Applied Surface Science 286 (2013) 334–343

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

Improvement in corrosion resistance of a nodular cast iron surface modified by plasma beam treatment

Xiu Cheng, Shubing Hu*, Wulin Song, Xuesong Xiong

State Key Laboratory of Material Processing and Die and Mould Technology, Huazhong University of Science and Technology, Wuhan, Hubei 430074, China

ARTICLE INFO

Article history:
Received 4 July 2013
Received in revised form
12 September 2013
Accepted 14 September 2013
Available online 21 September 2013

Keywords:
Nodular cast iron
Surface modification
Plasma beam
Tempering
Corrosion resistance

ABSTRACT

Nodular cast iron (NCI) specimens with corrosion-resistant surfaces were fabricated by plasma beam treatment and tempering (400 °C, 1 h), which consisted of plasma surface melting, plasma surface melting + tempering, plasma surface alloying and plasma surface alloying + tempering. In this manner, near-surface graphite nodules were eliminated, and inter-dendrites and eutectics with a hyper-eutectic structure appeared on the modified surfaces, as indicated by SEM. The corrosion behaviour of treated specimens in 3.5 wt% NaCl was characterised by electrochemical methods and compared with that of an untreated NCI specimen at 25 °C. The corrosion resistance ranked as follows: surface-alloyed and tempered specimen > surface-alloyed specimen ≈ surface-melted and tempered specimen > surface-melted specimen > the untreated NCI specimen. Metallographic as well as electrochemical corrosion studies illustrate the beneficial effects of surface modification in refining the microstructure and in enhancing the corrosion resistance of NCI.

1. Introduction

Nodular cast iron (NCI) has been widely used in various industrial fields, such as in automotive and machine parts, tubes, drawing moulds and even nuclear waste containers, due to their high strength, high yield limit, toughness and relatively low price, in addition to their excellent castability and machinability [1–4]. The microstructure of NCI consists of graphite phases within and iron matrix [5], where graphite plays the role of a cathode and the adjacent iron that of an anode, which accelerates the anodic dissolution of iron; specifically, during graphitic corrosion, only the network structure of graphite is left behind [6]. From the perspective of surface engineering, the presence of graphite in NCI is a potential problem. Therefore, it is imperative to prevent the formation of nodular graphite immediately beneath the surface of NCI [5], and near-surface graphite phases must be eliminated to improve the corrosion resistance of NCI.

Recently, high-energy beams such as electron beams [7,8], laser beams [1,2,9] and plasma beams [10,11] have been used extensively to eliminate superficial graphite nodules in NCI by rapid melting and cooling/solidification processes. Rapid cooling during solidification also leads to the formation of large amount of hyper-eutectic cementite instead of soft graphite [4,12]. However, because of the high cost of operating lasers and the need for a vacuum in electron beam, attention has been focussed on using inexpensive, flexible and easy-to-operate plasma beam apparatus for the surface treatments of cast iron.

A plasma beam is an extremely high-temperature flow usually possessing a power density of approximately 10^9 W/m^2, which allows for the rapid heating of almost every type of solid material to its melting or evaporating point via a type of rapid, non-equilibrium metallurgical process. The heating efficiency of plasma beam (85%) could be much higher than that of a laser beam (30%) in heating material surfaces [13].

Plasma beams provide significant advantages in treating iron-carbon alloys, including selective hardening, minimum part distortion, controllable case depth and structural refinement [14,15]. As high-energy-intensity heating sources, plasma beams are widely used for surface hardening to improve the corrosion resistance of surface-modified ferrous workpieces [16].

Plasma surface treatments, including plasma surface melting and plasma surface alloying, can be used as cost-effective alternative approaches for the elimination of near-surface graphite in cast iron.

Surface melting can enhance the surface properties of ferrous materials, such as their hardness, wear resistance and corrosion resistance. Such enhancement is possible because a high cooling rate can be achieved due to localised melting that results in non-equilibrium phases as well as refined microstructures [17,18]. In general, surface melting can lead to an improvement in the corrosion resistance of all analysed materials [19].

* Corresponding author. Tel.: +86 13995667466; fax: +86 27 87540057.
E-mail address: hushubing@163.com (S. Hu).

0169-4332/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.apsusc.2013.09.083

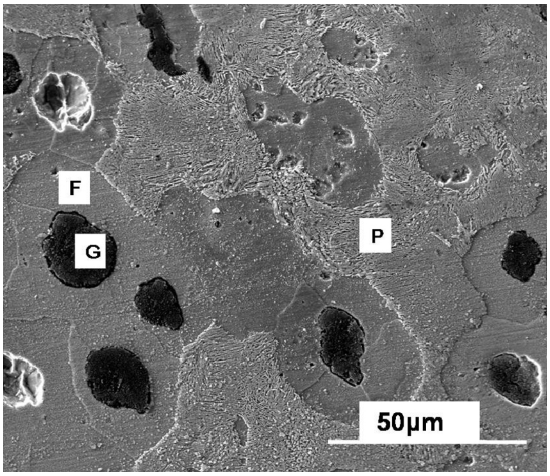

Fig. 1. Microstructure of as-received NCI, F: ferrite, G: graphite and P: pearlite.

