Qualitative Analysis of Metal Droplet Impact on Non-Solid Surfaces

M. Kresina, G. Schulte, K. Bauckhage

Sonderforschungsbereich 372 / Universität Bremen,
Badgasteiner Str. 3, 28359 Bremen, Germany
email: kresina@iwt.uni-bremen.de

It is the aim of these studies to investigate metal droplet impact at target conditions that are suitable to simulate the droplet impact conditions of a spray forming process. In a qualitative analysis the influence of parameters like thickness of the powder layers, powder size, impact velocity and target temperature on the impact process is investigated.

1. Introduction

In spraying processes concerned with molten metal – like spray forming or thermal spraying – the resultant product properties (e.g. porosity, grain size, adhesions strength) are critically determined by the behavior of individual droplets impacting onto the surface of a growing product e.g. a billet. The outcoming impact phenomena depend on the physical and thermal properties of the droplet as well as the target conditions.
In order to attain thorough understanding of the interrelations of these parameters a large number of analytical, experimental and numerical studies have taken place in the past few decades. Most studies dealing with the impact of molten metal droplets are focused on droplet impact on flat and solid surfaces. Droplet impingement phenomena regarding the substrate conditions, are for example investigated in terms of surface roughness contact angle and substrate temperature [1,2]. A few investigations were done on droplet impact on non-flat surfaces and they revealed a spreading and splashing behaviour, distinctly different to that of flat surfaces (3,4,5)
However, under practical conditions present in spray forming processes these conditions of impact exist only very rarely. Droplet impact takes place on surfaces that are not even non-flat, they are also neither complete solid, nor complete liquid. The surface of the deposit can be considered as a changeable mixture of that and it is undergoing a permanent variation in its local conditions and structures. According to the current understanding of the spray forming process, the target area of a spray formed product - the so-called mushy zone – consists of three zones (Fig.1a): a *surface layer*, consisting of very small solidified particles, a *middle layer* with a semi-solid composition, where the target material still has mobility – like a particulate system - and the *bottom layer,* where there is given no more mobility of the material, this zone is characterized by fast diffusion processes due to the high temperatures [6]. While the tiny already solidified droplets of the spray will impact and remain on the surface, the larger - mainly liquid - droplets have sufficient kinetic energy to penetrate into the middle zone, entraining parts of the surface layer.

The investigations presented in this paper deal with the impact of single molten metal droplets on powder layers in an approach to the non-solid surfaces conditions present in spray forming processes.

2. Experimental investigations

Experiments were conducted, where individual lead droplets impacted on powder layers of glass particles under varying conditions. The influence of impact velocity, layer thickness, layer material, and target temperature is investigated.

2.1. Experimental set-up

To model a mushy zone, powder layers of glass spheres were used, which were varied in respect of layer material, thickness and temperature. Fig. 1a illustrates the mushy zone embedded in the process environment and the powder layer of the model experiment. The prepared layers were integrated into an experimental set-up with a drop generator (Fig. 1).

