On-line Control of the spray forming process using phase-Doppler-anemometry

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The phase-Doppler technique is used for both analyzing and controlling the atomization result occurring during spray forming. Throughout this process a liquid metal jet is disintegrated by high-speed gas jets creating a wide size distribution of liquid droplets. Then, the metal droplets are caught by a substrate situated downstream in the spray thereby forming a metallic preform. The phase-Doppler technique is used to characterize the spray of metal droplets with regard to the size and velocity distributions of the particles. In addition, process quantities as particle flux and mass flux can be evaluated. In this work phase-Doppler-anemometry has been established as an important part of a detailed on-line process control as well as an important tool for analyzing the atomization process allowing the improvement of the entire procedure.

1. Introduction

Processes like spray drying, liquid extraction, powder metallurgy or spray forming, are significantly influenced by heat and mass transfer processes. The kinetics of these transport mechanisms can be clearly enhanced by increasing the fluid interface, i.e. by atomizing the corresponding fluid. With the aim to upgrade, to optimize and to control these disintegration processes the current transport phenomena of heat and mass have to be described and understood, supported by experimental data. In case of spherical particles dispersed in optical homogenous fluids (which is the result of most atomization processes) phase-Doppler-anemometry (PDA) is a suitable tool to create an adequate data background enabling the mentioned increase of process efficiency.

In the present work the atomization occurring during spray forming is on closer examination. During spray forming experiments liquid metal is atomized by inert gas. Subsequently, the liquid metal jet is disintegrated by high-speed gas jets causing a wide size distribution of liquid droplets. After disintegration the metal droplets are accelerated by the gas jets towards a substrate where the solid, liquid and partially solidified particles impinge and consolidate to form a growing deposit. Depending on the movement of the substrate relative to the atomizer, a material of different geometries can be produced, e.g. tubes, billets, sheets and plates. Detailed information concerning spray forming can be found in [1].

Some benefits of spray forming are:

- fine grain size
- low segregation
- near-net-shape capability

and typical fields of application are the manufacturing of products like tubes being employed in power stations and for offshore use. Other fields of use can be found in the automotive industry [2]. In **Fig. 1** a spray formed billet (the preform) and a cylinder liner (the final product) manufactured by the PEAK Werkstoff GmbH are depicted.

Fig. 1: Spray formed billet and a cylinder liner made from a spray formed billet (PEAK Werkstoff GmbH)

The properties of spray formed material are decided by cooling and solidification conditions [1]. Hence, the thermal conditions of the particles and the deposit must be controlled in order to manufacture a high-quality product. Since the heat transfer from the particles to the atomization gas is strongly dependent on the particle surface relative to its volume, particle cooling as well as solidification essentially depends on particle size. Consequently, the particle distribution that emerges during molten metal atomization substantially controls the thermal conditions in the spray and deposit, respectively. Provided, that the process parameters are set to certain values and are held constant throughout the process, the particles are hitting the deposit in a desired energetic status. Keeping such suitable process conditions, a high-graded deposit with regard to superior material properties can be produced.
However, unavoidable fluctuations of the process parameters directly affect the atomization result equating with a significant change of the heat exchange conditions between the particles and the ambient gas phase. The resulting disturbances of the entire process energy balance may lead to a deposit with an inhomogeneous microstructure. With the aim to analyze and to control the atomization process, the PDA technique can be employed to improve process insight. Furthermore, this technique can be used to control the disintegration process with regard to undesired process conditions [3, 4].

2. Phase-Doppler-anemometry

Both the fundamental principle and details of PDA have been reported elsewhere [5, 6] and therefore will not be discussed in this paper. Instead, some brief comments are made concerning the special requests of a PDA, which is employed during liquid metal

atomization: The highly concentrated environment of the PDA measurement volume and the rough surface of single solidified particles are affecting the signal response of the PDA. Thus, a special Fourier based signal analysis is necessary, enabling the detection of the PDA bursts embedded in the noise-infested signal band [7]. Furthermore, the disturbing influence of particles circulating in the spray chamber (but outside the spray cone) has to be eliminated using a beam protecting dust shield [8].

3. Spray analysis using PDA

Applying this modified and extended PDA to the spray forming process, reliable results can be obtained, characterizing the atomization result. To illustrate the capability of PDA to improve process insight, in this section the PDA technique is exemplary used to support atomizer development. For this, a close-coupled-atomizer (c-c-a) is compared to a free-fall-atomizer (f-f-a), schematically shown in **Fig. 2**.

