

Injection of Overspray in a Metal Spray – Local Mass Flux and Enthalpy Distribution

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In recent research activities the spray forming process is extended by an injection facility to feed powder into the spray cone. The thermal changes by adding particles at room temperature into the metallic spray of atomized molten droplets is widely unknown. Overspray of CuSn13.5 had been injected with varied PMR (Powder to Metal mass flow Ratio) and GMR (Gas to Metal mass flow Ratio) keeping the melt mass flow of CuSn13.5 constant. Rows of calorimetric probes with molten tin as collecting medium were used to measure local mass fluxes and average specific enthalpies in the spray cone of a free fall atomizer. A strong radial decrease of local mass flux and average enthalpy within the spray cone was determined. The collected local and integral average specific enthalpy decreased with increasing PMR and GMR. The measurements also show an increase of the compacting integral enthalpy flow at a distance z from the atomizer by a raise of the PMR. This effect is based on the convective heat transfer from the atomized droplets to the surrounding gas phase and the subsequent heat transfer from the gas to the injected particulates.

1. Introduction

In the spray forming process a molten metal is atomized by a free fall atomizer to achieve high amounts of surface area of the molten metal droplets for the subsequent rapid convective cooling by the gas phase. A log-normal distribution of droplet sizes d_p [1] causes individual particle acceleration characteristics and thereby convective cooling rates and thus leading to a mix of liquid, semisolid and solid particles compacting at the deposit surface and generating the preform [2]. A key towards a control of the spray forming process is the knowledge of the energy balance at the deposit surface. This means the knowledge of the local compacting enthalpy flux as energy input into the deposit and the local convective heat transfer to the gas phase which flows around the deposit as energy output [3]. Because of the fast achievement of a thermal equilibrium in the mixing layer by conduction between the compacting particles and the deposit [4], an energy balance of these two effects would lead to a description of the average liquid fraction ε ($0 < \varepsilon < 1$) in the zone of deposition. The average liquid fraction describes the deformability of the incoming material forming a dense product and in addition it describes the physical condition of the deposit surface as a collector influencing the separation efficiency of particles out of the spray.

For example if all particles as well as the deposit would be solid (with $\varepsilon = 0$), the particles would bounce off the surface or would combine to a highly porous material. On the other hand, if all particles and the deposit would be liquid (with $\varepsilon = 1$), the molten material would not find a cohesion and flow off the rotating substrate by centrifugal forces. A realistic assumption of the average liquid fraction lies in a range of $0 < \varepsilon < 0.3$ (depending on the material properties), based on measurements of the surface temperature by two-colour pyrometers [5] or by thermocouples [6]. The variation in between these values defines the quality of the product [7] and the process yield [8], as mentioned before. The process yield is defined as the ratio of deposited mass to the melted mass. Nevertheless, particles missing the compaction are summarized under the so called overspray and need to be re-melted (if possible). Overspray masses in a range of 10 to 30 wt.% in ratio to the melt mass are reported for standard spray forming conditions [9].

Adding a powder feeding facility combined with a pneumatic transport system to the spray forming process, makes it possible to use the overspray powder inline by means of re-injection. In recent research activities billet preforms were spray-formed with injection of overspray powder up to $\text{PMR} = 0.3$ [10]. The billets showed a significant raise in porosity for increasing PMR, by changes in the average liquid fraction and local enthalpy. The thermal cooling effect by the injected overspray mass (at room temperature) was balanced by reducing the GMR. Lowering the GMR reduces the convective heat transfer of the atomized droplets to the gas flow by smaller amounts of overall droplet area based on bigger droplet sizes out of atomization) and lower heat transfer coefficients by smaller gas velocities. Balancing the PMR with the adjustment of the GMR resulted in a reduction of gas consumption of 20 % and a raise of the process yield of 15 % by compacting re-injected particle [11]. These significant improvements make it necessary to investigate the changes in mass flux and local enthalpy in the spray by variation of the PMR as a new important process parameter.

