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# Wetting behavior of eutectic Al–Si droplets on zinc coated steel substrates

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ABSTRACT

Transient spreading behavior, joint properties and metallurgical compositions are investigated for different hot-dip and electro-galvanized zinc coatings. The main focus is set on the effect of coating thicknesses and droplet size. While most of the droplets are observed on surfaces at room temperature, the case of pre-heated substrates is also accounted for. Both the coating thickness and the droplet size have little effect on the resulting wetting angle compared to the effect of preheating or the absence of a coating. The transient spreading behavior significantly differs for different coating types. The coating thickness affects heat transfer into the substrate during the initial stage of wetting. The metallurgical composition shows that the coating is removed over a broad interfacial area, while it accumulates at the toe of the deposited braze metal most likely due to fluid dynamic effects.



## 1. Introduction

Joining of dissimilar materials is of significant importance in many fields of industrial manufacturing. Combining the lightweight properties of aluminium with the strength and formability of steel can provide increased safety and weight reduction, e.g. in the automotive industry. Laser or laser-hybrid welding and brazing gained significant attention for joining of dissimilar materials in the case of aluminium/steel and aluminium/titanium joints. An overview of this topic was given by Thomy (2009). To improve corrosion resistance, low-carbon deep-drawing steel sheets are typically hot-dip or electro-galvanized with zinc or zinc alloys in a continuous process. An overview of the various metallurgical properties of hot-dip galvanized steel substrates is given by Marder (2005). Song et al. (2012) showed that during hot-dip galvanizing, the pool of liquid Zn typically contains a small amount of Al (less than 1 wt.%), leading to an exothermal reaction resulting in a thin layer (~0.1 μm) of $Fe_2Al_5Zn_x$ between the steel substrate and the actual zinc coating. The kinetics of these reactions was described by Giorgi et al. (2005). In contrast, electro-galvanizing is a non-thermal process resulting in a nearly pure zinc coating on the steel substrate, the properties of which depend on parameters such as the applied voltage and plating time, investigated, e.g., by Popoola and Fayomi (2011).

Contrary especially to deep-penetration laser welding, where Schmidt et al. (2008) showed that the low evaporation temperature of the zinc may cause significant process instabilities and requires careful welding parameter selection, in laser brazing zinc coatings are generally considered to be helpful. As an example, Vollertsen and Thomy (2009) showed that these zinc coatings favour the wetting of aluminium on coated steel substrates. Numerous studies have been performed on the wetting and spreading process of different liquid metals on coated and uncoated steel substrates. Special attention was paid to the resulting wetting angle and wetting length in the case of joining of aluminium to steel by brazing aluminium on coated steel. Kreimeyer (2007) established that wetting length is a crucial factor of influence on the mechanical properties of the joint of dissimilar materials. In an experimental series presented by Moeller et al. (2011), wetting length and mechanical properties meeting industrial requirements in terms of tensile strength and intermetallic phase seam thickness were achieved.

In all brazing processes solid material (the substrate) is dissolved into the liquid phase (the braze metal). Especially during contact of liquid aluminium with solid steel, dissolution of steel occurs, resulting in the formation of brittle intermetallic phases after solidification. In the case of very short interaction time (as is the case in high-speed joining processes such as laser brazing) the interaction between liquid aluminium and solid steel is known to be dominated by reaction phenomena rather than diffusion effects, as Bouche et al. (1998) pointed out. Considering that the coating itself is molten during contact with liquid aluminium, the interfacial reaction can typically be described as a reactive wetting process. To characterize the effect of different alloying elements in the zinc pool on the wetting behavior during reactive wetting, isothermal hot-dip experiments are widely used.

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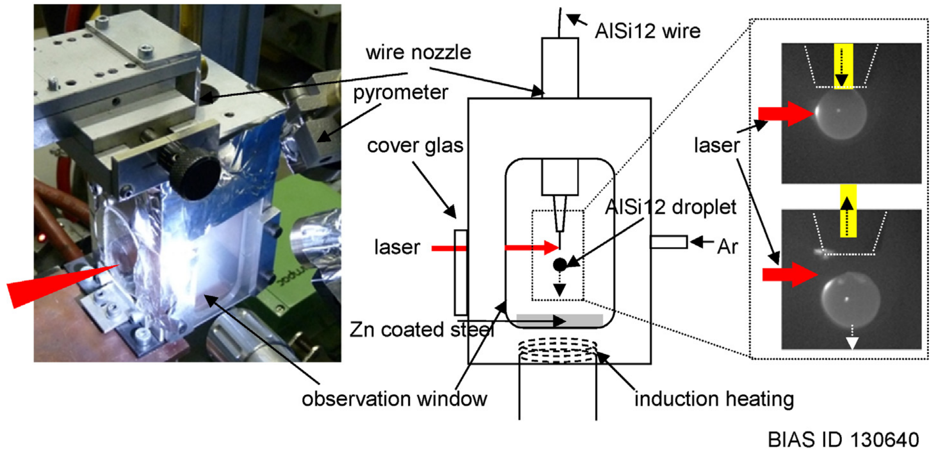


**Fig. 1.** Experimental setup for droplet generation and defined substrate wetting under inert gas atmosphere. Photography and sketch of the process chamber and droplet detachment sequence.

