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Effects of angular injection, and effervescent atomization on high-velocity suspension flame spray process

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ABSTRACT

This work presents the nanostructured coating formation using suspension thermal spraying through the HVOF torch. The nanostructured coating formation requires nanosize powder particles to be injected inside a thermal spray torch using liquid feedstock. The liquid feedstock needs to be atomized when injected into the high-velocity oxygen fuel (HVOF) torch. This paper presents the effects of angular injection and effervescent atomization of the liquid feedstock on gas and droplet dynamics, vaporization rate, and secondary breakup in the high-velocity suspension flame spray (HVSFS) process. Different angular injections are tested to obtain the optimum value of the angle of injection. Moreover, effervescent atomization technique based on twin-fluid injection has been studied to increase the efficiency of the HVSFS process. Different solid nanoparticle concentrations in suspension droplets are considered. In angular injection the droplets are injected into the core of the combustion zone; this immediately evaporates the droplets, and evaporation is completed within the torch. The value of 10°–15° is selected as the optimal angle of injection to improve the gas and droplet dynamics inside the torch, and to avoid the collision with the torch's wall. The efficiency of the effervescent atomization can be enhanced by using high gas-to-liquid mass flow rate ratio, to increase the spray cone angle for injecting the suspension liquid directly into the combustion flame. It is also found that the increment in the nanoparticle concentration has no considerable effects on the droplet disintegration process. However, the location of evaporation is significantly different for homogeneous and non-homogeneous droplets.

1. Introduction

The thermal spraying technology for producing thermal barrier and wear-resistant dense coatings can be modified with nanosize powder injection to obtain lower coating thickness. In the frame of thermal spraying techniques, a liquid feedstock system has been developed for injecting nanometre size to 10 μm size powder particles in thermal spraying torch [1–3]. The suspension spraying works well for several applications including thermal barrier coatings (TBC), tribofunctional and wear-resistant coatings, biofunctional coatings, fuel cell development, and creating coatings for catalytically active surfaces [3–6]. The HVOF based suspension spraying, named as high-velocity suspension flame spraying (HVSFS) process, uses nanosize powder in the form of liquid suspension [2]. The high-velocity oxygen fuel (HVOF) torches are modified, and the liquid feedstock is injected with the aid of suspension feeder and suspension injector [3,7,8].The HVOF applications use axial (internal) injections [6–10]. This suspension liquid is injected into the flame spray jet and under the action of the combustion gas thermal energy and high-velocity the suspension droplets disintegrate, evaporate and release the nanoparticles inside the torch. These nanoparticles/nano-agglomerates become heated, melted and accelerated towards a prepared surface, and produce a coating on it. The advantage is that the precursor can be nanosize, and the coatings can be thin, smooth and finely structured, even nanostructured [10]. This is not possible with standard dry powder feeders.

In the HVSFS process, the size of microstructural features within the coatings is governed by the liquid feedstock [11–13]. In studies reported in [14], the HVSFS process based on nanosize powder suspension resulted in small and well-flattened lamellae (thickness range 100 nm to 1 μm). The coating exhibited low porosity as compared to Air Plasma Spraying (APS) and HVOF coating and showed better sliding wear resistance [14]. In suspension spraying processes the size of nanostructured coatings depend on a number of parameters, including flame temperature and velocity, suspension feed rate, suspension concentration, suspension's solvent properties, and the atomization of liquid feedstock streams. It was further revealed that the nanoparticles agglomerates size and nanostructured coatings morphology are significantly

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dependent on the suspension's concentration, viscosity, and surface tension [8,15–21].

The HVOF process efficiency mainly depends on the type of torch, the coating material, the nanoparticles injection parameters, the type of liquid used for suspension preparation, and the distance between the torch and substrate. For increasing the effectiveness of this process, optimization of these parameters is essential. The flow physics inside the HVOF torch is difficult to be studied experimentally, and hence, Computational Fluid Dynamics (CFD) techniques are widely used to understand this. Various models are implemented to understand the complex flow physics, combustion chemistry, flames, and jets formation, and propagation involved in the thermal spraying processes [22–27]. Li and Christofides [22,28–31] highlighted the multi-scale behaviour of the overall process inside a HVOF thermal spray torch (Diamond Jet hybrid gun). They divide the process dynamics into two main parts, first is gas dynamics, and the other is particle dynamics (or in-flight particle behaviour). Both parts highly depend on specific parameters. Gas dynamics have a varied temperature, pressure, velocity, etc. depending on the type of fuel and fuel/oxygen ratio used for combustion. Particle dynamics is dependent on the injection mass flow rate, particle size and shape, injection velocity, the angle of spray and spray distance, etc. Moreover, the fuel/oxygen ratio plays a very important role in particle heating. State-of-the-art CFD techniques are required to make the actual process more effective by developing the role of these parameters and their optimization.

Dongmo et al. [12] performed the first numerical modelling of angular injection in the HVSFS torch. Both liquid ethanol droplets (300 μm) and solid Titania particles (0.5–50 μm) are injected as discrete phases. The evaporation of ethanol droplets shows significant cooling of the combustion gases at a 0° angle of injection. Hence, the authors modified the injection phenomena by simulating the flow with an angle of injection of 30°. They found that injection at an angle of 30° improves the rate of ethanol evaporation inside the combustion chamber (CC) and cooling is reduced. The disadvantage of angular injection is the impingement of droplets and particles to the CC walls and increase in the residence time of particles. Dongmo et al. [13] further analysed an optimized HVSFS torch, where the TopGun-G's is modified by designing a conical shape CC. It increases the process efficiency and helps to avoid nanoparticles contact with the CC walls. In these studies, the authors ignored the effect of nanoparticles loading on properties of pure ethanol, its evaporation process in the HVOF torch and on gas combustion dynamics.