2. Experimental Procedure

A mesh fraction 45 to 90 μm of CuSn13.5 overspray powder [11] was taken and filled into a volumetric screw conveyor, a micrograph of the powder is shown in **Fig. 1**.

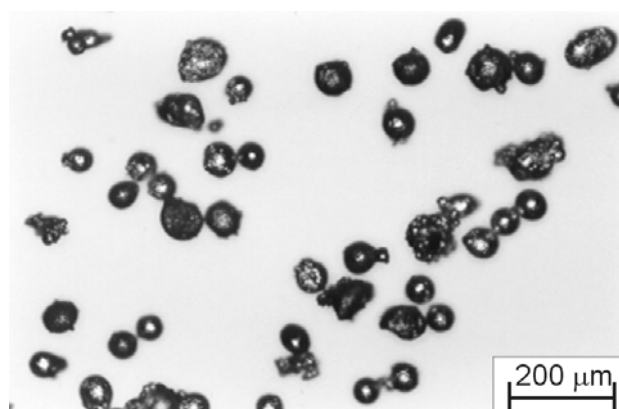


Fig. 1 Sieving analysis of the CuSn13.5 overspray powder, mesh fraction 45-90 μm .

The overspray powder was dosed into a conveyor pipeline by an injector and transported pneumatically towards a modified free fall atomizer, **Fig.2**. A third nozzle ring has been established concentric around the primary nozzle. This arrangement was chosen expecting the atomization nozzle sucking in the conveyed powder to the zone of disintegration and leading subsequently to a rotational symmetric and homogeneous “atomized droplets–injected particles” distribution in the far field of the spray cone. **Fig. 3** shows a photograph of the spray cone with a Gaussian shaped deposit at the bottom, as a visualization of the radial mass flux distribution.

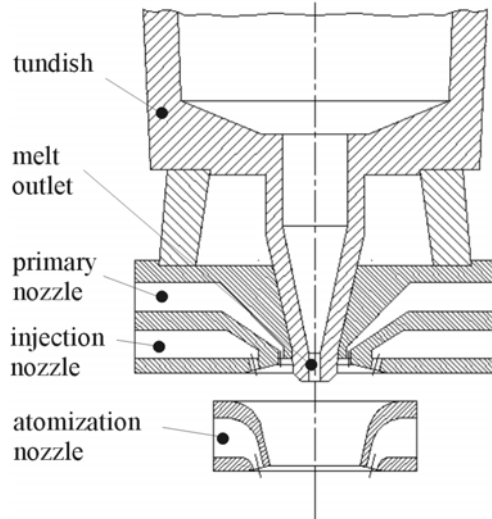


Fig. 2 Modified free fall atomizer.

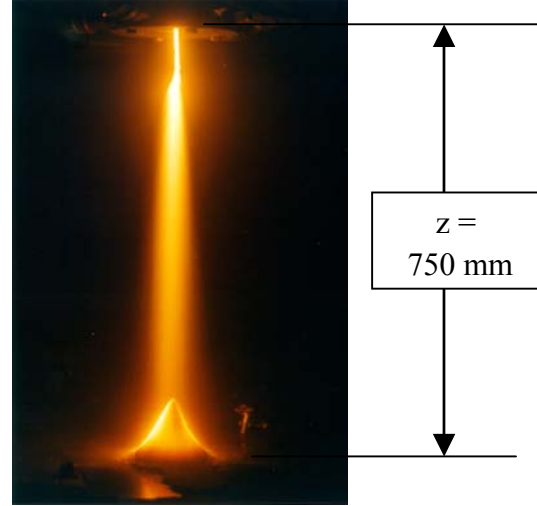


Fig. 3 Gaussian shaped deposit in the spray.