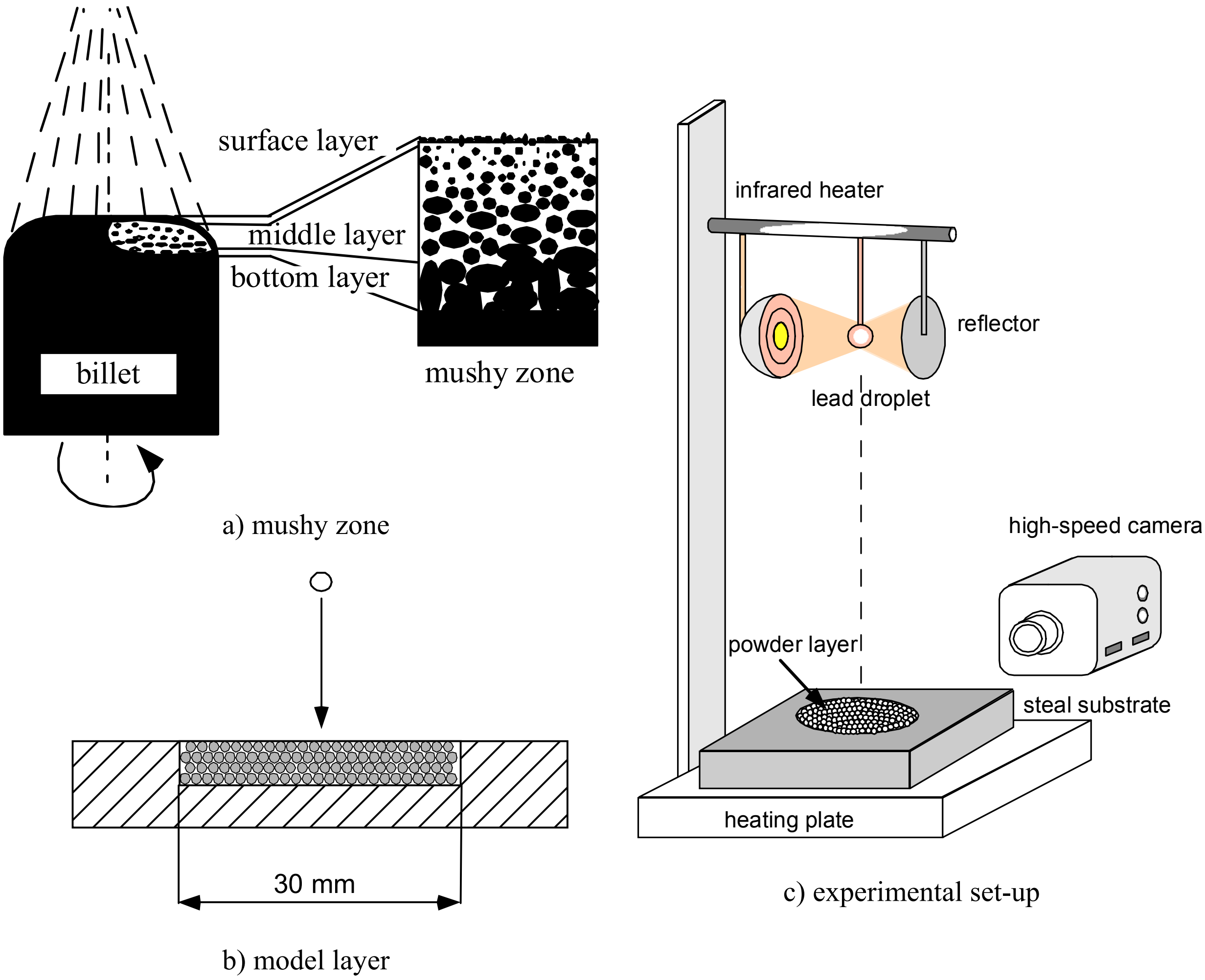

Fig. 1 Experimental set-up and target model

As drop generator a simple system, based on an infrared heater, is used. Solid particles are mounted at the tip of a temperature sensor and placed in the focus of the infrared heater. To achieve homogeneous melting, a reflector is used to melt the particle from both sides. In the liquid state, the particle forms a spherical droplet and falls under gravity. Drop diameters depend on the particle weight and were chosen to be 2.2 mm. The mean temperature of lead droplets at the moment of detachment is 483°C (standard deviation = 19°C) which corresponds to an overheating temperature of T_{oPb}.~ 150°C. The impact velocities (1.4 - 3.2 m/s) can be adjusted by varying the drop-off distance between melting set-up and target surface.

The target system comprises a steal substrate with 6 cylindrical cavities of different depth (1 – 10 mm) and glass spheres of different size fractions, which are filled into the cavaties, in order to get a defined layer thickness. The cavities have a radius of 30 mm which turned out to be sufficient to exclude an influence of the side walls on the impacting phenomena.

The target system can be heated from below by a heating plate, which allows temperatures up to 600°C. The temperature is measured at the top of the powder surface.

The time history of the impacting droplet is recorded using a Kodak Ektapro 4045 high-speed video system with a sequence set-up of 9000 frames/sec.

To compare the different outcomes of droplet impact on powder surfaces, the geometry of the created crown was measured directly, using the recorded images. Unlike in the case of liquid impact, it is not possible to define a maximum height or diameter of the crown. For this reason the geometry was measured from the pictures at a time of 10ms after the initial impact. Since there is no clearly formed rim at the crown, the height h_c was defined to be at the area where the powder sheet disrupts.

