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The Influence of Nozzle Design on HVOF Exit Gas Velocity and Coating Microstructure

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A simple device was constructed for determining a value for the average combustion gas velocity at the exit plane of a high-velocity oxyfuel gun. This device was used to measure the velocities of a standard factory-made barrel nozzle and a specially designed de Laval nozzle as a function of the fuel/oxygen ratio and the total mass flow rate. The Mach number of the de Laval nozzle was 1.42. The maximum combustion gas exit velocities determined for the standard and the de Laval nozzles were 1100 and 1550 m/s, respectively. The maximum velocity depends on the fuel/oxygen ratio but is independent of the total flow rate. The effect of increased combustion gas velocity on coating quality is demonstrated.

Keywords coating microstructure, gas velocity, HVOF, HVOF nozzle design, thermal spray

1. Introduction

The high-velocity oxyfuel (HVOF) method is increasingly used in the manufacture of metallic, carbide, and even ceramic coatings, because it provides unambiguous advantages. High-velocity oxyfuel thermal spraying takes place at a lower temperature (about 3000 K) than plasma spraying (which typically takes place at temperatures up to 13,000 K). This is a great advantage, especially when spraying compounds that can decompose at high temperatures. For example, tungsten carbide decomposes at high temperatures according to the reaction $WC \rightarrow W_2C + C$, with a resulting and well-documented degradation of functional properties. However, the partial pressure of oxygen in a tail flame can be quite high, resulting in the rapid oxidation of materials that have a strong affinity for oxygen (Ref 1).

High particle velocities are another, even more frequently emphasized benefit of HVOF spraying. This spraying method uses kinetic rather than thermal energy. The high-impact energy results in spray powder coatings that are both denser and less porous, and which exhibit enhanced adhesive properties with no significant chemical changes in the powder composition.

The cause of high particle velocities is always the momentum flux, ρv^2, of the combustion gas, where ρ is the density of the combustion gas and v is the gas velocity. High exit gas velocities result for several reasons. According to the theory of compressible fluid flow, provided that it is higher than the local velocity of sound ($M > 1$), gas velocity is a function of the temperature and pressure in the combustion chamber, average molecular weight, and nozzle geometry. At velocities exceeding the velocity of sound, the ratio of the pressure in the chamber to the pressure of the surrounding atmosphere is an important parameter. In a supersonic regime, however, velocity is not dependent on the total mass flow.

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It is clear that the fuel/oxygen ratio and the quality of the fuel play a part in HVOF spraying. Combustion gas exit velocities may vary from 900 m/s up to 1500 m/s, which might contribute to increased particle velocity. However, it is not only the high exit gas velocity that is required for the high particle velocities. In fact, as has been demonstrated by Swank et al. (Ref 2), particle velocity cannot be increased by simply increasing the gas velocity if the density of the gas simultaneously decreases. Particles are accelerated by a drag force, D, which can be expressed as:

$$D = \frac{1}{4} C_D \rho v_{rel}^2 A \qquad \text{(Eq 1)}$$

where ρ is the local gas density, v_{rel} is the difference in velocity between the particles and the gas, A is the area projected by the particle, and C_D is the drag coefficient.

According to the ideal gas laws, at constant pressure the local gas density is proportional to the inverse of the temperature, and the gas velocity is proportional to the square root of the temperature (Eq 1), so the drag force is proportional to the pressure in the chamber. Accordingly, at constant pressure the drag force also remains constant

On the other hand, increasing the pressure in the chamber increases the drag force and results in significant increases in particle velocity. This has been verified experimentally by Hackett and Settles (Ref 3), who observed an increase in particle velocity by a factor of about 2.5 when the chamber pressure was increased from about 4 atm up to 8.5 atm. The increase in velocity achieved is not linear, however. This is due to the reduced time that the particles are subjected to the drag force at higher velocities.

