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An Investigation on Splat and Flattening Behavior of Thermally Sprayed Copper on A Rough Surface: A New Approach

Satish Tailor · Nitesh Vashishtha · Ankur Modi · S. C. Modi

Metallizing Equipment Company Pvt. Ltd. E-101, MIA Phase-II, Basni, Jodhpur, India.

ABSTRACT

All thermal spray coatings are finally deposited on a rough and active grit-blasted surface of the job. But, available literatures are reporting splat and flattening behavior on a polished surface. There is a gap in thermal spraying to understand actual solidification on a rough surface. Therefore, in the present work an attempt has been made to study of splat formation of thermally sprayed copper onto grit-blasted rough surface. An optimization study is done to collect rounded/semi-rounded disk like splats to set spray parameters. Optimized parameters were also tested at four different gun traverse speeds to fabricate thin Cu coatings (30-50 μ m).

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Thermally spray technology are used to depositing thick coatings (above 50 μ m) on a metal, ceramic or fiber substrate of a variety of coating materials. Different types of feedstock such as metals, ceramics, and composites can be used in the form of powder, rod and wire for a wide range of industrial applications and efforts are being made for new applications [1-14]. To understand the deposition process in thermal spraying, there are four steps as shown in **Figure 1**. In this process, a high temperature flame is produced using either chemical or electrical energy to heat, melt and spray material introduced into the flame. Feedstock injected into the flame is more common in the form of powder but can also be in wire or rod form. Molten droplets are thus transported to an object to produce overlay coatings for protection or performance enhancement purposes [2, 15].

As the individual splat is unit cell for the entire coating buildup, the flattening and solidification of the individual particle on the substrate surface is the first fundamental process for the coating fabrication. Coating microstructure and corresponding properties are mainly depends on the flattening nature of each splat and its solidification [1-4]. In general, two typical types of splats, named disk-shaped splat and splash splat, can be obtained on the flat substrate surface under different conditions. Various investigations on splat formation have appeared in the literatures by theoretical, numerical and experimental methods in the past few decades [16-42]. A transition phenomenon in a flattening behavior of the thermal-sprayed particle on the flat substrate surface was introduced by the M. Fukumoto et al. [23, 43-45]. However, these findings are may not be applicable for splat formation in wire-flame spray and arc spray processes because of powder feedstock material was used. There are not enough studies available on splat formation and solidification of thermally sprayed wire feedstock. Study of splat formation and its solidification always is done with a powder feedstock on a polished

surface [16-42], but the final coating is deposited on a grit blasted rough surface. However, we still cannot answer why or how does the disk-shaped splat appear, and what is the essential of the splat formation process on a rough surface because of nearly all the previous studies observed the final splats on a polished surface without knowing the actual behavior of splat on a rough surface.

