Adhesion of Molten Metal Droplets Impacting a Stainless Steel Surface with High Velocity

Rajeev Dhiman, Sanjeev Chandra
Centre for Advanced Coating Technologies,
Department of Mechanical & Industrial Engineering,
University of Toronto, Toronto, Ontario, Canada.

Abstract

The adhesion of splats formed by impact of molten metal droplets was studied experimentally. Tin droplets (550 μm diameter) were produced using a drop-on-demand generator. To achieve high impact velocities the stainless steel coupons used as substrates were mounted on the rim of a rotating flywheel and heated using cartridge heaters. To hit a falling droplet with the substrate and photograph its impact, a timing circuit was used to synchronize three events with the position of the substrate: ejection of a droplet, triggering of the camera and a flash to provide illumination. The impact velocity was varied from 10 – 40 m/s whereas the substrate average roughness (2.0 μm) and the droplet diameter (~550 μm) were kept constant. We measured the adhesion strength of splats by a simple pull test. A wire was attached to the upper surface of each splat using epoxy and the force required to separate the splat from the substrate was recorded. A significant increase in adhesion strength was observed as the impact velocity was increased. Droplets formed circular splats when the surface temperature and impact velocity were both low. They broke up when velocity and surface temperature were both increased. At a given substrate temperature the final splat diameter increased as impact velocity was increased. This was attributed to the increased momentum of the droplet at higher impact velocities. Increasing the substrate temperature at a particular impact velocity leads to the splats breaking up, with the degree of rupture being greater at high impact velocities and substrate temperatures. Increasing surface roughness also promoted splashing of droplets.

1. Introduction

The high-speed impact of molten metal droplets onto a solid surface is a phenomenon encountered in numerous industrial applications such as spray forming and thermal spray coating. Molten droplets flatten as they impact, coalesce with each other and freeze, forming a dense layer. The shapes of the flattened splats formed are a function of both the roughness and temperature of the substrate, and the impact velocity of droplets.

Several experimental studies have examined splats formed by impact and flattening of individual molten metal droplets. Bianchi et al. [1] demonstrated that the shape of splats formed by spraying alumina or zirconia droplets from a plasma torch onto a stainless steel plate varied as substrate temperature was increased. Droplets landing on a cold substrate (below 100°C) splashed extensively after impact and had very irregular contours while those deposited on a hot surface (above 150°C) were disk-like, almost perfectly circular. Other researchers [2-7] also observed this change of splat shape and showed that the "transition temperature", above which disk splats were obtained, was a complex function of particle and substrate material properties [3], surface contamination [4,5] and surface oxidation [6]. Fukomoto, Huang and Ohwatari [7] conjectured that freezing along the bottom of an impinging droplet causes splashing: liquid flowing on top of the solid layer jets off and splashes. Delaying solidification, either by raising surface temperature or increasing thermal contact resistance at the droplet-substrate interface, is expected to suppress splashing. Kirchner and Prinz [8] studied the adhesion of steel droplets landing onto steel substrates from a height of 125 mm, and concluded that it is imperative to induce substrate remelting, by either superheating the droplet or pre-heating the substrate, to achieve strong metallic bonding between the droplet and substrate.

Though a large literature exists on thermal spray coating and spray forming, there have been few attempts to directly view molten droplets as they land on a solid substrate, freeze and coalesce to build up a deposit. Escure et al. [9] observed the impact of alumina droplets sprayed onto alumina/stainless steel substrates. Our objective in this study was to observe how impact velocity, substrate temperature and surface roughness affect splat shape and adhesion strength. We photographed molten tin droplets (0.55 mm diameter) as they landed onto two types of stainless steel coupons, one with a surface roughness (R_a) of 0.04 μm and the other with 2 μm. The impact and subsequent flattening of molten metal droplets as they hit a solid substrate is chiefly governed by Reynolds and Weber numbers. Table 1 below shows a comparison of the present study with typical thermal spray and spray forming processes.

Table 1: Dimensional comparision of present study with thermal spray & spray forming processes.

