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A study on the formation of iron aluminide (FeAl) from elemental powders

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ABSTRACT

The formation of iron aluminide (FeAl) during the heating of Fe–40 at.% Al powder mixture has been studied using a differential scanning calorimeter. The effect of particle size of the reactants, compaction of the powder mixtures as well as the heating rate on combustion behavior has been investigated. On heating compacted discs containing relatively coarser iron powder, DSC data show two consecutive exothermic peaks corresponding to precombustion and combustion reactions. The product formed during both these reactions is Fe_2Al_5 and there is a volume expansion in the sample. The precombustion reaction could be improved by a slower heating rate as well as a better surface coverage of iron particles using relatively finer aluminum powder. The combustion reaction was observed to be weaker after a strong precombustion stage. Heating the samples to 1000 °C resulted in the formation of a single and stable FeAl phase through the diffusional reaction between Fe_2Al_5 and residual iron.

DSC results for compacted discs containing relatively finer iron powder and for the non-compacted samples showed a single combustion exotherm during heating, with Fe_2Al_5 as the product and traces of FeAl. X-ray diffraction and EDS data confirmed the formation of FeAl as the final product after heating these samples to 1000 °C.

1. Introduction

Intermetallic compounds such as aluminides of transition metals like nickel, iron, titanium, niobium and cobalt have been widely studied due to their attractive physical and mechanical properties of critical importance in a variety of applications [1–5]. Among these compounds, iron aluminides are specially interesting due to their low density, low production cost, good mechanical properties and corrosion resistance at high temperatures [4,6,7]. Iron aluminides are about 30% lighter than commercial high temperature structural materials like stainless steel and nickel based superalloys [8]. Studies have shown that iron aluminides have good high temperature corrosion resistance in oxidizing and sulfidizing environments [9,10] found in typical industrial applications like power generation systems. This is attributed to the formation of dense and adherent alumina scales on the surface of the material. Natesan [11] confirmed these observations and concluded that the oxidation rates of iron aluminides in single-oxidant environments (like air or gases with low oxygen potentials) are significantly lower than those for chromia-forming commercial alloys. These properties allow intermetallic compounds in the Fe–Al system to be employed at high temperatures as structural materials, gas filters and heating elements [4,7].

Fig. 1 shows the binary phase diagram for the Fe–Al system which contains several intermetallic compounds. Two of these compounds, FeAl and Fe_3Al, are considered very attractive due to good strength and corrosion resistance at high temperatures [6–8,11].

FeAl, with a B2-ordered cubic CsCl structure, exists over a wide range of aluminum contents (35–50 at.%). The ordered $D0_3$ cubic structure of Fe_3Al is observed around 25 at.% Al and it is stable in the interval 23–36 at.% Al at low temperatures. The region of stability for Fe_3Al $D0_3$ structure tapers off at higher temperatures. Both B2 and $D0_3$ structures are perfectly ordered only when their compositions correspond to the stoichiometric compounds [8]. The high magnetic permeability shown by Fe_3Al makes it useful as a soft magnetic material. Relative to Fe_3Al, FeAl has a lower melting point, but a better oxidation resistance. FeAl also has a lower density and higher strength-to-weight ratio compared to steels and superalloys [2,5]. In addition, it exhibits relatively high electrical resistivity which makes it suitable for use as a heating element [2,3,13].

Iron aluminides can be produced by powder metallurgical methods involving powder consolidation [5,13–15] and sintering, which offer advantages such as net-shape processing and

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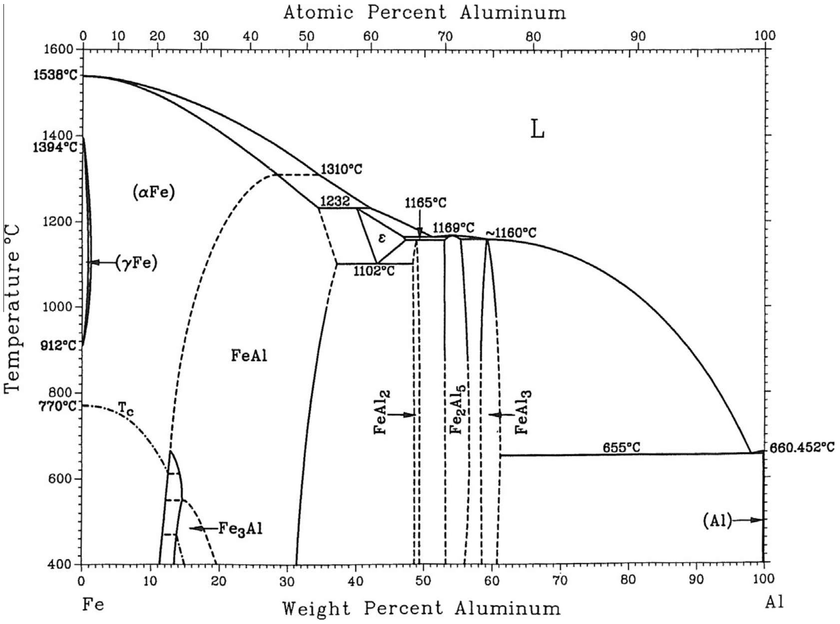

