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# Microstructure evolution of Fe-based nanostructured bainite coating by laser cladding

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ABSTRACT

A Fe-based coating with nano-scale bainitic microstructure was fabricated using laser cladding and subsequent isothermal heat treatment. The microstructure of the coating was observed and analyzed using optical microscope (OM), field-emission scanning electron microscope (FE-SEM), transmission electron microscope (TEM) and X-ray diffraction (XRD). The results showed that nanostructured bainitic ferrite and carbon-enriched retained austenite distributed uniformly in the coating. Blocky retained austenite was confined to the prior austenite grain boundaries resulting from the elements segregation. The bainitic microstructure obtained at 250 °C had a finer scale compared with that obtained at 300 °C. The volume fraction of austenite increased with increasing transformation temperature for the fully transformed bainitic coating. The bainitic transformation was accelerated as a result of the fine prior austenite generated during the laser cladding. The evolution of the carbon contents in bainitic ferrite and retained austenite revealed the diffusionless mechanism of the bainitic transformation.


## 1. Introduction

Recently, nanostructured bainitic steels with high carbon and high silicon concentration have attracted much attention because of their high strength (up to 2.3 GPa), high toughness (up to 30 MPa m$^{1/2}$), high hardness (up to 670 HV) and high ductility (up to 30%) [1,2]. The bainite in such steels is a carbide-free microstructure, which consists of ultrafine bainitic ferrite (can be as thin as 20–40 nm) and dispersed retained austenite. The excellent properties of these steels are related to the stability of the retained austenite during plastic straining, and the elimination of carbide in bainite [2]. High carbon concentration is one of the most important factors to enhance the stability of retained austenite. Meanwhile, the high silicon is employed to suppress the precipitation of cementite [3,4].

With addition of some other solute elements, the nano-scale bainite can be obtained at a very low temperature. The higher carbon content and lower transformation temperature can slow down the transformation rate [5]. Therefore, a rapid transformation process is needed for commercial application. Two methods are available to achieve the rapid transformation rate. One is to enhance the driving force accompanying the austenite–ferrite transformation ($\Delta G\gamma\alpha = G\alpha - G\gamma$) in bainitic steel by adding aluminum and cobalt (less than 2 wt.%). The other is to refine the grain size of austenite [6].

The fine prior austenite grain size can be obtained by a rapid cooling process, such as by laser cladding [7]. As a novel microstructure, research on laser cladded nanostructured bainite was seldom reported, and similar research with high rapid cooling process about the nanostructured bainite has been focused on welding. Hong et al. used post-weld rapid heat treatment on nanobainitic steel, but failed as a result of the precipitation of cementite [8]. Fang et al. attempted to generate high concentration bainitic ferrite weld joint on the nanostructure bainite base metal, while the crack was found as a result of the martensite formed in the weld zone [9]. However, the nanostructured bainite can be fabricated by using laser cladding due to the low heat in put, low dilution and small heat affected zone. And laser cladding is a potential way to manufacture nanobainitic steel components, such as heavy-duty gears and hot-rolled rod. In this paper, laser cladded Fe-based (Fe–0.8C–1.51Si–1.93Mn–1.59Co–1.06Al–1.08Cr–0.28Mo) coatings were fabricated by diode laser cladding system. The goals of this work were to generate fully nanobainitic coatings with an acceleration transformation rate, and to reveal the evolution of the nanostructured bainite in laser cladded coatings.

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**Table 1**
Chemical composition of the powder and substrate.

| | | C | Si | Mn | Cr | Mo | Co | Al | P | S | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Powder | wt.% | 0.80 | 1.51 | 1.93 | 1.08 | 0.28 | 1.59 | 1.06 | 0.008 | 0.01 | Bal. |
| | at.% | 3.527 | 2.847 | 1.86 | 1.1 | 0.155 | 1.429 | 2.08 | 0.0137 | 0.0165 | Bal. |
| Substrate | wt.% | 0.14 | 0.22 | 0.58 | – | – | – | – | 0.02 | 0.02 | Bal. |

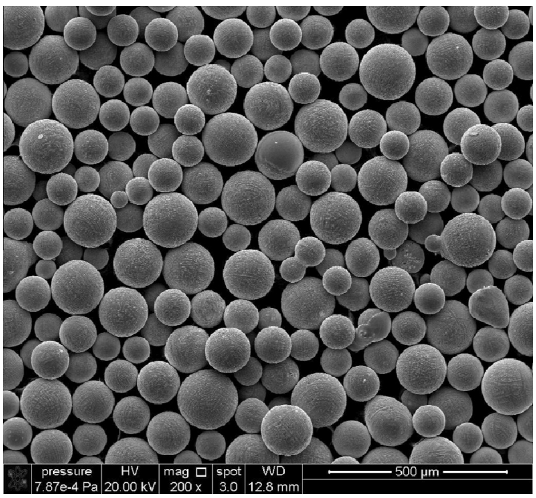


**Fig. 1.** Morphology of the Fe-based alloy powder for laser cladding.

## 2. Materials and experimental procedures

The laser cladded Fe-based coatings were fabricated by 3.5 kW Rofin DL-035Q diode laser system equipped with a powder delivery system and an argon shielding gas device. Fe-based spherical particles powder with size of 75–250 μm was chosen as the deposition materials, and the CCS-A steel plate was chosen as the substrate with dimensions of 150 mm × 15 mm × 12 mm. The morphology of the Fe-based powder is shown in Fig. 1. The chemical composition the powder and substrate are listed in Table 1.

