

Hypervelocity Impact Fusion—A Technical Note

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A very simple outline of the engineering theory for the implementation of hypervelocity oxygen fuel (HVOF) and hypervelocity air fuel (HVOF) processes is presented. Several calculations show that a condition can be reached where the impact energy of these processes can be optimized to produce a new class of coatings termed “hypervelocity impact fusion” coatings. The microstructures of these coatings exhibit minimum oxidation and very good bonding to the substrate.

1. Introduction

HYPERVELOCITY impact fusion (HVIF) is accomplished using either hypervelocity oxygen fuel (HVOF) or hypervelocity air fuel (HVOF) equipment. “Hypervelocity” is the preferred terminology in this article because the pressures are of much higher value than conventional oxygen fuel spray processes. The choice of equipment depends on the combustion pressure level. Thus, from 50 psi (3.4 bar) to about 150 psi (10.3 bar), the air-fuel burner is used, from 150 psi (10.3 bar) to 1200 psi (82.7 bar), oxygen-enriched air is necessary, and above 1200 psi (82 bar), pure oxygen is required. Note that 1 bar = 100,000 Pa and 1 psi = 6895 Pa; the pressure conversions have been rounded. Expansion from a high-pressure region (combustion zone) to atmospheric pressure results in significant temperature drops. Powder injection into a supersonic stream of static temperature below that of the melting point of the powdered material accelerates the solid particles to extreme velocity through a long nozzle tube. Impact heating melts the material upon striking the workpiece so that a coating is formed. It has been observed that these coatings exhibit minimum oxidation products and chemical reactions compared to other high-velocity processes.

This technical note contrasts the various high-velocity methods of thermal spray deposition. It is intended to indicate by simple calculations that the phenomenon of impact fusion is of benefit in promoting high bond strengths for these coatings.

2. Calculations and Discussion

2.1 High-Velocity Burners—Temperature and Velocity Relationships

Figure 1(b) shows an internal burner of the type used for both HVOF and HVOF spraying. The combustion temperature for a HVOF unit operating with fuel oil and oxygen (allowing for thermal losses to the coolant) is about 4800 °F (2650 °C).^[1] For regenerative air-fuel flow, the temperature is 3400 °F (1870 °C). The theoretical flame temperature of 5660 °F (3127 °C) for oxy-heptane^[1] reduces to about 4800 °F (2649 °C) when approximately 20% of the total heat available is lost to the cooling water. The graphs in Fig. 1 show the state of the hot gas expanding to

atmospheric pressure, and several combustion pressure levels are illustrated. For example, oxyfuel reactants burning at 60 psi (4.1 bar) (Fig. 1c) expand to supersonic velocity through the converging-diverging nozzle section of Fig. 1(b). An “overexpansion” case is shown, in which the pressure of the supersonic flow along the long accelerating duct is subatmospheric.

Consider a stainless steel powder with a melting point of 2700 °F (1480 °C) that is injected into the hot gas. The gas temperature in the duct (Fig. 1a) has fallen to about 3500 °F (1930 °C). The powder, if heated to near this gas temperature, could melt and lead to plugging of the long nozzle ducts. At 300 psi (20.7 bar), the particles reach a temperature of 2590 °F (1420 °C). This is 110 °F (61 °C) below the melting point of the stainless steel powder. No melting can occur and therefore no nozzle plugging. Much longer nozzle ducts may be used to achieve maximum particle impact velocities.