Parameter	Plasma Spray	HVOF	Wire-Arc	Spray Forming	Present study
D (μm)	50-70	20-50	50	60-100	550
V (m/s)	300-500	500-1000	100-200	100	10-40
Re (x10^4)	2.3-5.5	1.6-7.8	0.8-1.6	0.9-1.6	2.0-8.0
We (x10^4)	2.0-7.7	2.2-22	0.2-0.9	0.2-0.4	0.07-1.2

D: Droplet diameter
V: Impact velocity,
Re: Reynolds number,
We: Weber number

The droplet (powder) material for the plasma spray, high-velocity oxy-fuel (HVOF) spraying, wire-arc spraying and spray forming processes has been taken to be nickel, whereas the droplet material in the present study is tin. It is evident from the above table that the Reynolds and Weber numbers obtained in the present study are similar to some of the lower velocity industrial spray processes. The values for kinematic viscosity, surface tension and density of liquid tin (at 240^o C-the temperature of the droplet just before impact) and nickel (at the melting temperature=1455^o C) are shown in Table 2.

Table 2: Thermophysical properties of Nickel and Tin [10, 11].

Property / Metal	Density (Kg/m^3)	Surface tension (N/m)	Kinematic Viscosity x 10^{-7} (m^2/s)	Melting point (^{o}C)
Tin	6970	0.526	2.75	232
Nickel	7850	1.778	6.369	1455

We designed and built a molten metal droplet generator to produce tin droplets on demand. In order to achieve the required impact velocity, the substrate was mounted on a rotating flywheel. By synchronizing the time at which a droplet was ejected with the rotation of the flywheel, we ensured that the moving substrate hit airborne droplets with high velocity, and photographed the ensuing impacts. We varied substrate temperature (T_s=25-200°C), droplet impact velocity (10-40 m/s) and surface roughness (R_a=0.04 μm and 2 μm). We measured adhesion strength of individual splats.

2. Experimental Apparatus and Method

A schematic diagram of the experimental setup is shown in Figure-1 below. A droplet generator was used to produce uniform-size (~550 μm) tin droplets. The substrate was mounted on the rim of a flywheel to achieve high impact velocities. Catridge heaters were inserted into the back plate supporting the substrate to vary and control its temperature.