Recently, a conical or de Laval nozzle has been developed for use in HVOF spraying. In general, at supersonic velocities there are three different regimes of gas flow in a de Laval nozzle (Fig. 1). In the case of ideally expanded flow, the pressure at the nozzle exit plane is equal to atmospheric pressure (Fig. 1a). In this mode, thermal energy is converted ideally into the kinetic energy of the gas. If the pressure at the exit plane of the nozzle is lower than atmospheric pressure, the nozzle is operating in the overexpanded regime (Fig. 1c). In the underexpanded regime, the pressure at the exit plane is greater than atmospheric pressure (Fig. 1b). Under- and overexpanded regimes are characterized by shock diamonds. As has been pointed out by Hackett and Settles (Ref 3), it has not been determined whether an ideally expanded jet provides the optimum conditions for HVOF spraying (Ref 4-7).

The effect of increased gas velocity on particle velocity is thus not unambiguous. Nevertheless, according to Eq 1 the drag force increases as the square of the gas velocity provided the density of the gas remains unchanged. Consequently, flow dynamics is one of the essential characteristics of an HVOF system.

Several techniques are employed in the determination of gas velocities. An enthalpy probe combined with a mass spectrometer is probably the most commonly used method. This method is somewhat complex and does not yield the gas velocity in a straightforward manner. Accordingly, few experimental results have been published, and most of these were obtained with the Hobart TAFA JP-5000 gun (Hobart Tafa Technologies, Inc., Concord, NH, USA). Typically, the gas velocity has been determined as a function of only a single gas parameter—for example, the fuel/oxygen ratio (Ref 8-10).

Numerical modeling has been used more frequently to estimate gas velocities. In general, the experimental values obtained have been lower than the values predicted by theory.

In this paper we present a simple, inexpensive way of determining combustion gas velocity. The method is used to investigate the effect of hydrogen/oxygen flow rates and total gas flow rates on the HVOF gun combustion gas exit velocity. The velocity values were determined using two different types of nozzle geometry: a barrel nozzle and a de Laval (conical) nozzle. The results are discussed in terms of the theory of compressible fluid flow.

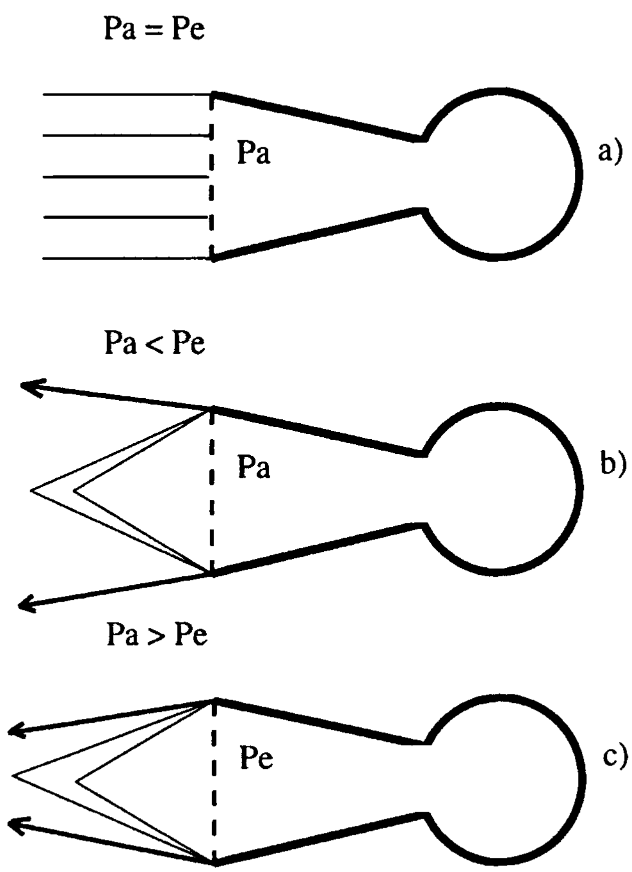


Fig. 1 Regimes of gas flow in a supersonic gas nozzle. Pa, atmospheric pressure; Pe, pressure at the exit plane of the nozzle. (a) Ideally expanded flow. (b) Underexpanded flow. (c) Overexpanded flow

