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Effect of chemical segregation on nanobainitic transformation in laser cladded coatings

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ABSTRACT

Laser cladding and subsequent isothermal holding were employed to fabricate the Fe-based nanobainitic coatings. The microstructures of the isothermal heat treated coatings were observed and characterized by using the optical microscope (OM), filed-emission scanning electron microscope (FE-SEM), field-emission transmission electron microscope (FE-TEM), energy-disperse X-ray spectroscopy (EDAX), and X-ray diffraction (XRD). The results showed that the elements of Mn, Cr, and Si segregated at the prior austenite interdendritic regions. The segregation of the solutes significantly affected on the kinetics of the nanobainitic transformation and the final microstructures obtained at the different isothermal temperatures. The bainitic transformation incubation time was reduced by the increasing of available driving force for nucleation. The bainitic sheaves grow across the interdendritic regions of the prior austenitic dendrites. The continuity and thickness of blocky austenite distributed at the prior interdendritic regions were sensitive to the transformation temperature, as a result of the threshold of the bainitic transformation varied with the chemical gradients near the segregated interdendritic regions.

1. Introduction

The increasing demand of the energy conservation and emission reduction, combine with the structure lightweight and improved safety, has stimulated attractions on the high strength and high ductility steels. The nanostructured steel is one of these kinds of steels used in modern transport industry [1,2,3,4]. Nanostructured bainitic steels are one of these nanostructured steels developed by the pioneering research by Bhadeshia and co-workers at Cambridge University [5], which has ultra-high strength (2.3 GPa), toughness (30 MPa $m^{1/2}$) and ductility (30%) [6]. The high carbon and high silicon concentration with several other elements in this steel avoid the formation of martensite and cementite [7], the microstructure of carbide free, nanoscale bainite ferrite and interval austenite films are the crucial factors of its outstanding properties [8,9,10]. The exceedingly long transformation time is the key obstacle that holds back the applications of this new generation of steels [11].

Several studies have been concerned to accelerate the overall bainitic transformation of high carbon steels. Vetters and Dong et al. [12] reported the effect of two steps of bainitizing to shorten overall heat treatment. Smanio and Sourmail reported a method with the existence of small amount of martensite prior isothermal holding to accelerate the bainitic transformation process [13]. These researches have been indicated, with special optimized heat treatment methods, the bainitic transformation could be accelerated without decreasing the mechanical properties. However, these methods are too complicated to apply for the commercial productions. The transformation also can be accelerated by making controlled addition of some solutes such as aluminum and cobalt in specific values (<2 vol.%). Garcia-Mateo et al. [14] have investigated this method in their studies. Another method is the using of prior austenite with the refined grain size to accelerate the transformation rate [15]. According to the previous study of the authors [16], the laser cladding and subsequent isothermal heat treatment have been employed to fabricate the nanostructured bainitic coatings in the short times. However, the formation of the refined prior austenite by the laser cladding process as well as the addition of aluminum and cobalt can accelerate the rate of bainitic transformation. Laser cladding is a process with rapid solidification, which the micro segregation can be modified compare with the normal solidification processes [17]. The alloying elements are always segregated at the interdendritic regions [18]. Mn, Cr, Si can markedly retard the bainitic transformation [11]. The bainitic nucleus preferential formed in the substitutional-solute depleted regions [19]. Laser cladding has a heterogeneous solidified microstructure, the substitutional-solute depleted and enriched regions in the cladded coatings will significantly affect the transformation kinetics and the final microstructures of the bainitic transformation.

The main objective of the present investigation is to show in a detailed study by SEM, TEM EDAX and X-ray diffractions how the laser cladded segregations affect the overall nanobainitic transformation kinetics. From the precise characterization of the solute elements

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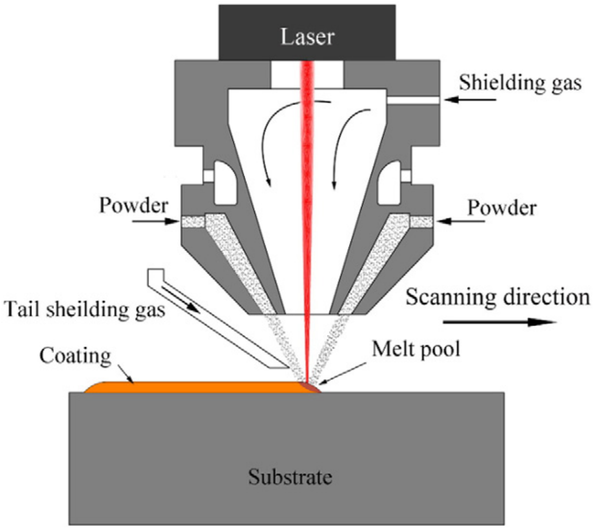

Fig. 1. A schematic diagram showing the constitutions of laser system and the specimen.

Table 1
Chemical composition of the powder and substrate (wt.%).