3.1. Atomizer systems

In general, the f-f-a is used for spray deposition. One of the most important reasons is the possibility of scanning the atomizer in order to produce different deposit shapes. Nevertheless, it is worth to mention that f-f-a has some disadvantages and limits, especially concerning the high gas consumption. Since the manufacturing of other geometries as for instance tubes requires no scanning, in addition c-c-a systems can be employed avoiding some of the disadvantages of free-fall-atomizers, i.e. gas consumption can be reduced [9].

3.2. Results

In the following some results are presented obtained during both f-f-a and c-c-a experiments. The chosen parameters are summarized in **Table 1.** Typically the pressure in the atomization nozzle is much lower for the f-f-a. Nevertheless, due to the design of the different atomizers the gas flow for the f-f-a is much higher resulting in an increased gas to metal ratio GMR. The differences in melt flow, distance between atomizer and substrate, and superheat of the melt can be neglected.

Table 1: Process parameters for spray forming 100Cr6 (1%C; 1.5%Cr) with c-c-a and f-f-a.

	experiment	gas pressure	gas flow	GMR	melt temperature	nozzle diameter
c-c-a	660	1.6 MPa	0.032 kg/s	0.26	1700 °C	3.5 mm
f-f-a	547	0.4 MPa	0.22 kg/s	1.39	1638 °C	4 mm

In **Fig. 2** the PDA measured velocity of the atomized particles is correlated to the corresponding diameter. In case of the particles generated by the c-c-a both individual particle velocities and the resulting mean value are presented. In order to achieve a clear arrangement, the particle velocity measured inside the spray of the f-f-a is only represented by the mean value. Due to the greater inertia of masses the physics gives rise to the fact that larger particles are slower than smaller ones. Comparing the particle velocities realized by the close-coupled-atomizer ($v_{1,0} = 55$ m/s) to these one reached during f-f-a ($v_{1,0} = 63$ m/s), only a slight variation can be made out. This may be a result of the significant reduced

GMR, i.e. observing the c-c-a only a low amount of gas has to accelerate a lot of particle mass. Taking conservation of momentum in consideration this is leading to a rapid decrease of the velocity of the carrier phase equating with reduced particle velocities.

As a measurement system counting individual particles, PDA measurements give additional information concerning the number of particles passing the probe volume per time unit, enabling determination of the particle flux and (considering the particle diameter and its density) the mass flux. In **Fig. 3** the PDA measured radial mass flux distribution is summarized. It is worth to mention that as a rule the PDA measured mass flux is lower than the real one[1]. This is a consequence of the fact that the accepted PDA counts depend on the attenuation and extinction of the laser light due to the high particle concentration within the spray. One can conclude from this relative radial distribution, that the total mass flow as the sum of the PDA measured mass flux at any point of the spray cone in most cases is reduced compared to the real mass flow brought to the process.

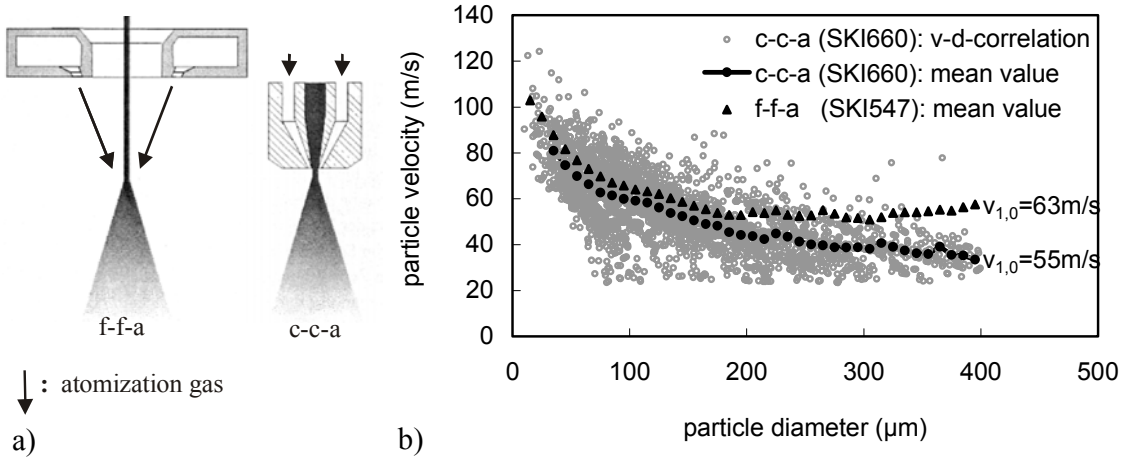


Fig. 2: Schematic diagram of both f-f-a and c-c-a and b) particle velocity versus particle diameter measured during the c-c-a experiments as well as measured during f-f-a experiments. Measurement position: r = 0 mm; z = 200 mm

