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Synthesis and fabrication of NiAl coatings with Ti underlayer using induction heating

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ABSTRACT

The objective of this work was to develop a new technique to synthesize and fabricate NiAl coatings on a steel substrate in one processing step. Induction heating was used as the ignition source to initiate the self-propagation high-temperature synthesis (SHS) reaction of Ni/Al, while titanium was used as the underlayer to facilitate the adhesion between the coating and the substrate. The temperature profiles during the process were measured to monitor the heating and synthesis reaction in the coating and underlayer. The microstructure and the phase compositions of the synthesized products were studied using SEM and XRD. The results showed that the SHS reactions of Ni/Al produced stoichiometric and substoichiometric NiAl such as $Ni_{0.58}Al_{0.42}$ and $Ni_{1.04}Al_{0.96}$ in the coating. The Ti underlayer joined the reaction. The reacted part changed into Ti_3Al–Ti_2Ni composite and the unreacted Ti formed an alloy with the NiAl. The mechanical properties of the synthesized products, evaluated using Vickers indentation, showed that the hardness of the underlayer was higher than that of the coatings and substrate, while the test at the substrate/underlayer interface indicated that the existence of a Ti underlayer had improved the adhesion between the coating and the substrate.

1. Introduction

NiAl is one of the intermetallics which has shown promise as a candidate for use as a protective coating in high temperature applications since it offers several advantages, such as high melting point (1911 K), relatively low density (5.86 g/cm^3), high hardness and good oxidation resistance at elevated temperatures [1,2]. Among the different techniques attempted to produce NiAl, the SHS process has been considered as an attractive method to synthesize NiAl and other intermetallics since it has a low energy requirement and takes a short processing time [3]. SHS is a type of combustion synthesis which transforms the reactants into products in a highly exothermic reaction. The combustion process is initiated by heating the front part of the sample to its ignition temperature using an external heat source. After the reaction is ignited, the heat produced by combustion reaction then propagates and heats up the adjacent layer to the ignition temperature so that the combustion reaction self propagates through the whole sample by itself. The additional heat source required to maintain the combustion process can therefore be eliminated thus making the process very efficient [4,5]. Owing to these significant advantages, the SHS process has been considered as an alternative to conventional technologies which require complex process preparation and expensive equipment [5].

Recent development of the SHS process has made it more attractive since it can be applied for coating fabrications [6]. A number of external heat sources such as concentrated solar energy [2,7], microwave [8,9], and induction furnace [10,11] have been used to ignite the SHS reaction of Ni/Al and help the deposition of the synthesized product onto a substrate to fabricate coatings in one processing step. The fabrication of a coating combined with the SHS reaction, however, leads to a problem in the adhesion between coating and the substrate [12]. The high combustion temperature of the SHS reaction releases a thermal shock during the synthesis which may result in the detachment of the coatings from the substrate. In addition, the temperature changes during cooling from the high combustion temperature of the SHS reaction can generate thermal stresses in the coatings due to the coefficient of thermal expansion (CTE) mismatches [13]. The thermal stresses will lead to the formation of cracks and a poor adhesion between coating and substrate. Reducing the thermal stresses is therefore required to build strong adhesion. An underlayer can be applied to reduce the thermal stresses in the coating and substrate [14]. Since the existence of the underlayer is mainly to facilitate adhesion, the underlayer is required to have a mutual diffusion at the interface between the coating and the substrate [15]. The material used as an underlayer is therefore required to melt during the synthesis process. A high melting temperature of the underlayer materials can be considered to minimize the CTE difference for high

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temperature applications. Reducing the thermal stress can also be achieved by increasing the temperature of the substrate [16]. To minimize the heating effect to a substrate, it is desirable to heat the surface of the substrate only, which can be done by fast surface heating. Induction heating has become an interesting heat source due to its capability to produce a high heat intensity within an electrically and magnetically conductive material in a short time with simple equipment. The process is clean and fast since the power goes directly to the material being heated and is concentrated at the surface [12,17].

The objective of the present work was to fabricate NiAl coatings on a steel substrate using a combination of induction heating and underlayer. The effect of the processing parameters on the combustion reaction of the Ni/Al was studied. The role of the underlayer on the microstructure of the synthesized products and the properties of the coating were investigated. The successful application of a NiAl coating on the steel substrate is expected to improve the limited use of steel at high temperature due to the risk of oxidation and corrosion.

2. Experimental methods

Carbon steel (Bright mild steel, RS Components, UK) with carbon contents of 0.15%, 16 mm in diameter and 3 mm in thickness was used as substrate. The surface of the substrate was ground and polished to produce a flat surface. Cleaning was accomplished with acetone in an ultrasonic bath for 15 min to remove dust, any oil film, and grease from the surface. The moisture in the surface was then evaporated with hot air. The powders used as the reactant were Inco Carbonyl Nickel type-123 (D_{50} = 4.5 μm, 99.85%), aluminum (D_{50} = 45 μm, 99.7%) and titanium (D_{50} = 106 μm, 99.46%) supplied by William Rowland, UK. The morphology of the reactants is given in Fig. 1. The Ni and Al powders were weighed with an atomic ratio of 1:1, and subsequently mixed and crushed using a ceramic mortar to produce a homogenous mixture. The mixture was dried in a furnace at 100 °C for 1 h. The Ni/Al mixture was then cold compacted with a compaction pressure of 200 MPa using a steel die. Ti powder used as underlayer was compacted below the Ni/Al pellet with the same pressure to form two compacted layers. The relative density of the compressed disc was 63.2%. After compaction, the finished thicknesses of the Ni/Al and Ti were 0.54 ± 0.01 mm and 0.31 ± 0.04 mm, respectively. The compacted pellets were then placed on a steel substrate for heating in the combustion chamber with an atmosphere of argon gas flowing at a rate of 15 l/min. The schematic diagram of the experimental set-up and the sample composed of coating, underlayer and the substrate are shown in Fig. 2.