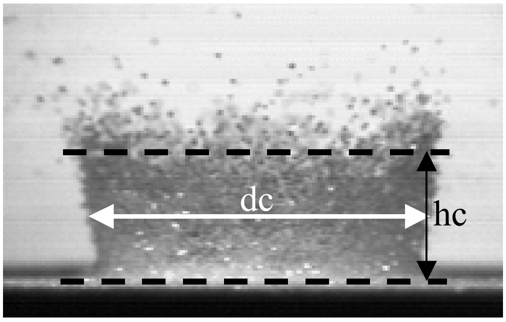

Fig. 2 Determination of height and diameter of the crown

2.2. Experimental results

To begin with, the outcome of droplet impact onto 4 principally different types of targets is described and compared. Fig. 3 shows 4 sequences of molten lead droplets (d_d=2.2mm) impacting with a velocity of 1.4 m/s on different kinds of targets. Each row of pictures shows successive stages of droplet impact with time from the initial impact indicated.

Sequence a) shows the impact of a lead droplet onto a solid steal target with an initial temperature of 25°C. After the first contact with the surface the droplet is flattening and spreading lateral in good contact to the surface. The maximum diameter is reached after 2 ms and no splashing can be observed. It can be assumed that solidification only sets in after reaching the maximum spreading diameter under the present conditions. From the present viewpoint, the complete process seems to be finished after 10 ms and the only change of the target is a slightly rise in the targets temperature due to heat transfer from the droplet [2]. Increasing the velocity up to 3.0 m/s [7] will lead to the onset of splashing. In that case secondary droplets are detaching from fingers that are formed around the edges of the splat.

Sequence b) illustrates the impact onto a solid waved surface with wavelength in the same order as the droplet diameter. The droplet hits the surface on the crest of a wave and spreads in radial directions with good contact to the surface. After reaching the adjacent wave crest, the liquid film spreads without surface contact, turns into lamellas and breaks up into secondary droplets, while the melt on the surface is contracting due to surface tension forces. Droplet impingement on an uneven substrate is almost always accompanied by splashing, it is

distinctly different from secondary drop formation on flat surfaces and it strongly depends on the local geometry at the point of impact [4].
In case of droplet impact on solid surfaces, the generated secondary droplets consist of the initial droplet material, hence the amount of material loss due to splashing is limited to the initial droplet mass.
In sequence c) a lead droplet is impacting into a shallow pool of molten lead. Shortly after the impact (200µs) while the droplet is just flattening to some amount a liquid rim is formed. After the droplet has completely disappeared in the liquid layer, a hemispherical crater is formed and the ejected volume of the pool builds a liquid sheet - the so-called crown - which rises above the original level of the liquid layer. After 2 ms the height of the crown reached its maximum while the diameter is still increasing. After the crown collapses, formation of a liquid column takes place in the center of the crater, and disappears again without splashing. In the case of droplet impact on liquid layers, splashing can be caused by detachment from the rim of the crown and the tip of the liquid column.

