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DETONATION COATINGS PRODUCED BY SPRAYING OF ALLOYED POWDERS BASED ON Fe–Al INTERMETALLICS

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ABSTRACT

The research results on the structure, phase composition and properties of detonation coatings produced by spraying a mechanical mixture of Fe powders and AlMg and TiAl alloys, as well as composite powders of the same composition synthesized by the mechanochemical method, are presented. It was found that in the coatings produced with the use of mechanical mixtures of powders, the synthesis of intermetallic compounds does not occur and the coatings consist of initial components and their oxides. Therefore, it is advisable to use powders produced by the method of mechanochemical synthesis as spray materials. This result in the formation of coatings, in which the main phase is the Fe–Al intermetallic compound. Coatings of the Fe–AlMg and Fe–TiAl systems, produced by spraying of composite powders, are characterized by a dense lamellar structure consisting of alternating layers of metal and oxide components. The coatings exhibit high oxidation resistance in the temperature range of 700–800 °C, comparable to the oxidation resistance of cast iron-aluminium alloys, and allow increasing the oxidation resistance of carbon steels by 6–20 times. The corrosion resistance of Fe–AlMg and Fe–TiAl detonation coatings in a 3 % NaCl solution exceeds the corrosion resistance of uncoated carbon steel by 13.3 und 28.0 times, respectively. The obtained results allow recommending the use of the developed coatings for protection of parts operating in aggressive environments at temperatures of up to 800 °C.

KEYWORDS: intermetallic compounds of the Fe–Al system, mechanochemical synthesis, composite powders, detonation spraying, coating, oxidation resistance, corrosion resistance

INTRODUCTION

Intermetallic alloys based on Fe–Al iron aluminides are challenging materials that are considered as substitutes for heat-resistant steels and alloys due to their combination of their physicomechanical and service properties, as well as low cost of their initial components [1–3]. In particular, iron aluminide-based intermetallic alloys are attractive materials for a number of industrial applications both as cast materials and as protective coatings at medium and high temperatures, due to their high mechanical properties, relatively low density, resistance to high-temperature oxidation and excellent corrosion resistance in oxidising and sulphurizing environments [4–6]. The disadvantages of Fe–A1 intermetallic alloys that limit their widespread practical use are their low ductility at room temperature, insufficient strength and creep resistance at temperatures above 600 °C. An increase in ductility and strength characteristics of Fe–Al intermetallics is achieved by introducing alloying elements into their composition through the formation of carbides and borides, solid solutions, and ternary intermetallic compounds in the alloy structure [7–10].

To deposit coatings based on intermetallics of the Fe–Al system with alloying elements, mostly methods of plasma, high-velocity oxygen fuel (HVOF) and detonation spraying are used [11]. As materials for spraying, powders produced by spraying and mechanical alloying are used; as alloying elements, Cr, B and Zr are used. The produced coatings based on Fe–A1 intermetallic are characterized by high corrosion resistance in various aggressive environments, wear resistance, resistance to thermal shock and high-temperature oxidation (up to 1000 °C); the hardness of the coatings is 3–5 GPa [11, 12].

The aim of this work was to study the structure, phase composition and properties of coatings produced by detonation spraying of powders based on Fe–A1 intermetallics alloyed with Mg and Ti.

MATERIALS AND RESEARCH PROCEDURES

For detonation spraying, composite powders (CP) of the compositions 86Fe + 14(Al5Mg) and 60.8Fe + 39.2 (62.5Ti37.5Al) (wt.%) were used, which were produced by the method of mechanochemical synthesis (MChS) by processing a mixture of powders in a planetary mill, and mechanical mixtures of the same composition (Table 1). The powder of iron as well as AMg-5 and T65Yu35 alloys was used as initial powders for producing mechanical mixtures and CP. The compositions of the powder mixtures were intended to produce Fe_3A1 intermetallic. When Ti and Mg are used as alloying elements, the properties of coatings based on Fe–Al intermetallic can be improved by forming solid solutions and incoherent compounds.