Fig. 1. Fe–Al binary phase diagram [12].

cost-effectiveness. It would be advantageous to start with metal powder mixtures as the consolidation process would be easier and cheaper than using powders of preformed intermetallics. In this context, formation of intermetallics in situ in a heated mixture of metal powders is of considerable interest. Such a process is called Combustion Synthesis, Reactive Synthesis or Self Propagating High Temperature Synthesis (SHS), in which a reaction between the reactant particles is initiated during heating. The reaction is exothermic and the generated heat can be utilized to make the process self-sustaining. Several authors like Munir et al. [16] and Mossino [17] have studied this method which can be used to fabricate near-net shape products. However, porosity levels in SHS products are high and can be minimized by sintering under pressure. Rabin et al. [18] have shown that near full density Fe_3Al and FeAl compounds can be obtained during the combustion reaction in a hot press by applying external pressure. Godlewska et al. [19] prepared FeAl (40 at.% Al) intermetallic powders using SHS in a loosely packed mixture of elemental powders. Compacted and sintered powder compacts were densified using hot forming methods. They observed that the strength and ductility of the product at room temperature were sensitive to grain size and adversely affected by the oxide phase distributed along the grain boundaries.

Gedevanishvili and Deevi [3] conducted dilatometric and DSC experiments up to 1350 °C to study the formation of iron aluminide and the sintering behavior in Fe–40 at.% Al powder mixtures. At a heating rate of 5 °C min^{-1}, they observed two exothermic peaks at 560 and 655 °C. These peaks were attributed to the formation of Fe_2Al_5 and FeAl respectively. The volume expansion observed in heated discs was linked to the formation of Fe_2Al_5. The reaction mechanism, expansion rate and product density were found to be strongly dependent on the heating rate.

Gao et al. [20] also studied the synthesis of FeAl using a Fe–40 at.% Al powder mixture. While heating the sample, they observed two successive exotherms in the interval 500–650 °C. These peaks correspond mainly to the formation of Fe_2Al_5 which transforms subsequently to FeAl by reacting with residual iron at higher temperatures. The authors have described the formation of pores during different stages of heating and noted the swelling of the sintered product to be quite significant.

Kang and Hu [21] studied the reactive sintering of Fe–Al compacted discs and found that the large swelling observed is mostly due to the formation of Fe_2Al_5. They suggested that the large thermal expansion is due to the rapid release of exothermic heat from several reactions occurring simultaneously within the sample, followed by a shrinkage due to heat dissipation. Large differences in the solid solubilities, melting points and diffusion rates [3,19,21] for the components lead to the development of pores which cause swelling in the sample.

Pochec et al. [22] have suggested a two-step mechanism for the formation of iron aluminides in Fe–50 at.% Al powder mixtures. They report the formation of two aluminum-rich phases $FeAl_3$ and Fe_2Al_5 due to a slow diffusion process at temperatures below 615 °C. The SHS reaction initiates above this temperature resulting in the formation of ordered FeAl phase together with the fragile $FeAl_2$ compound. FeAl is obtained as the final product after an additional homogenizing process.

In a Fe–Al diffusion couple study, Wang and Wood [23] found that $FeAl_3$ was dominant on the iron side of the Fe–Al interface at 600 °C, highlighting the diffusion of aluminum into iron grains. Intermetallic compound formation was also observed to be significant at the iron grain boundaries, confirming the higher mobility of aluminum atoms along the iron grain boundaries. They also observed the formation of Fe_2Al_5 above the melting point of aluminum through the diffusion of iron into aluminum melt. Although thermodynamic data indicate the formation of $FeAl_3$ before Fe_2Al_5, in general, Fe_2Al_5 forms as the major phase at the interface between aluminum and iron particles due to kinetic factors [24–26]. It may also be noted that the growth parameter is much larger for Fe_2Al_5 relative to FeAl [25,27,28].

The present study aims to continue the efforts to understand the key aspects of reactive synthesis of iron aluminides from elemental powder mixtures. Powder mixtures of Fe–40 at.% Al, both in the compacted and loose conditions, have been studied during a heating cycle in a differential scanning calorimeter. The effect of processing variables including particle size of reactants and heating rates have also been studied. The synthesized products have been characterized using scanning electron microscopy, energy dispersive spectroscopy and X-ray diffraction methods.