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Improvement of the electrochemical characteristics of medium carbon steel using atmospheric-controlled induction-heating fine particle peening

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ABSTRACT

Atmospheric-controlled induction-heating fine particle peening (AIH-FPP) using Cr and Mo shot particles was introduced to improve the electrochemical characteristics of AISI 1045 medium carbon steel in NaCl solution. AIH-FPP can form transferred and diffused layers of shot particles on the surface of carbon steel. The corrosion potential of the AIH-FPP-treated steel was higher than that of the untreated steel in a NaCl environment. Furthermore, a passivation region was observed in the carbon steel treated with AIH-FPP using Cr shot particles after peening with Mo shot particles through the formation of a surface-modified layer with high Cr and Mo concentrations in 20% NaCl solution.

1. Introduction

Metallic materials used as automotive components, marine parts and in atomic power plants are corroded under severe conditions; therefore, stainless steels with high corrosion resistance have been widely used in various engineering fields [1]. However, the use of stainless steels is more costly than structural steels due to the high amount of added metals, such as chromium, molybdenum and nickel. Therefore, surface modification processes have been introduced to improve the corrosion resistance of steels, including the medium carbon steel highlighted in the present study, because only the metal surface comes into contact with the external environment.

In particular, two types of treatments are effective methods to improve the corrosion resistance of steels without a protective layer: (i) the addition of elements (cadmium [2], chromium [3–6] and nitrogen [7,8]) to the surface of the substrate and (ii) application of a high corrosion resistance coating onto the substrate using electroplating [9,10], cationic gemini surfactant coating [11], epoxy resin coating [12], associating a phosphonic acid [13], polypyrrole coating [14], cold spraying [15,16] thermal spraying [17,18] and ultrasonic impact treatment [19,20]. For example, Oliveira et al. [2] performed ion implantation of tool steels with Cd ions (method (i)) by electrodeposition and reported that thicker Cd layers were more effective for corrosion protection in 3.5% NaCl solution. Wang et al. [15] reported that a cold spray improved the corrosion resistance of carbon steels through the formation of a thick Ti-coating (method (ii)) and corrosion resistance was significantly improved by the removal of small pores in the Ti-coating. For austenitic stainless steels (1Cr18Ni9Ti [21], AISI 304 [22,23] and AISI 316 L [24,25]) with a Cr_2O_3 passivation film, the electrochemical corrosion resistance can be improved by severe plastic deformation, such as shot peening [21–25], through grain refinement [26].

In our previous study [27], the authors have demonstrated that fine particle peening (referred to herein as FPP) using Cr shot particles can be used to diffuse Cr into steels without a protective layer at room temperature. The particle velocity in FPP is higher than that in conventional shot peening [28,29], which results in greater shot particle transfer observed using particles of hydroxyapatite [30,31], steel [32], carbon [33] and titanium [34,35]. To facilitate the diffusion of Cr into the substrate, we developed a surface treatment system that combined a high-frequency induction-heating (IH) system with FPP through the suppression of oxidation by control of the process atmosphere. This atmospheric-controlled IH-FPP (referred to herein as AIH-FPP) using Cr shot particles can produce a thick Cr diffused layer by variation of the processing parameters [36–38], which results in an improvement of the electrochemical characteristics of carbon steels. However, the corrosion

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potential of AIH-FPP-treated carbon steels is lower than that of austenitic stainless steel [34]. In particular, the corrosion resistance of medium carbon steel would be improved by AIH-FPP through the formation of a surface with high Cr and Mo concentrations, similar to a stainless-steel surface, because Mo can improve the repassivation ability and stability of the Cr_2O_3 passivation film formed on the surface [39,40].

The purpose of the present study was to improve the electrochemical characteristics of AISI 1045 medium carbon steel in NaCl solution by AIH-FPP using Cr and Mo shot particles in a N_2 atmosphere. Furthermore, the surface-modified layer formed on medium carbon steel treated with AIH-FPP is characterized and the mechanism for the electrochemical corrosion of AIH-FPP-treated carbon steel is also discussed.

2. Experimental procedure

2.1. Specimen preparation and characterization of the surface-modified layer

AISI 1045 medium carbon steel bars of 15 mm in diameter were machined into cylindrical specimens. After machining, the specimens were polished with emery paper (#240) to a thickness of 4 mm (referred to herein as the untreated series), and some specimens were polished to a mirror-finish using emery paper (#240 to #1200) and a SiO_2 suspension. Austenitic stainless steel specimens (AISI 316) were also prepared for comparison.

