A model is developed to describe dynamic interaction of particles with the carrier gas during detonation spraying. Equations of mass, energy, and momentum conservation are integrated numerically for the two-phase particle-gas flow with the Hugoniot boundary conditions at the detonation wave front. Velocity and temperature of the sprayed powder and the gas parameters are calculated self-consistently, taking into account effects of friction and cooling of the gas in the vicinity of the gun barrel and effects of particle-gas interaction on the parameters of the gas phase. Calculations are performed for tungsten carbide particles of 30 μm diam and a 1.8 m long detonation gun using a stoichiometric mixture of oxygen and propane. Distributions of gas and particle parameters along the barrel are calculated for various moments of time. Tungsten carbide particles of 30 μm reach an exit velocity of 1278 m/s and a temperature of 1950 K. Exit particle velocity is a nonmonotonic function of the loading distance, L, with a distinct maximum at L = 75 cm. The proposed model can be applied to a broad range of problems related to detonation coating technology and allows evaluation of the effectiveness of various designs and optimization of operational parameters of detonation spraying systems.

### 1. Introduction

Future progress of thermal spray technology and design of more advanced thermal spray equipment depends on understanding the fundamental principles of thermal spray processes and, in particular, knowledge about gas dynamics and thermodynamics of the two-phase gas-particle flow inside the spraying device. For example, use of a Laval nozzle (Ref 1), combination of subsonic and supersonic accelerating channels, and use of additional heating channels (Ref 2) allow improvements in the quality of the high-velocity oxygen fuel (HVOF) process and allow better control of the sprayed powder parameters. Knowledge about predetonation distances, critical cross sections for detonation wave propagation, and limits of detonability in various gas mixtures is essential for good design of gas detonation coating systems.

While many investigations have focused on studying the gas dynamics and modeling the HVOF thermal spray process (Ref 3-5), little research was directed to the study of the gas detonation coating process (Ref 6-8). Consequently, there is little understanding of the fundamental principles of detonation gun operation and the mechanisms of detonation coating formation. This paper presents a model that analyzes gas dynamics of the conventional detonation gun during the spraying process. The model allows the calculation of the thermodynamic parameters of the gas mixture and sprayed particles. Results are presented for a 1.8 m long detonation gun operating on oxygen-propane mixture and spraying tungsten carbide particles with the diameter of 30 μm.

This paper is organized as follows. Section 2 describes several designs of detonation coating systems and some parameters of their operation. Section 3 reviews known analytical solutions for the parameters of detonation products behind the detonation wave front. These solutions can be used for rough evaluation of detonation parameters and a fast estimate of the velocity and

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temperature of the sprayed particles. Section 4 formulates basic equations describing the dynamics of two phase flow inside the detonation gun. The described approach accounts for the effects of friction and cooling of the gas in the vicinity of a gun barrel and effects of particles on the parameters of detonation products. Section 5 describes the boundary conditions and the numerical procedure that was used to solve gas dynamics equations. Section 6 presents calculation results. Better understanding of fundamental principles of the complex gas detonation coating process will allow optimization of gas detonation coating technology and expand its application.