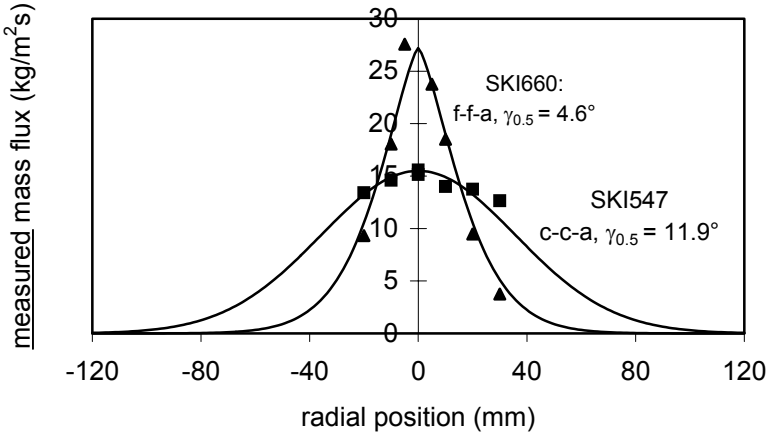


Fig. 3: PDA measured radial mass flux distribution created by the f-f-a and c-c-a. Measurement position: z = 200 mm, varied radial positions

[1] the "real mass flow" is calculated considering the initial metal mass and the total duration of experiment, i.e. the average value is estimated

Nevertheless, the difference in spreading of the spray depending on the used atomizer system is significant. As proposed in prior works [10, 11] the measured data can be approximated to a distribution being similar to a Gaussian one

$$\dot{m}_l(r) = \dot{m}_{l,max}(z) \cdot \exp\left[\ln\frac{1}{2}\left(\frac{\cdot r}{r_{0.5}(z)} \right)^k \right] \quad (1)$$

where $\dot{m}_{l,max}(z)$ is the maximum mass flux in the spray center ($r = 0$) dependent on the axial position z. The half-value of the spray cone radius $r_{0.5}$ is characterized by a local mass flux being half of the maximum value found on the spray cone axis. Due to the spray spreading, the half-value of the radius is increasing with an enlarging axial atomizer distance. The exponent k is used to vary the curve with regard to its radial gradient. Adjusting Eq. (1) to the measured mass flux and employing Eq. (2)

$$\gamma_{0.5} = \arctan\frac{r_{0.5}}{z} \quad (2)$$

is leading to a spreading angle $\gamma_{0.5} = 4.6°$ of the radius $r_{0.5}$ in case of the close-coupled atomizer and to an angle of $11.9°$ formed by the free-fall atomizer. The maximum value of the mass flux is increasing with a decreasing angle because of conservation of mass. And comparing the PDA measured mass flux with the one calculated being founded on the radial profile of a spray formed deposit is confirming this results.

Concluding one may say, PDA allows the analysis of molten metal disintegration. For instance, the PDA data can be used to support atomizer development.

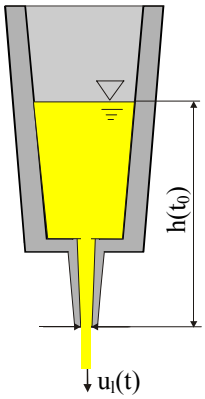
4. Process control

Up to now the analysis of the PDA signal was realized via a conventional personal computer. Thus, the presented results were obtained off-line. But extending this PDA to an on-line measurement system, even process analysis very close to real time becomes possible and the PDA can be used on-line to monitor the spray forming process.

For this, the signal processing has to be realized via hardware, i.e. a special PDA signal processor has been developed, the use of which allows the data evaluation in only a couple of seconds. The signal flow is as follows:

1. The analog PDA signal is converted to a digital one,
2. the signal is computed in a digital signal processor (DSP) considering the introduced Fourier analysis,
3. the resulting diameter and velocity distributions can be used for both monitoring the atomization process and controlling the process,
4. for controlling the process an adjustment signal is created by comparing the actual value of the mean particle diameter (or the mean particle velocity) to the corresponding set value,
5. the digital adjustment signal is converted to an analog signal, the quantity of which is influencing the valve for the atomization gas pressure.