Spraying of the coatings was carried out in the detonation spraying unit “Perun-C” applying the previously selected mode of spraying coatings based on

Table 1. Characteristics of powders for spraying [13]

Composition, wt.%	Production method	Phase composition
86Fe + 14(Al5Mg)	Mechanical mixing	Fe, solid solution of Mg in Al
	MChS	Solid solution of Mg in Fe_3Al
60.8Fe + 39.2(62.5Ti37.5Al)	Mechanical mixing	Fe, TiAl
	MChS	Solid solution of Al in FeTi ($Fe_{1-x}TiAl_x$)

Fe_3Al intermetallic, in which CP particles are heated to 0.8–0.9T_m and accelerated to the maximum velocity [14]. The following operating parameters were used for the unit: combustible gas (propane-butane) flow rate — 0.5 m^3/h, oxygen flow rate — 1.3 m^3/h, diluent gas (air) flow rate — 0.6 m^3/h, transport gas (air) flow rate — 0.4 m^3/h, shot frequency — 400/min, powder loading — 120 mg/shot, spraying distance — 110 mm. Powders with a particle size of 40–80 µm were used for spraying.

To study the coatings structure, the method of metallography (Neophot-32 microscope with a digital imaging attachment), and to study the phase composition — X-ray diffraction analysis (XRD) in DRON-3 diffractometer in CuK_α-radiation with a graphite monochromator at a step movement of 0.1° and an exposure time of 4 s at each point were used, followed by computer processing of digital data. Phase identification was performed using the ASTM database.

The oxidation resistance of the coated specimens was studied when heated in a muffle furnace of the SNOL 1.6.2,5.1/11-42 type in air environment at a temperature of 700–800 °C with an isothermal holding time of 5 h. The temperature in the furnace was regulated automatically and monitored by a 4530 type device, PP-S-1300 °C with an accuracy of ±5 °C. The mass increment of the specimens was determined in a VLR-20 analytical balance with an accuracy of 10^{-5} mg. The coatings were deposited on "acorn"-shaped specimens of St45 steel with a diameter of ~10 mm and a total surface area of ~5 cm^2. The specimens were placed in the furnace on a special stainless steel stand with holes for the specimens, which allowed air to reach the surface of the coating. After the experiments, the oxidation curves were plotted based on the results of the mass increment of the specimens.

The electrochemical properties of the coatings were studied using the potentiostatic method in a P-5827 potentiostat at a scanning rate of 0.2 mV/s at a temperature of 18–20 °C. Stationary potentials were measured relative to a chloride electrode. A 3 % NaCl solution and a 10% H_2SO_4 solution were chosen as the test environment. In the work, the depth corrosion