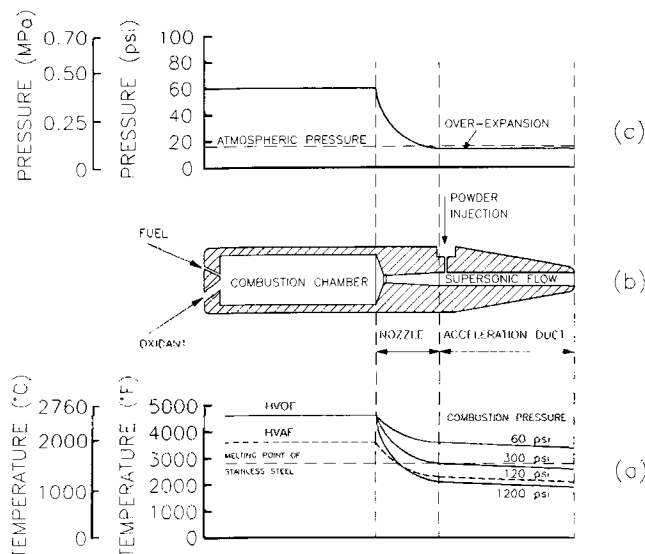


Fig. 1 Temperature and pressure variations within high-velocity oxygen fuel torches. (a) The expansion temperature drops for different combustion chamber pressures and temperatures. (b) Typical rocket-type burner with powder injection into a highly expanded jet flow. (c) Expansion from the combustion chamber to atmospheric pressure.

Key Words: HVOF, HVOF, impact fusion, pressure/temperature calculations

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Table 1 Sample Calculations for the HVOF Process at a Combustion Temperature of 4800 °F (2650 °C) and Pressure from 60 to 25,000 psi (4 to 1665 bar)

| | 60 psi | 120 psi | 300 psi | 600 psi | 1200 psi | 2400 psi | 10,000 psi | 25,000 psi |
|--|---------|---------|------------|------------|------------|------------|------------|------------|
| T_o | 4800 °F | 4800 °F | 4800 °F | 4800 °F | 4800 °F | 4800 °F | 4800 °F | 4800 °F |
| P/P_o | 0.02 | 0.11 | 0.048 | 0.024 | 0.012 | 0.0062 | 0.0014 | 0.0006 |
| a | 2980 | 2760 | 2680 | 2540 | 2340 | 2190 | 1990 | 1770 |
| T_j | 3537 | 3170 | 2748 | 2380 | 1960 | 1644 | 1275 | 855 |
| $T_p = 0.95T_j$ | 3337 | 2988 | 2587 | 2238 | 1839 | 1538 | 1188 | 812 |
| M | 1.75 | 2.1 | 2.5 | 2.94 | 3.4 | 3.8 | 4.4 | 5.1 |
| T/T_o | 0.76 | 0.69 | 0.61 | 0.54 | 0.46 | 0.40 | 0.33 | 0.25 |
| $V_j = M \times a$ | 5215 | 5796 | 6700 | 7467 | 7956 | 8322 | 8756 | 9027 |
| $V_p = 0.5V_j$ | 2607 | 2898 | 3350 | 3733 | 3978 | 4161 | 4378 | 4513 |
| $\Delta h_{\text{theoretical}}$ | 135 | 168 | 224 | 279 | 316 | 346 | 383 | 407 |
| $\Delta h_{\text{actual}} = 0.5\Delta h_{\text{TH}}$ | 68 | 84 | 112 | 140 | 158 | 173 | 191 | 203 |
| T_{rise} | 566 | 700 | ... | ... | ... | ... | ... | ... |
| h for melting..... | (a) | (a) | 99 | 85 | 55 | 34 | 10 | (-23) |
| T_{total} (percent melted)..... | 3903 | 3688 | 2700 (78%) | 2700 (67%) | 2700 (43%) | 2700 (27%) | 2700 (8%) | No coating |

Note: a = velocity of sound, T_j = jet temperature, T_p = particle temperature, and M = Mach No. (a) Particles molten prior to impact.

Table 2 Sample Calculations for the HVAF Process at a Combustion Temperature of 3400 °F (1870 °C) and Pressures from 60 to 600 psi (4 to 40 bar)

| | 60 psi | 120 psi | 300 psi | 600 psi |
|--|------------|-----------|------------|------------|
| T_o | 3400 °F | 3400 °F | 3400 °F | 3400 °F |
| P/P_o | 0.20 | 0.11 | 0.048 | 0.024 |
| T/T_o | 0.76 | 0.69 | 0.61 | 0.54 |
| T_i | 2473 | 2203 | 1894 | 1624 |
| $T_p = 0.95T_i$ | 2326 | 2070 | 1776 | 1520 |
| M | 1.75 | 2.1 | 2.5 | 2.94 |
| a | 2540 | 2460 | 2290 | 2175 |
| $V_j = M \times a$ | 4445 | 5166 | 5725 | 6394 |
| $V_p = 0.5V_j$ | 2222 | 2583 | 2862 | 3197 |
| $\Delta h_{\text{theoretical}}$ | 98 | 133 | 164 | 204 |
| $\Delta h_{\text{actual}} = 0.5\Delta h_{\text{TH}}$ | 49 | 67 | 82 | 102 |
| T_{rise} | ... | ... | ... | ... |
| h for melting..... | 22 | 8 | (-14) | (-27) |
| T_{total} (percent melted)..... | 2700 (17%) | 2700 (6%) | No coating | No coating |