2. Design Procedure for the de Laval Nozzle

The new nozzle was designed using the one dimensional model of a rocket engine presented by Sutton et al. (Ref 3, 4, 11). A pressure ratio (p_0/p, where p is atmospheric pressure and p_0 is the chamber pressure) of 3 was selected for use in the design (Ref 12). This included an increase in the chamber pressure of the factory-made barrel nozzle by a factor of two. The new nozzle was designed using the new p_0/p ratio (Ref 3-5). Because hydrogen was the fuel gas, the isentropic constant, γ, is 1.2 (Ref 4, 11). Using this constant and the p_0/p ratio given above, the Mach number, M, can be calculated:

$$M^2 = \frac{2}{\gamma - 1}\left[\left(\frac{p_0}{p_e}\right)^{(\gamma-1)/\gamma} - 1\right] \quad \text{(Eq 2)}$$

This yields a value of 1.42 for the Mach number. In order to calculate the local velocity of sound, the adiabatic temperature of the chamber and the average molecular mass, m, of the combustion gas were determined. Calculations were performed using HSC software (Ref 11), which makes use of the JANAF database. A value of 17.5 to 9.8 g/mol was obtained for the average molecular mass m at a fuel/oxygen ratio of 2 to 4. The stagnation or adiabatic temperature (T_0) of the chamber was 2540 to 2877 °C.

Heat dissipation in the chamber was estimated to be 15%. The effective stagnation temperature, $T_{0\eta}$, and the temperature at the exit plane of the nozzle, T_e, were:

$$T_{0\eta} = 0.85\, T_0 \quad \text{(Eq 3)}$$

$$\frac{T_e}{T_{0_\eta}} = \left(\frac{p_e}{p_0}\right)^{(\gamma-1)/\gamma} \quad \text{(Eq 4)}$$

In order to obtain the velocity of the combustion gas at the nozzle exit plane, the local velocity of sound in the gas at the throat must be known. According to the theory of compressible fluid flow, the velocity of the combustion gas at the exit plane of a throat is equal to the local velocity of sound, a, which can be calculated as:

$$a = \sqrt{\frac{\gamma T R}{m}} \quad \text{(Eq 5)}$$

where γ is the adiabatic coefficient of the combustion gas (1.1 to 1.4), T is the temperature in the combustion chamber (2000 to 3200 °C), m is the average molecular mass of the gas in the combustion chamber, and R is the universal gas constant. Accordingly, the combustion gas velocity at the nozzle exit plane is:

$$v = a \times M \quad \text{(Eq 6)}$$

The theoretical gas velocities for some fuel/oxygen ratios are given in Table 1. In order to manufacture the nozzle, the ratio of the surface areas at the throat and at the exit plane, A_t/A_e, must be known:

$$\left(\frac{A_e}{A_t}\right)^2 = \frac{1}{M^2}\left[\left(\frac{2}{\gamma - 1}\right)\left(1 + \frac{\gamma - 1}{2}M^2\right)\right]^{(\gamma+1)/(\gamma-1)} \quad \text{(Eq 7)}$$

The design procedure does not provide the length and shape of the nozzle. In this case, a straight conical shape was employed. The length was the same as that of the standard nozzle of the HV-2000 gun. The standard barrel (19 mm nozzle) and de Laval nozzles are shown in Fig. 2.

In the calculations above, it is assumed that reactions do not continue in the nozzle but are frozen in the chamber, that the flow in the nozzle is frictionless, and that there is no heat loss in the nozzle. In the real process, reactions do continue in the nozzle at a level that depends on the fuel, the fuel/oxygen ratio, pressure, and so on. In spite of this, it turns out that these factors can be ignored in the design process because, even with an approximate approach, the gas velocity can be significantly increased.

