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The characteristics of combustion in a centrifugal-thermite process

LIU MU, SHENG YIN, WEI YANPING, LAI HEYI
Department of Powder Metallurgy, University of Science and Technology Beijing, Beijing 100083, People's Republic of China

Combustion velocities and the combustion temperature of thermite have been measured in a centrifugal-thermite process. On the basis of these experimental data, the characteristics of combustion in a centrifugal-thermite process are discussed.

1. Introduction

A centrifugal-thermite process was developed to produce ceramic-lined composite pipes with high resistance to corrosion, abrasion, and thermal shock. Merzhanov and Yukhvid [1] initiated the fundamental research on the process in 1975. The principle of the centrifugal-thermite process is shown in Fig. 1. A hollow body of thermite in a steel pipe is formed by centrifugal force. During the exothermic thermite reaction, the combustion temperature increases to above 2453 K [2], and the molten Al_2O_3 product and the iron product are separated into stratified layers. The Al_2O_3 ceramic layer is formed on the inner surface, and the iron layer is located in a region between the outer steel pipe and the ceramic layer. Odawara and Ikeuchi [2] investigated the characteristics of combustion in a centrifugal-thermite process and produced ceramic-lined composite pipes of length 6000 mm. He concluded that in a hollow body of thermite formed by centrifugal force, combustion propagated along the inner surface of the hollow body first, and subsequently into the reactant, causing the thermite reaction to take place about the same time in the direction of the pipe length. The boiling points of aluminium and Fe_2O_3 are less than the combustion temperature, so the thermite reaction would mainly proceed in a reaction of gas phases, resulting in the combustion propagating along the inner surface first [2]. This combustion propagation mechanism is beneficial to the formation of uniform ceramic layers in the direction of the pipe length

In previous work, densification, stress and the cause of cracking of ceramic layers of ceramic-lined composite pipes, were reported [3–5]. Here, the characteristics of combustion in a centrifugal-thermite process are discussed.

2. Experimental procedure

A roller-type centrifugal machine was used to produce ceramic-lined composite pipes longer than 3 m. Carbon steel pipes with a 108 mm outer diameter, a 98 mm inner diameter, and length 3000 mm were used. -100 mesh Fe_2O_3 powder, $-100+200$ mesh aluminium powder, -200 mesh aluminium powder, and -100 mesh SiO_2 powder were used. Fe_2O_3 and aluminium were mixed stoichiometrically for the reaction $Fe_2O_3 + 2Al = Al_2O_3 + 2Fe$.

A steel pipe filled with thermite was placed in the centrifugal machine. In a centrifugal force of 105 $\boldsymbol{g}$ ($\boldsymbol{g}$ is the acceleration due to gravity), the thermite was ignited with a tungsten filament at its end. Temperature was measured using an optical fibre infrared thermometer. Combustion velocities in the direction of the pipe length were obtained by means of temperature measurements along the pipe length.

3. Results and discussion

Combustion velocities of thermite compacts and combustion velocities in the direction of the pipe length are shown in Table I and Table II.

A hollow body was formed by centrifugal force in the thermite inside the steel pipes (see Fig. 1). In Tables I and II we can see that the combustion velocities of the thermite with aluminium powder less than 200 mesh were $1500\ mm\,s^{-1}$ in the direction of the pipe length and independent of SiO_2 content. This is 18–75 times larger than without -200 mesh aluminium powder. It is concluded that -200 mesh aluminium powder causes the combustion velocities of the thermite to increase dramatically first in the direction of the pipe length.

In this experiment, the combustion temperatures exceeded the boiling points of aluminium and Fe_2O_3 in each case. It is difficult to explain the significant differences of the combustion velocities with the gas reaction mechanism suggested by Odawara and Ikeuchi [2]. Dust clouds of aluminium powder can ignite and explode in the atmosphere. The effect of aluminium particle size on the explosiveness is shown in Fig. 2 [6]. The lower explosive limit (LET) is the minimum dust concentration that will permit ignition, and thus an explosion. Dust clouds of aluminium powder without -200 mesh aluminium powder cannot ignite and explode. The explosibility of dust clouds of aluminium powder increases with increase in the percentage of −200 mesh aluminium powder.