AIH-FPP was performed in a N_2 atmosphere for the mirror-finished AISI 1045 specimens to form a surface-modified layer with high corrosion resistance. Fig. 1 shows a schematic illustration of the AIH-FPP treatment system used in the present study. The polished specimen was placed in the IH coil, and the atmosphere in the chamber was purged by supplying N_2 gas through the peening nozzle. When the oxygen meter (measurement tolerance of 0.3 vol%) of the chamber showed 0.0 vol%, AIH-FPP of the specimens was performed using 30–50 μm diameter Cr shot particles at a peening pressure of 0.5 MPa and at a particle supply rate of 0.20 g/s under the conditions given in Fig. 2 (referred to herein as the Cr series). In addition, Mo shot particles were also used in the AIH-FPP process, as detailed in Section 3.2. Specimens were subsequently heated for 60 s at 1373 K after FPP to form a Cr diffused layer on the basis of our previous study [38]. The surface microstructure of the AIH-FPP-treated specimens was characterized using optical microscopy, scanning electron microscopy (SEM), and energy dispersive X-ray spectrometry (EDX). AIH-FPP treatment can form nitrided layer on titanium alloys in a N_2 atmosphere [41,42], but nitrides are not formed on AISI 1045 steels in the present study because nitriding for steels are

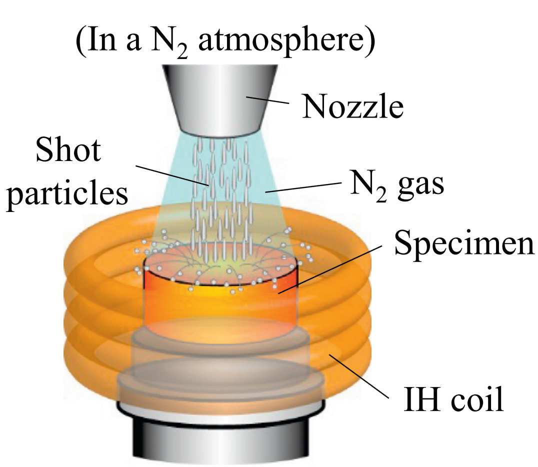

Fig. 1. Schematic illustration of the AIH-FPP treatment system.

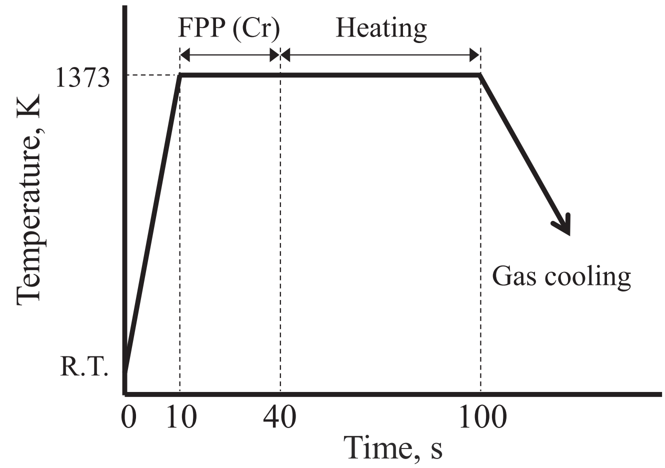

Fig. 2. Thermal history during the AIH-FPP process with Cr shot particles.

generally conducted in NH_3 atmosphere.

2.2. Electrochemical polarization tests

Electrochemical polarization tests were conducted using a three-electrode electrochemical cell connected to a computer-driven potentiostat under the two sets of conditions given in Table 1. One condition is based on the JIS G 577 standard (environment 1), and the other condition is suitable for examination of the electrochemical characteristics of materials with high corrosion resistance (environment 2). The test specimen was used as the working electrode, platinum as the counter electrode, and Ag/AgCl as the reference electrode. The electrolyte solutions of 3 wt% and 20 wt% NaCl were deaerated with nitrogen gas for 1.2 ks prior to use and maintained at 343 K to examine the corrosion potential of AIH-FPP-treated steels under severe conditions. Pardo et al. [40] reported that an increase of temperature increased the corrosion reaction of austenitic stainless steels. In addition, acid (H_2SO_4) was added to the saline solution used in environment 1 (low pH saline solution). In the anodic potentiodynamic polarization test, the potential was increased to the value when the current density reached 10^0 mA/cm^2 at a scanning rate of 0.3 mV/s. Corrosion potential, E_{corr}, was measured as the potential showing the transition between the cathodic and anodic curves. In the present study, breakdown potential, E_{BD}, of AISI 1045 steels was defined as the value of potential at which the current increased very fast to quantitatively evaluate the effect of AIH-FPP on the electrochemical characteristics of AISI 1045 medium carbon steel. The breakdown potential was known as the potential which results in a change from a stable passive current density to that of a rapidly increasing current density [43].

Before testing, specimens were pre-treated to suppress crevice corrosion because the electrochemical polarization tests were conducted under severe conditions (environment 2). Fig. 3 shows a schematic illustration of the procedure for specimen preparation for the electrochemical polarization tests, the details of which can be found elsewhere [44].

Table 1
Conditions for electrochemical corrosion tests.

	Cl, wt%	Temperature, K	pH
Environment 1	3	343	2.5
Environment 2	20	343	7.0