3. Experimental Setup and Measurements

Thorpe and Richter (Ref 13) have suggested that the recoil measurement technique should be used to compare actual and theoretical results as well as modifications to burner design. In the spray gun, the starting point for gas velocity measurement is the recoil equation. This can be derived by applying Newton's second law (the conservation of momentum) to the stationary HVOF spray gun (Ref 6, 14) (Fig. 3). One-dimensional flow is assumed with a steady exit gas velocity of v_x and a fuel/oxygen flow rate of $\dot{m}$. A control surface CS, passing through the exit plane of the nozzle, limits a control volume CV. The thrust (recoil) F acts in the direction opposite to v_x, and for the static test the reaction will act on the control volume. The momentum equation for this volume is:

$$\sum F_x = \frac{d}{dt}\int_{CV} \rho v_x dV + \int_{CS} v_x d\dot{m} \quad \text{(Eq 8)}$$

The first term, body force, vanishes since v_x is zero and the flow in the nozzle is assumed to be steady within the control volume CV. For the second term, force on the control surface CS, there is a momentum flux out of the control surface:

$$\int_{CS} v_x dm = \dot{m} v_x \quad \text{(Eq 9)}$$

On the other hand, force balance gives:

$$\Sigma F_x = F + A_e(p_e - p_a) \quad \text{(Eq 10)}$$

where the last term is pressure force, p_e is the pressure at the nozzle exit, p_a is the ambient pressure, and A_e is the exit area of the nozzle. Combining Eq 9 and 10 yields:

$$F = \dot{m} v_x + (p_e - p_a)A_e \quad \text{(Eq 11)}$$

If the pressure in the nozzle is equal to the external pressure, that is, $p_e = p_a$, there is an ideal expanded flow. Then $f = \dot{m}v_x$. In both the over- and underexpanded states, the latter term is nonzero, and ignoring it could result in an error on the order of 500 m/s in the value obtained for combustion gas velocity at the nozzle exit plane.

If recoil and exit pressure are measured, gas velocity can be calculated according to:

$$v_x = \frac{F - (p_e - p_a)A_e}{\dot{m}} \quad \text{(Eq 12)}$$

The setup for the determination of recoil force is shown in Fig. 4. The gun (1) was mounted on the plane (2), which pivoted at (4). The force transducer (3) was used to monitor the recoil force. The accuracy of the force transducer was ±0.5% and the reproducibility of the complete measuring system ±0.5%. The static pressure in the nozzle was determined using a piezoelec-

Table 1 Combustion gas velocities predicted by a one-dimensional model of gas flow, with corresponding experimental values, momentum flux in the nozzles, and combustion chamber temperature

Parameter	Value				
H_2/O_2 ratio	2.0	2.5	3.0	3.5	4.0
T_0, °C	2877	2877	2760	2718	2540
m, g/mol	17.5	14.65	12.6	11.3	9.9
ρv^2, N/m^2					
de Laval nozzle	162,452	150,021	145,776	143,301	...
Barrel nozzle	69,770	81,912	77,014	79,300	...
a, m/s	1100	1205	1264	1334	1337
Gas velocity, m/s					
de Laval nozzle, theoretical	1420	1711	1794	1894	1898
de Laval nozzle, experimental	1360	1430	1490	1550	...
Barrel nozzle, theoretical	1100	1205	1264	1334	1337
Barrel nozzle, experimental	983	1056	1083	1101	...