The commercial alloy CuSn13.5 (produced by spray forming) was chosen as melt material. A mass of 30 kg of the alloy had been melted and heated up to $T_M = 1140\text{ °C}$, which gave a superheat of $T_S = 155\text{ K}$ for a liquidus temperature $T_{liq} = 985\text{ °C}$. The density of CuSn13.5 is at 20 °C $\rho_{20} = 8800\text{ kg/m}^3$ and at 1140 °C approximately $\rho_{1140} = 7800\text{ kg/m}^3$. The average melt mass flow in the stationary experimental phase was $M_M = 720\text{ kg/h}$ with a maximum deviation of $\pm 3\%$ for different runs. The melt stream was disintegrated by nitrogen gas with a GMR = 1.15 and 0.85 for the varied PMR. The overspray powder was injected with PMR values of 0, 0.1, 0.2 and 0.3.

A caloric probe was developed by Buchholz to measure locally the average specific enthalpies of particles in metal sprays of steel and copper alloys [12]. Tin was used as collecting medium, because of its high boiling temperature in comparison to water and quench oil. Accuracy measurements were carried out by mixing experiments with a tin-tin melt. The measured temperatures showed a deviation of 5% from the calculated temperatures due to the heat loss of the probe [12]. Additionally, reproducibility experiments at an arc spraying plant and at the spray forming plant with the steel C35 were carried out and it showed a maximum deviation of $\pm 7\%$ [8, 12]. 4 Rows of 7 caloric probes were designed, based on the single probe principle. A row of caloric probes can be seen in **Fig. 4**. The probe head is made of brass and has a conical shape and a sharp edge to avoid particle agglomeration at the opening. In each probe tin granules are filled into a ceramic crucible which is positioned on an adjustable heating plate. In order to minimize heat losses the crucible and the heating plate are embedded by insulating material layers. A thermocouple (type K, diameter of 1 mm) with a quite good response characteristic (0.18 s to measure 90% of the temperature change in fluids) is placed at the bottom in the center of the crucible.

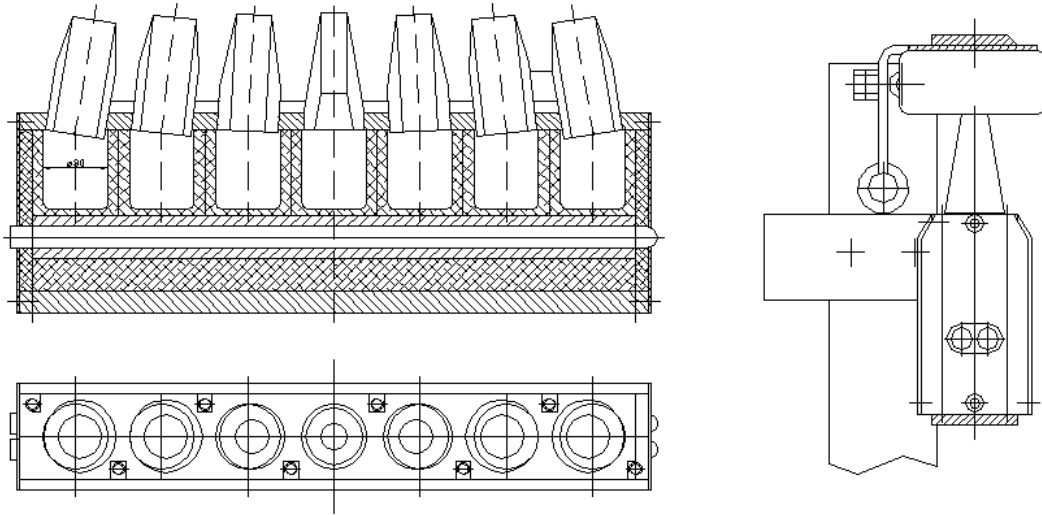


Fig. 4 Sketch of a caloric probe row.