	C	Si	Mn	Cr	Mo	Co	Al	P	S	Fe
Powder	0.81	1.55	1.96	1.13	0.32	1.59	0.93	0.008	0.01	Bal.
Substrate	0.14	0.22	0.58	–	–	–	–	0.02	0.02	Bal.

distributions in the prior austenitic dendrites, as well as the analysis of kinetics of the nanostructured bainitic evolutions under different transformation temperature, the chemical composition thresholds of the formations near the interdendritic regions and their effects will be revealed. Also, the effect of the segregation of elements on the transformation kinetics and the final microstructures will be revealed in this study, which are crucial determinations for the overall transformation process of the nanobainitic in the laser cladded coatings.

2. Materials and experimental procedure

The coating material was fabricated by using laser cladding system that consists of 3.5 kW continuous wave diode laser (Rofin DL-035Q), a system with the five-axis robotic control trajectory of the laser scanning, and a powder coaxial nozzle feeding system with shielding gas device. Considering the Fe-based powder was easy to be oxidized and to cause oxide inclusions, a tail argon gas shielding device after the coating nozzle was used to protect the coatings from oxidizing (Fig. 1).

The experiment was conducted on a heating platform, which was used to preheat the mild steel substrate, and the preheating temperatures were 20 °C higher than the following isothermal holding temperatures. After cladding, the specimens were transferred to the furnace for isothermal heat treatments. During the transferring, a thermometer was used to monitor the temperature of the specimens to make sure that the temperatures of the specimens were not below the isothermal temperatures. After a certain time for the isothermal holding, the specimens were quenched at ambient temperature. Fe-based spherical powder with the particle size of 75–250 μm was chosen as the deposition material, which was fabricated by plasma rotation electrode process. The nominal compositions of the substrate and powder materials were listed in Table 1. The parameters of the laser cladding and subsequent isothermal heat treatments were listed in Table 2. The optimized laser powers of 2.3, 2.4 and 2.5 kW were used for the cladding of 320, 270 and 220 °C preheated substrates, respectively. 10 to 12 specimens were prepared to study the transformation process with different transformation times under three transformation temperature, the transformation times of each specimens were list in Table 2.

After the cladding and heat treatment, the specimens were sectioned (across top-surface, longitudinal-section and cross-sectional plane for the three dimensions metallographic observation) and polished, then etched by using 4% nital and picric acid solutions. The microstructure of the coatings was studied by optical (AxioCam MRc5, Carl Zeiss) and field-emission scanning electron microscope (NOVA NanoSEM 230, FEI) equipped with energy-disperse X-ray spectroscopy (EDAX) system (AZtec X-Max 80). The thin foils for TEM were prepared by twin-jet electropolisher at minus 30 °C in a solution of 5% perchloric acid and 95% ethyl alcohol and an operating voltage at 40 V. The thin foils were characterized by transmission electron microscopy (TEM JEOL JEM-2100F) equipped with Energy Dispersive Spectroscopy (EDAX) system (Aztec X-Max^N 80 TLE), operated at 200 kV. The secondary dendrite spacings were revealed by means of the linear intercept method (etched by saturated picric acid). Phase quantitative analysis was performed using X-ray diffraction (XRD Rigaku D/Max 2500).

3. Results and discussion

3.1. Solidification microstructure

Fig. 2 shows the coatings obtained after cladding and isothermal treatment which firstly preheated at different temperatures. The dilution zones of the coatings are the areas that between the planar growth layer (including the planar growth layer) and the original surface of the substrate (as shown in Fig. 2d). Different heat inputs (different laser powers) are used for the different preheating temperatures to ensure the dilution of the coatings is low (<5%), because the chemical composition should not be deviate from the nominal value.

The dilution rate (η) of the cladded coatings under different preheating temperatures and heat inputs are calculated by using the equation of $\eta = \frac{S_2}{S_1+S_2}$, where S_2 is the dilution zone of the coatings as can be seen in Fig. 2, and S_1 is the area of the coating above the original surface line of the substrate. The calculated dilution rates of the coatings are listed in Table 3.

The bainitic microstructure of the solid-state phase transformations after the laser cladding is guaranteed to be nanoscale thermodynamically with the nominal composition of the coatings.

Table 2
Processing parameters for laser cladding and isothermal transformation.

Laser cladding		Preheating and isothermal transformation	
Laser power (kW)	2.3/2.4/2.5	Preheating temperature (°C)	320/270/220
Scanning velocity (mm/s)	10		
Spot diameter (mm)	2.5 × 3.5	Transformation temperature (°C)	300/250/200
Powder feed rate (g/min)	30		
Shielding gas flow rate (l/min)	5	Transformation time (h)	0.083/0.25/0.5/0.75/1/1.5/2/3/4/6/8/16 for 300 °C
Tail shielding gas flow rate (l/min)	15		0.083/0.251/2/3/4/8/12/16/20/24 for 250 °C
			2/4/8/12/24/48/72/120/180/240 for 200 °C