2.2 Sample Calculations

The aim in this section is to calculate the final rise in particle temperature due to the impact of the stainless steel against the substrate. A sample calculation for the HVOF system shown in Fig. 2 operating at 60 psi (4.1 bar) is shown in the first column of Table 1. Particle velocity is assumed to reach 50% of maximum jet velocity. Particle temperature (on an absolute temperature basis) has been set at 95% of the jet temperature. The particle velocity and temperature values have been chosen arbitrarily so that comparative calculations can be performed. Although it is expected that the precise value of these parameters may change, it is expected that the trends observed by these sample calculations will still be valid. A k value of $C_p/C_v = 1.2$ has been used with the necessary thermodynamic data taken from Ref 2.

For the case shown in Fig. 2, the conditions chosen are essentially those for JetKote™ (tradename of Thermadyne Inc.).^[3] The impacting particles are most probably plastic with many smaller molten particles. Nozzle lengths must be limited to those that do not allow full melting of these smaller particles, as “plugging” could result. In Table 1, the data in the second column approximate the J-Gun™ (tradename of Whitco Inc.)^[4] operation. Although HVIF conditions are not produced at these lower

HVOF pressure levels (120 psi or 8.3 bar), the plastic particles strike at high velocity, with impact heating playing an important role in producing the resulting high-quality coatings.

For 300 psi (20.7 bar), the kinetic energy term of the first law of thermodynamics ($V^2/2g$) yields 224 Btu/lb (520 kJ/kg) on a theoretical basis, which reduces to 112 Btu/lb (260 kJ/kg) for practical purposes. Note that the term V is particle velocity, g is the gravitational constant, and j converts foot-pounds to Btu. After providing the necessary heat to reach the melting point, 99 Btu (230 kJ/kg) remain, whereas 127 Btu (295 kJ/kg) are required for full melting. The particles are thus in their plastic state, having received 78% of the heat required for full melting, as indicated by the T_{total} value shown at the bottom of this column in Table 1.

At increased pressures, the percentage of full melting drops slowly until a pressure of about 12,000 psi (800 bar) is reached. Additionally, the particle temperatures at increased up-stream pressures fall off more rapidly than the positive temperature contribution from heating due to the kinetic energy. Thus, beyond 12,000 psi (827 bar), impact heating is insufficient to fuse the particles, and they “bounce off.” A pressure of 12,000 psi is impractical to use, but 2400 psi (165 bar) is easily available by

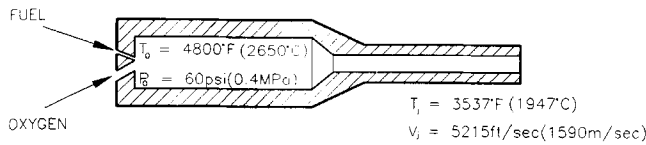


Fig. 2 Experimental conditions for sample calculations shown in Table 1.

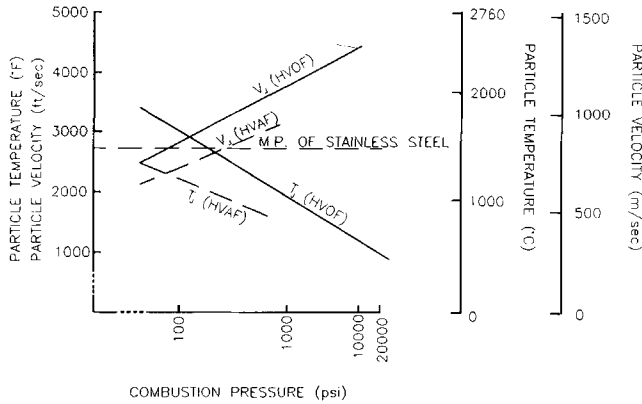


Fig. 3 Particle impacting velocity and temperature as a function of combustion pressure.

pumping liquid oxygen to the required injection pressure. It may be possible for metallurgical fusion to take place at these extreme pressures. It appears that HVOF operation at high pressure may become an important adjunct to HVAF, because particle impact velocities are increased significantly.