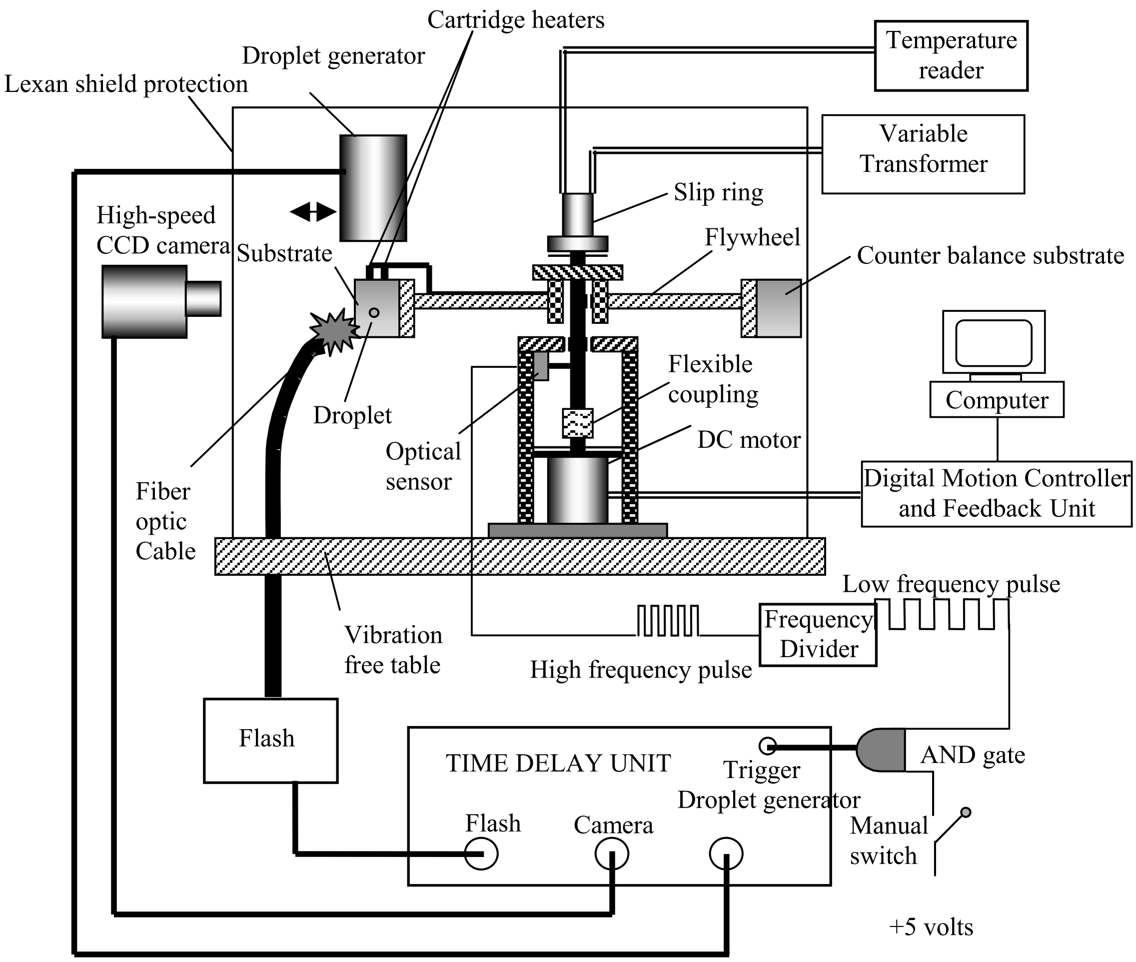

Figure 1: Schematic diagram of the experimental apparatus.

A CCD video camera was used to photograph droplet dynamics during impact. A timing circuit was employed to ensure the synchronization of droplet impact and triggering of the Flash and Camera. A detailed description of the apparatus has been given elsewhere [12].

The droplet generator was mounted on a horizontal traverse so that it could be moved back and forth at a constant speed to cover the entire test coupon with droplets and form an entire coating if required; alternately, we could deposit only a few droplets to examine individual splats. Figure 2 shows a photograph of a coupon with several splats on it.

To measure adhesion strength of individual splats, a short length of 1 mm diameter aluminium wire was attached to the splat with epoxy. Care was taken to ensure that the epoxy was confined to the splat only and did not reach the substrate. A small hole was drilled in the aluminium wire through which a thin steel wire was threaded (see Fig. 3).

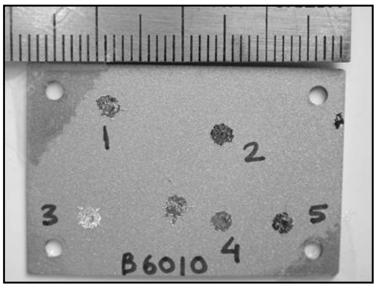

Figure 2: Tin splats (marked 1, 2, 3 etc) produced on a Grit-blasted S.S. substrate. Droplet Diameter ~ 550µm.

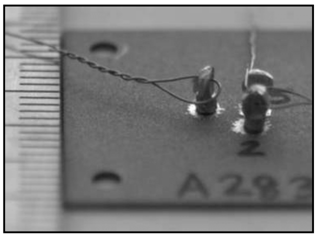

Figure 3: Small wire pieces glued onto the splats and a thin steel wire threaded through them subsequently.

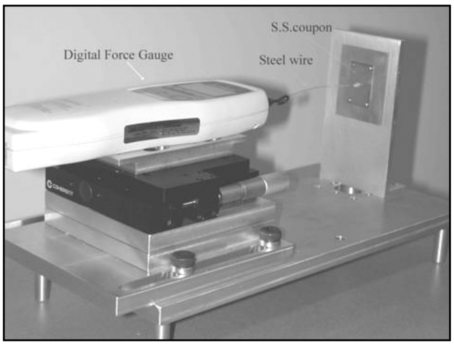

Figure 4: A simple Adhesion Pull test machine depicting the adhesion test being conducted.

The substrate was mounted on a vertical bracket and the steel wire attached to a digital force gauge (Fig. 4). The gauge was supported on a micrometer stage and moved at constant velocity using a stepper motor.

A tensile force was applied to the steel wire until the splat detached from the surface, and the force required to pull the splat off was noted. The area of the splat in contact with the substrate was measured with image analysis software by photographing the splat and importing the image into a computer. The adhesion strength was defined as the force required for detaching the splat divided by its area.

