Journal of Materials Processing Technology 227 (2016) 59–70

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Drop on demand generation from a metal wire by means of an annular laser beam

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ARTICLE INFO

Article history:
Received 5 March 2015
Received in revised form 3 June 2015
Accepted 31 July 2015
Available online 3 August 2015

Keywords:
Droplet generation
Drop-on-demand
Metal wire
Annular laser beam

ABSTRACT

In the paper a novel system for drop-on-demand (DoD) generation from a metal wire is presented, whose main component is a newly developed laser droplet generation head, consisting of annular laser beam shaping optics and a wire feeding system. In the pendant droplet formation phase of the DoD generation, a laser pulse is used to melt the wire-end, which is fed into the focus of an annular laser beam. The formed pendant droplet is then detached by means of a detachment pulse, which induces Rayleigh–Plateau instability of the molten column of wire above the neck of the pendant droplet. The main process parameters, including the laser pulse and wire feeding parameters as well as the additional parameters which influence particular phases of the DoD generation process, have been identified. The empirical correlations between the influencing process parameters and the droplet characteristics, including droplet diameter and temperature, were determined, based on the analysis of high speed IR records of the process, images being acquired by an optical microscope and temperature data being acquired by pyrometers. As an example, DoD generation from a commercially pure 99.6% Ni wire (Nickel 200) of 0.6 mm diameter is considered. It is shown that droplets with diameters ranging from 0.85 to 1.25 mm can be generated, with a resolution of 50 μm and a standard deviation of 15 μm. The temperature of the detached droplet remains above the melting point of the Ni wire, and increases with the droplet diameter within the range from 1650 to 1750 °C. Some examples of Ni droplets deposited on a Ti sheet surface are presented, with the aim of demonstrating the capability of the proposed system, and motivating further applications in which drops on demand having a high temperature and a precisely defined diameter need to be generated, while limiting the thermal loading of the surroundings.

1. Introduction

Metal droplets are the basic elements which are involved in the droplet-based innovative manufacturing technologies (Chun et al., 1993; Liu, 2000) which are in high demand in many different industrial applications. A particularly challenging droplet-based manufacturing technology that is still under development is printing technology (Liu and Orme, 2001a,b), which can be used for industrial applications such as rapid prototyping (Zhang et al., 2003), 3D structuring (Yamaguchi et al., 2000), and the freeform fabrication of components (Qi et al., 2012). Metal droplets can also be used for narrowly specialized micro-casting applications (Zarzalejo et al., 1999). Additionally, high energy droplets can be applied for the high-temperature-resistant lead-free joining of electronic contacts (Dreizin, 1997), for the joining of dissimilar materials (Albert et al., 2011) and of coated, temperature-sensitive materials (Jerič et al., 2009). In order to fulfill the requirements of particular application, various droplet generation systems and processes, have been developed.

For the generation of low melting point droplets ($T_{melt} < 427\,^{\circ}C$), materials in the liquid phase are used the most frequently. Methods of continuous droplet generation are based on liquid metal stream break up due to induced stream instability which can be caused by low-energy mechanical vibration (Liu and Orme, 2001a,b), or by electromagnetic forces (Shimasaki and Taniguchi, 2009). In DoD generation a liquid metal is squeezed out through a nozzle by applying a high energy pulse which can be generated by a piezoelectric actuator (Wehl et al., 2003), a vibration plunger (Sohn and Yang, 2005), or a pneumatic actuator (Cheng et al., 2005).

However, in the case of high-temperature melting point droplets ($T_{melt} > 427\,^{\circ}C$), materials that are initially in the solid phase are more suitable. In the most commonly used method in the case of continuous droplet generation based metal transfer, which is used in gas metal arc welding (GMAW), an electric arc is applied

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http://dx.doi.org/10.1016/j.jmatprotec.2015.07.026
0924-0136/

between the fed wire electrode and the droplet deposition or joining spot (Hu and Tsai, 2007). DoD generation can in this case be achieved by controlling the arc (Wu et al., 2004) or by wire feeding control (Zhang et al., 2002). A TIG arc based micro welding system has been employed for 3D structuring (Horii et al., 2009), where the arc discharge current is used to control the properties of deposited micro beads (Terakubo et al., 2005). The main drawbacks of these methods are the large heat affected area at the joining spot and the high thermal loadings in the surroundings due to the electrical arc. As such, arc-based methods are not suitable for droplet based applications in which temperature sensitive components are used. The electrical arc between the wire and the joining spot can be omitted by using cathodes around the fed consumable wire anode (Conway et al., 2002). However, the system has limits in the providing of sufficiently small droplets and the presence of high thermal loadings in the surroundings, which still prevents applications in the electronics industry where temperature-sensitive components are used.