2. Background

2.1 Principles and Operational Parameters of Detonation Spraying Systems

Whereas most of the thermal spray techniques use continuous sources of energy to accelerate sprayed powder, the gas detonation coating process is intermittent by nature. The typical detonation coating gun (Fig. 1) consists of (1) the accelerating channel of rectangular or round cross section, which is closed at one end, combined with the systems of (3) powder and (2) gas supply, and (4) the ignition system, which periodically generates the ignition spark inside the channel. Particular designs of gas and powder supply systems as well as the gun barrel geometry vary and are discussed here. The operating cycle of the detonation gun includes the following stages (Ref 9). The channel is filled with a fuel mixture at atmospheric pressure and room temperature, and the powder is injected into the accelerating channel. The mixture is then ignited by a spark plug. This produces a wave of deflagration (combustion) that propagates along the channel. If the detonation conditions are satisfied (limits of detonation in gas composition, pressure, temperature), the deflagration wave transforms into a detonation wave after passing a distance called the predetonation distance, L. The detonation wave is characterized by the very stable thermodynamic parameters and represents a shock wave, which initiates a chemical reaction in the gas mixture by the action of great pressure and temperature in the wave front. The detonation wave and hot detonation products accelerate and heat the powder particles, which form (6) a hard coating upon collision with (5) the substrate. Then, the barrel is purged with inert gas (this stage can be eliminated in some designs) and filled with a fuel gas, and the process repeats with the frequency of 1 to 15 Hz. The extreme parameters of the detonation wave (supersonic speed, strong gas compression) typically produce excellent quality coatings (Ref 7, 10) of metals, carbides, oxides, or compounds.

Two unique features separate the gas detonation coating process from other coating technologies. First of them is an extremely low amount of heat transfer to the gun barrel and to the sprayed substrate. The detonation process occurs on a very short time scale and is "almost adiabatic." The velocity of the detonation wave depends on the type of fuel gas used and on the volume fraction of the fuel gas in the combustible mixture. It ranges from 1090 m/s in the reaction of carbon monoxide and oxygen, 2CO + O₂, to 3525 m/s in the detonation of hydrogen, H₂ + 0.5O₂ + 2.5H₂. For such velocities, it takes the detonation products and the powder particles an average of 0.5 to 4.0 ms to exit the barrel. This point is illustrated in Fig. 2, which shows exit of detonation products from the detonation gun barrel. The time interval between the photographs is 50 μs. During this short time, the amount of heat transferred to the sample and the gun barrel is very low. Typically the substrate temperature stays below 150 °C, and with additional cooling, it can be brought down to room temperature. This fact makes the detonation process very suitable for spraying low-melting point materials and precision parts without the risk of causing chemical transformations and deformations in them. It makes it possible to spray powders that may evaporate at high temperatures, for example boron carbide. The intermittent nature of the process also allows simplification of the gun cooling system or even complete elimination of it.

A second feature of the process is the simplicity of operation and reliability. High-pressure gas and cooling water supply systems are not needed. Typical gas pressures are 1 atm, and the cooling water flow rate is 0.1 to 0.2 gal/min, which is much lower than for a typical HVOF spraying system. Consumption of electrical power is minimized to 100 W (Ref 11). These features make the process very economical in industrial conditions. Good designs of gas detonation systems should provide the conditions necessary for stable existence of the detonation wave and for maximum utilization of energetic potential of the particular gaseous mixture used. Geometry of the gun barrel and design of the powder supply system, which influences reliability and efficiency of the detonation system, can greatly affect the overall quality of the system.

Selection of geometrical parameters of the system is closely related to the properties of the combustible mixture. Numerous gases have the detonation effect in reaction with oxygen at normal conditions. Among them are hydrogen H₂, carbon monoxide CO, methane CH₄, acetylene C₂H₂, propane C₃H₈, pentane C₅H₁₂, benzene C₆H₆, carbon disulfide CS₂, dicyan C₂N₂, and others. In principle, they all can be used for detonation spraying, and they produce reactions at different temperatures and detonation speeds. For example, reaction temperature in the reaction H₂ + 0.5O₂ in the presence of nitrogen is 2596 K whereas in the reaction of dicyan C₂N₂ + O₂, the temperature is 5960 K (Ref 12). Among the commonly used detonation spraying fuel gases is acetylene, which produces high velocity (3091 m/s) detonation wave, high temperature of the reaction (5570 K), and large compression ratio (55.4) (Ref 12). Acetylene has a very short predetonation distance of a few centimeters and can be detonated easily. Other commonly used fuel gases are propane, butane, methane, propylene, and their mixtures. These natural gases are safer in use and cheaper. However, they have longer...