3. Results and Discussion

Figure 5 shows the effect of varying both impact velocity and substrate temperature on the shape of splats formed on the rough substrate (R_a = 2.0 μm). Each column shows splats deposited at one of four velocities (10, 20, 30 or 40 m/s). Each row shows splats deposited on surfaces at a different temperature, ranging from room temperature to just below the melting point of tin (232°C). At a given substrate temperature the final splat diameter increased as impact velocity was increased, since the molten droplet gains enough energy to overcome the barriers posed by the surface asperities. At 40 m/s, however, the initial momentum becomes so high that it significantly increases the splashing, resulting in considerable loss of material, and hence the final splat diameter gets reduced.

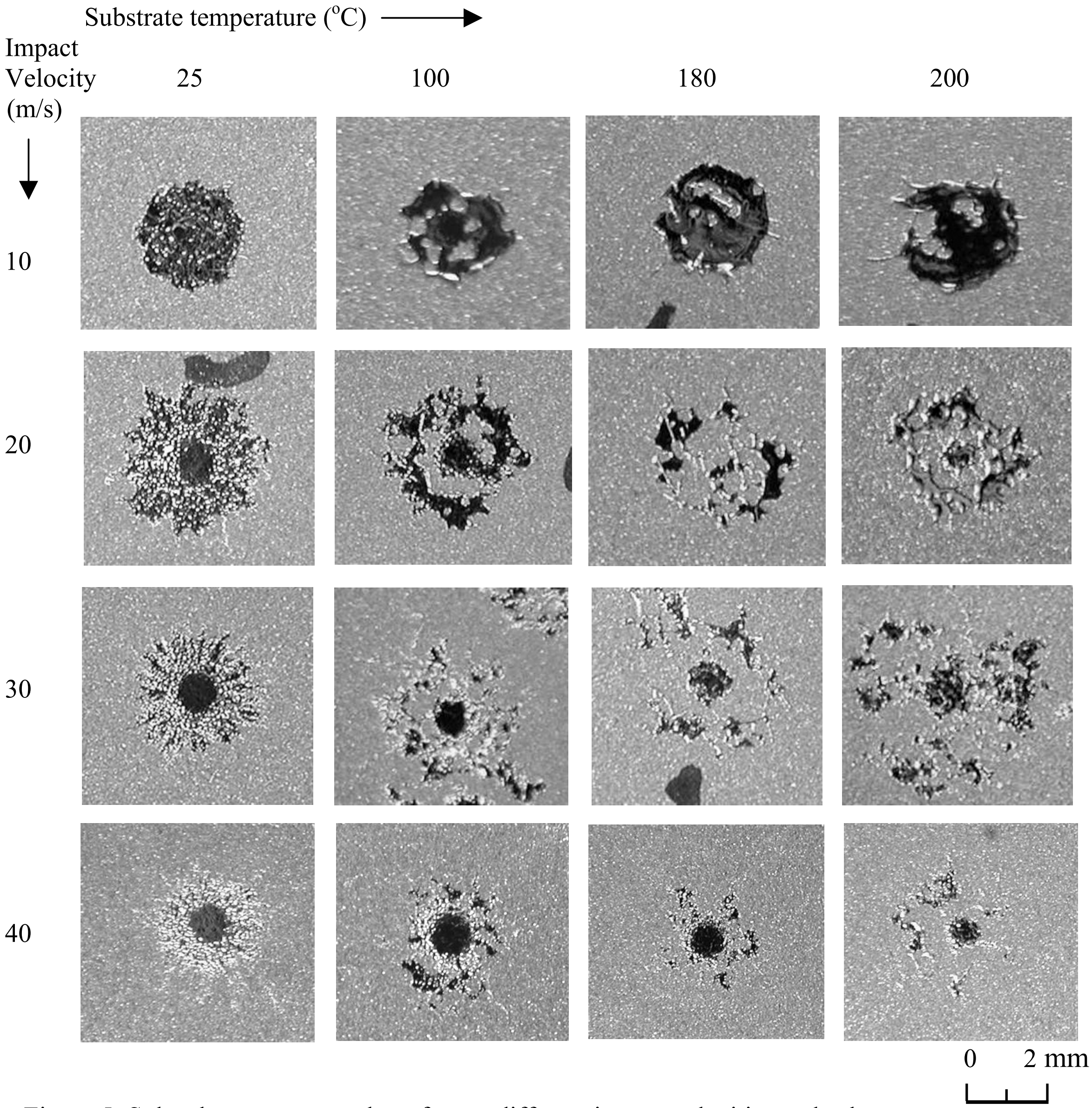

Figure 5: Splat shapes on a rough surface at different impact velocities and substrate temperatures (Droplet diameter ~ 550 μm, Substrate average roughness R_a = 2.0 μm).

