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The evaluation of NiAl- and TiAl-based intermetallic coatings produced on the AISI 1010 steel by an electric current-activated sintering method

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ABSTRACT

In this study, NiAl- and TiAl-based intermetallics were coated on the AISI 1010 steel substrate by one-step pressure-assisted electric current-activated sintering (ECAS) process. Ni, Ti and Al elemental powders were mixed by the stoichiometric ratio corresponding to the NiAl and TiAl intermetallic phases' with molar proportion of 1:1. It was observed that the synthesised coatings have a good adherence and many small pores in it. The phases formed in the NiAl coating layers confirmed by XRD analysis were NiAl as a major phase, Ni_3Al and NiO trace phases. However, TiAl coatings include Ti_3Al, TiO_2 and Ti trace phases were detected in addition to TiAl major phase. The distribution of the elements from the surface to the interior on the cross section of the coating layer was verified with energy-dispersive X-ray spectroscopy (EDS) analysis. EDS analysis showed that iron atoms were dissolved in the NiAl and TiAl coating layers during the coating process.

1. Introduction

Surface coating is a cost-effective method of improving the surface properties of a bulk material [1]. Metallic materials can be protected against wear and high-temperature oxidation by the formation of intermetallic coatings. In the case of aluminide coatings, the formation of surface oxides, mainly Al_2O_3, provides protection because of the oxides' sufficiently slow growth rates [2]. NiAl and TiAl are materials that have potential uses in the aircraft and automotive industries because they have a high melting temperature (1911 K, 1713 K), a low density (5.91 g/cm^3, ~3.9 g/cm^3), good thermal conductivity (76 W/m·K, 22 W/m·K), and excellent corrosion resistance at high temperatures [3,4]. If NiAl and TiAl coatings on carbon steel are obtained, the oxidation and corrosion resistance, as well as the substrate, will be improved. Currently, the coatings can be obtained with techniques such as Physical Vapour deposition (PVD) [5,6], the self-propagating high temperature method [7], the mechanical alloying method [8], and the high velocity oxygen-fuel (HVOF) thermal spraying [1].

In the present work, we examined the electric current-activated/assisted sintering (ECAS) method for the production of NiAl and TiAl intermetallic coatings on carbon steel. In the ECAS method, powders or a cold-formed compact to be consolidated are inserted into a container, while pressure is applied and maintained for a given period of time. Heat is provided by passing an electric current through the powders and/or their container, thus exploiting the consequent Joule effect. This method is characterised by its technological and economic advantages over conventional sintering methods. These advantages include faster heating rates, lower sintering temperatures, shorter holding times, consolidation of difficult-to-sinter powders, no need for cold compaction, less sensitivity to the initial powder characteristics and the ability to produce near-final configurations very rapidly [9–11].

The aim of this study was to investigate the formation of dense, homogeneous NiAl and TiAl intermetallic coatings on plain carbon steel by one-step pressure-assisted electric current-activated sintering process without using any controlled atmosphere. The process combines effects of both the electric current and pressure. The electric current has been used for the ignition of the mixture of coating powders placed on the surface of AISI 1010 plain carbon steel substrate and for supplying the energy needed to complete the reaction and to generate the NiAl or TiAl coating in situ. Also, in order to decrease the amount of porosity and obtain a dense coating structure, a pressure is directly applied on the powders placed on steel substrate which being in the mould. Although, there are a lot of study realised on intermetallic coatings on the steel samples, but there is no remarkable study realised by on-step pressure-assisted electric current-activated sintering process in the open literature.

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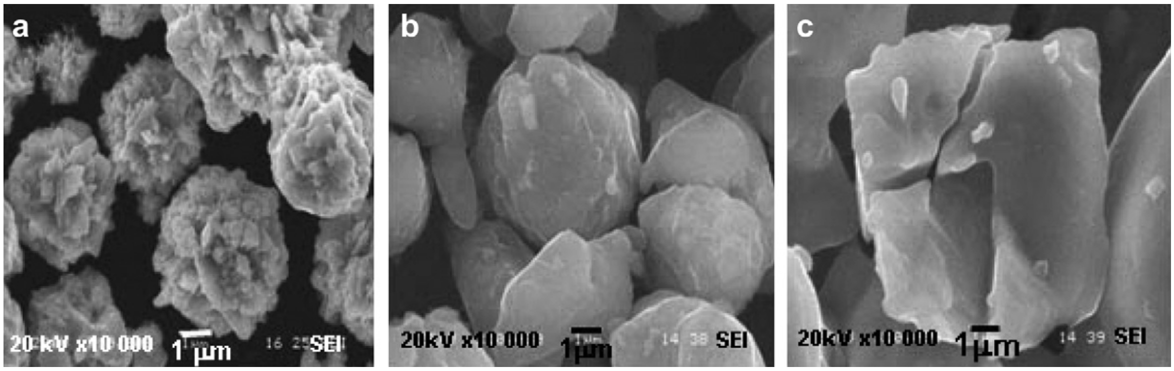

Fig. 1. SEM micrographs of the elemental powders: (a) Ni, (b) Al and (c) Ti.