Moreover, to improve the process efficiency of generating the dense nanosized coating, the atomization of droplets is essentially required for suspension carrying high concentrations of suspended particles. The atomization of liquid feedstock can be controlled by the atomizer nozzle design and its injection parameters [32–34]. Many researchers have studied the phenomenon of atomization and some specific work is highlighted here. The theory explained by Castleman in 1930 [35], states that atomization is due to the aerodynamic interaction between the liquid and gas leading to an unstable wave growth on the liquid jet surface. The fast moving air strikes the water jet. Hence, the portion of the liquid mass is drawn out into fine ligaments and turns into small droplets. The higher the air speed, the smaller the size of ligaments/droplets [35]. The atomization of liquid jet is a step-wise process [36]. The near field jet breakup process is dominated by the shedding of liquid sheets and ligaments. The far field has a secondary breakup phenomenon in which the disintegrated liquid lumps from the jet are fragmented by the high-velocity air jets.

The disintegration of liquid feedstock droplets can increase the efficiency of the thermal spraying process, and it is achieved by using an atomizer or a mechanical injector [37–39]. Depending on the availability and application requirements, different atomization gases and processes can be used for atomizing the liquid streams. One method is to introduce atomization-gas by a gas envelope around the liquid jet injection [38]. The high-velocity oxygen gas exerted a force on the liquid jet and atomized the stream into fine droplets. The nanoparticles coating obtained after this type of atomization had a narrow particle size distribution, ranging from 10 to 20 nm [38]. For solution precursor atomization, nitrogen gas was used for the formation of ceramic [39]. The nitrogen flow tube was aligned with the axis of the flame nozzle, and the liquid was fed through the second capillary tube at right angles. The nitrogen flow atomizes the precursor stream at the tip of the liquid-carrying capillary. The syringe pump was used for liquid injection with a flow rate of 50 μl/s and atomizing nitrogen gas flow rates are set to 0.028 l/s. By using this atomization technique, characterization of the spray was performed by the phase-Doppler particle analyzer system that acquired 20,000 simultaneous droplet size and velocity measurements. The droplet size distribution observed from phase-Doppler particle analyzer was in the range of 1–20 μm with a number averaged diameter of about 10 μm. The droplet velocities were in the range of 5–30 m/s, while the number averaged droplet velocity was measured to be 16 m/s. The average splat size was about 30–35 μm, which was generated from droplet sizes of 1–20 μm upon impact [39].

Furthermore, another type of atomization method is effervescent atomization. This technique is twin-fluid atomization, in which a small amount of gas is injected into the liquid before the exit orifice to form a bubbly mixture of gas and liquid. On emerging from the nozzle, due to the pressure difference, gas bubbles rapidly expand and shatter the liquid into ligaments and fine droplets. This method offers the advantage of smaller drop sizes at low injection pressure and atomizing even high viscosity liquids effectively [32–34,40–44]. The droplets size and distribution are dependent on the suspension concentration, viscosity, and surface tension which was extensively analysed by the researchers [33,43,45,46].

Researchers also presented the numerical modelling of effervescent atomization's internal and external flow regimes [33,41,43,44,46]. Esfarjani and Dolatabadi studied the droplets disintegration and two-phase flow structure inside the effervescent atomizer [47] using a broad range of nanoparticles types and concentrations for suspension plasma spray process where no effect on the performance of effervescent atomizer was observed [47]. Furthermore, to capture the external two-phase flow of an effervescent atomizer, a three-dimensional model based on the Navier-Stokes equation is developed by Qian et al. [33]. They analysed the effect of varied injection parameters on the Sauter Mean Diameter (SMD). Based on extensive computations, a fitting formula, by using curve fitting techniques, is obtained that relates the droplet SMD to the operating conditions including injection pressure, gas-to-liquid mass flow rate ratio (GLR), injector exit diameter, and liquid physical properties including viscosity and surface tension [33]. Their results showed that liquid viscosity has a small effect on droplet size and its distribution, and the effervescent atomizer can work efficiently even with highly viscous fluids.

Moreover, they also suggested that smaller liquid density and surface tension will give finer droplet atomization, and the atomization phenomena can easily be studied by droplet Weber ($\mathrm{We} = \frac{\rho_d v_{rel}^2 d}{\sigma}$) and Ohnesorge number ($\mathrm{Oh} = \frac{\mu}{\sqrt{\rho_d \sigma d}}$) [46]. They also simulated the effect of atomizer operating conditions on particle characteristics in suspension plasma spraying (SPS). Their model predicted the nanoparticles size, trajectory, velocity, and temperature during the Radio Frequency SPS [48]. The disintegration of droplets is influenced by variation in GLR, atomizer orifice exit diameter and injection pressures. Smaller values of GLR would decrease the atomization while the larger orifice diameter would result in larger liquid droplets, and the smaller value of the injection pressure could also affect the atomization process adversely. Hence, for increasing the efficiency of effervescent atomization higher values of GLR and injection pressure with smaller orifice exit diameter should be used [33,43,48].

Furthermore, Fung et al. [49] experimentally and numerically studied the spray atomization under low pressures. The primary atomization Linear Instability Sheet Atomization (LISA) model available in