The specific enthalpy measurement principle is based on a temperature measurement and thereby on the energy balance of the molten tin (Sn) and those particles (Pa) which impinge into the molten tin within the small tubes of the probe. The temperatures are measured for the conditions before and after particle penetration (Mix), respectively:

$$H_{Sn,Probe} + H_{Pa,Spray} = H_{Sn,Mix} + H_{Pa,Mix} + Q_{Convection} + Q_{Conduction} + Q_{Radiation} \quad \text{Eq. 1}$$

Rapid solidification and equilibrium temperature is assumed for the particles in the tin melt, because of the high conductivity. The heat losses due to convection (low temperature gradient between heated gas and molten tin $T_{Sn} \sim 300 \text{ }^{\circ}\text{C}$), radiation (temperatures below $500 \text{ }^{\circ}\text{C}$) and conduction (low thermal conductivity of the insulation material) are negligible and Eq. 1 simplifies to:

$$H_{Sn,Probe} + H_{Pa,Spray} = H_{Sn,Mix} + H_{Pa,Mix} \quad \text{Eq. 2}$$

The enthalpy H is defined as the product of mass M and the specific enthalpy h as a function of temperature T . Assuming the entire particle Mass in the spray cone is collected in the probe ($M_{Pa,Probe}$ is equal to $M_{Pa,Spray}$) and Eq. 2 solved for the average local enthalpy of the particles $h_{Pa,Spray}$ gives Eq. 3:

$$h_{Pa,Spray} = \frac{M_{Sn,Probe}}{M_{Pa,Probe}} \cdot [h_{Sn}(T_{Mix}) - h_{Sn}(T_{Probe})] + h_{Pa}(T_{Mix}) \quad \text{Eq. 3}$$

In the experiments about 80 g of tin in the probe crucibles were heated up to app. $300 \text{ }^{\circ}\text{C}$ and positioned in a distance of $z = 750 \text{ mm}$ from the tin melt level to the atomizer. Through molten droplet penetration, the tin melt temperatures raised up to a maximum of $450 \text{ }^{\circ}\text{C}$. The specific enthalpy for a molten material is defined as:

$$h(T) = \int_{\vartheta=T_B}^{T_{sol}} c_p(\vartheta) \cdot d\vartheta + \Delta h_{latent} + \int_{\vartheta=T_{liq}}^T c_p(\vartheta) \cdot d\vartheta \quad \text{Eq. 4}$$

In Eq. 4 is $T_B = 20\text{ °C}$ the reference temperature, for pure Sn is $T_{\text{sol}} = T_{\text{liq}} = 232\text{ °C}$ the solidus and liquidus temperature and $\Delta h_{\text{latent}} = 60,1\text{ J/g}$ the latent heat. In **Fig. 5** the heat capacity c_p and the specific enthalpy h of Sn and CuSn13.5 over the temperature range from 20 to 600 °C is shown [13].