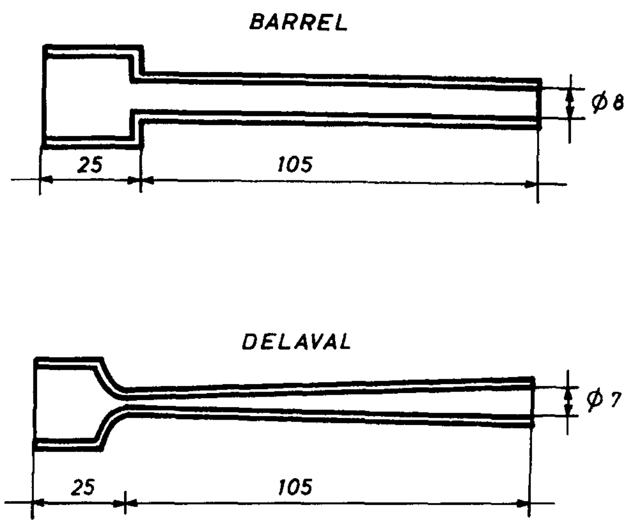


Fig. 2 Barrel and de Laval HVOF nozzles. Dimensions given in millimeters

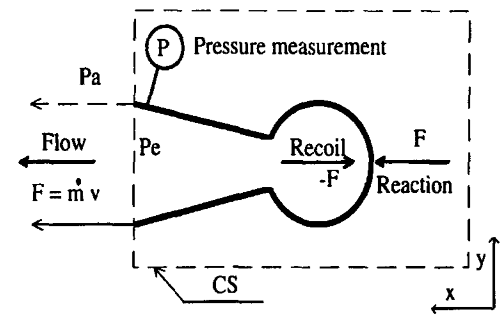


Fig. 3 Recoil measurement principle

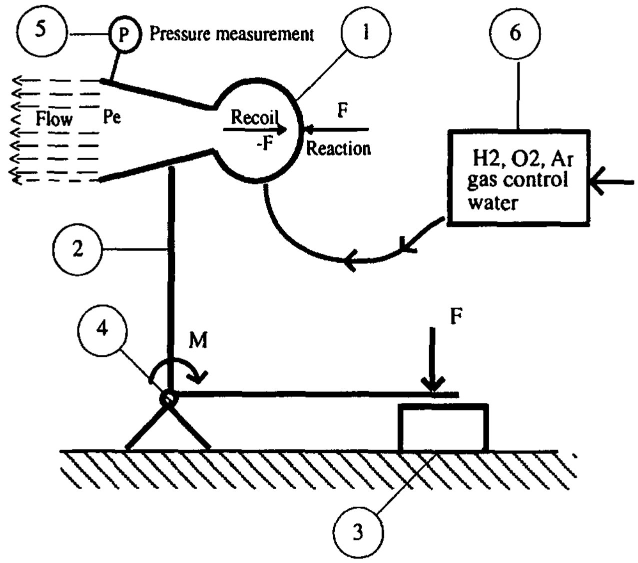


Fig. 4 Experimental setup for exit gas velocity measurement

tric pressure sensor (5) with an accuracy of ±0.3% at a distance of 2 mm from the exit plane. The pressure at the exit plane was measured inside the copper nozzle through a 0.1 mm diam hole (Fig. 3). Gas flow (m) was measured using mass flowmeters (6).

Both the recoil force and static exit pressure were determined at hydrogen flow rates of 400 to 650 L/min and oxygen flow rates of 150 to 275 L/min. These flow rates correspond to fuel/oxygen ratios in the range of 1.6 to 3.4. The experimental recoil force (F) and exit plane pressure (p_e) were used to calculate the average flow velocity (v_x) of the combustion gas according to Eq 12.

4. Results and Discussion

The average combustion gas velocities for the standard and the de Laval nozzles are shown as a function of the fuel/oxygen ratio and the mass flow rates in Fig. 5 and Table 1. The average gas velocity in the standard barrel nozzle varied from 850 to 1100 m/s. In the de Laval nozzle, the average velocities were about 50% higher and varied from 1200 to 1560 m/s. The static pressure at the exit plane of the de Laval nozzle varied from –0.5 to 0.5 bar, indicating that the nozzle was operating either in the over- or underexpanded mode, depending on the total gas flow rate.

Only choked flow velocities are shown in Fig. 5, because pressure measurements less than the prevailing atmospheric pressure were unsteady. Choked flow conditions were observed when the nozzle exit pressure was higher than the prevailing atmospheric pressure (i.e., $p_e > 1$ atm).

The one-dimensional model of compressible gas flow used in the simplified design procedure provides only a single Mach number M for the spray nozzle; in this case, it was 1.42. The Mach number depends on the ratio p_0/p_a between the chamber pressure and the ambient pressure, the shape of the nozzle, the ratio of the surface areas at the throat and the exit plane (A_t/A_e), and the isentropic constant.

The gas velocities at the exit plane, on the other hand, are determined by the local velocity of sound at the nozzle throat. As shown in Fig. 5, the gas velocity at the exit plane also clearly depends on the fuel/oxygen ratio. This is due to the reduction in the average molecular mass of the combustion gas when the flow of hydrogen is relatively higher (17.5 to 11.5 g/mol). The reduction in the average mass of the combustion gas results in an increase in the local gas velocity at the throat, with a corresponding increase in the velocity at the exit plane. The Mach number remains constant. The other factor that can change the gas velocity and that can be varied is the gas temperature (2550 to 2877 °C). The combustion gas velocity, however, is independent of the total gas flow at a fixed fuel/oxygen ratio; this can also be seen in Fig. 5. The gas flow increases the density of the combustion gas, and this increases the drag force that accelerates the particles according to Eq 1. It is presumed that the highest particle velocities are obtained at the highest gas velocity and highest total flow.

