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Effect of Gas Conditions on HVOF Flame and Properties of WC-Co Coatings

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Abstract

The flow conditions of both fuel and oxygen gases to produce a supersonic flame with a high velocity oxy-fuel (HVOF) gun are experimentally investigated. The range of both fuel and oxygen flows to produce supersonic flame is limited by the choking condition and influenced by the gas pressures. The velocity of a typical flame was estimated to be over 1500 ms^{-1}. The flame conditions also influence the structure and property of HVOF sprayed WC-Co coatings. The increase in the pressures of both fuel and oxygen tends to suppress the decarburization of WC during spraying. The flows of the both gases greatly influenced the properties of WC-Co coatings.

1.0 Introduction

High velocity oxygen fuel (HVOF) flame is characterized as a thermal spraying heat source with high velocity and moderate temperature (~2,700°C) compared to conventional flame spraying and plasma spraying. A dense coating with high adhesive strength can be obtained because of high velocity, particularly with carbide-based cermet materials such as WC-Co and Cr_3C_2-NiCr alloys. Since the introduction of the HVOF device, Jet-Kote, in the early 1980s (1), it has gained much interest in the thermal spray field. Consequently, several different types of HVOF systems were successfully developed in late 1980s and early 1990s. Those systems include Diamond-Jet (2), Top-Gun (3), CDS (Continuous Detonation Spraying) (4), J-Gun (5), and HVAF (6). Except for J-Gun and HVAF systems which use liquid fuel, most systems employ high pressure fuel gas such as propane, propylene, and high pressure oxygen (HVAF using air instead

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of oxygen) which are ignited and burned in a confined chamber to produce the high pressure flame. The pressure and flow of gases will determine the characteristics of the flame. Although much attention has been given to the optimization of gas conditions through investigating the influence of gas flow and pressure, there are few reports which experimentally investigate the effect of gas flow and pressure on the generation of supersonic flame in HVOF systems.

Recent interest in the numerical simulation of supersonic flames (7, 8) emphasized the need to understand the influence of gas conditions on the generation of supersonic flame.

In the present paper, the effects of gas pressure and flow on the generation of supersonic flame were experimentally investigated using a newly developed HVOF system and the effect of gas conditions on the structure and properties of HVOF sprayed WC-Co coatings was studied.

2.0 Experimental Procedure and Materials

The HVOF device used in the experiments was a locally developed torch (CH-2000 type). Figure 1 illustrates schematically the cross-section of the nozzle. The nozzle has a constant diameter of 8 mm. In this system, the flow of gases can be adjusted under given gas pressures. Both fuel and oxygen gases as well as powder carrier gas under certain pressures and flows are injected into the combustion chamber, where gases are mixed and burned, and the resultant flame exits through the nozzle. Whether the flame under certain conditions reached supersonic was determined by observing whether the shock diamonds appeared in the flame. In order to determine the lower limit of gas flow to produce a supersonic flame at any given oxygen and propane pressures, a supersonic flame was first generated at certain oxygen flow and propane flow, and then the flow of propane was slowly decreased until the shock diamonds in the flame disappeared. The velocity of the flame was estimated according to Mach angle of shock diamonds in the flame.

Fuel gas used was propane and powder carrier gas was argon. During the experiments, the pressure of argon was kept at 0.3 MPa. The spray material was angular WC-17% Co powder (Zigong YF-17) manufactured through a sintered-crushed process, grain size of which ranged from 10 μm to 44 μm. The powder was composed of WC and Co phases. The spray distance was kept at 150 mm during spraying.

The structure of WC-Co coatings was characterized by X-ray diffraction (XRD). The microstructure of the coating was characterized by optical microscopy and scanning electron microscopy. The microhardness was measured under a load of 200 gf.