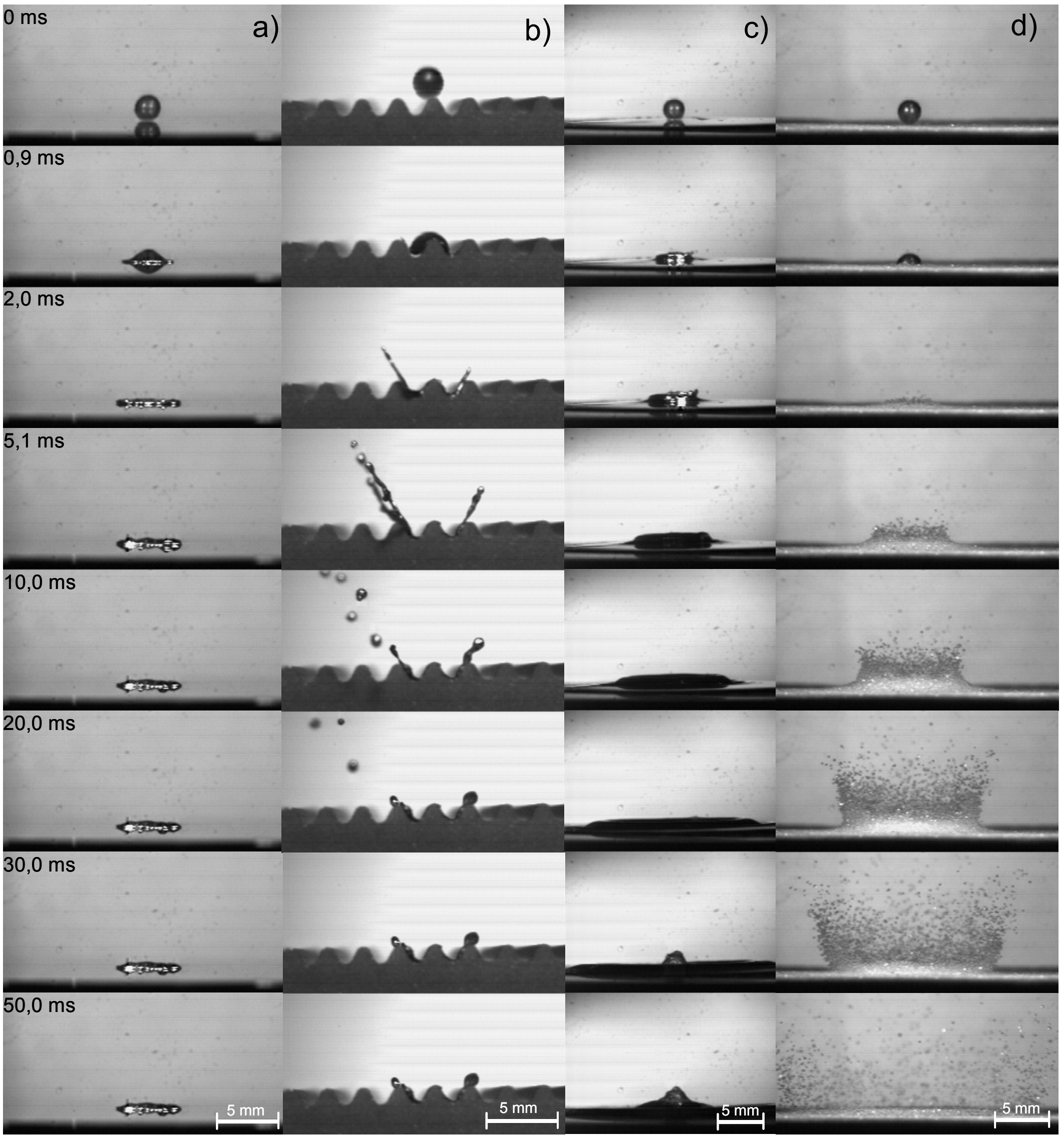

Fig. 3 Comparison of the droplet impact (d_d=2,2mm, v_d=1,4m/s) onto different targets
a) solid steal target, b) sinusoidal steal target c) layer of molten lead (thickness=3mm), d) layer of glass powder (thickness=3mm)

Sequence d) shows the impact of a metal droplet onto a 3 mm layer of glass particles (mean diameter 184 µm). Initially after the impact the droplet disappears quickly in the target powder, covering the powder particles below the point of contact. A hemispherical cavity with a radius much larger than the initial droplet diameter is formed, and in the circumference a cylindrical powder sheet rises up, furthermore referred to as the crown. Height and diameter of this crown are increasing with time. This part of the impact process is similar to the impact on liquid layers. But since there is no bonding between the particles and no such force as surface tension the height and diameter of the crown are larger. Also the crown is not "collapsing" after reaching a maximum height, but it is falling apart The inclination of the crown is changing with increasing time. While in the beginning the crown inclines to the inside, followed by a phase of vertical rising, after 20 ms the incline of the rising direction has changed to the outside. At this stage the crown starts to fall apart, unlike in the case of droplet impact on a liquid sheet, where the crown collapses after reaching a maximum height. The formation of a column does not take place. After the droplet falls into the powder layer it solidifies on the powder layer covering some particles, or – in the case of thin layers - it falls through the powder layer and spreads on the bottom and solidifies. Only at very low velocities and thin layers (1.4 m/s; 1mm), the droplet contracts after reaching a maximum spreading diameter due to surface tension forces, and may slightly bounce.
Fig. 4 shows the impact of lead droplets onto powder layers (mean diameter = 184 µm) of different thicknesses with a velocity of 2.4 m/s. Starting with a thickness of 1 mm it can be seen, that increasing the thickness of the layer results in a decreasing angle of inclination and

