Aerodynamic Study on Supersonic Flows in High-Velocity Oxy-Fuel Thermal Spray Process

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To clarify the characteristics of gas flow in high velocity oxy-fuel (HVOF) thermal spray gun, aerodynamic research is performed using a special gun. The gun has rectangular cross-sectional area and sidewalls of optical glass to visualize the internal flow. The gun consists of a supersonic nozzle with the design Mach number of 2.0 followed by a straight passage called barrel. Compressed dry air up to 0.78 MPa is used as a process gas instead of combustion gas which is used in a commercial HVOF gun. The high-speed gas flows with shock waves in the gun and jets are visualized by schlieren technique. Complicated internal and external flow-fields containing various types of shock wave as well as expansion wave are visualized.

Keywords: supersonic flow, internal flow, shock wave, thermal spray.

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Introduction

Thermal spraying is a technique for enhancing surface characteristics of a material, or extending its service life. In most thermal spraying processes, a high-temperature gas flow, which is subsonic speed, accelerates and heats coating particles to high velocities and temperatures. These particles strike on a surface of a substrate to form strong and dense coating. Such coatings serve as wear-resistant, corrosion-resistant or temperature- resistant barriers under various conditions in aggressive environments.

Among many types of thermal spraying technique, high-velocity oxy-fuel (HVOF) thermal spraying process, schematically shown in Fig.1, seems to be promising. The HVOF gun is an internal combustion device similar in nature to a rocket engine. The gun consists of a combustion chamber, a convergent-divergent nozzle followed by a straight passage called barrel. Oxygen gas and fuel such as hydrogen, propylene or kerosene combine inside the combustion chamber where the fuel is ignited. The combustion gas enters the convergent- divergent nozzle where it is accelerated to supersonic speed. Then, the gas exits the gun as a supersonic jet against the substrate. The coating particles are injected into the high-speed gas flow in the barrel, and then they are accelerated and heated by the gas flow inside the barrel and in the jet towards the target substrate. When the particles impact on the surface, they are flattened and, as they cool and solidify, they shrink into a tough coating with strong mechanical bond to the substrate.

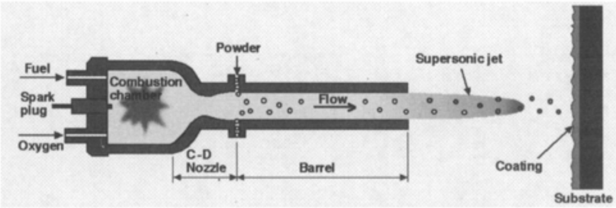

Fig.1 HVOF thermal spray gun in operation

The gas speed in the HVOF process is the highest in many types of thermal spraying techniques, resulting in highest particle velocity than those achieved in the conventional flame-spray process. The previous experimental

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work[1] shows that the higher speed of the coating particles seems to give higher quality of coatings. Although the HVOF process is widely used ranging from automotive brake discs and piston rings to gas turbine blades and nozzle guide vanes, the design of the gun has been primarily empirical, and the understanding of dynamics of gas-flow and particles is based on engineering intuition and analysis of coated layers produced by the process.

To advance the HVOF thermal spraying technology, detailed understanding of the process is needed. The understanding of gas dynamics in HVOF gun is one of the most important research areas because particles are accelerated and heated in the downstream direction after injected in the supersonic gas stream. It is well known that the final coating-quality strongly depends on particle velocities and temperatures at the moment when particles impinge on the substrate. From the view point of gas-dynamics, Hackett, et al.[2] visualized jet flows from an HVOF gun. The internal flow of the gun, however, has never been experimentally clarified yet. The understanding of the gas flow in the gun is also necessary to avoid a problem of spitting phenomenon[3] caused by fused particles flying in the gun.