The abrasive wear of selected WC-Co coatings was characterized using a Suga-wear tester (made in Japan by Suga Tester Co. Ltd.). The principle of the tester has been given in detail elsewhere (9). In the present study a load of 29.7 N was applied. Total weight loss after 3200 cycles was measured. The surface of WC-

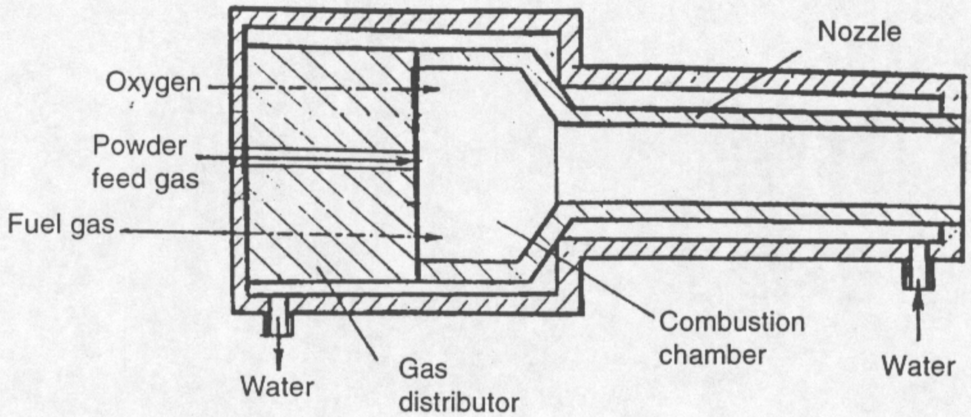


Figure 1: Schematic diagram of experimental gun nozzle structure.

Co coatings was prepared to a surface finish of R_a less than 0.5 μm using diamond disk prior to the wear test.

3.0 Experimental Results

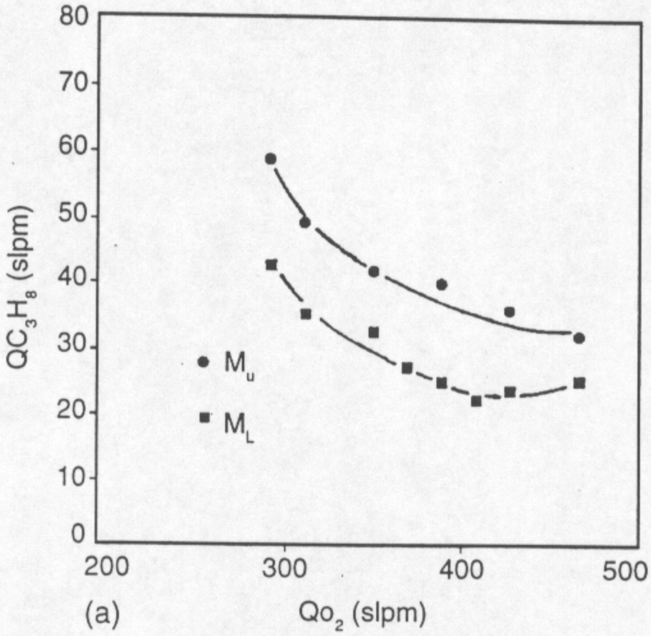
3.1 Characteristics of Supersonic Flame

3.1.1 Effect of Fuel Gas Pressure on the Generation of HVOF Flame

Figure 2 shows the range of gas flows in which a supersonic flame can be obtained at an oxygen pressure of 0.55 MPa and powder carrier gas (argon) flow of 27 l min^{-1} under a pressure of 0.3 MPa. The pressure of fuel gas was 0.3 MPa and 0.25 MPa in Figure 2 (a) and (b), respectively. The lower curve shows critical conditions to produce a supersonic flame jet for the gas flow combination of propane and oxygen, which is referred to as curve ML. The upper curve represents the maximum flow conditions to produce a supersonic flame jet using present experimental device under the given gas pressures, which was referred to as MU. It should be indicated out that both ML and MU curves give the gas flow range in which the Mach number of the flame at exit of nozzle is equal to 1 and the curve MU only means the upper limit of gas flow which can be introduced into combustion chamber at given gas pressures. However, the velocity of free flame jet is definitely increased from ML towards MU curve. It was found that gas pressures had limited effect on the lower limit ML curve and significant effect on the upper limit MU curve. With an increase in fuel gas pressure the upper limit curve will move upward and allow a wider flow range to produce a supersonic flame as shown by Figure 2. Furthermore, it is also clear that the upper limit of fuel gas flow decreased with increase in oxygen gas flow rate.