In the following some on-line PDA results are presented. To demonstrate the capability of the modified PDA unit to diagnose e.g. variations of the melt mass flow, the final state of a spray forming run is on closer examination. This phase is starting with delivering the last bit of melt to the tundish. At this moment there is no more possibility to compensate the running out of molten metal, leading to a steady decrease of the metal level h(t) in the tundish. Due to the coupled diminishing of the metal-static pressure, which is proportional to the decrease of the metal bath height h(t), a continuous reduction of the melt flow-rate $u_l(t)$ is starting.



$$u_l(t) = C_D\sqrt{2gh}\,, \tag{3a}$$

$$\dot{M}_l(t) = C_D \cdot \rho_l \frac{d_{out}^2}{4}\pi \cdot \sqrt{2gh} \tag{3b}$$

PDA measurements carried out exactly during this unsteady period of process should lead to a discernible reduction in metal mass flow and as a result therefrom in a decreasing measured mass flux of melt particles. In **Fig. 4** the PDA measured mass flux on the spray cone axis (r = 0) is shown.

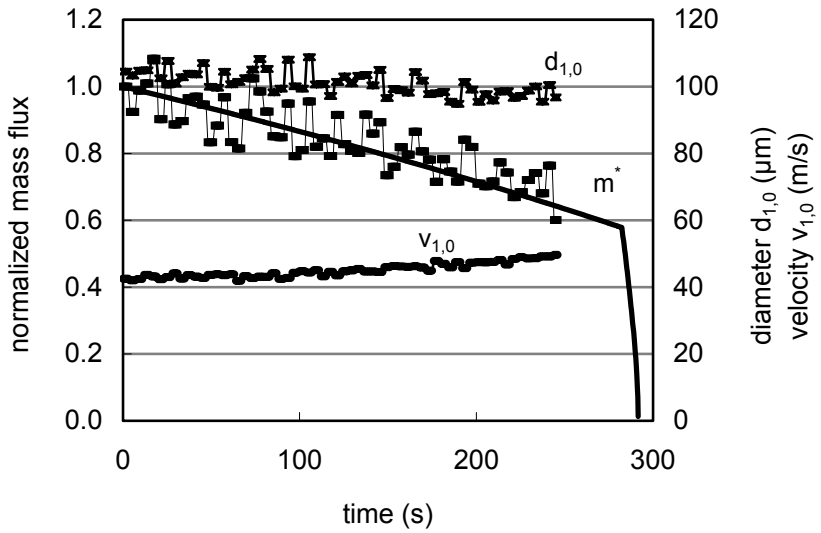


Fig. 4: Particle velocity and diameter measured during the unsteady period. In addition, the normalized mass flux is shown, the quantity of which is calculated employing the PDA data

Furthermore, the real mass flux is added to **Fig. 4**, calculated considering the real mass flow as given by Eq. (3) and the well-known spreading behavior of the spray cone (chapter 3). The mass fluxes are normalized

$$\dot{m}_l^*(t) = \frac{\dot{m}_l(t)}{\dot{m}_l(t_0)}, \tag{4}$$

in order to eliminate the mentioned deficit in PDA measured data, where $\dot{m}_l(t_0)$ is the mass flux at the beginning of the unsteady phase. Even though mass flow and mass flux, respectively, only decrease with the square root of the metal height, its influence to the running out of the melt can be determined using PDA.

On the other hand, the time dependent taking down of the metal mass flow is synonymous with an enlargement of the GMR. Thus, in **Fig. 4** a slight decrease of the measured particle diameter (with reference to footnote[2] the mean value of it) can be recognized. On the other hand, since the inertia masses in movement are proportional to particle size, the particle velocity is increasing with a diminishing metal mass flow. To sum it up, it can be said that even the influence of slight variations of the molten metal mass flow to the average value of the particle diameter and its velocity can be detected by PDA.