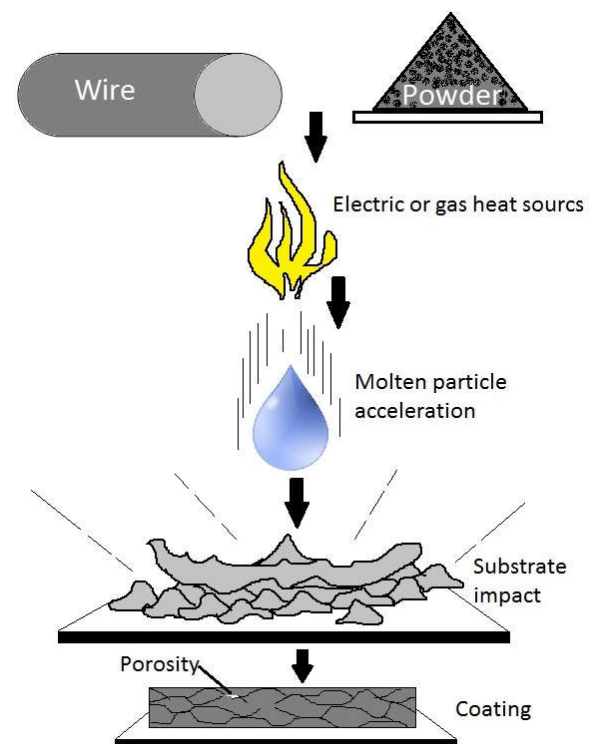


Figure 1: Coating buildup in thermal spray process

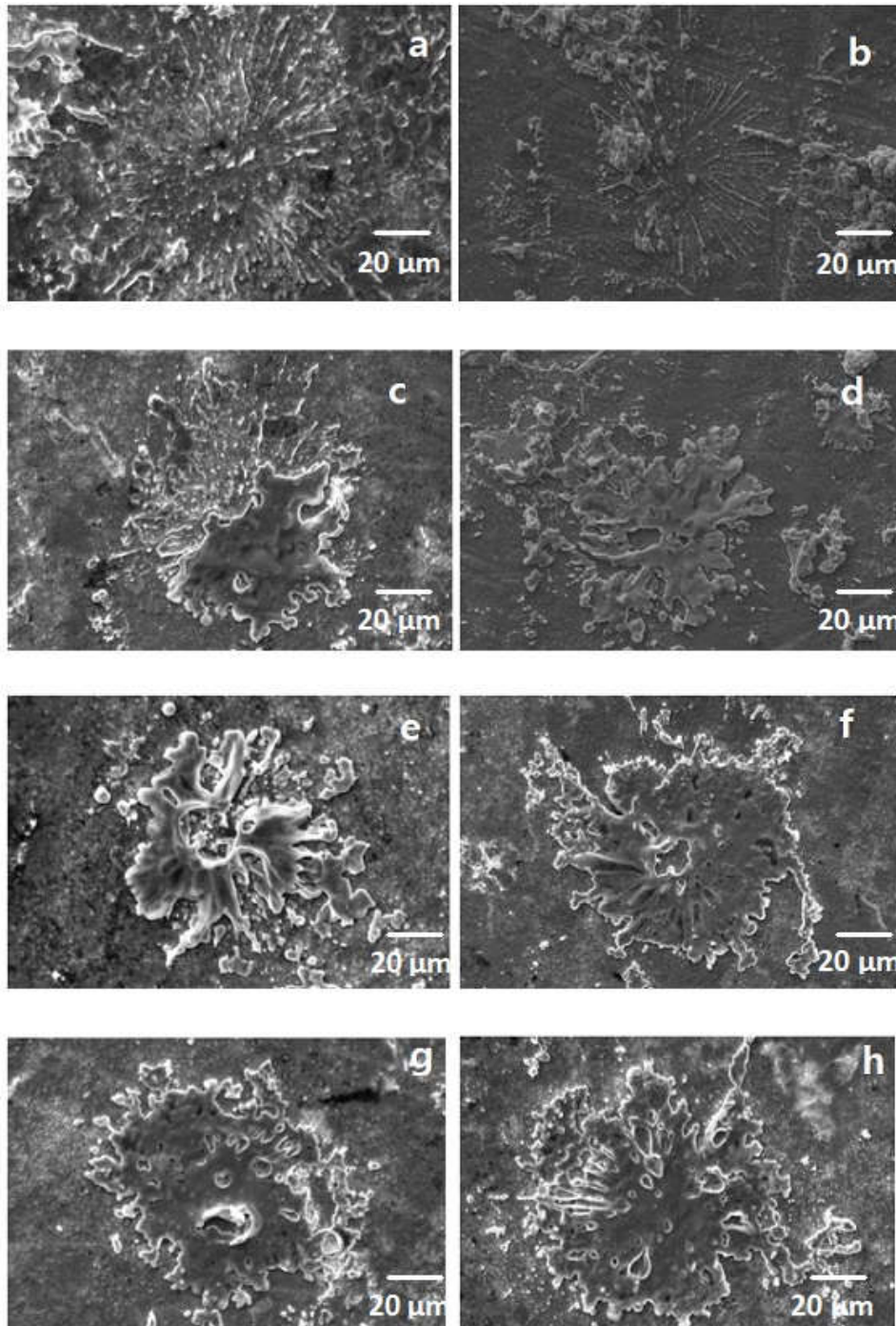


Figure 2: Splash splat formation having different morphologies obtained during the optimization of spray parameters

Therefore, there is a need for a detail study of this aspect using wire feedstock on a grit blasted rough surface. It is necessary to study in detail the basic process of flattening behavior of the sprayed particles on a grit blasted surface, not only from the point of view of scientific interest, but also from that of technical consequences as well. In the present work, an attempt has been made to understand of splat formation and its solidification mechanism of thermally sprayed copper wire onto grit blasted surface of a low carbon steel substrates using newly developed wire based HVOF system (W-HVOF HIJET 9610®).

Copper wire (99.9% pure) 3.17 mm in diameter was used as a feedstock material in the preparation of the coating

samples. The coatings were deposited onto low carbon steel substrates. Prior to spraying substrate should be clean. Substrates were cleaned with acetone for 5 minutes in order to remove any oil marks, pitting and other foreign particles attached with surface and also grit blasted with alumina (Al_2O_3) in order to increase surface roughness of the surface, in order to improve the adhesion strength of the coating with substrate. After grit blasting, substrates were cleaned with compressed air to remove any grit particles attached on the surface. Substrate roughness was found to be $R_a \sim 2-2.5 \mu m$.