3.1.2 The Velocity of Typical Supersonic Flame

Figure 3 shows an appearance of a supersonic flame obtained under the



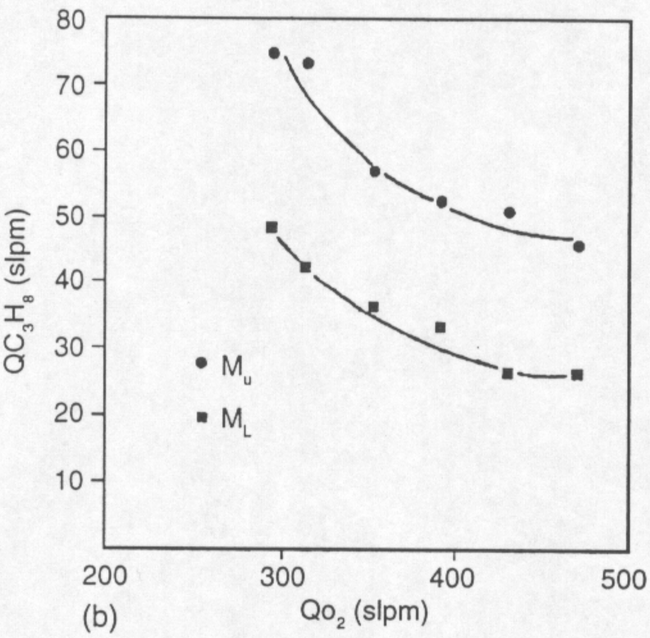


Figure 2: Gas flow range to generate a supersonic flame under oxygen pressure of 0.55 MPa and different propane gas pressures; (a) 0.25 MPa and (b) 0.3 MPa.

oxygen flow of 584 l min^{-1} at 0.55 MPa, propane flow of 32 l min^{-1} at 0.3 MPa and powder carrier gas flow of 27 l min^{-1} at 0.3 MPa. The first and second shock diamonds yielded Mach angles of 43.3° and 44°. According to gas compositions and estimated flame temperature of 3073 K, the flame velocities corresponding to

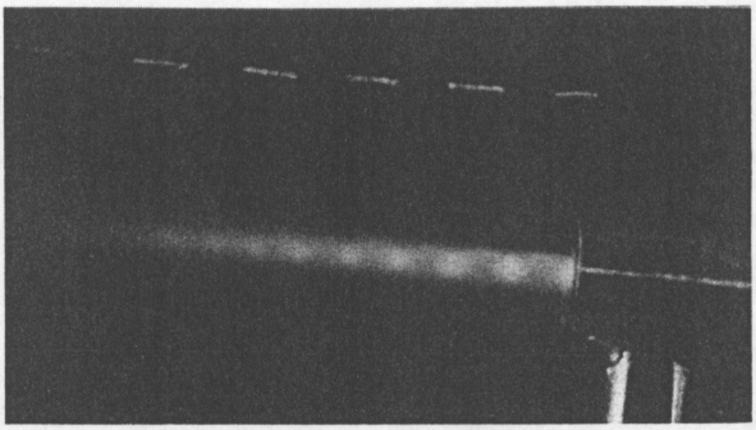


Figure 3: General appearance of a typical supersonic flame, oxygen: 0.55 MPa and 584 min^{-1}, propane 0.3 MPa and 32 l min^{-1}, and argon 0.3 MPa and 19 l min^{-1}.