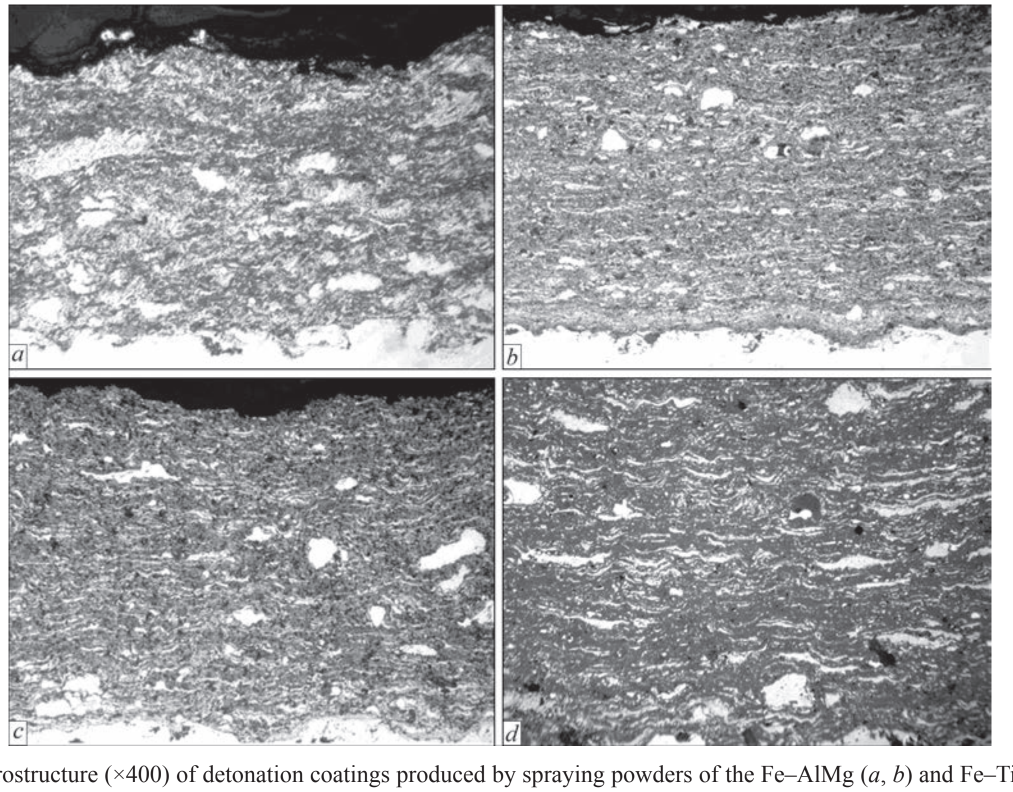

Figure 1. Microstructure (×400) of detonation coatings produced by spraying powders of the Fe–AlMg (*a*, *b*) and Fe–TiAl (*c*, *d*) systems using mechanical mixtures (*a*, *c*) and MChS powders (*b*, *d*)

index of coatings (K_c) and corrosion inhibition coefficient (γ) were calculated [15, 16].

RESEARCH RESULTS AND DISCUSSION

The coatings of the Fe–A1Mg and Fe–TiAl systems produced by spraying mechanical powder mixtures, exhibit a coarse lamellar structure consisting of alternating layers of light and dark oxide lamellae with the presence of melted partially deformed powder particles in the structure (Figure 1, *a*, *c*). In the case of using MChS powders for spraying, coatings are formed with a more homogeneous thin-lamellar structure with a small number of incompletely deformed particles (Figure 1, *b, d*). At the same time, in the coatings of the Fe–TiAl system, a smaller number of unmelted particles is observed, which may be associated with the phase composition of sprayed powders, which determines the degree of particles melting during the spraying process and the degree of their deformation during the formation of the coating layer.

Studies of the phase composition of the coatings produced by spraying powders of mechanical mixtures of the Fe–A1Mg and Fe–TiA1 systems have shown that synthesis of the Fe–A1 intermetallics formation does not have time to complete, and only oxidation of initial powder components Fe, A1, Mg and Ti occurs (Figure 2, *a*, *c*). The absence of Fe–A1 intermetallics formation during spraying of mechanical mixtures is explained by a low probability of collision and coagulation of particles in the spray jet and their high cooling rate during the formation of the coating layer, which limits the interaction of powders with the reaction of new phase formation between the initial components. In the case of spraying MChS powders, coatings are formed on the base of FeAl intermetallic with the presence of oxidation products of powder components (Figure 2. *b, d*). In contrast to coatings produced by spraying mechanical mixtures, coatings produced from MChS powders contain only a small amount of pure iron. The coating of the Fe–TiAl system contains the phase of the initial TiAl powder material and a product of iron and TiAl alloy interaction — Fe_2Ti phase. The magnesium component in the coating of the Fe–AlMg system, as in the case of spraying a mechanical mixture, is present in the form of a complex $MgAl_2O_4$ oxide.

Due to the fact that intermetallic Fe–Al phases are not formed in the coatings of the Fe–AlMg and Fe–TiAl systems produced by spraying mechanical mixtures, but initial components and their oxides remain, the coatings produced by spraying MChS powders were used for further studies of oxidation and corrosion resistance.

Figure 3 shows the kinetic dependences of the oxidation of detonation coatings and 45 steel in the