Table 1 shows the momentum flux (ρv^2) of the supersonic gas flow. The momentum flux has been calculated for both types of nozzles. Calculations—based on the measured gas velocity, the calculated equilibrium temperatures, and the molecular mass of the combustion gas (HSC)—showed that the momentum flux of the de Laval nozzle is two times greater than that of the barrel nozzle.

The conversion of thermal energy in the de Laval nozzle is significantly better than in the barrel nozzle. For example, in the

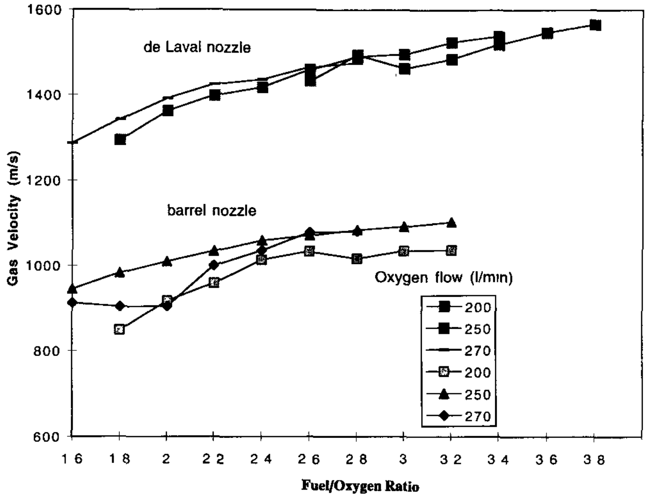


Fig. 5 Gas velocity in the combustion chamber of the HVOF spray gun for the two types of nozzles

case described here, at gas parameters H_2/O_2, 700/250 L/min, the power associated with the kinetic energy of the gas in the barrel nozzle is 3.6 kW and for the de Laval nozzle is 7.8 kW. The increased kinetic energy of the combustion gas provides the particles being sprayed with correspondingly higher kinetic energy.

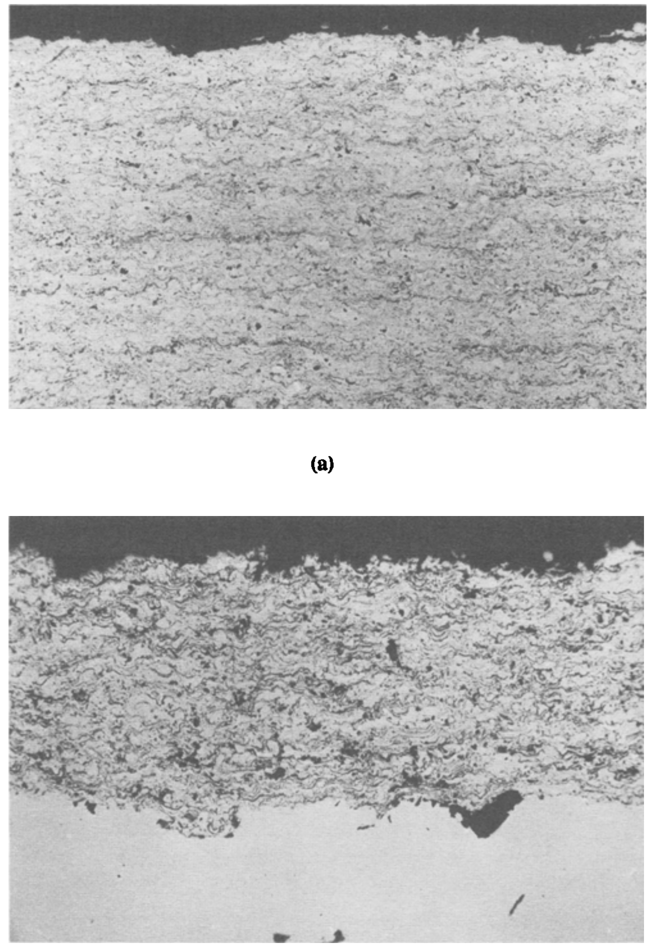
It should be pointed out that if the flow is underexpanded, a supersonic gas flow can accelerate upon leaving the exit plane of the nozzle. Such a supersonic gas velocity can be several hundred meters per second higher than the measured velocity at the nozzle exit, but this question is not investigated in this study (Ref 6, 10).