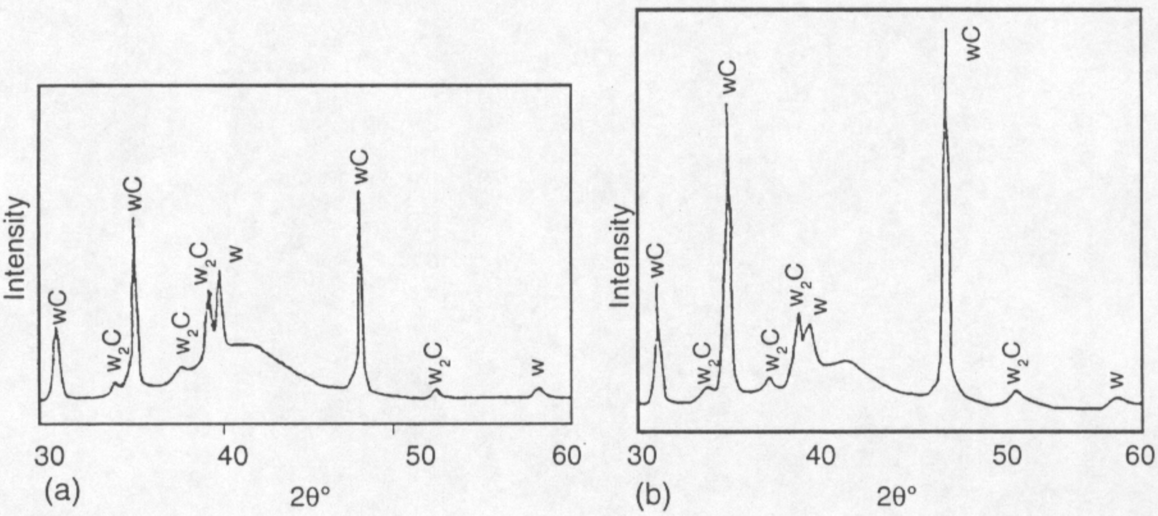


Figure 4: Effect of propane gas pressure on the X-ray diffraction patterns of WC-Co coatings sprayed at oxygen pressure of 0.55 MPa and flow of 362 l min^{-1}, and propane gas flow of 40 l min^{-1}, propane gas pressures are (a) 0.25 MPa and (b) 0.3 MPa, respectively.

first and second shock diamonds were estimated to be 1,541 m s^{-1} and 1,520 m s^{-1}, respectively.

3.2 Effect of Gas Pressure and Flow on the Structure of WC-17% Co Coatings

Figure 4 shows the diffraction patterns of two WC-Co coatings sprayed at oxygen flow of 362 l min^{-1} at pressure of 0.55 MPa and propane flow of 40 l min^{-1} at different pressures. It can be recognized that the decarburization of WC during spraying occurred, which resulted in the formation of dicarbide and metallic tungsten in the coating. Furthermore, a broad peak can also be found in the patterns, which

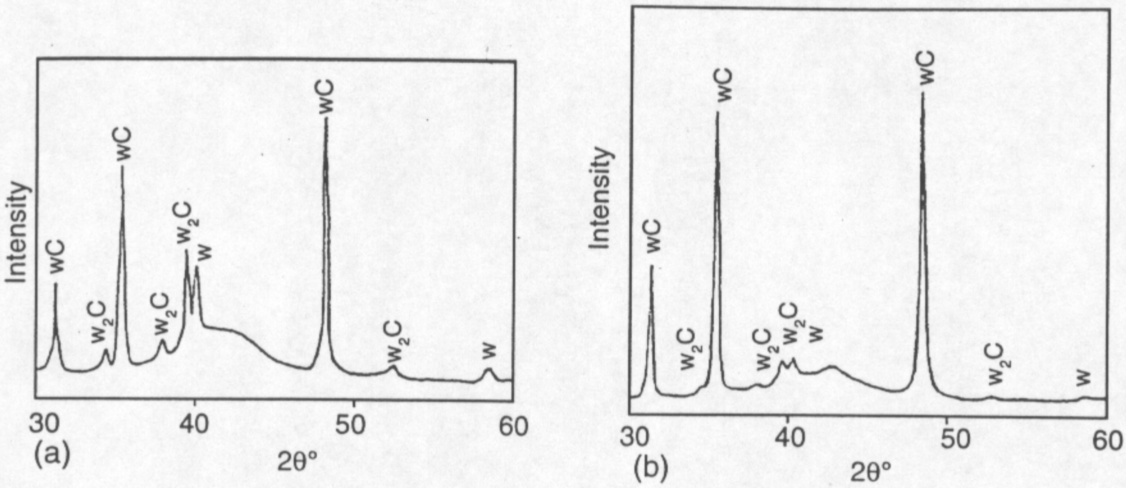


Figure 5: Effect of oxygen gas flows on the X-ray diffraction patterns of WC-Co coatings sprayed at oxygen pressure of 0.55 MPa and propane gas flow of 40 l min^{-1} at pressure of 0.3 MPa, oxygen flows are (a) 332 l min^{-1} and (b) 482 l min^{-1} respectively.

