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The effect of bond coat composition on oxidation behavior of basalt base glass and glass–ceramics

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A B S T R A C T

In the current study, the effect of bond coat composition and single versus double layers on the interfacial properties of basalt glass-based coatings were investigated. Two bond coats, Ni-5 wt.% Al (METCO 450 NS) and Ni – Cr-6 wt.% Al (Metco 443 NS) were atmospheric plasma sprayed (APS) onto a commercial AISI 1040 steel substrate. These bond coating powders were used to observe the effect of a bond layer and multiple bond layers on certain mechanical properties, bonding strength and oxidation behaviour. Basalt was melted in a platinum crucible at 1500 °C for 1 h and cast into water. Basalt glass granules were ground and employed as a coating powder. After the APS process, amorphous coating layers were transformed to crystalline glass–ceramic with a heat treatment process. X-ray diffraction analysis (XRD) was used for glass–ceramic transformation and phase analysis. Scanning electron microscopy (SEM) examinations revealed that there is a uniform coating layer at the macroscopic scale. Cohesive bonding is dominant for both single and double bond-layered samples. It has been observed that the percentage of cohesive strength was approximately three to five times higher than that of the adhesion strength.

1. Introduction

Basalts are dark-coloured, fine-grained igneous rock. Basalt is the most common type of extrusive igneous rock and the most common rock type at the Earth's surface. Most basalts are volcanic in origin and were formed by the rapid cooling and hardening of lava flows [1]. Basalt can vitrify by means of melting and sudden cooling.

Thermal spraying is an effective and flexible method for producing thick coatings (from microns to millimetres) and has been used extensively in the following industries: aerospace, pulp and paper, machinery manufacturing, petroleum and petrochemical industry, biomedical applications, etc. [2]. The thermal coating processes are flame spray, arc spray, detonation-gun, high velocity Oxy-fuel (HVOF), and plasma spray. The plasma spray process can be carried out in different ways, such as under vacuum, with an inert gas, and at atmospheric pressure. Atmospheric plasma spraying (APS) is an economical and effective method that can be used with various machine parts to reduce surface degradation. In APS, a plasma–gas mixture, which is generally a mixture of argon and hydrogen, is injected inside an anode. A high-intensity direct current arc is produced between the tip of a cathode and the cylindrical anode. Plasma-sprayed ceramic coatings have been widely used for many applications to improve resistances to wear, corrosion, oxidation, erosion, and heat [3,4].

The structures and properties of plasma spray coating layers are determined by specific processing parameters such as gas flows, torch power, and nozzle shape that determine spray particle conditions such as the particle size, temperature, and velocity before impact [5]. One of these parameters is the bond coating powder species. There are many bond coating powders available for different thermal coating applications. The most widely used thermal barrier application bond coating alloys are made up of Ni, Cr, and Al elements (composition in different weight percent) [6]. A traditional bond coating alloy composed of Ni–5 wt.% Al has been used for decades due to its superior adhesion [5]. Bond coat layers are very significant in terms of the thermal compatibility between the substrate and the top coating layer. Bond coats are important not only for thermal compatibility but also the mechanical and chemical properties. In these types of coatings, presence of bond layer between ceramic and metallic character is necessary to provide better adsorption of coating particles on the substrates. If not good adherence, the coatings can be damaged by mechanical effects and peeling off the surface without any effects. Thermal spray bond coat powders include Al, Ni and Cr metals, commonly. Al is in basalt composition as oxide form. Ni has excellent wetting properties even for joining or repairing cracks and good thermal properties. In addition, Ni and Cr elements have some positive effects on the oxidation. Because of this, the selection of the bond coating powder determines some of the behaviours of coatings, such as the oxidation resistance and permeability.

Basalt base glass–ceramics are employed in solid waste and aggregates disposal lines, it is called cast basalt, commercially. This name has originated from their production method. Basaltic rocks are melted after the crushing and milling processes, melted basalt can be shaped as cylindrical, easily. For using as a pipework lining, the cast basalt is cast into cylinders. Cast basalt pipe lines can be used as the pipes produced

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from basalt, fully and it can be used as the interior surfaces of the fiberglass, stainless steel pipes. Basalt has a high wear resistance and a high hardness for these applications. Utilization of the basalt as a thermal spray coating material thanks to these superior properties were studied.

In the present study, two different bond coating alloys were employed, and the interfacial characteristics were observed. The effects of bond coating alloys on the oxidation resistance and bond strength were investigated.