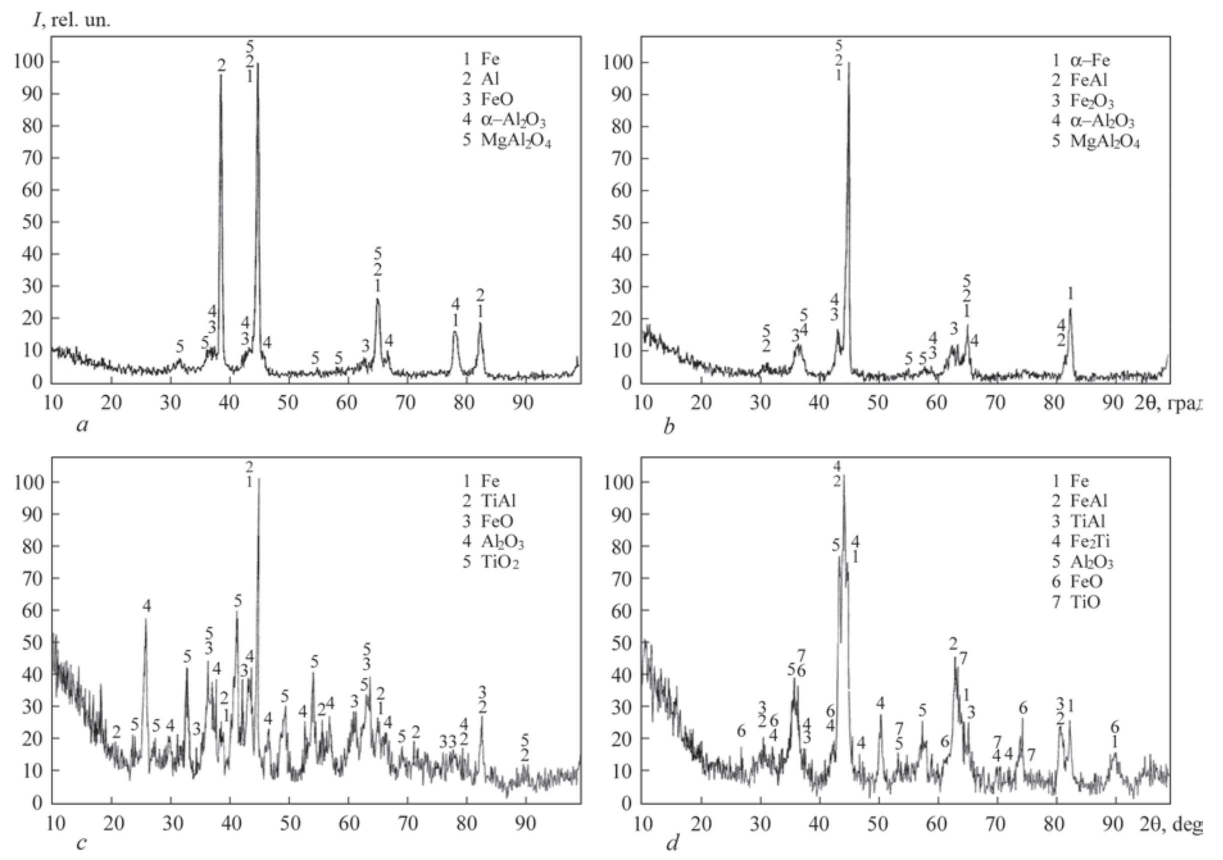

Figure 2. X-ray diffraction patterns of detonation coatings produced by spraying Fe–AlMg (*a*, *b*) and Fe–TiAl (*c*, *d*) powders using mechanical mixtures (*a*, *c*) and MChS powders (*b*, *d*)

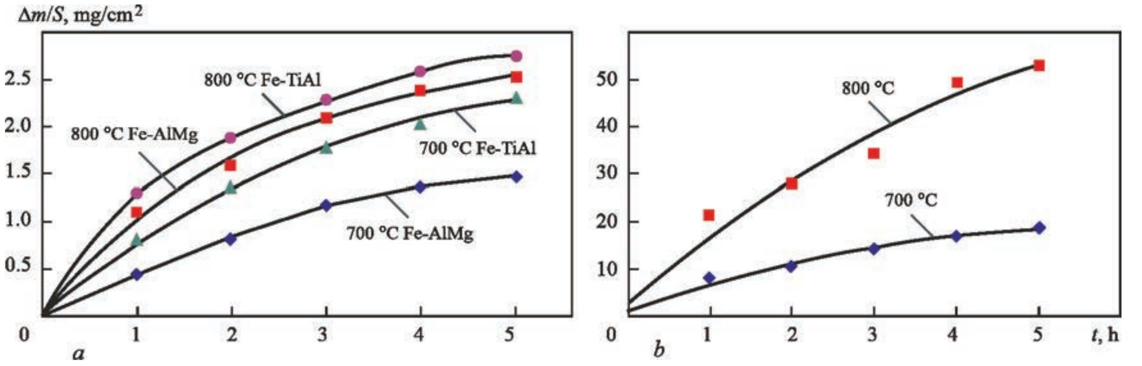

Figure 3. Kinetic oxidation curves: *a* — detonation Fe–A1Mg and Fe–TiAl coatings; *b* — steel 45 without coating

Table 2. Results of electrochemical tests of detonation Fe–AlMg and Fe–TiAl coatings in various aggressive environments