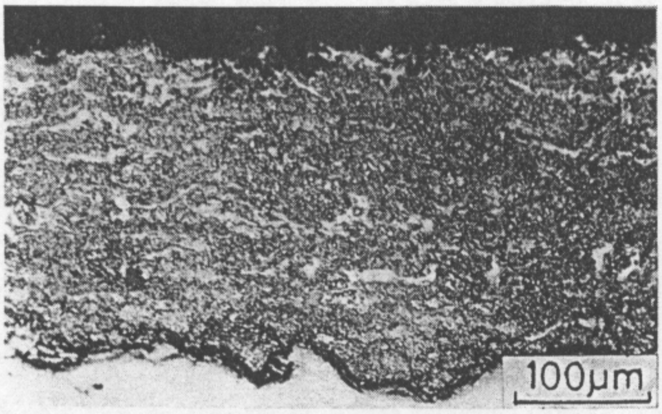
corresponds to the formation of amorphous phase in the coating (10). A comparison of the two patterns revealed that the increase in fuel gas pressure could suppress the decarburization of WC even under the same gas flow conditions. However, it was also found that the increase in fuel gas flow under a given pressure would promote the decarburization of WC.

Figure 5 illustrates the x-ray diffraction patterns of WC-Co coatings sprayed at different oxygen gas flows at 0.55 MPa and same fuel gas flow condition. It can be seen that with the increase in oxygen flow the decarburization of WC can be effectively suppressed.

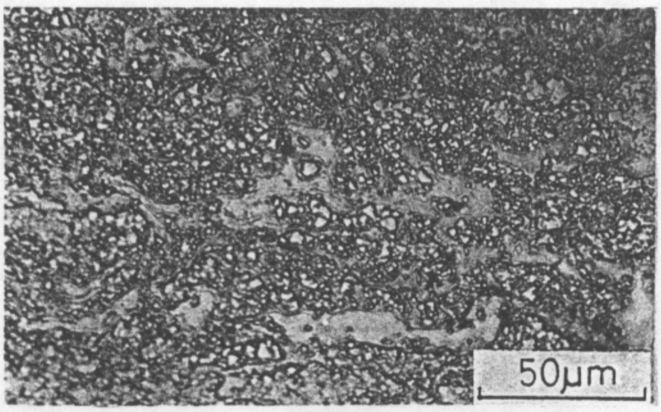
Figure 6 shows the microstructures of typical WC-Co coatings sprayed at the gas pressures of 0.55 MPa and 0.3 MPa and gas flows of 315l min^{-1} and 39l min^{-1} for oxygen and propane, respectively. It can be found that a dense coating with WC carbide particles evenly distributed was obtained.

3.3 Effect of Flame Conditions on the Hardness of WC-17% Co Coatings

Figure 7 shows the effect of oxygen gas flow on the microhardness of WC-17% Co coatings. As shown in Figure 7, it was found that at a given oxygen pressure (for example 0.55 MPa) with increase in oxygen flow, the coating hardness increased to a maximum value and then decreased. The same tendency was also found with the increase in propane flow shown in Figure 8. The maximum hardness of HVOF WC-17% Co coating was 1280 Hv_{200} (mean value).



(a)



(b)

Figure 6: Typical microstructure of WC-Co coating sprayed with the conditions: oxygen: 0.55 MPa and 315 l min^{-1}, propane: 0.3 MPa and 40 l min^{-1}.

3.4 Abrasive Wear of WC-Co Coatings

Figure 9 shows the abrasive wear results of HVOF WC-Co coatings sprayed under two different conditions. Two WC-Co coatings were sprayed under the same propane pressure of 0.4 MPa and oxygen pressure of 0.55 MPa. However, the coating "A" was sprayed at oxygen flow of 558 l min^{-1} and propane flow of 44 l min^{-1}, while the coating "B" was at oxygen flow of 480 l min^{-1} and propane flow of 29 l min^{-1}. It can be found that at a high flow condition, in particular, a high fuel gas flow, the abrasive wear weight loss was increased. This is consistent with the effect of flow conditions on the coating hardness.