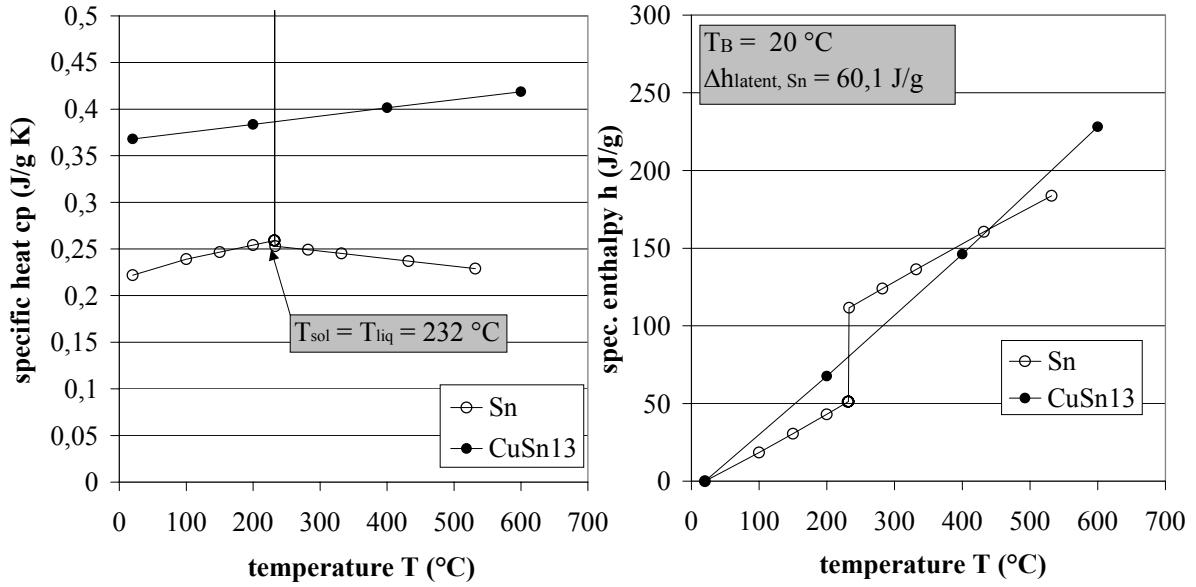


Fig. 5 Specific heat c_p and specific enthalpy h versus temperature T of Sn and CuSn13.5.

Besides the specific enthalpy h the local mass flux of the particles in the spray cone can be determined by measuring the collected particle mass $M_{\text{Pa,Probe}}$ and the sampling time Δt :

$$\dot{m}_{\text{Pa,Spray}} = \frac{M_{\text{Pa,Probe}}}{\Delta t} \quad \text{Eq. 5}$$

The integral enthalpy flow of the collected particles in a distance z to the atomizer is the rotation-integral of the product of the average local specific enthalpy and the local mass flux. The integral enthalpy flow $\dot{H}_{\text{integral}}(z)$ in ratio to the melt enthalpy flow \dot{H}_0 out of the tundish towards the atomizer depends on the melt flow $\dot{M}_M = 720\text{ kg/h}$ and its specific enthalpy $h(T_M) = 641\text{ kJ/kg}$ at the temperature $T_M = 1140\text{ °C}$ of CuSn13.5:

$$\frac{\dot{H}_{\text{integral}}(z)}{\dot{H}_0} = \frac{2 \cdot \pi \int_0^r h_{\text{Pa,Spray}}(r) \cdot \dot{m}_{\text{Pa,Spray}}(r) \cdot r \, dr}{\dot{M}_M \cdot h(T_M)} \quad \text{Eq. 6}$$

The physical state of the spray at the region of deposition has to be at an average liquid fraction of app. $\varepsilon = 0$, as mentioned earlier. This means a average specific enthalpy of $h = 362\text{ kJ/kg}$ at $T_{\text{sol}} = 910\text{ °C}$ for CuSn13.5. The ratio of the enthalpy flow at the deposition region to the enthalpy flow towards the atomizer, taking the injected particle and melt mass flow into account, respectively:

$$\frac{\dot{H}(\varepsilon=0)}{\dot{H}_0} = \frac{\dot{M}_M \cdot \text{PMR} \cdot h(T_{\text{sol}})}{\dot{M}_M \cdot h(T_M)} = \text{PMR} \cdot \frac{h(T_{\text{sol}})}{h(T_M)} \quad \text{Eq. 7}$$

3. Results

In Fig. 6 the measured local mass fluxes versus spray cone radius for varied PMR and GMR are shown. The local mass flux strongly decreases with growing radius and at $r = \pm 108$ mm almost no particles were collected anymore. The raise of injected overspray mass results in an increase of the maximum mass flux in the center of the spray cone at $r = 0$ mm. A decrease of the GMR from 1.15 to 0.85 reduces the mass flux in the center independent of the PMR.