In fact, the on-line PDA data can be used as input quantity for the atomization gas control loop of the spray forming process, **Fig. 5a**. In its most simplified form the gas control loop consists of the PDA measurement unit, the regulating valve and the control unit allowing the automatic adjustment of the mean particle velocity or diameter by varying the atomization gas pressure. **Fig. 5b** summarizes the on-line measured particle velocity and the corresponding atomization gas pressure p_g versus duration of experiment. In case of particle velocity the actual as well as the desired value are shown, i.e. using the closed control loop a definite particle velocity $v_{1,0,set}$ is proposed and the required adjustment of the current particle velocity $v_{1,0,act}$ by varying the atomization gas pressure p_g is observed. The graphs agree with the well-known correlation of particle velocity and gas pressure. Therefore, with an increasing gas speed the immediate increase of particle velocity can be made out using PDA. By contrast, some more time is needed to adjust the actual particle velocity to the set velocity, e.g. in **Fig. 5b** $\Delta t = 27\,s$ and $\Delta t = 35\,s$ are needed to realize the necessary adaptation of the current particle velocity to the set value. Nevertheless, time consumption for adjustment is of that scale that influencing control throughout a current process is realizable. A comparable result can be obtained with regard to the particle diameter, [1].

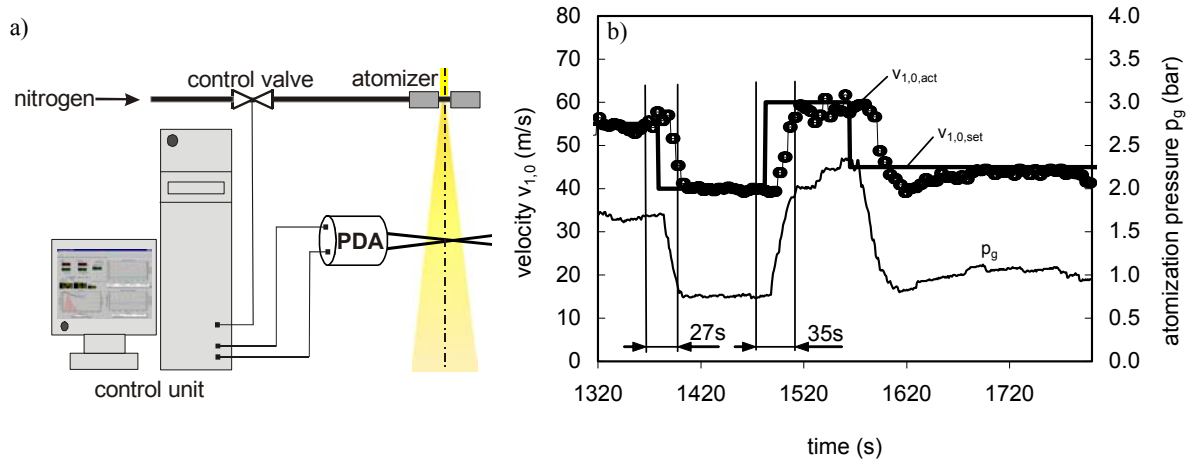


Fig. 5: a) Schematic diagram of the control loop and b) the particle velocity modified by adjusting the atomization gas pressure

[2] in the following only the mean values of the particle diameter and velocity are shown

5. Conclusions

PDA is an appropriate tool for determining the properties of particles, which are dispersed in a continuous phase. Not only particle diameters but also the corresponding velocity distributions can be estimated. And in addition the particle flux and the mass flux, respectively, can be calculated using the PDA data. With that, PDA can be classified as an important tool for investigating (among others) the multiphase-flow appearing during the process of liquid metal atomization.

In present case the conventional technique of metal atomization is extended by the process section of deposition, leading to a relative new method for manufacturing metal preforms. This process is called spray forming. During spray forming the energetic state of the compacting metal droplets (resulting in a growing metallic deposit) is essentially to the later quality of the deposit microstructure. Since the heat transfer from the particles to the atomization gas is strongly dependent on the particle surface relative to its volume and mass, respectively, the energetic state of the impacting particles is decided (in addition to the melt temperature, etc.) by the disintegration process.

Thus, in this work the PDA technique is used to analyze and to control the atomization process. On the one hand this is leading to an extensive data background supporting for instance the further development of atomizer systems. On the other hand by extending a conventional PDA to an on-line PDA the introduced spray forming procedure even can be monitored. To sum it up it can be said, that PDA can be classified as an appropriate instrument for analyzing and controlling liquid metal disintegration complementing the standard measurement of temperatures and pressures.

6. Acknowledgement

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7. References

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