A Study of Ceramic-Lined Composite Steel Pipes Prepared by SHS Centrifugal-Thermite Process

Yuxin Li*, Letao Jiang, Qing Lu, Peikang Bai, Bin Liu, Jianhong Wang
College of Material Science and Engineering, North University of China, Taiyuan 030051, China

Abstract: $\text{Al}_2\text{O}_3$ ceramic-lined steel pipe was produced by self-propagating high-temperature synthesis centrifugal thermite process (SHS C-T process) from $\text{Fe}_2\text{O}_3$ and $\text{Al}$ as the raw materials. The composition, phase separation and microstructures were investigated. The result showed the ceramic lined pipe is composed of the three main layers of various compositions, which were subsequently determined to be Fe layer, the transition layer and the ceramic layer. Fe layer is composed of austenite and ferrite, the transition layer consisted of $\text{Al}_2\text{O}_3$ ceramic and Fe, the ceramic layer consisted of the dendritic-shaped $\text{Al}_2\text{O}_3$ and the spinel-shaped structured $\text{FeAl}_2\text{O}_4$.

Keywords: SHS Centrifugal thermite process; Composites; Ceramic-lined pipes; Microstructure

1. Introduction

Self-propagating high-temperature synthesis (SHS) is a new technique for material synthesis. Synthetic materials using SHS have characteristics of low energy consumption, short synthetic time, high production quantity, high product purity and no environmental pollution [1]. SHS when combined with centrifugal technique can be used to produce ceramic-lined composite pipes. It overcomes shortcomings of some traditional processes [2-4], such as low thickness (<1 mm) of the ceramic layer, poor interface bonding, and high cost. In recent years, many investigations have examined the use of SHS C-T reactions to coat steel pipes with ceramic layers [5-8]. Products of these processes have been utilized widely as conduits for cement, oil, and coal slurry.

SHS C-T ceramic-lined pipes [7-11] were based on the $\text{Fe}_2\text{O}_3$+$\text{Al}$ thermite reaction system. The combustion temperature of the C-T reaction under adiabatic conditions can reach up to 3622 K, which is higher than the boiling point of Al (2740.15 K) and melting point of $\text{Fe}_2\text{O}_3$ (1650 K). The combustion products comprise, at least, one heavy Fe phase(7.86g/cm$^3$) and a light $\text{Al}_2\text{O}_3$ ceramic phase (3.98g/cm$^3$)[12]. According to literature, the density of the ceramic layer is about 2.9 g/cm$^3$ [13]. Generally, the ceramic layer is joined to the base steel by an intermetallic Fe-rich layer. The iron-rich layer and $\text{Al}_2\text{O}_3$ ceramic layers are mechanically interlocked by a mosaic structure [13-15]. Its structure is one of the key features of composite pipes produced by the SHS C-T method. The difficulty in obtaining a metallurgical joint between the metallic and ceramic layers is the result of mismatch in their chemical and physical properties, including different chemical bonding and coefficients of

* Corresponding author: liyuxin326@hotmail.com
In addition to the mentioned problems, cracks in a ceramic-lined pipe can cause severe performance deterioration and greatly reduce fracture toughness, heat-shock resistance and corrosion resistance. The disadvantages in ceramics-lined pipes fabricated by SHS C-T process have limited their application and motivated further studies on the microstructure in ceramic lined pipes.

In the present studies, the ceramic lined pipes were prepared by the centrifugal thermite process. The microstructure, composition, and elemental analysis of the base metal, the transition layer and the ceramic layer were investigated.

2. Experimental procedures

For the present experiments, a mixture of thermite material was prepared by stoichiometrically mixing aluminum powder (99.9% purity, 38 μm) and ferric oxide powder (99.0% purity, 16μm). A carbon steel pipe was used. The pipes had an inner diameter of 75 mm and a wall thickness of 7 mm, and were 150 mm long. Rust and oil films were removed by acid and alkali cleaning solutions, respectively. The preparation of ceramic lined pipes by the centrifugal thermite process is based on the following thermite reaction:

$$\text{Fe}_2\text{O}_3 + 2\text{Al} = \text{Al}_2\text{O}_3 + 2\text{Fe} \quad \Delta H = 836 \text{ KJ/mol} \quad (1)$$

The Fe$_2$O$_3$ powder and the Al powder are evenly mixed and placed on the steel pipe. The steel pipe is then fixed on the centrifuge. When the steel pipe rotates around an axis, the powdery thermite mixture is pressed against the inward surface of the pipe by the centrifugal force, and a layer is formed. The thermite reactant is ignited and the reaction as described in Eq. (1) takes place. This reaction emits an enormous amount of heat, and the temperature of the system immediately increases to 3622 K. The inner surface of the pipe melts and forms a composite with the reactants by inducing the thermite reaction in the centrifuged pipe, as shown in Fig. 1. The pipe was kept rotating at a high speed until product solidification was completed. The cooled ceramic-lined steel pipe was cut into pieces that were 20mm wide and 8mm high. The microstructures of the transition layer, the ceramic layer, and the interfaces between the layers were observed by scanning electron microscopy (SEM) (Model JSM-5310, Japan) equipped with energy-dispersive spectrometer (EDS) (Model Link-ISIS, Britain) and phases identification was carried out by X-ray diffraction (XRD) (Model D/Max 2500PC Rigaku, Japan), using Cu K$_\alpha$ radiation.