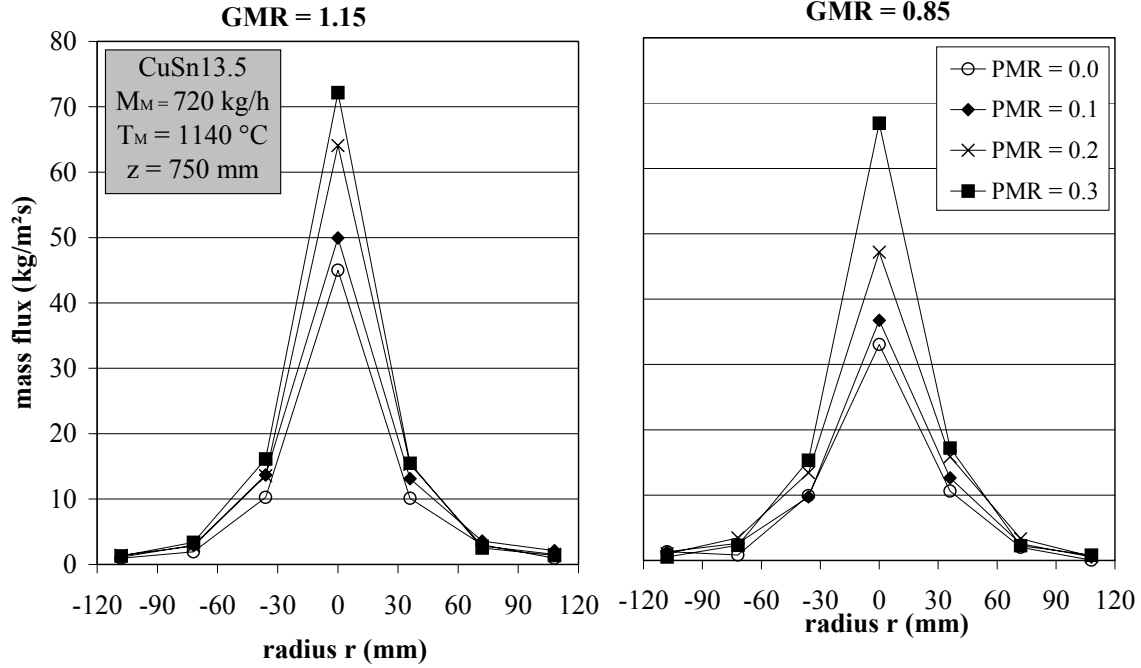


Fig. 6 Local radial mass flux distribution at a distance $z = 750$ mm.

The low amounts of collected mass of the probes at $r = \pm 108$ mm made it impossible to determine the specific enthalpy h accurately. The measured local average specific enthalpies h of the collected CuSn13.5 particles versus spray cone radius at the varied process parameters are shown in Fig.7.

It can be seen that the injection of cold overspray particle mass into the process quantified by the PMR reduces the local specific enthalpy h in the spray. Lowering the GMR results in a slight increase of the local specific enthalpy in the center of the spray at $r = 0$ mm. The reduced convective heat transfer caused by lower gas velocities and bigger droplet sizes can mainly be recognized by the increase of the specific enthalpy h at $r = \pm 36$ and 78 mm.

The product of the determined local mass flows and the specific enthalpies leads towards the integral enthalpy flow. The calculated ratios of $\dot{H}_{\text{integral}}(z) / \dot{H}_0$ (see Eq. 6 with $r = 78$ mm) versus PMR are shown in Fig. 8.

The compacting enthalpy flow increases with raised PMR and lowered GMR. Increasing enthalpy flow by reduced GMR is based on the reduced convective heat transfer in the spray. Particles injected at room temperature into the spray of molten droplets are heated by the convective heated gas phase or by conduction in the case of particle collisions. The enthalpy

transferred to the injected particles does not bypass the collecting probe or deposit like the gas phase does.