After ignition, the thermite reaction produces a large amount of gas because of the high combustion temperature. This gas agitates the thermite, thus producing aluminium dust clouds with a sufficiently high concentration to explode. Meanwhile, these dust clouds contain Fe_2O_3 powder, which assists the explosion of the aluminium dust clouds because it provides oxygen. The dust cloud explosion again suspends the thermite particles in the hollow body of the thermite and causes "second", "third", ... , explosions, so the heat from the dust cloud explosions is enough to ignite the whole inner surface of the hollow body.

Explosive combustion through dust clouds of aluminium powder propagates very quickly. The combustion through the aluminium dust clouds is similar to the combustion of premixed gases [7]. Premixed gas combustion in a hollow body propagates first in the laminar condition, then in the turbulent condition. In the laminar condition, the combustion velocity is slow and constant. However, in the turbulent condition, the combustion velocity increases dramatically. In a circular hollow body, the distance of combustion propagation in the laminar condition is two to ten times longer than the diameter [8]. Combustion velocities through dust clouds of aluminium powder are shown in Table III [7]. In this table, we can see that in the turbulent condition, the maximum velocity is close to that of sound and 300–400 times higher than that in the laminar condition. The data were measured in vertical glass tubes, 1 in. ($\sim$2.54 cm) diameter and 4 f ($\sim$1.22 m) long, closed at the bottom.

On the basis of the above facts, it is concluded that in the centrifugal-thermite processes, the aluminium dust clouds of powder less than −200 mesh explode in the hollow bodies of the thermite, igniting the entire surface of the hollow bodies almost instantaneously which caused the combustion of the thermite to propagate in the direction of the pipe length, along the inner surface first.

Fig. 3 shows temperature measurements of a steel pipe along the pipe length [2]. It is seen that the time delay of the abrupt increase in temperature was about 1 s from T_{c1} to T_{c2} (1400 mm length), but almost 0 s from T_{c2} to T_{c3} (also 1400 mm). Thus the combustion velocity increased dramatically causing the combustion propagation from T_{c2} to T_{c3} to be almost instantaneous. Odawara [2] did not explain the dramatic difference in the time delays of the abrupt increase of temperatures.

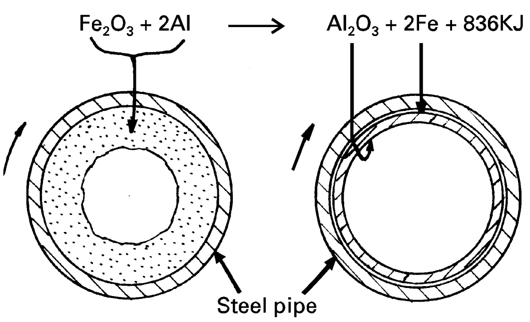

Figure 1 The principle of a centrifugal-thermite process.

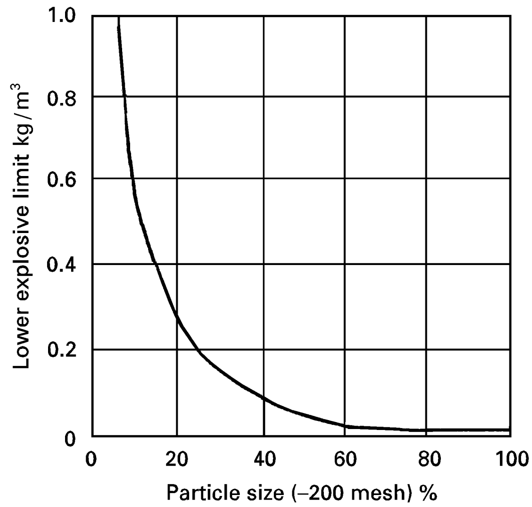

Figure 2 The effect of aluminium particle size on explosibility of dust clouds of aluminium powder.