Fig. 1. General scheme of the ceramic-lined steel pipe before and after reaction.
3. Results and Discussion

Fig. 2 shows a typical multilayer cross section of the product. It can be seen from Fig. 2(a) that the ceramic lined pipe is composed of the three main layers of various compositions, which were subsequently determined to be Fe layer, the transition layer and the ceramic layer. The EDS results show separated layers of various compositions in the cross section. Fig. 2(b) shows the microstructure of Fe layer. It can be seen that this layer seems to be highly dense and has very low porosity. Based on the EDS result, the layer is Fe rich. It is composed of two phases: the matrix is austenite and the remainder is ferrite.

Fig. 2. The typical microstructure of multilayer cross section of the product: (a) the overall cross section; (b) Fe layer (zone 1); (c) the transition layer (zone 2); (d) the ceramic layer (zone 3); (e) the ceramic layer (zone 4).
Fig. 2(c) shows the microstructure of the transition layer. It can be seen that a remelt phenomenon and cracking appear. It may be reason as follows: in the transition layer, the partition of the ceramic and metal is not completed, the ceramic (Al$_2$O$_3$) would remain in Fe as brittle inclusions, which would decrease plasticity of the steel and cause stress concentration and brittle fracture. Fig. 2(d) shows the microstructure of the ceramic layer. The micrographs taken in the mode of back scattered electron diffraction reveal black colored phases of Al$_2$O$_3$ and lighter-colored phases of FeAl$_2$O$_4$. The black dendritic-shaped Al$_2$O$_3$ is surrounded by spinel-shaped structured FeAl$_2$O$_4$. It can be seen that the dendritic-shaped Al$_2$O$_3$ is distributed in the ceramic layer with large dark pores. Because the melting temperature of Al$_2$O$_3$ (2054 °C) is higher than FeAl$_2$O$_4$ (1780 °C), alumina seems to nucleate and grow first. Then FeAl$_2$O$_4$ get solidified and crystallized on the already formed Al$_2$O$_3$ grains [17]. Fig. 2(e) shows the microstructure of zone 4 of the ceramic layer. It can be seen that the dendritic-shaped Al$_2$O$_3$ is identified as the dominant phase. The reason of the formation of dendritic structured Al$_2$O$_3$ is that the quick heat release through the pipe outer surface in the SHS-centrifugal thermite process leads to the temperature gradient through the melt layer, resulting to the formation of dendritic structured grains.

Fig. 3 shows elemental line scanning along with SEM micrographs for the ceramic layers. It can be seen from Fig. 3 that the distribution of the elements is not completely uniform, in addition to a large amount of Al and O elements, Fe elements are found in the ceramic layers (see Fig. 3 (d)). We do not know why Fe elements appear in the ceramic layers. It may be attributed to the fluctuation of the centrifugal force. That will be our task in our further study.

Fig. 4 shows microstructures and elemental distribution maps of a typical multilayer cross section of the overall ceramic lined pipes. It can be seen that highly concentrated aluminum and oxygen clearly appear and evenly distribute all over the surface of the ceramic layer, in addition, iron element appears in the surface of the ceramic layer (see Fig.4(c) and Fig. 4(d)). This result is consistent with the Fig.3. Iron element mainly distributes the surface of the steel layer and the transition layer (see Fig. 4(b)).
4. Conclusions

In this study, $\text{Al}_2\text{O}_3$ ceramic-lined steel pipe was produced by the thermite process under a centrifugal force. The microstructure, composition, and elemental analysis revealed phase formation of $\text{Al}_2\text{O}_3$, $\text{FeAl}_2\text{O}_4$ and $\text{Fe}$ inside the carbon steel pipe, whereas the product’s element concentrations and microstructures varied in different layers. Especially, in addition to a large amount of Al and O elements, Fe elements are found in the ceramic layers.

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5. References


**Садржај:** Челичне цеви обложене $\text{Al}_2\text{O}_3$ керамиком су израђене високо температурским термалним процесом из $\text{Fe}_2\text{O}_3$ и $\text{Al}$. Испитиване су фазни састав и микроструктура. Резултати су показали да се керамичка цева састоји из три главна слоја различитог састава, слој $\text{Fe}$, преносни и керамички слој. Слој $\text{Fe}$ је састављен из ферита и аустенита, преносни слој из $\text{Al}_2\text{O}_3$ и Fe, керамички слој је сачињен из $\text{Al}_2\text{O}_3$ dendritnог облика и $\text{FeAl}_2\text{O}_4$ спинела.

**Кључне речи:** високо температурски термални процес; композити; челичне цеви обложене керамиком; микроструктура