Surface alloying offers a versatile approach to the production of surface layers with a wide range of structures and compositions on a variety of substrates; moreover, the structures may consist of fine grains as a result of the relatively rapid cooling rates that can be achieved from the melt. Consequently, an improvement in corrosion resistance may also be achieved by surface alloying via microstructural homogenisation and refinement and the formation of new alloys on surfaces [20]. The micro-alloying of suitable elements on surfaces may also help enhance surface properties such as corrosion resistance [7].

There have been many studies that have investigated the mechanical properties of NCI [8,9,20] submitted to laser and electron beam treatments, but there are few published works on the corrosion characteristics of NCI surfaces modified by plasma beam treatment.

In this study, a plasma beam was used as a heating source to modify the surface of NCI, eliminate superficial graphite nodules and hence improve the corrosion resistance of NCI. The surface treatments included plasma surface melting (M method), plasma surface melting + tempering (MT method), plasma surface alloying (A method) and plasma surface alloying + tempering (AT method). Furthermore, the corrosion resistance of the treated specimens compared with that of ferrite and pearlite NCI substrate (S specimen) was tested by potentiodynamic polarisation and electrochemical impedance spectroscopy (EIS).

2. Experimental

2.1. Materials

The starting material NCI (QT600-3) was produced by Dongfeng Company. The NCI was machined into plates with dimensions of 120 mm × 80 mm × 20 mm for plasma surface treatment. Fig. 1 shows a micrograph of an NCI specimen (S specimen), which consists of graphite nodules with an average diameter of 20 μm surrounded by ferrite and pearlite. The chemical composition of the specimen is presented in Table 1.

Alloy powders with a particle size of 1–3 μm were used as an alloying layer material, the chemical composition of which is listed in Table 2. The powders were mechanically mixed and dispersed in kerosene to form alloy coatings.

Table 1
Chemical composition of NCI (wt%).

C	Si	Mn	S	P	Mg	Cu	Fe
3.41	2.23	0.42	0.033	0.045	0.048	0.37	Balance

Table 2
The composition of alloy powders (wt%).

WC	Ni	TiC	Cr	Si	La_2O_3	Fe
3	15	20	15	2	0.2	Balance

2.2. Plasma surface treatment

Plasma surface melting (M method), plasma surface melting + tempering (MT method), plasma surface alloying (A method) and plasma surface alloying + tempering (AT method) were used to modify the surfaces of the NCI specimens.

Plasma surface melting and alloying was carried out using a homemade set-up for combined transferred and non-transferred arc plasma beam treatment, as shown in Fig. 2. An atmospheric, high-density plasma was generated by the equipment, and the ionisation degree was less than 0.1%. The plasma pressure was greater than 0.1 MPa.

The specimen and nozzle served as the anode, and a tungsten needle served as the cathode (Fig. 2). The nozzle diameter selected for testing was 2 mm, and the distance between the nozzle and the specimen was 4 mm. The plasma torch was controlled by a small variable-speed DC motor; thus, the speed of the torch could be adjusted and held constant throughout the test. The argon used in the process served as both a plasma gas and shielding gas, the flow rates of which were both 1 L/min.

In the surface-melting process, a plasma beam with a Gaussian energy density distribution was defocussed on the surface of the NCI substrates without a pre-layer.

For surface alloying, a homemade alloy coating was sprayed to form a pre-layer with a thickness of 200 μm using an ejection gun on the NCI substrates before the plasma surface alloying process. The scanning speed during the plasma surface-alloying process should be lower due to the pre-layer. In the plasma surface-alloying process, the plasma beam energy melted the alloying coatings and substrate surface, and the alloy elements then seeped into the substrate to form a new alloy surface.

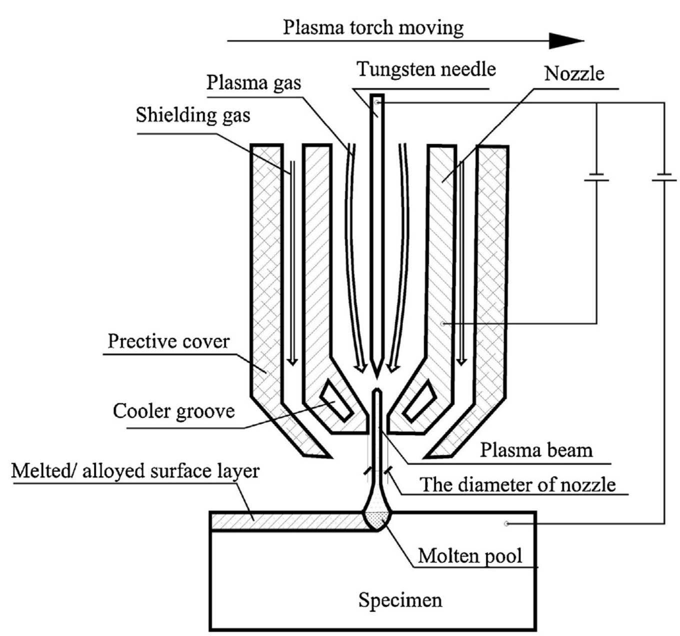

Fig. 2. Schematic diagram of the plasma beam heating of the nodular cast iron.