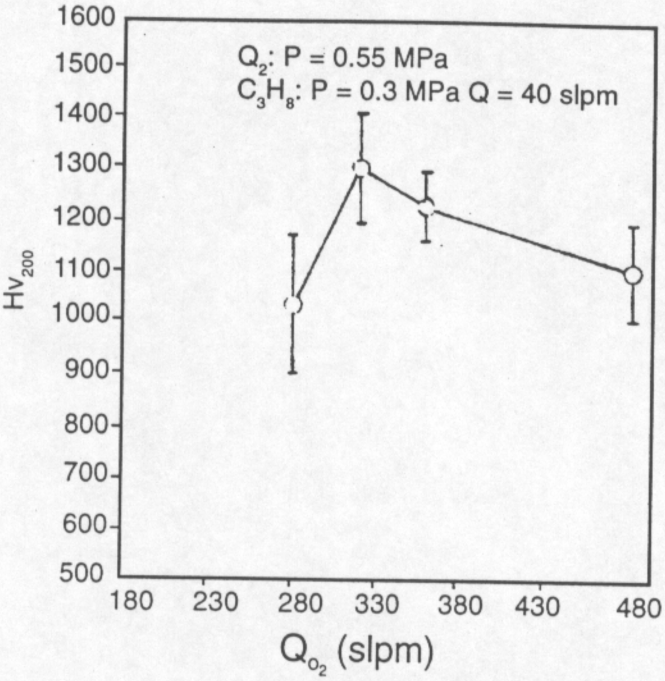


Figure 7: Effect of oxygen flows on Vickers hardness of WC-Co coatings (oxygen pressure: 0.55 MPa, propane: 0.3 MPa and 40 l min^{-1}).

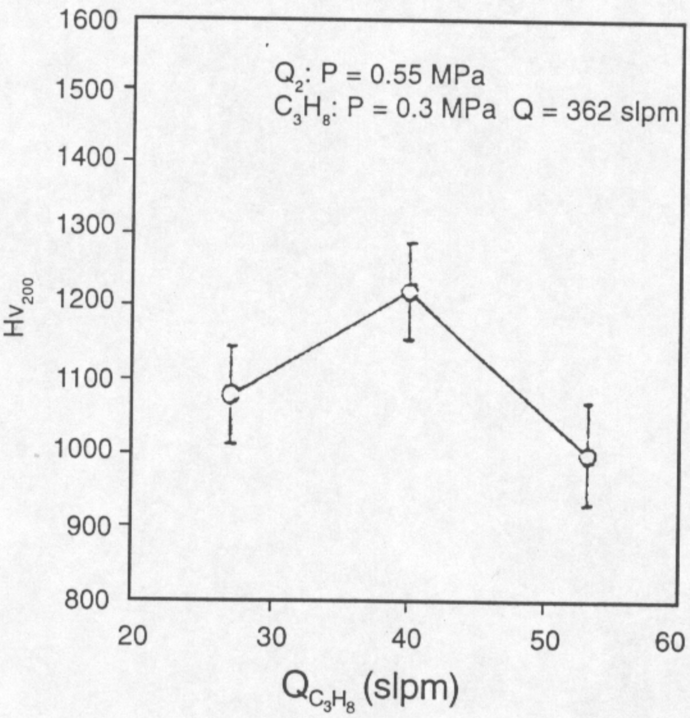


Figure 8: Effect of propane gas flows on Vickers hardness of WC-Co coatings (oxygen: 0.55 MPa and 362 l min^{-1}, propane: 0.3 MPa).