In the present investigation, special attention is paid to visualize high-speed internal gas flows as well as jet flows of an HVOF gun. For that purpose a special HVOF gun with rectangular cross sectional area is manufactured and used. The gun has sidewalls of optical glass to visualize the internal flows. Although the commercially available HVOF gun uses combustion gas to accelerate and heat particles, compressed dry air instead of combustion gas is used in our experiment.

Experimental Equipment and Procedure

Modeled HVOF gun

A schematic diagram of the modeled HVOF gun used in this study is shown in Fig.2. The HVOF gun has rectangular cross-sectional area. The gun consists of a throat, supersonic nozzle and barrel. The 6.5 mm high throat is followed by a linearly diverging supersonic nozzle. Generally speaking, since precisely uniform flow is not of utmost interest in an HVOF nozzle, a simple linearly diverging supersonic nozzle was used for this study. The design Mach number of the supersonic nozzle is 2.0 based on one-dimensional isentropic theory. A barrel of 110 mm in length and 11 mm in height follows the supersonic nozzle. The width of the gun is constant of 11 mm from the inlet of the throat to the barrel exit. Two pairs of 10 mm-thick optical glass were used as optical windows as well as side-walls of the barrel to visualize the gas-flow in the barrel. The gun has powder injection ports of 1.5 mm inner diameter located at the center of the width, 13 mm downstream of the barrel inlet on both topside and bottom-side walls. Overview of the gun is shown in Fig.3. The HVOF gun was installed to a stagnation chamber that corresponds to a combustion chamber for the real HVOF gun. Compressed dry air was supplied to the stagnation chamber up to 0.78 MPa through an electrically controlled valve. In this study, the pressure in the stagnation chamber, p_{os}, was kept constant at a desired value ranging from 0.20 MPa to 0.78 MPa within accuracy of $\pm 3\%$. The substrate was placed at 77 mm downstream of the barrel exit.

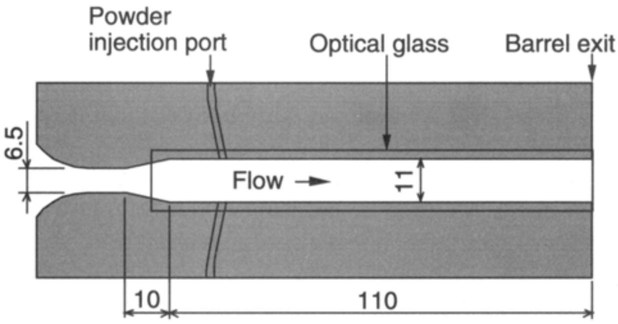


Fig.2 Diagram of modeled HVOF gun (unit: mm)

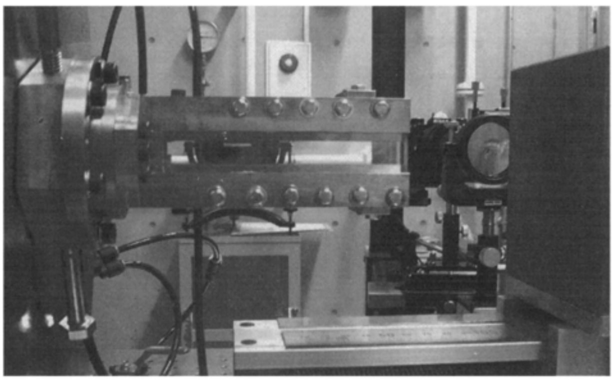


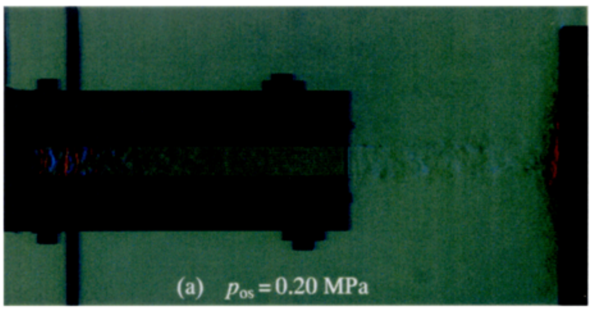
Fig.3 Experimental set up of modeled HVOF gun

Visualization technique

The high-speed air flows inside the HVOF gun and jet flows exiting from the barrel were optically visualized by color schlieren technique. All the schlieren pictures were taken by a digital camera (Nikon D2H) that had resolution of 2,464 × 1,632 pixels. The shutter speed of the camera was set 1/4 second. A xenon light with duration of 14 μs was used as a light source. A color filter was set at a focal point in front of the camera perpendicular to the flow direction to capture shock waves.