The coatings were deposited onto the preheated substrate by a coaxial laser cladding process. The wavelength of the laser beam is in a range from 808 nm to 940 nm, and the spot size of the laser at the focal length (165 mm) is 2.5 mm × 3.5 mm. A group of optimized laser process parameters have been chosen for laser cladding, the laser process and the isothermal transformation parameters are listed in Table 2. The laser cladded coatings were transferred into the furnace for isothermal transformation immediately. The surface temperature of the coatings was monitored using a digital thermometer to ensure the temperature was just above the setting temperature of the furnace before the transferring. After finishing isothermal transformation, the specimens were quenched into the water.

The microstructure of the coating was observed using OM (Zeiss Axioplan 2) and FE-SEM (JEOL JEM-7600F) after etching in 4% nital (4% nitric acid and 96% ethanol). TEM specimens were machined to 3 mm diameters rods and electropolished with a twin-jet electropolisher at −30 °C in a mixture of 5% perchloric acid and 95% ethylalcohol at 40 V. A TEM (JEOL JEM-2100F) operated at 200 kV was used to examine the thin foils.

X-ray experiments were conducted using a Ultima IV X-ray diffractometer and a scanning rate of 1° min$^{-1}$ over the range $2\theta = 35–105°$, with unfiltered Cu Kα radiation. The system was operated at 40 kV and 30 mA. The volume fraction of retained austenite and carbon contents were calculated by integrated intensities of (1 1 1), (2 0 0), (2 2 0) and (3 1 1) peaks of austenite and the (1 1 0), (2 0 0), (2 1 1) and (2 2 0) peaks of ferrite. Four peaks were used to avoid the bias resulting from any crystallographic texture in specimens. Lattice parameters were evaluated by means of Cohen's [10] method together with some other extra considerations described in detail in Ref. [11]. The carbon contents in bainitic ferrite and austenite were calculated from the lattice parameters obtained by the corresponding diffraction peaks according to Ref. [12].

The microhardness along the cross profile of the coatings was measured by a Vickers microhardness tester with a 1 kg load and 15 s loading time.

## 3. Results and discussion

### 3.1. CCT/TTT diagram

An assessment of the isothermal transformation kinetic was made using a JMatPro software with steel database which was developed by Sente Software Corporation. The software was applied to calculate continuous cooling transformation (CCT) diagram and time–temperature transformation (TTT) diagram of the Fe–0.8C–1.51Si–1.93Mn–1.59Co–1.06Al–1.08Cr–0.28Mo coating during the cooling and followed isothermal holding stages, respectively, as shown in Figs. 2 and 3. The calculated CCT and TTT diagrams of the Fe-based coating are guideline for the isothermal heat treatment. During the calculation, the average grain size number of the prior austenite was set as 10 (about 10 μm), which was determined by the liner intercept method under the standard ASTM: E112-13.

The calculated CCT diagram of Fe–0.8C–1.51Si–1.93Mn–1.59Co–1.06Al–1.08Cr–0.28Mo contains several cooling curves with different cooling rates from 900 °C to ambient temperature (Fig. 2). There is no intersection of the cooling curve and pearlite transformation (0.1 at.%) curve at cooling rate of 10.0 °C/s. Due to the rapid cooling rate ($10^4$–$10^6$ °C/s) in laser cladding, the pearlite was not formed in the coatings during the solidification process.

Fig. 3 shows the calculated TTT diagram of Fe–0.8C–1.51Si–1.93Mn–1.59Co–1.06Al–1.08Cr–0.28Mo steel. It can be seen that the bainite transformation starts at 410.7 °C, and the martensite

**Table 2**
Laser cladding and isothermal transformation parameters.

| Power (W) | Laser cladding | | | | Isothermal transformation | |
|---|---|---|---|---|---|---|
| | Substrate preheating temperature (°C) | Scanning speed (mm/s) | Powder feeding rate (g/min) | Shield gas flow (L/min) | Transformation temperature (°C) | Transformation time (h) |
| 2500 | 270 | 8 | 30 | 5 | 250 | 4, 6, 8, 12, 24, 48 |
| | 320 | | | | 300 | 4, 6, 8, 12, 24 |