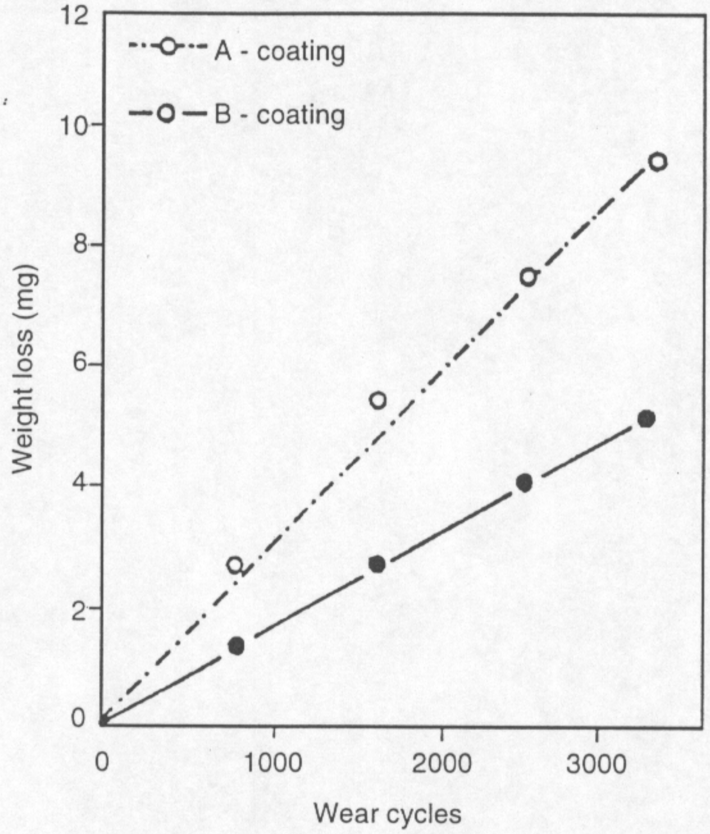


Figure 9: Abrasive wear weight loss against wear cycles for two HVOF WC-Co coatings sprayed at pressures of 0.55 MPa for oxygen and 0.4 MPa for propane. The gas flows for A-coating are 558 l min^{-1} for oxygen and 44 l min^{-1} for propane, and for B-coating are 480 l min^{-1} and 30 l min^{-1}, respectively.

4.0 Discussion

4.1 Effect of Gas Conditions on the Generation of Supersonic Flame Jet

Experimental results showed that only certain combinations of fuel gas and oxygen flows can result in the formation of supersonic flame jet. The pressures of both fuel and oxygen gases influenced the flow range within which supersonic flame jet can be produced and with the increase in both gas pressures the flow rate ranges will also be increased.

According to gas flow dynamics, the gas velocity is a function of variables such as gas composition, pressure, flow, temperature, density, and the area through which the gases travel (11). The maximum gas velocity within a constant diameter nozzle (present experiment) is limited to the local sound velocity. The gas stream can only reach the sonic velocity at nozzle exit and becomes supersonic in the free jet. The local sound speed (c) in a perfect gas is defined by:

$$c = \sqrt{kRT} \quad (1)$$

where, *k:* ratio of specific heat, *R:* gas constant, and *T:* local temperature.

The local Mach number (M) is defined as the ratio of local gas velocity (ν) to local sonic velocity (c). The gas conditions in which Mach number of gas reaches 1 is referred to as critical state. When the exit velocity of flame reaches $M = 1$, the state is considered "choked". Under such conditions, the free flame jet can reach supersonic speed through shock waves. Both friction of gas flame with tube wall and heat input due to the combustion can promote the increase in the gas velocity, i.e., Mach number towards critical condition. The former is known as the Fanno flow and the latter the Rayleigh flow. It was found that under present experiment conditions, the critical state cannot be reached by a cold gas mixture. Heat input through combustion is necessary to raise the pressure of flame in nozzle exit to exceed the critical pressure and also to accelerate gas flame Mach number to 1 and make it reach critical state at the exit. To achieve this, a certain combination of gas velocity and heat input is required. With decrease in gas velocity, heat input must be increased, and vice versa. In the present experiments, regarding to large difference in fuel gas and oxygen flows, it can be considered that the increase in the flow of fuel gas mainly contributes heat input to flame and the increase in oxygen flow raises the gas velocity. Therefore, in order to keep the critical state at exit any decrease in fuel gas flow will require corresponding increase in oxygen flow, as shown experimentally in Figure 2. As the lower gas flow limit curve ML was only influenced slightly by gas pressure, it can be concluded that such a limit is greatly determined by nozzle dimension.