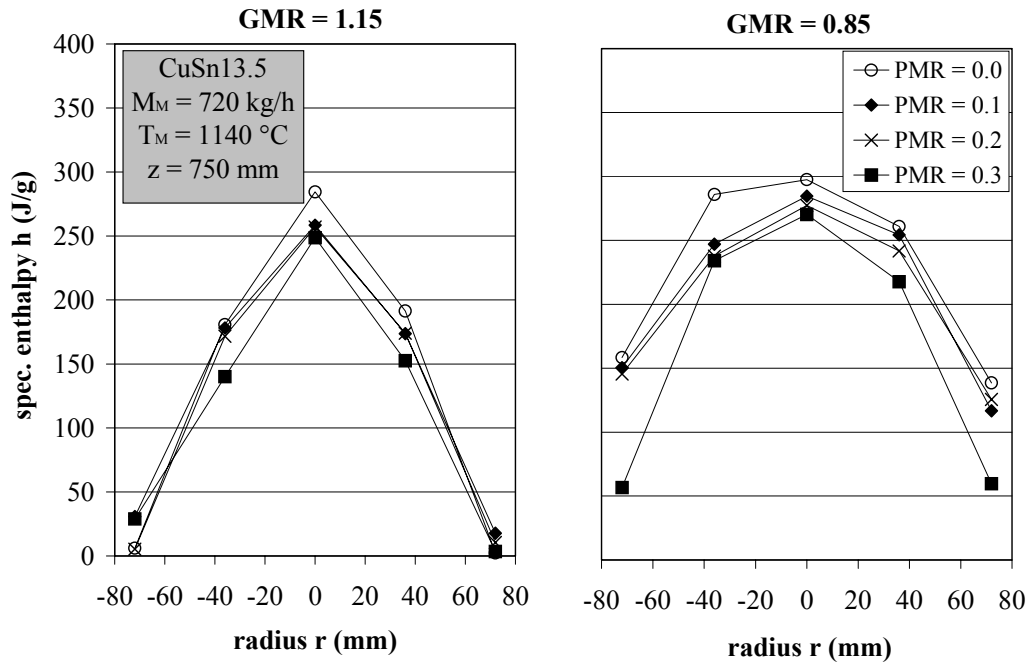


Fig. 7 Average specific particle enthalpy h versus radius in a distance $z = 750$ mm.

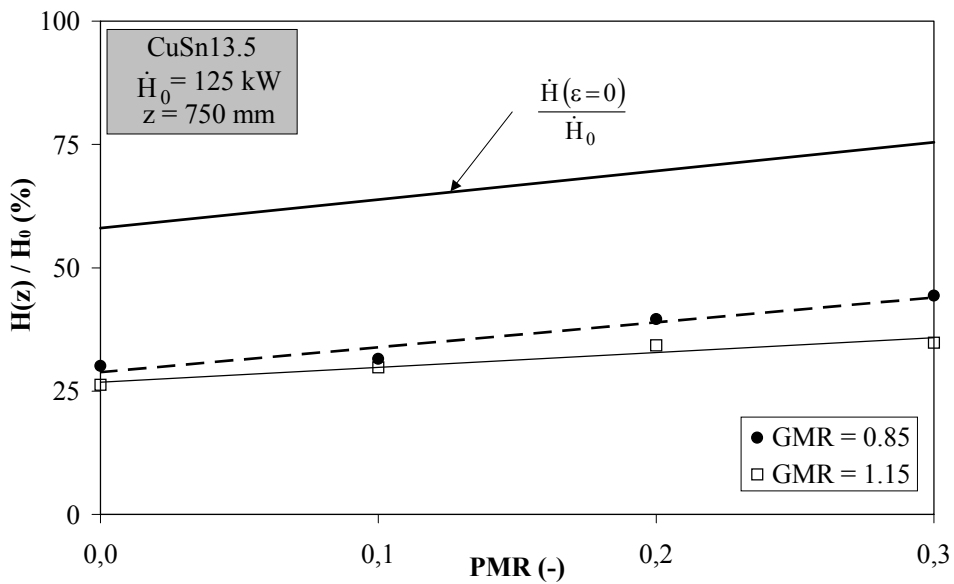


Fig. 8 Integral enthalpy flow ratio $\dot{H}(z)/\dot{H}_0$ at $z = 750$ mm versus PMR.

Additionally, a line is shown in Fig. 8 which gives the hypothetical enthalpy flow ratio which is assumed to be needed for acceptable compaction conditions with an average liquid fraction of $\epsilon = 0$, see Eq. 7. In the spray forming process these thermal conditions are achieved by positioning the deposit in a closer distance of for instance $z = 400$ mm [10,11]. Because of the aggressive environment of a much denser spray closer to the free fall atomizer it is not possible to position the calorimetric probes in such distances. Calculating the thermal state of the spray closer to the atomizer for $z = 200$ to 750 mm by numerical simulations of the two phase flow will be done in the future.