Considering the drop-on-demand (DoD) generation process, which fulfills the requirements for the application of high melting point materials and low thermal loading in the surroundings, various laser based droplet generation methods have been proposed. The application of a laser beam besides the processing of high melting point materials has several other benefits, including precise control of the temporal and spatial energy input, and a short time of heating impact, which results in a small heat-affected area and low thermal loading of the surroundings. The proposed laser based methods differ with regard to the form of the source material being used for droplet generation, and include preformed metal balls (Quentin et al., 2013), metal foil (Jeromen et al., 2014), and metal wire (Jahrsdörfer et al., 2003). Using source material in the form of a wire provides material and flexibility and can be used to generate droplets with different diameters (Govekar et al., 2007). Laser droplet generation from a wire has good proven potential for various droplet-based spot and continuous micro-joining applications (Govekar et al., 2009), especially for the joining of dissimilar materials, and for thin foils and temperature sensitive metallizations in the electronics industry (Albert et al., 2011), as well as for the joining of zinc-coated metal sheets (Jerič et al., 2009).

In the conventional LDG process a Gaussian laser beam pulse is used to melt the end of the fed metal wire, and to detach the formed pendant droplet from the solid part of the wire-end. In past research into the use of LDG process using a metal wire, several LDG prototype systems using a single beam (Jerič et al., 2009) and several (three) laser beams (Jahrsdörfer et al., 2003), have been developed. The main disadvantages of these systems are the uneven distribution of the laser beam light at the wire-end circumference in the case of a single beam, and the complexity of the system in the case of three laser beams, what can lead to high instability of the LDG process (Krese et al., 2011). Using a Gaussian laser beam, the forced detachment of a pendant droplet can be achieved on demand by the force of the vapor recoil pressure (Kokalj et al., 2006), but this method is accompanied by droplet splashes, high variance of the droplet diameter, and a lateral scatter of the detached droplets.

To avoid the above-mentioned problems, a novel annular laser beam droplet generation (A-LDG) system has been designed. The system uses a single annular (i.e., ring-shaped) laser beam that is guided coaxially with the wire and focused onto the circumference of the wire-end. The annular shape of the laser beam ensures uniform heating of the wire-end around its whole circumference. Additionally, due to the properties of the annular laser beam, forced droplet detachment on demand is achieved by the Rayleigh–Plateau (R–P) instability of the molten wire column above the pendant droplet neck (Kuznetsov et al., 2014). This results in a significant reduction in the extent of droplet splashes, lower droplet diameter variance, and lower lateral scatter of the detached droplets. In addition, the use of an annular laser beam, coaxially with the wire, enables pre- and post-heating of the droplet deposition spot.

In this paper the novel A-LDG system and process are presented. With this aim, the experimental setup and the system for A-LDG from a metal wire are first described. Next, the DoD generation process is analyzed in detail with respect to the process phases and parameters. The results of A-LDG process characterization and the correlations between the process parameters and the droplet characteristics are then presented for the case of DoD generation from a commercially pure 99.6% Ni wire (Nickel 200) having a diameter of 0.6 mm. Preceding the conclusions, examples of Ni droplets deposited on a Ti sheet surface are shown in order to demonstrate the capability of the proposed A-LDG system, and potential applications of DoD generated droplets.

2. Experimental setup

The experimental setup for A-LDG from a metal wire is shown schematically in Fig. 1a. The setup consists of a laser source system, beam shaping optics, a wire feeding system, and the process monitoring and control system, which are here below described in greater detail.

2.1. The laser source system and beam shaping optics

The laser source used in the experimental setup is an industrial Nd:YAG pulsed laser of $\lambda = 1064$ nm wavelength, with Gaussian distribution of the laser beam intensity. The laser emits pulses with time-dependent profile of power in the range from 0.5 to 8 kW and a duration from 0.3 to 20 ms. The maximum pulse frequency is 300 Hz with an average power of 250 W. The energy limit of a single laser pulse is 30 J.

The emitted laser beam is guided through the beam shaping optics, where it is collimated and transformed into the annular shape by the pair of axicons and a convergent lens. The annular beam is guided coaxially to the axis of the wire by means of two reflective mirrors, and finally focused on the wire-end circumference by a focusing lens.

The measured annular laser beam caustic is presented in Fig. 1b. The annular laser beam can be described as a hollow cone with a thin wedge-shaped wall. The wedge angle of the wall is $\gamma = 2.5^{\circ}$. The vertex half-angle of the cone, i.e., the half-angle of the beam convergence is $\theta = 27^{\circ}$. The height h_{LB} of the annular laser beam spot projected vertically onto the wire surface depends on the wire diameter D_w. In the case of $D_w = 0.6$ mm the height h_{LB} amounts to 0.80 mm. The corresponding annular laser beam relative intensity distribution I/I_{max} captured by the IR camera slightly above the focus position is shown in Fig. 1c.

2.2. The wire feeding system

In order to generate a droplet, the wire-end has to be fed coaxially into the annular laser beam focus. For this purpose a wire feeding system consisting of a spool, a wire straightener, a wire feeding servo drive, and a guidance tube, is used. For precise feeding of the wire during the LDG process, the wire feeding servo drive is closed loop controlled. The servo drive provides a resolution of the wire displacement of 20 μm, with a maximum wire feeding acceleration/deceleration of 30 m/s^2, and a peak velocity of 0.35 m/s. Wires with diameters within the range from 0.25 to 1 mm can be used.

Coaxiality of the wire and the laser beam is achieved by means of a guidance tube, which is used to guide the wire into the annular laser beam focus. To ensure sufficiently precise lateral positioning of the wire-end, the wire that is unwound from the spool is straightened by a 4-plane wire straightener.