Coating	3 % NaCl solution				10 % H_2SO_4 solution			
	E_c, V	i_c, A/cm²	K_c, mm/year	γ	E_c, V	i_c, A/cm²	K_c, mm/year	γ
Fe–AlMg	–0.3	$3.5\cdot10^{-6}$	0.038	13.3	–0.26	$4.4\cdot10^{-5}$	0.452	1.3
Fe–TiAl	–0.28	$1.1\cdot10^{-6}$	0.018	28.0	–0.22	$2.4\cdot10^{-5}$	0.256	2.4
Steel 45 without coating	–0.50	$5.0\cdot10^{-5}$	0.5035	–	–0.20	$2.5\cdot10^{-4}$	0.6022	–

temperature range of 700–800 °C. From the nature of the curves in the entire studied temperature range, it follows that the oxidation mechanism in all cases is subject to a parabolic time law, which indicates that the diffusion stage is the limiting link in the process.

The obtained results indicate high oxidation resistance of Fe–AlMg and Fe–TiAl detonation coatings, which exceeds the oxidation resistance of carbon steel by 6–10 times at 700 °C and by 18–20 times at 800 °C. The value of the mass increment *Δm/St* for all the coatings does not exceed 0.6 mg/cm·h, which is comparable to the oxidation resistance characteristics of cast iron-aluminium alloys and slightly exceeds the oxidation resistance of plasma coatings produced by spraying unalloyed FeAl powders [17, 18].

Comparing the results of the oxidation kinetics for detonation coatings from FeAl-based alloyed powders, one can note a higher oxidation resistance of the Fe–AlMg coating than the Fe–TiAl coating. This is most likely predetermined by the presence of aluminium-magnesium $MgAl_2O_4$ spinels in the Fe–AlMg coating, which have a higher resistance to high-temperature oxidation than aluminium, iron, and titanium oxides formed in the Fe–TiAl coating during the spraying process.

Electrochemical studies have shown that the protective properties of coatings in a 3 % NaCl solution are by an order higher than those in a 10 % H_2SO_4 solution, which may be associated with different types of depolarisation of the corrosion process (hydrogen in a sulphuric acid solution, oxygen in a 3 % NaCl solution) [16].

It has been shown that in a sulphuric acid solution, detonation coatings deposited on 45 steel reduce the corrosion current by an order and increase the corrosion resistance by 1.3–2.4 times (Table 2). The higher protective properties are demonstrated by detonation coatings in a 3 % NaCl solution. The carried out tests have shown that in a 3 % NaC1 solution, the corrosion rate of 45 steel with detonation coatings is reduced by 13.3–28.0 times compared to steel without coating. In terms of corrosion resistance, FeAl-based detonation coatings are not inferior to coatings deposited by the plasma method [19].

The difference in the corrosion resistance of Fe–AlMg and Fe–TiAl coatings is explained by the peculiarities of their microstructure. Corrosion can occur at the interfaces of the distribution of deformed particles (splats) in the coating layer, and thanks to the formation of a homogeneous structure with the presence of thin oxide layers over the entire coating area, Fe–TiAl coatings have higher corrosion properties in the studied electrolytes.

CONCLUSIONS

Fe–Al-coatings were developed, produced by detonation spraying, in which mechanical mixtures of iron powders with aluminium Al5Mg alloy and TiAl intermetallic were used as materials for spraying, as well as powders of the same compositions, produced by mechanochemical synthesis.

It was found that under the conditions of detonation spraying, when using mechanical mixtures of powders, it is impossible to provide an active interfacial interaction between the components and the formation of intermetallic phases in a coating does not occur. In the case of using MChS powders, coatings based on FeAl intermetallic with a dense lamellar structure are formed, consisting of layers of metal and alternating oxide components.

The results of studies of the oxidation resistance of detonation coatings of the Fe–A1Mg and Fe–TiAl systems indicate their high resistance to high-temperature oxidation in the temperature range of 700–800 °C. The use of Ti-alloyed powders for spraying allows increasing the oxidation resistance of carbon steel at 700 °C by 6 times, and at 800 °C by 18 times; in the case of Mg-alloyed powders, the oxidation resistance of carbon steel increases by 10 times at 700 °C and 20 times at 800 °C.

It was found that the application of Fe–AlMg and Fe–TiAl detonation coatings allows improving the corrosion resistance of carbon steel in a 3 % NaCl solution by 13.3 and 28.0 times, respectively.

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CONFLICT OF INTEREST

The Authors declare no conflict of interest

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