2. Experimental

Carbonyl-Ni powders (99.8% purity, 4–7 μm), Ti (99.5% purity, less than 44 μm) and Al gas atomised powders (99% purity, 15 μm) were used as the starting powder mixture for the formation of produce NiAl- and TiAl-based intermetallic coatings. The powder mixture were prepared with two different compositions which were: 50 at.% Al, 50 at.% Ni and 50 at.% Al, 50 at.% Ti. To obtain uniform mixtures, the powders were ball-milled in an Ar + 2% H gas atmosphere for 10 min with 0.1 ml of ethanol added. The substrate used for this study was AISI 1010 plain carbon steel. Before the coating process, all substrates (diameter: 10 mm, thickness: 5 mm) were ground using 600-grid emery paper to obtain a good surface finish. AISI 1010 carbon steel was placed in a mould with a diameter of a 15 mm, which was lubricated with a thin layer of boron nitride. The mixed coating powders were put on the surface of the steel substrate placed in the mould. The specimen was kept in an open atmosphere and then in order to provide the contacting of individual powders in the initial period of the process, the samples was pressed by a die with a compression load of 100 MPa, for 1 min. A direct electric current (1100–1200 A, voltage: 2.9–3.4 V) was applied to steel substrate with a pressure of 25 MPa for 15 min in order to manufacture coatings. After sintering, the specimens were unloaded and cooled to room temperature in an open atmosphere. The morphologies of the samples and the presence of the phases formed were examined by with scanning electron microscopy (SEM-EDS) and X-ray diffraction (XRD) analysis. The micro-hardness of the test materials was measured using by a Vickers indentation technique with a load of 0.5 N.

3. Results and discussion

Fig. 1 shows the morphologies of as-received Ni, Ti and Al powders. The carbonyl Ni powder particles were generally spherical and has rough surface and with a diameter of 4–7 μm. The Al gas atomised powders were generally spherical shape and the dimensions is less than 1 μm in size. The Ti powder has sharp corners and was less than 44 μm in size.

In pressure-assisted electric current-activated sintering, an electric current is simultaneously applied with a mechanical pressure to consolidate or synthesise the coating and to densify specific products into the desired configuration and density [9]. The microstructures of NiAl and TiAl intermetallic coatings formed on the surface of the substrate are shown in Fig. 2. As shown in this figure, the NiAl intermetallic coating layer included many small pores (Fig. 2(a)). The TiAl intermetallic coating layer possessed a coarser grain structure than the NiAl intermetallic coating layer, and some pores were present among the grains (Fig. 2(b)).

The samples seem to have good adherence because no cracks were observed at the interface between the matrix and coating layers. As it can be seen in Fig. 2(a,b) the interface between coating layer and steel matrix do not include porosity. There are good match between thermal expansion coefficients of NiAl ($14.6 \cdot 10^{-6}$/K [12]), TiAl ($14.4 \cdot 10^{-6}$/K [13]) and AISI 1010 steel ($14.3 \cdot 10^{-6}$/C [14]). Therefore, both TiAl and NiAl coatings were well adhere to the steel samples and there is no any crack at interface. In addition, Vickers indenter was applied at the interface of steel matrix and coating layer under the load of 10 N and any cracks was not formed at interface as well (Fig. 3a,b).

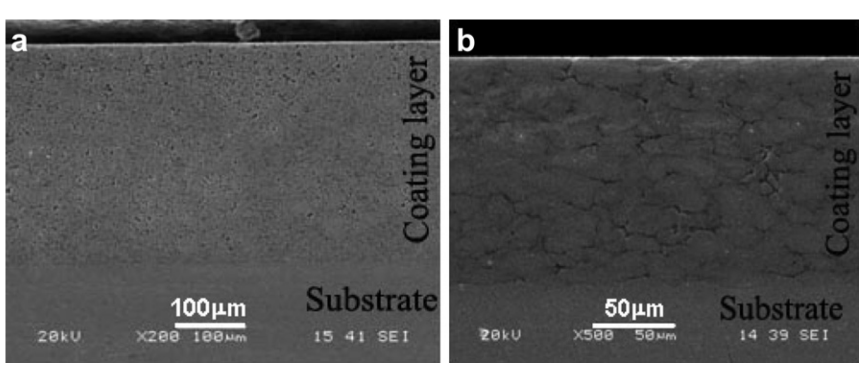

Fig. 2. SEM images of coated samples: (a) NiAl and (b) TiAl.