However, the wetting process during brazing or welding is not isothermal. Previous experiments have revealed an accumulation of zinc during spreading on galvanized steel in the outer bound of the seam toe, e.g. by Zhang and Liu (2011) in MIG brazing. This was observed for different liquid metals, wetting conditions and processes, e.g. by Koltsov et al. (2010) in case of copper droplets wetting zinc-galvanized steel and by Peyre et al. (2007) in laser beam overlap brazing of zinc coated steel with liquid aluminium or by Tan et al. (2013) for magnesium alloy. The microstructure of these zinc-rich zones has been investigated by Agudo et al. (2007) and found to contain between 20 at.% and 60 at.% of zinc.

Up to now, little is known about the actual fluid dynamics inside the molten metal drop during the wetting of a zinc coated surface in brazing. It is not clear how the distribution of zinc in the propagating liquid is determined by fluid dynamics inside the liquid and/or diffusion and solubility effects. However, Thomy and Vollertsen (2012) have shown in their experiment that the zinc coating is crucial to the brazing process, both with respect to the stability of the brazing process as well as to the properties of the joints. Consequently, for the case of non-isothermal wetting at very short interaction times, an experimental data base on the temporal thermal and dynamic behavior of the liquid melt on zinc coated surfaces is required.

The aim of this study is to characterize the thermal and dynamic behavior during the wetting of liquid aluminium droplets on different zinc-coated steel substrates together with the resulting wetting angle and metallurgical appearance. To this end, an experimental setup is developed to produce droplets with reproducible temperature and size from a commercial aluminium–silicon filler wire (AlSi12). Special attention is paid to the influence of the coating thickness on the transient spreading process, droplet cooling and resulting wetting angle.

## 2. Experimental methods

### 2.1. Experimental model system and procedure

An experimental model system was designed to generate liquid aluminium droplets of reproducible size and properties dripping onto a galvanized steel substrate (at room temperature (RT) or preheated (PH)) under argon gas atmosphere to prevent oxidation. It consists of a process chamber that contains an adjustable nozzle for the aluminium wire and a clamping device for the coated steel sheets (Fig. 1). A slightly defocused Trumpf TruDisk 8002 solid state laser beam (wavelength 1030 nm) is irradiating the tip of the wire with a fixed power of 900 W, thus generating a constantly growing drop of liquid aluminium while the wire is fed with a speed of 25 mm/s. As the diameter of the laser beam is approx. 1.5 mm in the axis plane of the protruding wire, the complete droplet remains irradiated during its growth. After a short, adjustable irradiation time $t_{ir}$ the wire is drawn back into the nozzle, stripping off the liquid at the tip of the wire. Subsequently, the droplet is falling down onto the substrate from a defined height of $h_d = 22$ mm.

The falling process, the impingement and the subsequent wetting process are recorded at 2000 fps with a high-speed camera through an observation window in the process chamber. In addition to the camera, a 2-color pyrometer is aligned to the area of impact. It acquires the highest temperature in an area of about 5–6 mm in diameter (see Fig. 2) at a frequency of 500 Hz. The peak temperature is measured when the droplet enters the radiation cone of the slightly inclined pyrometer spot (see Fig. 2). The measured peak temperature is defined as the impinging temperature $T_{d,im}$. The temperature then typically decreases rapidly until it drops below the value of 500 °C. Although this is not exactly the solidification temperature of the aluminium alloy (approx. 577 °C for eutectic Al–Si alloy according to Murray and McAlister (1984)), the time between the peak temperature and this point is defined as a characteristic time $t_{Sol}$ indicating the solidification process.

To measure droplet mass $m_d$, the wetted specimen is weighted before and after wetting. By varying irradiation time $t_{ir}$ before the wire is drawn back into the nozzle, $m_d$ can be altered. During the experimental series, three different irradiation times were used ($t_{ir}$ = 1.4 s/1.9 s/2.4 s), producing droplets with an average mass of about 90 mg, 110 mg and 140 mg. Fig. 3 gives the impinging temperature $T_{d,im}$ and masses $m_d$ for the three different irradiation times.

The standard deviation of the droplet mass is very small (∼3 mg), guaranteeing a very reproducible droplet size. The standard deviation of the impinging temperature amounts up to ∼ 80 °C (∼5% of the mean value), which is small enough to enable systematic investigations. The mean temperature of the droplet is not affected the irradiation time. Hence, the droplet size can be altered independently from it.

To enable wetting experiments on zinc coatings with defined pre-heating temperature, an inductive device, positioned underneath the specimen, is used. It guarantees a homogeneous preheating temperature $T_S$ throughout the area of impact and can be used to approximate the conditions of real-world local brazing processes, where there is heat input not only into the braze metal, but also (and significantly so) into the base metal.