Increasing the substrate temperature at a particular impact velocity leads to the splats breaking up, with the degree of rupture being greater at high impact velocities and substrate temperatures. At low substrate temperatures droplets solidify rapidly, and there is less time for the droplet to break up. As the substrate temperature increases the droplet remains liquid for a longer time, allowing the splat to rupture in several places. Also, as impact velocity increases, the increased momentum of the splat promotes splashing and fragmentation of the splat.

Increased impact velocity also promoted better adhesion of droplets to the substrate. Figure 6 shows the measured adhesion strength of splats impacting on a surface at a temperature of 25°C with velocities varying from 10 to 30 m/s. The adhesion strength increases by almost 600% over this velocity range. Each point in Fig. 6 is the average of 8 measurements. Error bars mark the maximum and minimum adhesion strengths measured. We could not measure adhesion strength on surfaces at higher temperature because the splats broke up after impact and we could not attach a wire to them.

The splat shapes were significantly different on the smooth polished substrate (R_a = 0.04 μm) as depicted in Fig 7. We observed a transition temperature of 160-170^o C at which the splat shape changed from splash-type to disc-type. Increasing the impact velocity and substrate temperature resulted in an increase in the final splat diameter. At low substrate temperatures (25 & 100^o C), rapid solidification of the impacting droplet restricts it from spreading freely. The splat characteristics were different at low (10 & 20 m/s) and high (30 & 40 m/s) impact velocities. Although the final splat diameter at these temperatures appears to be almost the same, its thickness was greater at low impact velocities, since there is a considerably less loss of material due to splashing.

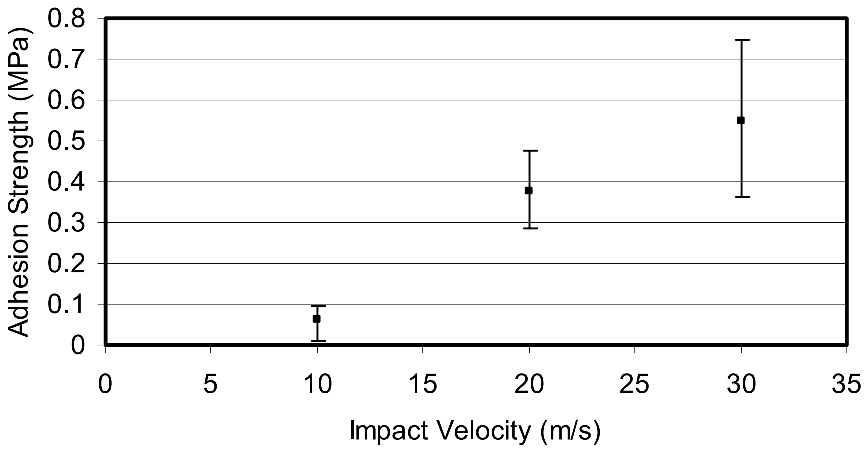

Figure 6: Variation of Adhesion Strength of a single splat with Impact velocity (Substrate temperature = 25^o C, Substrate average roughness R_a = 2.0 μm).

On the other hand, at high substrate temperatures (180 & 200^o C), the droplet stays in liquid state for a longer time, and hence can spread to a greater diameter. Also, now the final splat diameter increases significantly as the impact velocity is raised, until splashing becomes predominant when the final size of the splat starts to reduce again. In the extreme case, if the solidification is delayed (due to the increase in substrate temperature) so much that the droplet remains liquid even after its maximum spread, recoil results, which is evident when we compare the final splat shapes at 180 & 200° C in Fig 7, especially at an impact velocity of 10 m/s where almost all the material pulls back, accumulates towards the centre and eventually solidifies. This kind of recoil was not observed on the rough substrate (R_a=2.0 μm) since the surface asperities slow down liquid flow and restrict movement towards the centre.