The data of Table 1 and 2 are plotted in Fig. 3. Extreme particle impact velocities are associated with the greatest operating pressures. An HVOF system at 2400 psi (165 bar) produces particle velocities over 4000 ft/s (1200 m/s). The rate of velocity increase falls off with increasing combustion pressure. Thus, there may be little advantage to going beyond 2400 psi.

The terms HVOF and HVAF describe the type of combustion oxidizer used. Each of these processes can operate in the HVIF mode (see Fig. 4). Lower pressure of about 150 psi (10.3 bar) is best handled using HVAF.^[5] Above 150 psi, “bounce-off” results. For chamber pressures between 300 and 1100 psi (20.7 and 75.8 bar), the recommended mixture should contain about 60% oxygen, whereas 2400 psi (165 bar) is required for pure oxygen.

2.3 Coating Microstructure/Process Relationships

Figure 4 shows the conditions of the combustion chamber pressure and oxygen content of the oxidizer to produce various types of coatings. The area within the shaded trapezoid represents the three operational conditions of the impact fusion process. Above the top line of the trapezoid, the impacted particles do not reach their melting point and will bounce off the substrate. Below the bottom line particles are plastic or even fully molten prior to impact.

From Fig. 4, it is evident that the degree of plasticity of impacted particles is controllable. For example, assume a hypo-

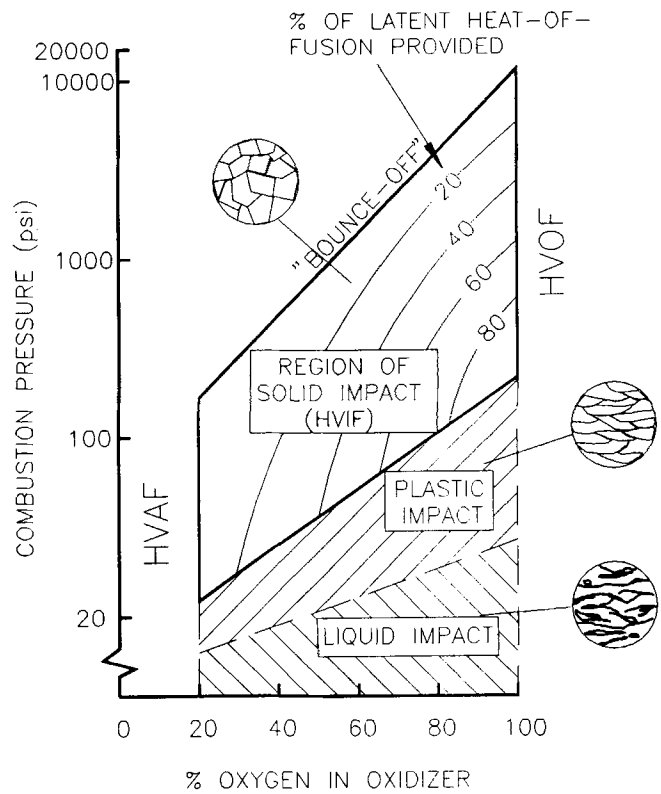


Fig. 4 Region of impact fusion as a function of oxygen percent and combustion pressure.

thetical case where HVOF and HVAF devices are used to produce the same impact velocity. The particle temperature is, for example, 2200 °F (1204 °C) for the air-fuel case to 2600 °F (1427 °C) for the oxyfuel. Even though only 6% of the latent heat is provided in the HVAF case, the coating is found to be excellent. The HVOF process provides several times that quantity of heat, and several questions can be raised concerning comparison of the coatings. For example, the effect of increasing fluidity may significantly influence the characteristics and performance of the coatings.

It appears that basically different coating structures are associated with each of the distinct regions of Fig. 4. For fully molten impact, the particles flatten out and break into smaller masses, often with air spaces interspersed throughout the coating. Wide bands of oxides are present. For plastic impact, particle flattening is evident with the grains encased in thin oxide layers. Solid impact produces a granular coating with the least amount of flattening. Oxide boundaries were not easily detected.

