated. Chemical composition of the NCI roll and NCI chain is close. However, microstructure, phases and mechanical properties of them are different. NCI rolls are composed of pearlite, ledeburite and graphite while NCI chains are composed of pearlite, ferrite and graphite. Furthermore, the wear condition of the NCI rolls [9] and cast steel rolls [4] is at high temperature (about 500 C). The present work aims to improve the service lives of NCI engine chains used in automobiles. The wear test in this investigation is ball-on-plate oil lubricant sliding wear test at room temperature to simulate the work condition of NCI chains. Different laser specific energy is

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used for forming the wear resistant layers. Its effect on microstructure evolution, lattice parameters, phases, micro- and nano-hardness, elastic modulus and further on the wear behavior of the laser surface alloyed layers with C–B–W–Cr composite carbide powders on NCI chains was investigated. Furthermore, the differences between the alloyed layers on NCI chains and NCI rolls fabricated with the same powders under the same processing parameters are compared.

2. Materials and methods

The substrate is nodular cast iron ($340HV_{0.05}$), chemical composition of which is listed in Table 1. A DL-HL-T10000 continuous wave CO_2 laser (manufactured by Shenyang Dalu Laser Whole Set Equipment Limited Company, Shenyang, Liaoning, China) is used for the alloying experiment. C–B–W–Cr composite carbide powders with a particle size of 30–500 nm are used as the alloying layer material. The powder was composed of 40–70 wt% boron carbide, 15–30 wt% tungsten carbide, 0–15 wt% titanium carbide and 5–20 wt% chromium carbide. Carbides were supplied by Shanghai Jiuly Abrasives Co., LTD, China. They were mechanically mixed together, dissolved in liquid ethanol and sprayed on the NCI chain surface with the thickness of 25–30 μm by means of an ejection gun to form the pre-layer on the NCI substrate. Laser processing parameters are listed in Table 2. After laser treatment, specimens were sectioned, mounted, ground, polished and etched with an etchant ($FeCl_3$ 20 g+HCl 50 mL+H_2O 100 mL). The microstructure was examined using an optical microscopy (OM, GX71, OLYMPUS, Japan) and a scanning electron microscopy (SEM, JSM 7001F, JEOL, Japan) with energy dispersive X-ray analysis (EDS). A transmission electron microscope (TEM, TECNAI G^2 20, FEI, USA) was also used to analyze the microstructure at the accelerating voltage of 200 kV. After mechanical and chemical polishing to a thickness of 0.08 mm, discs with a diameter of 3 mm were punched from the alloyed layer. Specimens for the TEM examination were prepared in a Precision Ion Polishing System (PIPS, Model 691, Gatan, USA). The thickness of the alloyed layer was measured using the laser co-focus stereo-microscopy (OLS3100, OLYMPUS, Japan). Average value of measurements at five different locations was taken as the average thickness. Phases presented in the layers were identified using an X-ray diffractometer (XRD, X'Pert Pro MPD-PW 3040/60, PANalytical B.V., Netherlands) with Cu K_α generated at 40 kV and 40 mA, and a scanning speed of 1°/min. The micro-hardness of the cross section from the layer surface to the substrate was measured using a micro-hardness tester (Wdpert 401 MVD™, Wilson, USA) with a load of 50 g and a dwell time of 10 s. An average value of micro-hardness was taken from five measurements of points along the central line of the molten pool in the cross section of the laser alloyed samples. Nano-indentation and elastic modulus tests on the polished sections of alloyed layers were performed by a nano-indendation tester (NHT^2+MST, CSM, Switzerland) at room temperature. A loading-unloading test mode was used and a test force 10 mN, a loading speed 20 mN/min and a duration time 10 s were adopted. During measurements, the load and indentation depth were recorded. An average value of nano-hardness was taken from five measurements. Average data of five measurements were then used to construct loading–unloading plots.

Lubricant sliding wear tests of the NCI chain substrate and laser alloyed layers in sample A and B were performed on a ball-on-disk apparatus (UMT-2 tribometer, CETR, USA) in ambient air using the straight line reciprocating wear form. Their surfaces were ground and polished with 1200 grit paper and rinsed with alcohol. Then, chain lubricant (Shell Lubricant which is used in automobile chains) was brushed on the wear surface before wear test. The counter-body was a sintered carbide ball with a diameter of 9.5 mm. The applied load was 80 N. The workbench was set to rotate at a fixed speed of 300 rpm and the test time was 60 min. The reciprocating length of the wear track was 5 mm. The wear ball was changed prior to each test to ensure reproducibility in the wear conditions. Friction coefficient was recorded and the stable value was used for comparison. The microstructure of the worn surface was observed using SEM, true color con-focal microscope (CSM700, ZEISS AXIO, Germany), and the wear mechanism was analyzed.

Table 1
Chemical composition of the nodular cast iron (wt%).

C	Si	Mn	P	S	Mg	Re	Fe
3.5–3.9	2.3–3.0	0.3–0.8	< 0.08	< 0.03	0.05–0.1	–	Bal.

3. Results and discussion

3.1. OM, SEM and EDS observation

Microstructure of the NCI substrate is shown in Fig. 1(a), which indicates that the substrate is composed of ferrite, pearlite and nodular graphite, among which ferrite is the dominent phase, i.e this NCI is with a ferritic matrix. Cross section morphology of sample A and B are shown in Fig. 1(b) and (c), among which there are cracks along the central lines in the molten pool in layer A (not shown in Fig. 1(b)). Layer B is pore and crack free with an average thickness of 0.4004 mm, which is much thicker than that of the pre-layer (0.025–0.03 mm), indicating the alloying of substrate materials and the pre-placed powders. Several graphite can be detected in the alloyed layer due to the forces in the motlen pool when the powders and substrate are irradiated by laser. Comparison between layer A and layer B indicates that there are more graphite nodules in layer B than that in layer A as indicated by red arrows.

Microstructure of different parts in the cross section of the samples is shown in Fig. 2. Fig. 2(a) and (b) are corresponding to the alloyed layer in sample A and Fig. 2(c) and (d) are from the lower part of the alloyed layer and the bonding zone between the alloyed layer and substrate in sample B, respectively. Microstructure in the alloyed layer is dependent on the chemical composition and cooling rate in the molten pool during heating and cooling. Fig. 2(a)–(c) shows that microstructure of the alloyed layers consists of dendrites and eutectics. Microstructure in Fig. 2(a) and (b) is composed of pro-eutectic carbides (dendrites) and

Table 2
CO_2 laser processing parameters.

Sample	Laser power (P, kW)	Scanning speed (V, m min^{-1})	Spot diameter (D, mm)	Laser specific energy, $P/(D \times V)$ (J/mm^2)	Overlap ratio (%)	Average thickness of alloyed layers (mm)	Average microhardness of the alloyed layer ($HV_{0.05}$)
A	3.6	6.5	1.1	30.3	33.3	0.3978	1117
B	4	4	1.5	40	33.3	0.4004	964