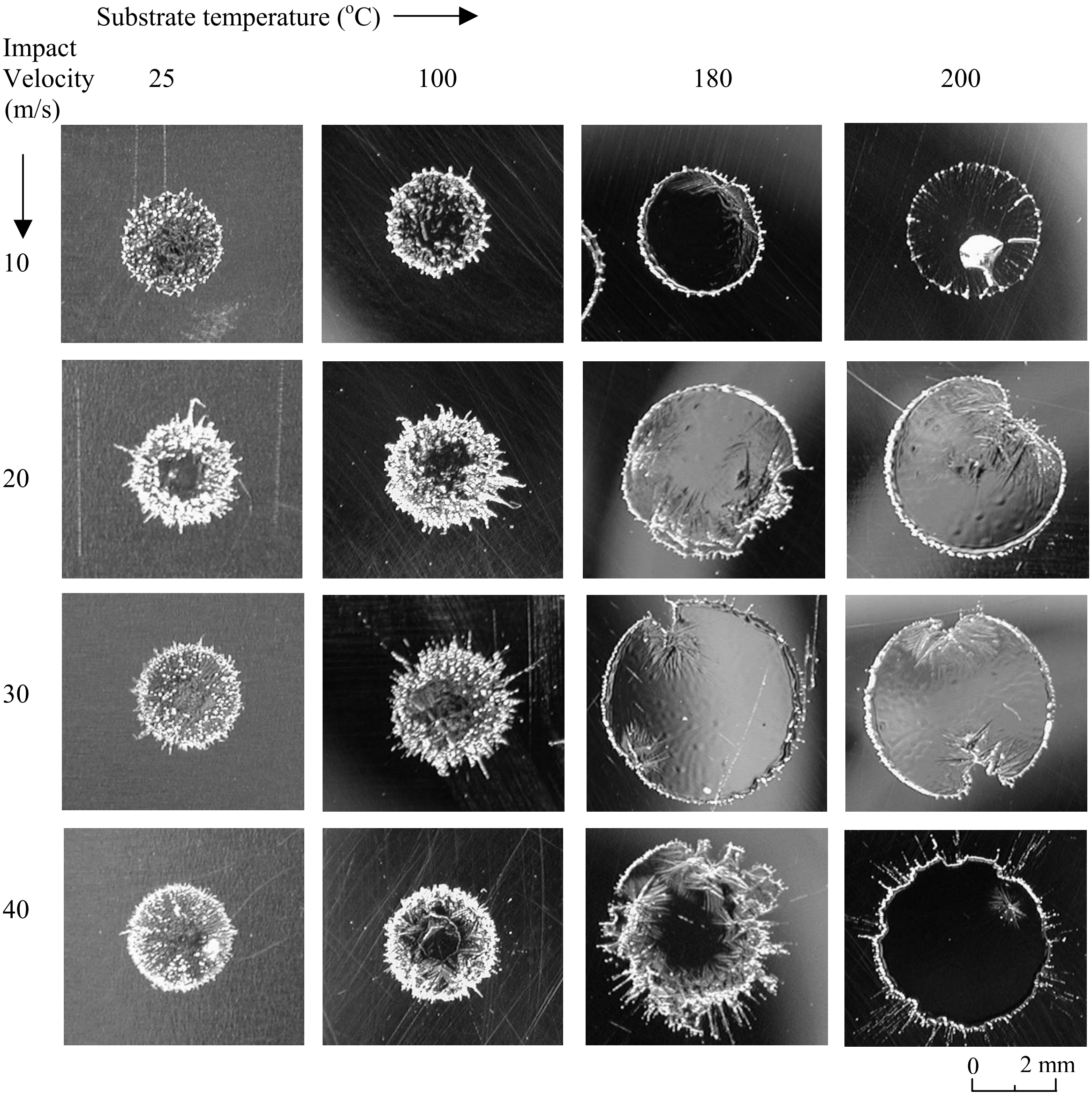

Figure 7: Splat shapes on a smooth surface at different Impact velocities and substrate temperatures (Droplet diameter ~ 550 μm, Substrate average roughness R_a = 0.04 μm).

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