4. Summary

CuSn13.5 overspray particles at room temperatures have been pneumatically injected by a modified free fall atomizer into the zone of atomization of a CuSn13.5 melt stream. In the spray downstream from the disintegration of droplets and from the injection of particles rows of caloric probes have been positioned in a distance of $z = 750$ mm. The local mass flux and average specific enthalpy had been determined for varied GMR and PMR and showed a strong radial decrease. The maximum mass flux in the center of the spray increased with increasing PMR and GMR. An inverse effect showed the results of the average specific enthalpy due to the cold injected mass. A significant increase of the average specific enthalpy had been recognized in the periphery of the spray for a reduced GMR. The measurements also show an increase of the enthalpy ratio $\dot{H}(z)/\dot{H}_0$ by a raise of the PMR. This effect is based on the convective heat transfer from the atomized droplets to the surrounding gas phase and the subsequent heating of the injected particles. The description of the thermal state in the spray closer to the atomizer will be done in the future by numerical simulations of the two phase flow.

5. Acknowledgements

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6. References

- [1] **Ziesenis J., Bauckhage K.** *Absorption and Scattering of Light by Highly Concentrated Two-phase Flows*, Particle Characterization & Particle Systems, 2002
- [2] **Uhlenwinkel V., Buchholz M., Kramer C., Bauckhage K.** *The Characterization of the Spray Cone of a Free Fall Atomizer and its Influence on the Spray Forming Process*; Proc. Int. Conf. on Powder Metallurgy, PM²TEC, Granada, Spain, 1999
- [3] **Meyer O., Schneider A., Uhlenwinkel V., Fritsching U.** *Convective heat transfer from a billet due to an oblique impinging circular jet within the spray forming process*; International Journal of Thermal Science, in press
- [4] **Xu Q., Gupta V., Lavernia E.** *Thermal Behaviour During Droplet-Based Deposition*; Acta Materialia, Nr. 48, pp. 835-849, 2000
- [5] **Buchholz M., Ellendt N., Uhlenwinkel V.** *The Effect of Deposit Temperature on the Sticking Efficiency during Spray Forming*;
- [6] **Mingard K. P., Alexander P. W., et al.** *Direct Measurement of Sprayform Temperatures and the Effect of Liquid Fraction on Microstructure*; Acta mater., Vol. 46, No. 10, 1998
- [7] **Cai W., Lavernia E.** *Modeling of porosity during spray forming*; Materials Science and Engineering, A226-228, pp. 8-12, 1997
- [8] **Buchholz M.** *Untersuchung des Kompaktieverhaltens an sprühkompaktierten Bolzen*; Phd - Thesis, Universität Bremen, 2002
- [9] **Hummert K.** *Sprühkompaktieren von Aluminiumwerkstoffen im industriellen Maßstab – Stand der Technik*; Kolloquium des SFB 372, Band 1, pp. 199-215, Universität Bremen, 1996
- [10] **Uhlenwinkel V., Schneider A. et al.** *Effect of Particle Injection during spray forming of Cu - Sn Billets* Proceedings of the Int. Conf. PM²TEC, Orlando, 2002.
- [11] **Schneider A., Uhlenwinkel V. et al.** *Overspray Injection in Spray Forming - Study on the Effects in CuSn13,5 Billets*, Proceedings of the SDMA2003 + ICSF V, Bremen, 2003, in Press.
- [12] **Buchholz M., Uhlenwinkel V., v. Freiberg A., Bauckhage K.** *Specific enthalpy measurement in molten metal spray*; Materials Science and Engineering A326, 2002
- [13] **Mills K.** *Recommended values of thermophysical properties of selected commercial alloys*; Woodhead Publishing, ASM International, Ohio, USA, pp. 233-244