Induction heating equipment (model Easy Heat, manufactured by Cheltenham Induction Heating Limited, UK) with a maximum power of 2 kW and maximum frequency of 387 kHz was used as the heat source. A helical coil was chosen as it was a suitable match to the shape and size of the samples. The coil was placed over the sample, where the distance between the bottom of the coil and the top surface of the sample was approximately 3 mm. The tests were started by adjusting the current and time of induction heating according to the heating requirement. Water circulation flowing inside the coil was turned on prior to the induction process to avoid coil overheating. When the SHS reaction was initiated, induction heating was turned off manually approximately 1 s after ignition. The currents in the coil were set at 150 A, 200 A, 250 A and 300 A to study the effects of heating rates on the SHS reaction of the Ni/Al. The combustion temperatures were measured using a combination of type–K thermocouple which has a temperature range of −50–1100 °C and a non-contact infrared pyrometer type Marathon MM which has the capability to measure high temperatures in the range of 540–3000 °C. For the temperature measurement using the thermocouple, the method adopted was to embed the thermocouple in a shallow groove of approximately 1 mm depth cut into the surface of the sample. A fixture of granite was used to help with the positioning of the thermocouple. For the temperature measurement using the pyrometer, the emissivity of Ni/Al and Ti were chosen to be 0.82 and 0.95, respectively, based on calibration using the measured temperature of the pyrometer and thermocouple. The pyrometer was used to monitor the temperature at the surface.

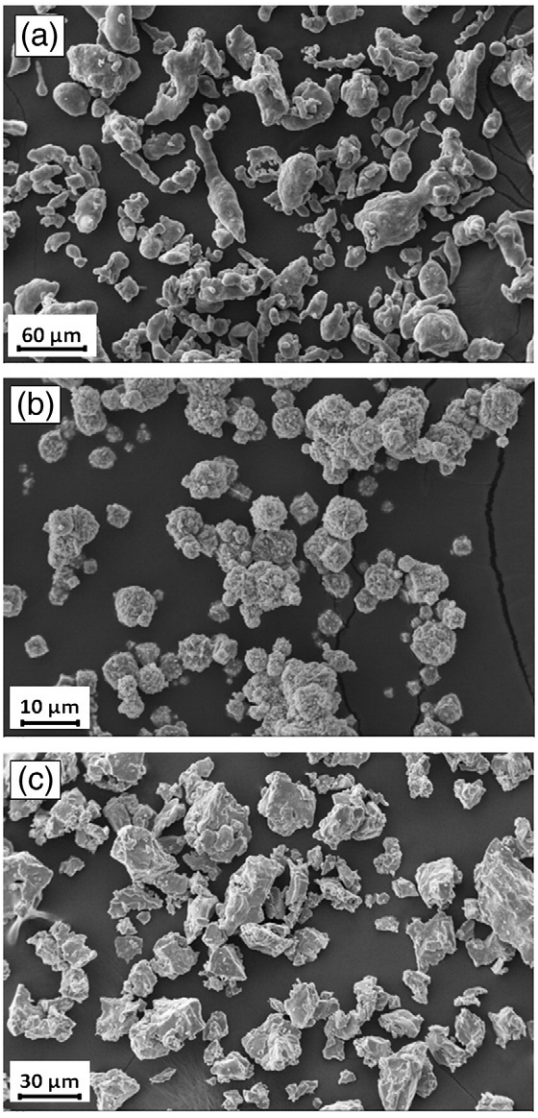

Fig. 1. SEM micrographs of the reactant powders: (a) Al; (b) Ni and (c) Ti.

The microstructure characterization of the products was carried out using SEM (Zeiss EVO50, Germany) and XRD (RINT2000 vertical goniometer) techniques utilizing a scanning rate of 4 °/min. The samples used for the microstructure analysis were cut from the middle section of the synthesized products and subsequently mounted in epoxy resin. The samples were ground using silica papers with 180 and 600 grit, polished with a sequence of abracloth, nylap, and trounoire papers (MetPrep, UK) with diamond paste decreasing from 9, 3, to 1 μm, and etched with a mixture of methanol and nitric acid with a volume ratio of 98: 2. A Vickers indentation tester was used to evaluate the hardness and the interfacial adhesion between the coatings and the substrate. The hardness measurement was conducted using a load of 0.1 N for 15 s, while the adhesion was tested using a load of 20 N. The observation of the microhardness distribution from the surface to the substrate was performed using 5 points for each zone with the same distance from the surface in order to reduce the error caused by the hardness evaluation.