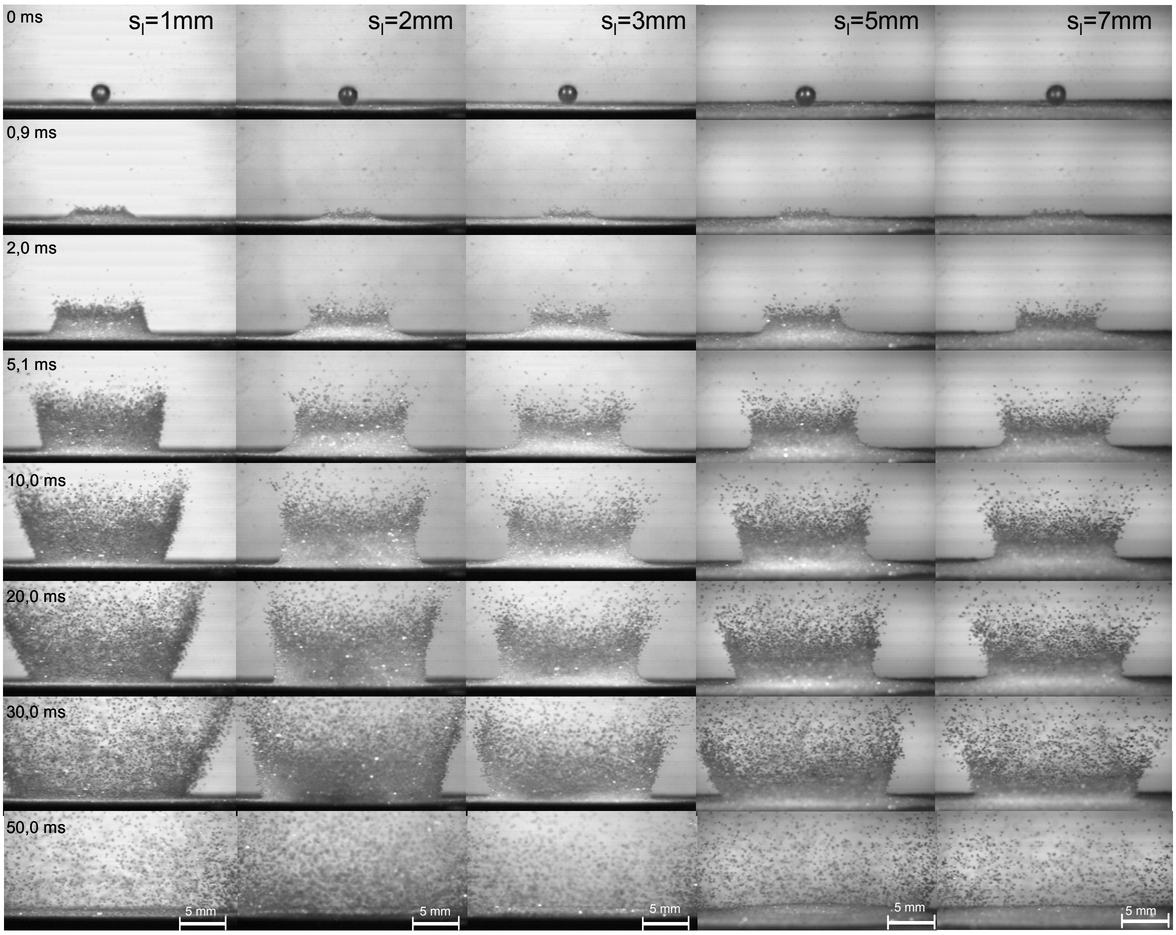

Fig. 4 Droplet impact (d_d=2,2mm, v_d=2,4m/s) at different layer thickness s_l (glass powder = 184µm)

a decreasing height and diameter of the powder sheet. The droplet looses, with deeper penetration into the powder layer, more of his incoming kinetic energy while at the same time the amount of powder particles available for flow ejection is increasing. As it can be seen from the sequences, exceeding a 5 mm thickness of the powder layer no longer leads to a significant change in the powder sheet formation. The droplet/powder layer interaction is no longer influenced by the ground below the layer, therefore somewhere between 3 and 5 mm there must be the threshold value for the transition from a layer to a pool under these impact conditions.