Cu-splats were collected on grit blasted substrates using a patented technology (Patent number 214843, Indian Patent



Figure 3: SprayWatch results showing droplet temperature and velocity at optimized spray parameters

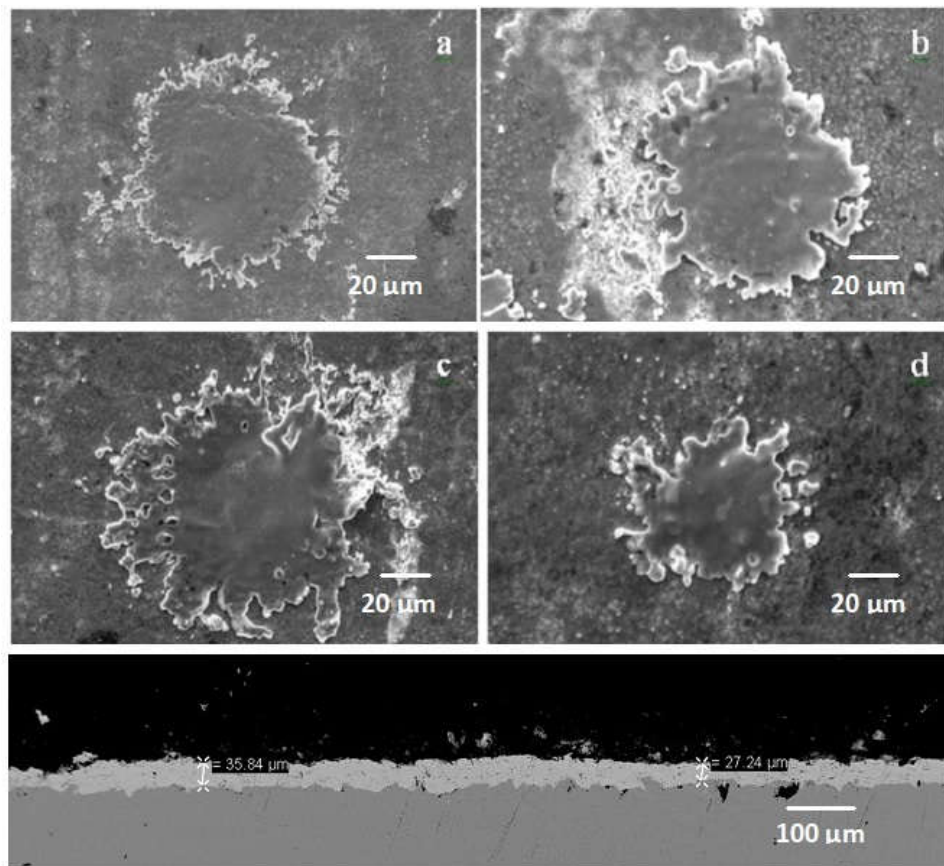


Figure 4: Splat formation at optimized spray parameters at four different gun travel speeds, (a) 0.30 m/s, (b) 0.40 m/s, (c) 0.45 m/s and (d) 0.50 m/s, (e) XRD pattern of as-sprayed thin Cu 0.40 m/s speed

application number 2529/DEL/1997) W-HVOF thermal spray system (trade name: HIJET 9610®, Ms. Metallizing Equipment Company Pvt. Ltd. Jodhpur, India). HIJET®-9610 is a new technique in itself, which is a combination of arc/flame spray and HVOF thermal spray processes. It deposits porous free, very dense coatings at a very economical cost. This system can deposit thick as well as thin metallic coatings (2 mm maximum and 10 to 40 µm

minimum) and opens the possibility to use the wires feedstocks in HVOF process, because thermal spray grade powders are very expensive than wires. It could be a promising solution for various industrial applications where only thin coating is required. In W-HVOF process, oxygen-propane or oxygen-liquefied petroleum gas (LPG) can be used as fuel gases. Present study was carried out using oxygen-LPG due to unavailability of propane in India.

Detailed information about the system and results of deposited coatings can be found elsewhere [5]. Forty experiments were performed using different spray parameters in order to get rounded/semi-rounded splats on rough surface to optimize the processing parameters primarily air flow, spray distance and wire feed rate. Optimized spray parameters are listed in **Table 1**.