When the critical conditions are satisfied the mass flow within nozzle reaches maximum value, referred to as critical mass flow (m^*), which is defined as follows:

$$m^* = \rho^* \nu^* A^* \qquad (2)$$

where ρ^* is critical gas density, ν^* critical gas velocity, and A^* is critical area. The above equation can be given by total gas pressure P_0^* and total gas temperature T_0^* at Mach = 1.

$$m^* = \frac{P_0^* A^*}{\sqrt{T_0^*}} \left[\frac{K}{R} \left(\frac{2}{K+1} \right)^{\frac{K+1}{K-1}} \right]^{\frac{1}{2}} \qquad (3)$$

At certain fuel gas pressures, when gas flame reaches critical state further increase in fuel gas flow will lead to the increase in burning strength and pressure of the combustion chamber, e.g. P_0. This allows more mass flows of gases according to Equation (3). However, the flow rate will be limited by the balance between chamber pressure and fuel gas pressure. As a result, the MU curves as shown in Figure 2 which represent the upper limit of fuel gas flow were obtained. Therefore, gas pressure will influence the gas flow range within which a supersonic flame can be obtained.

In order to obtain a supersonic flame at nozzle exit the gas flow conditions must be adjusted to the upper side of ML curve. The further increase in free flame jet can be realized through the increase in both fuel and oxygen flows. The increase in oxygen flow towards right side in the range of two curves in Figure 2 would contribute greatly to the increase in the flame velocity, while the increase of fuel gas flow towards the upper range of the curves would mainly lead to the increase of temperature of supersonic flame. It should be noted that the upper limit MU curve could be influenced by the dimensions of combustion chamber and gas injection methods.

4.2 Effect of Gas Conditions on the Structure of HVOF WC-Co Coating

The results show that the decarburization of WC occurs during HVOF spraying (12). The degree of decarburization depends greatly upon the flame conditions. When WC-Co is sprayed using HVOF flame in high oxygen flow range, as shown in Figure 2, the decomposition of WC became less intense than when a flame in the range of high fuel gas flow was used. This is because the supersonic flame velocity in the flow range between MU and ML lines would be increased with an increase in oxygen flow rate, while the flame temperature might be decreased with the increase in oxygen flow rate. Moreover, high pressure and flow rate of oxygen gas will lead to the generation of supersonic flame with high velocity. This resulted in reduced decarburization of WC during spraying as seen from Figure 5 and the dense microstructure. Therefore, it can be considered that a supersonic flame generated at a high oxygen pressure and flow suppresses effectively the decarburization of WC during HVOF spraying.

4.3 Effect of Gas Conditions on the Coating Properties

Hardness of a WC-Co coating is usually cited as an indication of the coating's mechanical property. As shown by experimental results, the Vickers hardness was influenced by gas conditions such as pressures and flow rates. The increase in both propane and oxygen flow rates leads to the increase in hardness to a maximum value of 1280 Hv_{200} and after which there is a decrease in value. This result is consistent with the trend obtained using a Jet-Kote system (13). Generally, the porosity and decarburization levels are two important factors influencing coating hardness for a certain feed stock. The increase in oxygen flow consistently accelerates WC-Co particles to high speeds and suppresses the decarburization of WC. This may also lead to decrease in particle temperature. On the other hand, the increase in fuel gas flow will raise flame temperature and consequently the decomposition of WC. However, in order to obtain a dense coating an adequate heating of the WC-Co powder is required. From the hardness data and abrasive wear test results shown in Figure 9, it can be considered that an adequately large oxygen flow and relatively low propane flow are beneficial to the mechanical performance of HVOF WC-Co coatings.

5.0 Conclusions

The flow conditions of both fuel and oxygen gases to produce a supersonic flame were experimentally investigated using a novel HVOF experimental system. The effects of gaseous conditions on the structure and properties of subsequently sprayed WC-Co coatings were examined. The results revealed that under certain oxygen and fuel pressures, there exists a range of flows for both oxygen and fuel gases in order to generate a supersonic flame. The minimum fuel gas flow to obtain a supersonic flame is dominated by choking condition and influenced by oxygen flow rate. A low fuel gas flow requires a high oxygen flow. On the other hand, a low oxygen flow requires a high fuel gas flow. The maximum fuel gas flow for the generation of a supersonic flame will be limited by fuel gas pressure and decreased by the increase in oxygen flow. The increase in gas pressures tends to extend the gas flow range to obtain supersonic flame. The flame conditions largely influence the structure and properties of sprayed WC-Co coatings. The decarburization of WC occurred during spraying tends to be suppressed with the increase in flame velocity and the decrease in flame temperature. However, a HVOF WC-Co coating sprayed using the flame with high velocity and adequate temperature would give good mechanical performance.

6.0 Acknowledgments

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