2. Experimental procedure

In the current study, an AISI 1040 steel substrate was sectioned to the dimensions of 20 mm in diameter and 10 mm in height, and then the substrates were exposed to ultrasonic cleaning with acetone and ethyl alcohol. These samples were sand-blasted with 35-grit alumina. The grid blasting machine is manual grit blasting equipment of Cetingil made with 8 mm WC nozzle. The surface of substrates was grit blasted by Al_2O_3 under 0.2 MPa pressure, an angle of 45°, a spray distance of 60 mm. Ultrasonic cleaning was carried out the substrade, again. The resulting average roughness of the substrate surface (Ra) after grid blasting that measured Perthometer M4P surface roughness tester is between 3.3 and 4.5 μm. To provide thermal compatibility between the top coating layer and the substrate, two different bond coating powders were applied. The first bond coating powder is the Ni-5 wt.% Al (METCO 450 NS), and the second powder is Ni-18.5 wt.% Cr-6 wt.% Al (METCO 443 NS). All samples were coated with the first bond coating powder (METCO 450 NS), and then some samples coated with METCO 450 NS were exposed to second bond coating powder (METCO 443 NS). Thus, two group coatings were produced as single and double bond layered coatings. The coating process is manual type, the substrates were not subjected to pre-heating process. After the each passes, the thickness was measured and the process was continued until required thickness was obtained. The substrate was heated with the plasma torch for 10 s to approximately 150–200 °C, the substrate temperature can be reached up to 350–400 °C during the plasma spray cotaing process in the present study. Therefore, the effect of the bond coat layer on the interfacial characteristics was investigated.

Basalt rocks obtained from the Konya region of middle Anatolia were employed for this study. The basalt powders used in the coating process were analysed using a Perkin–Elmer 2300 atomic absorption spectrometer. The chemical compositions of the basalt and the plasma coating parameters are given in Tables 1 and 2, respectively. The same coating parameters were used both for the bond coat(s) and the top coat. The basaltic rocks were crushed by using a ring miller and then sieved to create powder sizes of −100 and +53 μm. The basalt powders were melted in a platinum crucible by using a Heraeus furnace at 1500 °C. The melted basalt was cast into water. Using this process, amorphous granules were obtained. These granules were crushed and sieved to create powder sizes of −53 and +45 μm. These powders were applied both single and double bond layered coatings by using the atmospheric plasma spray process. After the plasma spray process, the coatings were amorphous due to the plasma effect of the coating process. As you know, thermal spray coating processes can reach to high temperature due to the working principle. The particles fed into the plasma gun are exposed to very high temperature and then suddenly cooling occurs after the adhesion to the substrate. This broad thermal cycle causes the formation of glass for the coating materials which can be vitrified after the coating process. Because these coatings were glass structures, a controlled heat treatment was performed to transform the glass–ceramic. Differential thermal analysis (DTA) was used to detect the glass transition and crystallisation temperature of the coatings. It is noted that the heating rate in DTA was 10 °C/min, and the heating rate in the controlled crystallisation experiments was 5 °C/min. The controlled crystallisation treatment was performed in an argon atmosphere by using a Protherm tube furnace. The coatings were crystallised at 950 °C for 1 h by using the DTA results. The sample code system shown in Table 3 was produced for characterisation tests. Four group coatings were obtained as single and double bond layered, glass and glass–ceramic coatings.

The obtained coatings were exposed to X-ray diffraction analysis (XRD) and scanning electron microscopy (SEM) studies. XRD analysis was employed to determine the glass–ceramic transformation and the crystalline phases. X-ray diffraction analysis was conducted by using a Rigaku D-max 2200-type diffractometer with Cu–K_α radiation, which has a wavelength of 1.54056 Å to analyse the phases present in the coatings over a 2θ range of 0–90°. SEM was performed by a JEOL-6060 to observe the microstructure of the coatings and the oxidation test results.

Microhardness and fracture toughness values from indentation technique tests were obtained with a Future Tech FM-700 micro hardness indenter. The indentation tests were carried out on polished cross-sectional coatings with loads of 10 gf and 100 gf for the hardness and fracture toughness measurements, respectively. The microhardness was calculated from the diagonal length of the indentation optically determined for each indentation, using the following Eq. (1) [7]:

$$HV = 1.8544\left(P/a^2\right) \tag{1}$$

where Hv is the Vickers hardness, P is the applied load (kg), and a is the average of the diagonal half lengths (mm). The fracture toughness was calculated using the Evans–Charles equation [8]:

$$K_{IC} = 0.0824\left(P/c^{3/2}\right) \tag{2}$$

where K_{IC} is the fracture toughness, P is the load, and C is half of the crack length.

According to ASTM C-633 standards, bonding strength tests at a velocity of 0.5 mm/min were conducted to understand the effect of the bond coating powder on adhesion and cohesion by using the DARTEC tensile test machine. The coated samples machined into cylinders with dimensions of Ø 20 × 10 mm were used for this test. Before tensile tests, the top surfaces were glued to a steel rod having dimensions of Ø 20 × 50 mm using epoxy at the temperature of 100–120 °C for 3 h. The surfaces of steel rods were grit blasted by Al_2O_3 to provide better adhesion in the same parameter that performed for the substrates before

Table 1
Chemical compositions of basalt.

Oxides	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	P_2O_5	L.O.I
wt.%	45.88	18.2	9.95	9.28	6.62	1.64	4.76	1.04	2.63

Table 2
Plasma spray coating parameters.

Coating parameter	Value
Plasma gun (MB)	3
Current (A)	500
Voltage (V)	64–70
Gas flow for Ar (l/min)	50
Gas flow for H (l/min)	15
Spray distance (mm)	130
Powder feed rate (g/min)	39
Carrier gas flow (l/min)	3–6

Table 3
Sample code table.

Sample description	Code
Glass coatings with single bond layer	G_1
Glass coatings with double bond layer	G_2
Glass–ceramic coatings with single bond layer	GC_1
Glass–ceramic coatings with double bond layer	GC_2