Results and discussions

Figure 4 shows typical schlieren pictures of air flow in the HVOF gun and jet flow taken by schlieren technique. The direction of the air flow is from left to right in the pictures. The carrier gas (air) is also injected in the supersonic flow of the gun except for Fig. 4 (a) through powder injection ports at a total pressure of 0.25 MPa. Figure 4 (a) is a picture taken at p_{os} = 0.20 MPa without carrier gas injection. In the figure there are three vertical shock waves in the upstream part of the barrel. This set of shock waves is called shock train [4] that often appears in a supersonic internal flow. The shock train in Fig. 4 (a) is generated by the interaction between a normal shock wave and turbulent boundary layer. The supersonic flow in the diverging nozzle is decelerated to subsonic speed through the shock train. Then, the subsonic flow discharges into the atmosphere from the barrel. Figure 4 (b) is a picture taken at p_{os} = 0.30 MPa. Oblique shock waves originate at the junctions of the diverging nozzle and the barrel. The shock train is pushed downstream close to the barrel exit because the chamber pressure p_{os} is increased compared to that of Fig. 4 (a). As a result, supersonic-flow region is extended to the downstream region in the barrel. The jet flow exiting the barrel seems to decelerate to subsonic speed after flowing two to three times the barrel height. A schlieren picture taken at p_{os} = 0.40 MPa is shown in Fig. 4 (c). In the figure, the flow is supersonic throughout the barrel. Since oblique shock waves are seen at the barrel exit, the flow condition of Fig. 4 (c) can be called over-expanded. The jet flow seems to impinge against the substrate at supersonic speed since clear contrast of color can be seen throughout the jet flow. A schlieren picture taken at p_{os} = 0.55 MPa is shown in Fig. 4 (d). Since no shock waves can be seen at the barrel exit and the jet boundary is parallel to the flow direction at the barrel exit, the static pressure at the barrel exit is considered to be almost equal to the ambient pressure. Therefore, the flow condition of Fig. 4 (d) is regarded as correct-expansion. If the gas flow is assumed to be isentropic in the gun, the correctly-