The results in Fig. 5 illustrate the influence of impact velocity on the crown formation. Height and diameter of the crown of powder – formed after 10 ms – are shown in dependency on the impact velocity for three different layer thicknesses.The crown height and diameter clearly increase with increasing impact velocity. For a 2 mm thickness of the layer, the height is varying from about 2.8 mm for the lowest velocity up to 5.3 mm for the highest velocity. The crown diameter formed by a 2 mm thick layer varies from 9.3 mm to 12.8 mm. It can also be seen from this diagram that, with increasing thickness of the powder layer, the crown diameter increases more slightly.

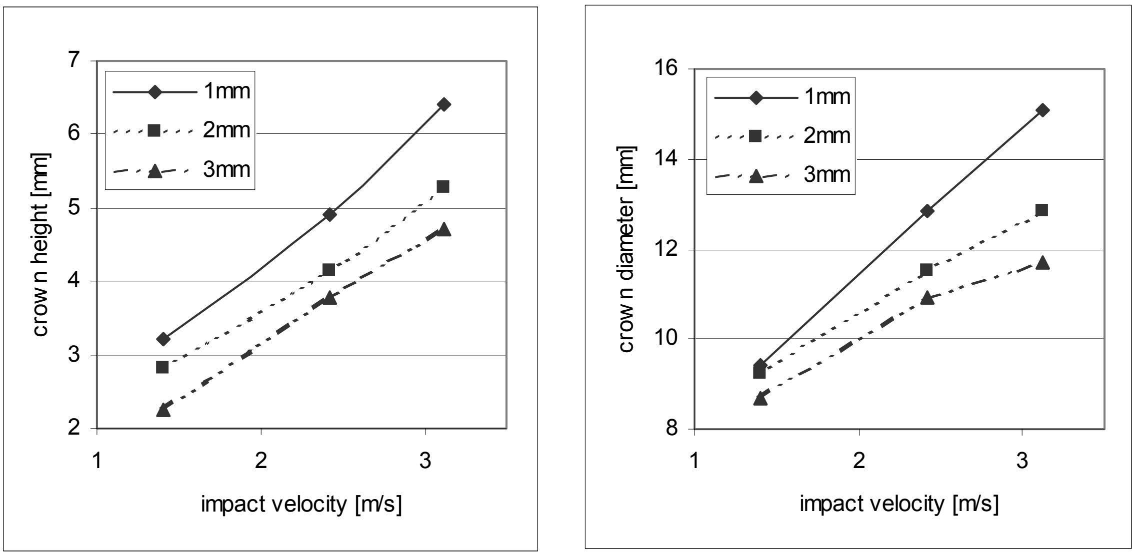

Fig. 5 Dependency of height and diameter of the crown on the droplets impact velocity

In Fig. 6 droplet impact on 4 layers of different particle sizes of the powder are shown. It can clearly be seen that the crown shows a maximum in height and diameter for a powder with a mean particle diameter of d_P = 184 µm (sequence b). Increasing the powder size leads to a decreasing height of the crown due to the higher inertia of the powder particles. For the impact onto a powder layer with a mean particle diameter of 720 µm, there is no significant crown anymore. The powder surface is disturbed, but only few particles are thrown away and loose complete contact to the surface. Further increase of the particles' size will no longer cause a flow ejection of the particles, since the kinetic energy of the incoming droplet will not be sufficient to impart an impulse. Impact on powder layers with a mean particle size smaller that 184 µm will result in a smaller height and diameter of the crown. It can be assumed that frictional force between the particles is increasing due to the smaller particle diameters which results in a larger contact area.