TABLE I Combustion velocities of thermite with −100 + 200 mesh aluminium powder

SiO_2 contents in thermite (wt %)	Combustion velocities in the direction of pipe length ($mm\,s^{-1}$)	Combustion velocities of thermite compacts ($mm\,s^{-1}$)	Combustion temperatures of thermite compacts (°C)
0	80	10.5	> 3000
4	25	8.5	2900
7	20	7.5	2750

TABLE II Combustion velocities of thermite with aluminium powder. 90 wt % −100 + 200 mesh and 10 wt % − 200 mesh

SiO_2 contents in thermite (wt %)	Combustion velocities in the direction of pipe length ($mm\,s^{-1}$)	Combustion velocities of thermite compacts ($mm\,s^{-1}$)	Combustion temperatures of thermite compacts (°C)
0	1500	11	> 3000
4	1500	8.5	2850
7	1500	7.5	2750

TABLE III Velocities of aluminium dust cloud flame propagation

Particle size (μm)	Concentration ($kg\,m^{-3}$)	Velocities of combustion in the laminar condition ($m\,s^{-1}$)	Velocities of combustion in the turbulent condition ($m\,s^{-1}$)
0–40	0.2	0.45	220
80 wt % 0–6 20 wt % 6–40	0.14	1	295

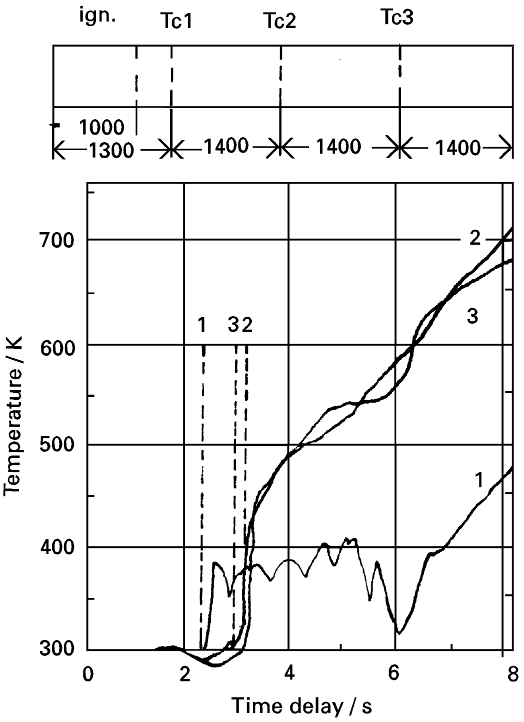

Figure 3 Temperature curves of a steel pipe in a centrifugal-thermite process.

Odawara and Ikeuchi's result [2] is consistent with that of Cassel *et al.* [7]. From T_{c1} to T_{c2}, the combustion through the aluminium dust clouds propagated in the laminar condition taking 1 s. From T_{c2} to T_{c3}, the combustion propagated in the turbulent condition, so the combustion velocity increased dramatically, which resulted in nearly no time elapse. This steel pipe was 318.5 mm diameter [2]. The distance from T_{c1} to T_{c2} was about five times as long as this, which is consistent with the law that the distance of combustion propagation in the laminar condition is two to ten times as long as the diameter in a circular hollow [8].

In a centrifugal-thermite process with thermite with no aluminium particles less than -200 mesh, combustion propagation would proceed mainly in the gas reaction, so the combustion velocities in the direction of the pipe length (see Table I), which were dependent on the content of SiO_2, were slower than that with -200 mesh aluminium particles. However, they were higher than that of thermite compacts because the hollow body is beneficial to the propagation of the gas phase. The combustion temperature and the amount of gas phase decreased with increasing of SiO_2 content, so the combustion velocities in the direction of the pipe length and the combustion velocities of the thermite compacts, decreased and tended to become close (see Table I).

4. Conclusions

1. In a centrifugal-thermite process with a sufficiently high percentage of -200 mesh aluminium particles, the combustion velocity of the thermite increases dramatically and is much higher than that of thermite without -200 mesh aluminium powder.
2. Explosive combustion through aluminium dust clouds in a hollow body of thermite ingnites the whole inner surface of the hollow body almost instantaneously, first causing combustion of the thermite propagate in the direction of the pipe length along the inner surface. This is the reason why the combustion velocity of the thermite with sufficient -200 mesh aluminium particles is much higher than that of thermite without -200 mesh aluminium powder.

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