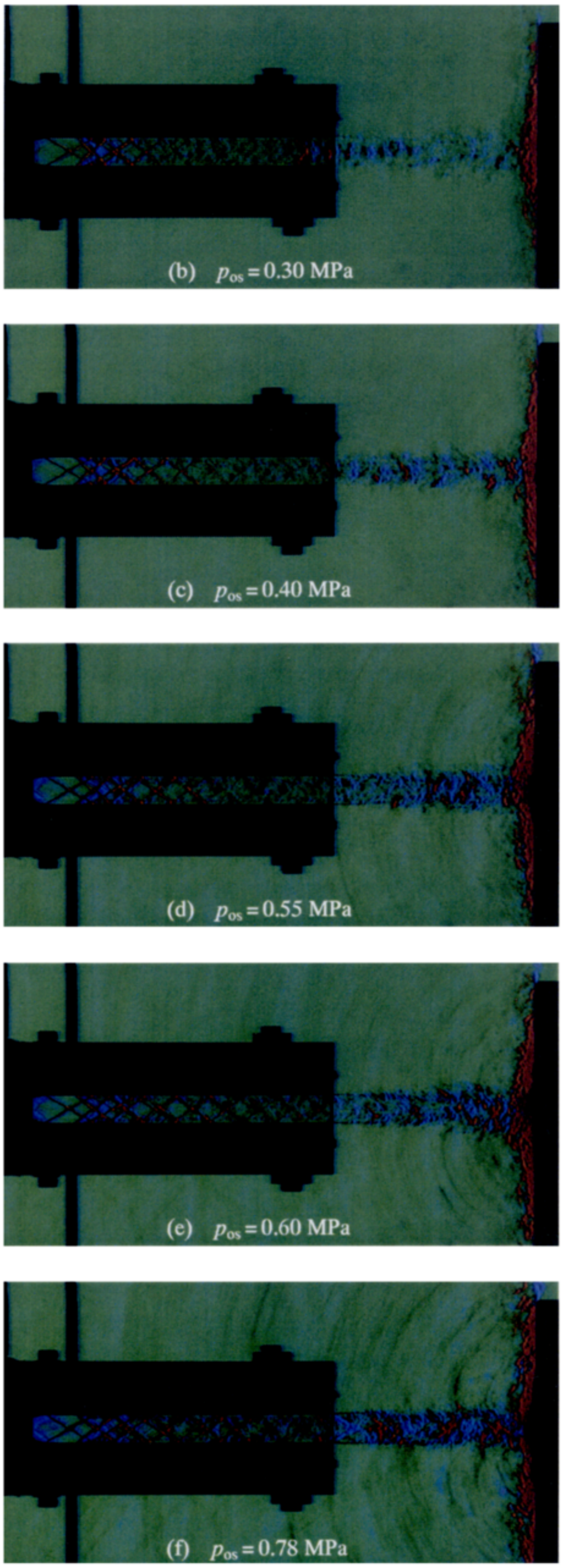


Fig. 4. Schlieren pictures of internal flows and jets

expanded jet is obtained at p_{os}=0.78 MPa for the present nozzle of the design Mach number of 2.0. However, due to the wall friction along the barrel wall, the gas flow is decelerated in the downstream direction. Then, the static pressure increases in the same direction to achieve correct-expansion in Fig.4(d). The figure shows that the internal flow of the present HVOF gun can not be regarded as isentropic flow but Fanno flow due to gas-dynamic friction along the barrel wall. A schlieren picture taken at p_{os} = 0.60 MPa is shown in Fig.4(e). In the figure, the internal flow of the gun does not change compared to Fig.4(d). Since weak expansion waves originate at the corners of the barrel exit, the jet flow is slightly under-expanded. A schlieren picture taken at p_{os} = 0.78 MPa is shown in Fig.4(f). The jet is expected to be correctly-expanded at p_{os} = 0.78 MPa if the flow is assumed to be isentropic. However, clear expansion waves originate at the corners of the barrel exit. That is, the extent of under-expansion of the jet is larger than that for Fig.4(e).

Conclusions

High-speed gas flows in the modeled HVOF gun with rectangular cross-sectional area were studied from the view point of aerodynamics. The gun had a supersonic nozzle with the design Mach number of 2.0 followed by a straight passage called barrel. Compressed dry air was used to generate supersonic flows through the gun. The stagnation pressure upstream of the nozzle p_{os} was set constant up to 0.78 MPa. The gas flows inside the gun as well as the jet flows were visualized by the schlieren technique. Results obtained in the present study are summarized as follows.

1. Shock train is generated in the HVOF gun for chamber pressure of 0.2～0.3 MPa.
2. Oblique shock waves repeat reflection toward the downstream direction in the barrel at chamber pressure greater than 0.3 MPa.
3. The gas flow in the HVOF gun becomes supersonic throughout the barrel at chamber pressure greater than 0.4 MPa.
4. Almost correctly-expanded jet is obtained at chamber pressure of 0.55 MPa which is smaller than the value obtained by the isentropic theory.

Acknowledgement

The schlieren pictures in this study were taken by the digital camera at the Instrumentation Center, The University of Kitakyushu.

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