Table 1: Optimized spray parameters for the W-HVOF sprayed Cu-splats

Spray Parameters	Values
Oxygen Flow	230 slpm
LPG Flow	55 slpm
Air Flow	550-650 slpm
Spray Distance	17.78 cm
Wire and size	Copper, 3.17mm
Wire Feed Rate	160 cm/min

Slpm* Standard liter per minute

The advancement of the W-HVOF process is that the temperature reaches at the melting point of the wire and due to high velocity, high degree of atomization take place; resulting in, complete melting and there are no unmelted or no semi-molten particles were found in the coatings. Further, to prove this statement, splats were collected on as-blasted rough surface and further studied. By controlling the spraying parameters, mainly the air flow, spray distance and wire feed rate, many types of splats were obtained. During optimizing the air flow, spray distance and wire feed rates were varied in the range of 300-700 slpm, 3-8 inches and 120-170 cm/min, respectively. The splat flattening behavior reveals that the droplet's kinetic energy and its molten status are critical in determining the splat morphology on a rough surface. It was also noted that the in-flight particle temperature and velocity at the point of impact have a significant effect on the final morphology of the splat. During spray parameters optimization at a higher particle velocity, many types of splash splats were obtained on grit blasted rough surfaces with different morphologies as shown in **Fig. 2 (a-h)**. Due to excess higher particle velocity splash splats with a center splat surrounded by a ring of fragments or numerous splash fingers connect with the central solidification core were formed as shown in **Fig. 2 (a-c)**. After controlling the spray parameters semi-disk-shaped splats were obtained, but not fully rounded and also having pores after the solidification as shown in **Fig. 2 (d-h)**, which leads porosity in the coating.

After forty numbers of experiments, fully melted semi-rounded disk-shaped splats with only a regular central disk were obtained on the grit blasted substrate surface under designated conditions. These spray parameters (**Table 1**) were identified as optimized spray parameters to deposit coatings. At these optimized spray parameters, droplet velocity and temperature were measured by SprayWatch (**Fig. 3**) and found to be 534 m/s and 2210^o C, respectively. These optimized spray parameters were also tested for four different traverse speeds at 0.30 m/s, 0.40 m/s, 0.45 m/s and 0.50 m/s, in order to investigate the splat formation mechanism at different traverse speed on a rough surface. Substrate temperature was maintained in between 30-50^o C by compressed air jet. From the **Fig. 4 (a-d)**, it can be seen that all four different gun travel speeds, fully melted semi-rounded disk-shaped splats were obtained.

No oxide contents were found in the XRD analysis. However, in thermal spraying generally, oxides are formed. In EDS analysis of Cu-splat, it was found that Oxygen content is very low that its peak does not appear in the results. Thus, it means high particle velocity (534 m/s) in the W-HVOF prevents oxide formation during the spraying. In the W-HVOF flame is reducing in nature, it means that supplied oxygen gas was fully consumed to build a proper flame. Further, it can be attributed to the fact that due to it is lacking oxygen in the flame retardant and a shorter dwelling of particles within the flame reduces in-flight oxidative processes. Controlling oxide formation in the thermal spraying process is the advantage of this W-HVOF system. Its well known that oxidation in the coating alters its electrical properties.

After splat optimization study, a thin metallic coating less than 50 μm was deposited on the low carbon steel substrate in order to investigate the coating microstructure and its mechanical properties. **Figure 4e** shows the cross-section of as-sprayed thin copper coatings. A very dense and micro-cracks free microstructures can be seen. Porosity in the coating found to be 1-2%. Bend test was performed as per ASTM E290-14 to check delamination characteristics of the thin Cu coating and it was considered as a test to check the adhesion strength of the thin coatings. Strip bend test of the thin Cu coating shows that generated cracks are minor and acceptable. The adhesion strength of the coating was tested using a portable PosiTest pull-off adhesion tester as per per ASTM-D4541, D7234, ISO 4624. The specimens were directly adhesive-bonded onto the Cu-coated substrate. The adhesion strength of thin Cu coatings was found to be 20 Mpa, which is good for thermal sprayed thin coating. Thin copper coating's other mechanical and electrical properties have been reported elsewhere [46-47].

In summary, splat formation and its flattening behavior of thermally sprayed metal wires have not been studied in details so far. Therefore, in the present work splat formation and flattening behavior of thermally sprayed Cu wire have been investigated on a rough surface. Cu-splats were collected onto a grit blasted low carbon steel substrate by using newly developed W-HVOF process (HIJET 9610[®]). After optimization study spray parameters were set to achieve semi-rounded disk like splats. Results show that no cracks were observed in the splat after solidification, complete melting take place and there are no unmelted particles were found. Furthermore, thin coating properties were tested. A uniform thin Cu coating ($\sim 35 \mu\text{m}$) was successfully deposited. Porosity in the coating is found to be 2-3%, adhesion strength of thin Cu coating is found to be 20 Mpa. In addition, bend test showed good coating bonding with the substrate.

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