Figures 5 to 7 are photomicrographs of coatings produced by HVAF equipment operating in the HVIF mode. Coating densities are high, and excellent adherence to the substrate is evident, at least as indicated by the coherent nature of the microstructures. The Inconel 625 coating/substrate interface exhibits regions where metallurgical bonding (if not already occurring) might result if the particles strike at much increased velocity. This coating was deposited using a combustion pressure of 60 psi (4 bar) to yield an estimated impact velocity of about 2200 ft/s (670 m/s) (see Table 2). An HVOF coating of this same ma-

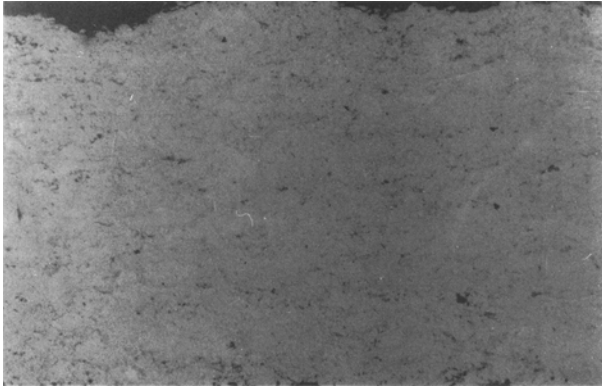


Fig. 5 75Cr₃C₂-25NiCr coating prepared using an Aerospray 250 unit with a chamber pressure of 60 psi (4 bar).

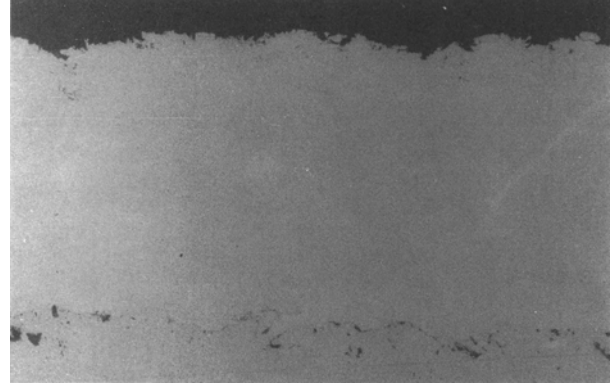


Fig. 7 Inconel 625 coating prepared using an Aerospray 250 unit with a chamber pressure of 60 psi (4 bar).

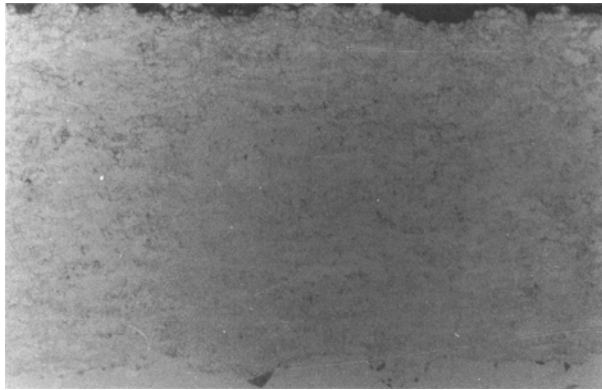


Fig. 6 73WC-20CrC-7Ni coating prepared using an Aerospray 250 unit with a chamber pressure of 60 psi (4 bar).

material at a chamber pressure of 1200 psi (80 bar) would transfer more heat to the workpiece due to the increase of the impact velocity to 3978 ft/s (1212 m/s). The relative impact energy increase under the two conditions above is 3.2-to-1; as found from the ratio of HVOF to HVOF velocity data (*i.e.*, the square of 3978/2222) presented in Tables 1 and 2.

3. Conclusions

The calculations within this article, with many operational assumptions, are intended as a guide to understand the HVIF

mode, particularly the effects to be expected with significant increases in impact velocity of the solid particle. The article indicates how the HVOF and HVOF processes can be operated in modes to achieve impact conditions so that a more desirable microstructure is formed. The overall goal of this work is to form a substantial amount of metallurgical bonding, and the promise of the present work is that further effort may achieve significant results in this direction.

Acknowledgments

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