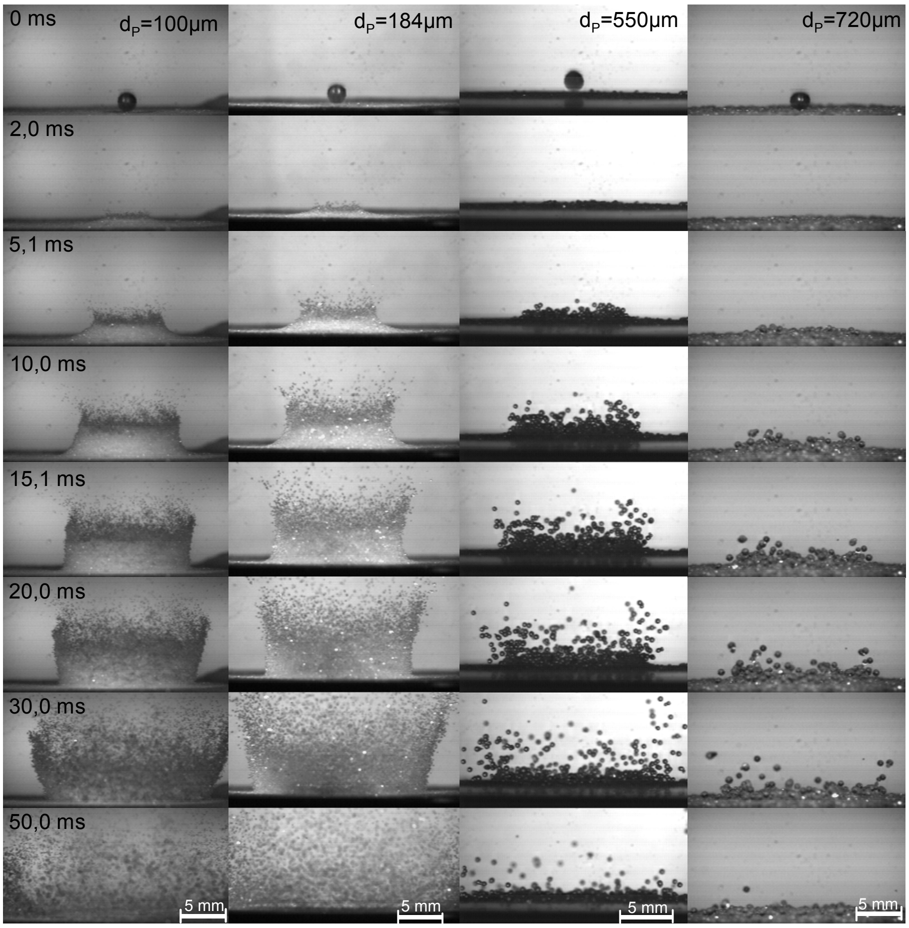

Fig. 6 Droplet impact (d_d=2,2mm, v_d=2,4m/s) onto layers of different powder size fractions d_P

A variation of the target temperature from 20°C to 350°C – which is 30°C above the melting point of lead – was investigated for layer of a 2 mm thickness. There is no evident influence of the target temperature on the crown formation at all. This observation proves that droplet solidification – under the present conditions - sets in after the spreading diameter of the lead droplet has reached its maximum. It has to be kept in mind, that the droplet's temperature is about 150°C above the melting point. For lower temperatures of the droplet, solidification will start at an earlier stage of the spreading process and may change with an increasing target temperature.

3. Summary / Conclusion

The impact of single molten lead droplets on powder layers with different properties was investigated. It was the aim of these studies to investigate the metal droplet impact at target conditions that are suitable to simulate the droplet impact conditions of a spray forming process. In a qualitative analysis, the results were compared with impact phenomena resulting from droplet impact on solid and liquid targets in order to find analogies to these cases which have been object of research in the last few decades.

The experimental results revealed that the outcome of droplet impact on powder layers exhibit principle similarities to impact on shallow liquid pools, especially in the first stage of crown formation. However, depending on the powder particles size the geometrical

dimensions of a crown of powder – height and diameter – exceed the dimensions of a liquid crown. Also in similarity to liquid layers, the crown's dimension increase with increasing velocity. Within the investigated thickness of the powder layers (1-10mm) increasing the thickness leads to decreasing dimensions of the crown up to a threshold value, which represents the transition from a layer to a pool of infinite depth. Under the present conditions, varying the target temperature up to the melting temperature of lead, shows no influence on impact phenomena at all.
Further studies will investigate the impact of droplets onto layers of metal powders and two-phase targets focusing on the effect of droplet and target temperature.

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4. References

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