4.1 *Measurement Error and Calculation Approximations*

The velocities determined for the de Laval nozzle are smaller than those predicted on the basis of the simple design procedure, 1420 to 1898 m/s (Table 1). This is due to these assumptions made in the calculations:

- The gas composition is homogeneous and invariant throughout the HVOF combustion chamber and in the nozzle.
- The gas obeys the perfect gas laws.
- There is no friction.
- There is no heat transfer across the nozzle walls, the flow therefore being adiabatic.
- The gas flow is steady and constant, and the expansion of gas takes place in a uniform manner without shock.
- The flow direction is axial when the gas leaves the nozzle.
- The gas velocity and pressure are uniform across the nozzle.
- Chemical equilibrium is established within the combustion chamber and does not shift in the nozzle.

The recoil of the HVOF gun was measured to an accuracy of ±1%, as was the measurement of the mass flow. Therefore, these measurements cannot produce a significant error in the calculated results. The measurement of pressure at the exit plane may be a source of error because of the assumption that the pressure is uniform over the entire cross section of the nozzle, neglecting any boundary layer effect. Measurements using the pressure transducer can be made to an accuracy of ±1%. Measurements of gas velocity do not provide maximum values, only average ones, but conservation of momentum means that the measurement method is independent of variations in the velocity profile. It is considered that the gas velocity measurement is more accurate than the calculations since there is only one relatively major assumption: that the nozzle exit pressure is uniform over the whole of the nozzle exit plane.



(a)

(b)

Fig. 6 Microstructure of sprayed Cr_3C_2-NiCr coating. (a) De Laval nozzle. (b) Barrel nozzle

4.2 *Coatings*

The effect of increased gas velocity was also tested on the coatings. Improved coating quality was achieved because a higher gas velocity increased the particle velocity (Eq 1). The improvement in coating quality is apparent in Fig. 6, which shows the microstructure of the Cr_3C_2-NiCr coating deposited by the barrel nozzle and by the de Laval nozzle. The porosity and oxide content of the coating sprayed using the de Laval nozzle (Fig. 6a) is significantly reduced when compared to the coating sprayed using the barrel nozzle (Fig. 6b). In addition, the overall microstructure of the coating sprayed with the de Laval nozzle is more uniform than the coating sprayed using the barrel nozzle. The coatings were sprayed using the same gas parameters (H_2/O_2, 750/250 L/min), corresponding to gas velocities of 1020 m/s in the barrel nozzle and 1560 m/s in the de Laval nozzle.

5. Conclusions

Gas velocities in the HVOF spray gun were measured at the exit planes of a standard barrel nozzle and a specially designed de Laval nozzle. The effect of changing gas flow rates and fuel/oxygen ratios were tested. The de Laval nozzle produced a significantly higher gas velocity than the standard barrel nozzle through better conversion of the chamber pressure into kinetic energy of the combustion gas. Higher fuel/oxygen ratios increase gas velocity because of the lower molecular mass of the exit gas. Increasing the mass flow results in higher static pressure and gas density in the nozzle, and the nozzle is changed into an underexpanded mode.

Measurements showed that the two nozzles behaved in accordance with the theory of compressible flow. Measurements of the gas velocity with the different nozzles indicated that there is hidden potential for increasing the gas velocity in HVOF spraying and that this potential has not yet been fully exploited. Gas velocity can be raised by increasing the chamber pressure and by designing the HVOF gun nozzle for higher Mach numbers. Coating experiments have shown that higher gas velocities improve coating quality by reducing oxide content and porosity.

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